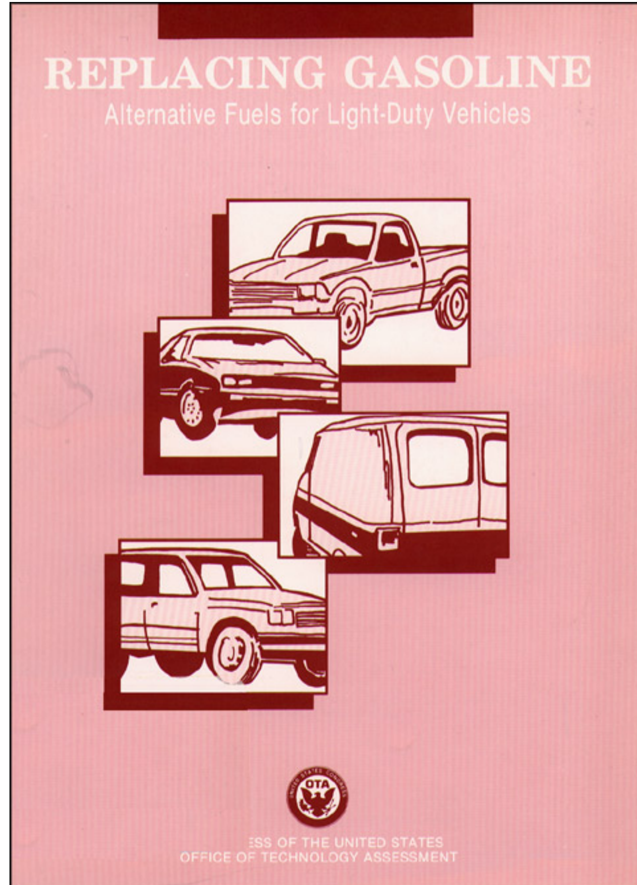
Replacing Gasoline: Alternative Fuels for Light-Duty Vehicles

September 1990

OTA-E-364
NTIS order #PB91-104901



Recommended Citation:

U.S. Congress, Office of Technology Assessment, *Replacing Gasoline: Alternative Fuels for Light-Duty Vehicles, OTA-E-364* (Washington, DC: U.S. Government Printing Office, September 1990).

For sale by the Superintendent of Documents
U.S. Government Printing Office, Washington, DC 20402-9325
(order form can be found in the back of this report)

Foreword

Among the several major issues that Congress has addressed in the process of reauthorizing the Clean Air Act, the future role of alternative highway transportation fuels in reducing urban smog is one of the more prone to argument. Past attempts to reduce pollution levels from highway vehicles have focused primarily on the vehicles themselves; adjustments to fuels were considered mainly when these were necessary to allow vehicular controls to work (eliminating lead from gasoline was necessary to avoid poisoning the catalytic converters on the vehicles). As vehicular emissions control efficiencies rose past 90 percent and further improvements became more difficult, however, attention turned to the idea that some alternatives to gasoline have combustion and/or other physical and chemical properties that might allow the achievement of ultra-low emissions levels. The fuels of interest include methanol (wood alcohol), ethanol (grain alcohol), natural gas, electricity, and hydrogen.

In this report, requested by the House Committee on Energy and Commerce and the Senate Committee on Energy and Natural Resources, which is part of OTA's ongoing assessment of *Technological Risks and Opportunities in Future U.S. Energy Supply and Demand,* OTA gives a broad overview of the qualities of the competing fuels and examines in depth some of the most contentious issues associated with the wisdom of active Federal support for introducing the fuels. Areas of uncertainty that affect the debate on Federal support include fuel cost (including costs of building new infrastructure and modifying vehicles); the air quality effects of the new fuels; effects on energy security; other environmental impacts of the fuels; and consumer acceptance of the changes in vehicle performance, refueling procedures, costs, and other facets of the transportation system that would follow a large-scale introduction of any of the fuels. The report singles out for special examination the arguments concerning the costs, energy security implications, and air quality impacts of introducing methanol fuels into the fleet. However, the other fuels have similar levels of uncertainty and contentiousness.

As this report goes to press, the oil-driven crisis in the Middle East mounts daily and could erupt at any time into major conflict. Alternative fuels will play a minor-to-negligible role in near-term responses to that situation, because the time required to make fundamental changes in our energy supply and demand require years, if not decades. In the longer term, however, if the United States desires to take advantage of the opportunities with alternative fuels to reduce the likelihood and impacts of future such events of armed conflict or to capitalize on the potential substantial environmental advantages inherent in these fuels, we must adopt a sensible, long-term national investment commitment to effect those changes.

JOHN H. GIBBONS
Director

Replacing Gasoline: Alternative Fuels for Light-Duty Vehicles— Advisory Panel

John Sampson Toll, *Chairman*
University of Maryland

James H. Caldwell, Jr.
ARCO Solar, Inc.

Daniel A. Dreyfus
Gas Research Institute

Frederick J. Ellert
General Electric Co.

David R. Johns
David R. Johns Real Estate Group

David Lee Kulp
Ford Motor Co.

Jessica Mathews
World Resources Institute

Edward H. Mergens
Shell Oil Co.

Nathan Rosenberg
Stanford University

Edwin Rothschild
Citizen/Labor Energy Coalition

Milton Russell
University of Tennessee

Maxine Savitz
Garrett Ceramic

Charles A. Berg
Northeastern University

Robert Wallace
Peabody Holding Co.

Jack W. Wilkinson
sun co., Inc.

Robert Williams
Princeton University

Mason Willrich
Pacific Gas and Electric Co.

NOTE: OTA appreciates and is grateful for the valuable assistance and thoughtful critiques provided by the advisory panel members. The panel does not, however, necessarily approve, disapprove, or endorse this report. OTA assumes full responsibility for the report and the accuracy of its contents.

OTA Project Staff—Replacing Gasoline: Alternative Fuels for Light-Duty Vehicles

Lionel S. Johns, *Assistant Director, OTA*
Energy, Materials, and International Security Division

Peter D. Blair, Energy and Materials Program Manager

Project Staff

Steven E. Plotkin, *Project Director*

Administrative Staff

Tina Brumfield   Lillian Chapman   Linda Long

Contributors

Rosina Bierbaum, *OTA Oceans and Environment Program*

Robert M. Friedman, *OTA Oceans and Environment Program*

Jana B. Milford, *University of Connecticut*

Contractor

Energy & Environmental Analysis, Inc., Arlington, VA

Reviewers

David Greene
Oak Ridge National Laboratory

Mark DeLuchi
University of California, Davis

Daniel Sperling
University of California, Davis

James Mackenzie
World Resources Institute

Edward H. Mergens
Shell Oil Co.

David Lee Kulp
Ford Motor Co.

Eugene Eklund
12907 Asbury Drive

Dave Gushee
Library of Congress

Daniel J. Townsend
ARCO Products Co.

Michael Jackson
Acurex Corp.

Carl Moyer
Acurex Corp.

William J. Schumacher
SRI International

Dixon Smith
Chevron U.S.A. Inc.

Bruce Beyaert
Chevron U.S.A. Inc.

Paul Holtberg
Gas Research Institute

Charles L. Gray, Jr.
U.S. Environmental Protection Agency

Phil Lorang
U.S. Environmental Protection Agency

Julie Hayden
U.S. Environmental Protection Agency

Robert Bruetsch
U.S. Environmental Protection Agency

J. Dillard Murrell
U.S. Environmental Protection Agency

David Bartus
U.S. Environmental Protection Agency

Robert P. Howell
19 Elkin Court

Jerrold L. Levine
Amoco oil co.

Terry Reuner
Amoco oil co.

Thomas J. Lareau
American Petroleum Institute

Alan C. Lloyd
South Coast Air Quality Management District

Michael Kelly
Jensen Associates, Inc.

Christopher Flavin
Worldwatch Institute

Nicholas Lenssen
Worldwatch Institute

John Young
Worldwatch Institute

Harry Schwochert
General Motors Corp.

Margaret A. Walls
Resources for the Future

Robert Williams
Princeton University

Joan Ogden
Princeton University

Brad Holloman
New York State Energy Research and Development Authority

Eric Vaughan
Renewable Fuel Association

Gordon Allardyce
Chrysler Motors

Barbara Goodman
Solar Energy Research Institute

Tom Cackette
California Air Resources Board

Jana Milford
University of Connecticut

K.G. Duleep
Energy and Environmental Analysis, Inc.

Thomas Bull
Food and Drug Administration

Glyn Short
ICI General Chemicals

Contents

Boxes

Figures

Tables

Related OTA Reports

- Catching Our Breath: Next Steps for Reducing Urban Ozone. Focuses on the health-based air quality standards for ozone; addresses the problem of regional oxidants; evaluates the cost-effectiveness of controlling various sources of hydrocarbon emissions for lowering ozone levels. 0-412, 7/89; 252 p.

  GPO stock #052-003-01158-l; $10.00
  NTIS order #PB 90-130 451/AS

- U.S. Oil Production: The Effect of Low Oil Prices--Special Report. Examines issues that influence the future direction of U.S. oil production. These issues include: the expected profitability of new investments in drilling; the potential of new oil exploration, development, and production technologies; the nature of the remaining oil resource base; and structural changes in the oil industry. E-348, 9/87; 144 p.

  NTIS order #PB 88-142484

- U.S. Natural Gas Availability: Gas Supply Through the Year 2000. Analyzes the key technical and physical parameters that deter-n-ine the resource base, production rates, and costs of all categories of below-ground natural gas; critically reviews current estimates of the resource base, estimates the potential production rates of natural gas, and the uncertainties in these estimates; and assesses future technology trends and R&D needs that may accelerate these trends. E-245, 2/85; 260 p.

  NTIS order #PB 86-109 162/AS

- U.S. Vulnerability to an Oil Import Curtailment: The Oil Replacement Capability. Provides an analysis of the technical potential for replacing large quantities of oil in the United States over a 5-year period by fuel substitution and conservation in the event of an extended oil supply shortfall and price rise; analyzes the macro-economic consequences of the shortfall and various rates of oil replacement by the technologies. E-243, 9/84; 160 p.

  NTIS order #PB 85-127 785/AS

NOTE: Reports are available from the U.S. Government Printing Office, Superintendent of Documents, Washington, DC 20402-9325 (202) 783-3238; and the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161-0001 (703) 487-4650.

OVERVIEW

Recent interest in alternative fuels for light-duty highway vehicles (automobiles and light trucks) is based on their potential to address three important societal problems: unhealthy levels of ozone in major urban areas; growing U.S. dependence on imported petroleum; and rising emissions of carbon dioxide and other greenhouse gases. This assessment examines the following alternative fuels: methanol, ethanol, natural gas (in either compressed (CNG) or liquid (LNG) form), electricity (to drive electric vehicles (EVs)), hydrogen, and reformulated gasoline.

Substituting another fuel for gasoline affects the entire fuel cycle, with impacts not only on vehicular performance but on fuel handling and safety, materials requirements, feedstock requirements, and so forth. The variety of effects, coupled with the existence of the three separate "policy drivers" for introducing alternative fuels, create a complex set of trade-offs for policymakers to weigh. Further, there are *temporal* trade-offs: decisions made now about promoting short-term fuel options will affect the range of options open to future policymakers, e.g., by emplacing new infrastructure that is more or less adaptable to future fuel options, or by easing pressure on oil markets and reducing pressure for development of nonfossil alternative fuels. Table 1 presents some of the trade-offs among the alternative fuels relative to gasoline.

Much is known about these fuels from their use in commerce and some vehicular experience. Much remains to be learned, however, especially about

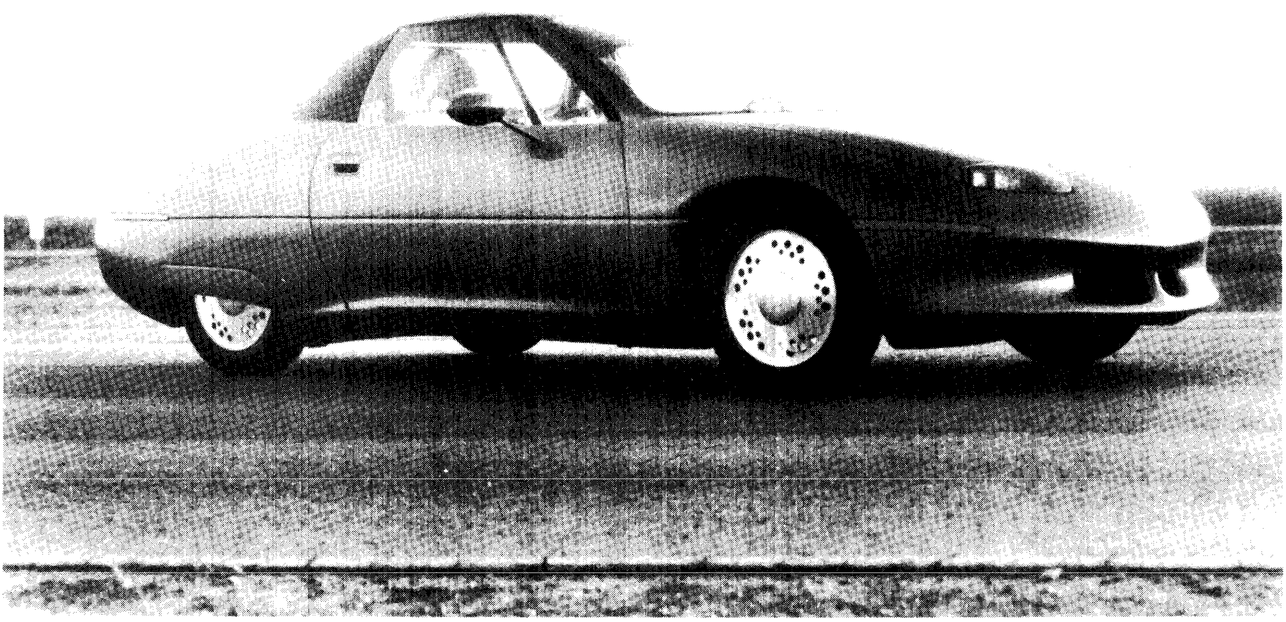


Photo credtt General Motors Corp.

GM's Impact electric vehicle, though a prototype requiring much additional testing and development, represents a promising direction for alternative fuel vehicles: a "ground up," innovative design focused on the unique requirements of the fuel sources, in this case electricity.

Table I—Pros and Cons of Alternative Fuels

	Advantages	Disadvantages
Methanol	Familiar liquid fuel Vehicle development relatively advanced Organic emissions (ozone precursors) will have lower reactivity than gasoline emissions Lower emissions of toxic pollutants, except formaldehyde Engine efficiency should be greater Abundant natural gas feedstock Less flammable than gasoline Can be made from coal or wood (as can gasoline), though at higher cost Flexfuel "transition" vehicle available	Range as much as 1/2 less, or larger fuel tanks Would likely be imported from overseas Formaldehyde emissions a potential problem, esp. at higher mileage, requires improved controls More toxic than gasoline Ml 00 has non-visible flame, explosive in enclosed tanks Costs likely somewhat higher than gasoline, esp. during transition period Cold starts a problem for Ml 00 Greenhouse problem if made from coal
Ethanol	Familiar liquid fuel Organic emissions will have lower reactivity than gasoline emissions (but higher than methanol) Lower emissions of toxic pollutants Engine efficiency should be greater Produced from domestic sources Flexfuel "transition" vehicle available Lower CO with gasohol (1 O percent ethanol blend) Enzyme-based production from wood being developed	Much higher cost than gasoline Food/fuel competition at high production levels Supply is limited, esp. if made from corn Range as much as 1/3 less, or larger fuel tanks Cold starts a problem for E1OO
Natural Gas	Though imported, likely North American source for moderate supply (1 mmbd or more gasoline displaced) Excellent emission characteristics except for potential of somewhat higher NO_x emissions Gas is abundant worldwide Modest greenhouse advantage Can be made from coal	Dedicated vehicles have remaining development needs Retail fuel distribution system must be built Range quite limited, need large fuel tanks w/added costs, reduced space (LNG range not as limited, comparable to methanol) Dual fuel "transition" vehicle has moderate performance, space penalties Slower refueling Greenhouse problem if made from coal
Electric	Fuel is domestically produced and widely available Minimal vehicular emissions Fuel capacity available (for nighttime recharging) Big greenhouse advantage if powered by nuclear or solar Wide variety of feedstocks in regular commercial use	Range, power very limited Much battery development required Slow refueling Batteries are heavy, bulky, have high replacement costs Vehicle space conditioning difficult Potential battery disposal problem Emissions for power generation can be significant
Hydrogen	Excellent emission characteristics-minimal hydrocarbons Would be domestically produced Big greenhouse advantage if derived from photovoltaic energy Possible fuel cell use	Range very limited, need heavy, bulky fuel storage Vehicle and total costs high Extensive research and development effort required Needs new infrastructure
Reformulated Gasoline	No infrastructure chanqe except refineries Probable small to moderate emission reduction Engine modifications not required May be available for use by entire fleet, not just new vehicles	Emission benefits remain highly uncertain Costs uncertain, but will be significant No energy security or greenhouse advantage

SOURCE: Office of Technology Assessment, 1990.

what a large-scale supply system would cost and how it would perform relative to the gasoline system. Key sources of uncertainty are:

- rapidly changing vehicle and fuel supply system technology;
- for most of the fuels, limited experience with transportation use, often confined to laboratory or prototype systems that don't reflect constraints imposed by mass production requirements or ''real world" maintenance problems;
- sensitivity of costs and performance to numerous (and difficult to predict) future decisions about regulating, manufacturing, financing, and marketing the fuel systems—for example, design decisions trading off vehicle performance and fuel efficiency; and
- continuing evolution of the competing gasoline-based system, for example, further improvements in catalytic controls.

In particular, most of the fuels have substantial potential for long-term technology advances that could drastically alter costs and impacts: advanced batteries for EVs, enzyme hydrolysis processes for producing ethanol from lignocellulose materials, and so forth.

Given these uncertainties and potentialities, projections of the costs and benefits of alternative fuels rely on a series of assumptions about technology successes, capital charges, feedstock costs, vehicle efficiencies, shipping methods, and so forth that are single points in a range of possible values. Changing these assumptions to other still-plausible values will change the cost and benefits results, sometimes drastically.

Meeting Society's Goals

Air Quality Effects

All of the fuels offer some potential to reduce urban ozone and toxic emissions. Hydrogen, electricity, and natural gas offer large and quite certain *per vehicle* reductions (though emissions from power generation must be considered in evaluating electricity's net impact on air quality). Methanol and ethanol (as M85 and E85, mixtures of the alcohols with 15 percent gasoline to improve cold starting), offer smaller and, at this time, less quantifiable but probably still significant reductions. For methanol, improved control of formaldehyde is critical to its emissions benefits. The potential for reformulated gasoline is speculative, because the makeup of this fuel is not yet known. *For most of the fuels, insuring that the potential benefits are actually obtained requires vehicle emission standards that properly account for the differences in chemical composition (and ozone-forming potential) between alternative fuel-related emissions and gasoline-related emissions.*

The areawide ozone-reduction benefits of all fuels are limited by projected reductions in the emissions "target' for the fuels-the share of urban ozone precursor emissions attributable to light duty vehicles. This share is expected to decrease from 45 to 50 percent during the mid to late 1980s to 25 to 30 percent by 2000.

Energy Security

The most likely near-term alternative fuels—reformulated gasoline, methanol, and CNG--do not offer the kinds of energy security advantages expected from options such as coal-derived liquid fuels, which rely on a domestic feedstock. Moderate quantities of CNG--enough to replace at least a few hundred thousand barrels per day of gasoline, perhaps somewhat more-could come from domestic and other North American sources; the rest would be imported by ship, as LNG, from distant sources. Most likely, virtually all methanol will be imported by ship. And reformulated gasoline, which merely reshapes gasoline rather than replacing it, should have little effect beyond that caused by the addition of oxygenates that may be made from natural gas or biomass. Nevertheless, use of methanol and CNG still can enhance energy security by reducing pressure on oil markets and diversifying to an energy feedstock (natural gas) whose resource base is less fully developed than oil's, and thus has a greater potential for new sources of supply—and a less easily manipulated market. The degree of additional security may be enhanced if the United States supports the development of secure methanol or LNG supply sources and if investors insist that supplier nations be large equity holders (and thus, risk-sharers) in the capital-intensive supply system.

The longer term options, e.g., hydrogen and electric vehicles, and ethanol or methanol from lignocellulosic materials, offer excellent energy security benefits if their costs are competitive with alternatives.

Global Warming

The potential of alternative fuels to affect greenhouse gas emissions is primarily a *long-term* potential. Those fuels and technological systems most likely to be used in the next few decades should *not* have a large impact, either positive or negative, on net emissions. For example, combustion of methanol or natural gas produces less CO_2 per unit of energy output than gasoline; however, producing and transporting these fuels will, in most cases, be more energy intensive than producing and transporting gasoline. Their net emissions of CO_2 and other gases, weighted by their relative warming impact and added over the entire fuel cycle, are likely to be only slightly smaller than the emissions generated by gasoline. Ethanol's net greenhouse emissions gain some benefit from the regrowth of the feedstock corn, but most or all of this benefit will be counteracted by other energy losses in the farming and fuel production system. Electricity for recharging EVs, if generated with today's power system, will rely heavily on coal-fired powerplants and cannot reduce greenhouse emissions significantly.

And reformulated gasoline is most likely to have slightly higher greenhouse emissions, assuming that refining energy will increase somewhat.

All of these fuels, and hydrogen as well, have the *long-term* potential to generate much lower levels of greenhouse gases if they turn to renewable, low-chemical-input biomass feedstocks or solar or nuclear-generated electricity. For example, both ethanol and methanol can be produced from wood and other lignocellulose material, methanol by gasification, ethanol by enzyme hydrolysis. Though neither process currently is economically competitive with standard alcohol production methods, further development of both processes should reduce costs. Electric and hydrogen-powered vehicles (the latter using hydrogen produced by electrolyzing water) can use electricity produced essentially without CO_2 emissions from nuclear or solar sources or biomass materials. Even gasoline can be produced by gasifying lignocellulose materials, with strong net greenhouse benefits. Also, for all the fuels, there are numerous shorter term efficiency improvements and process changes that can produce small reductions in net greenhouse emissions.

Other Key Issues

costs

Estimates of the likely cost of alternative fuels at the pump may plausibly vary over a wide range because of their dependence on assumptions about the relative success of solutions to existing technical problems, feedstock sources and prices, manufacturer design decisions, and other uncertain factors. OTA's examination of the potential costs of methanol, for example, reveals a range from below gasoline costs to 50 percent above gasoline costs. In a transition period when it is being introduced, however, methanol should be significantly more expensive than gasoline unless oil prices escalate during this period. Over time, costs could come down because of economies of scale realized as the system gets larger, better technology, and lower demanded returns as the supply system is stabilized and risk is reduced; on the other hand, at some point the natural gas feedstock costs will rise with increasing demand. The midpoint of the long-term cost range is somewhat higher than gasoline cost.

Similar wide ranges of potential costs apply to all of the fuels (except reformulated gasoline, which is expected to be perhaps $0.10 to $0.30/gallon more expensive than gasoline), though the ranges may be shifted upwards or downwards from methanol's range. Ironically, the cost to society of introducing alternative fuels will rise if gasoline conservation programs succeed in stopping the growth of gasoline demand, because the cost of new infrastructure for the fuels would not then be offset by a reduced need for new gasoline infrastructure.

Commercialization Hurdles

Commercialization of alternative fuels is made difficult by gasoline's entrenchment in the light-duty fuels market. Gasoline has the advantages of very large investments in existing supply infrastructure; long years of consumer acceptance and familiarity; and a regulatory structure for fuels handling and use designed specifically for that particular fuel. For example: with the exception of reformulated gasoline, which can be considered simply an additional, more expensive grade of gasoline rather than a true alternative, none of the alternative fuels will permit a vehicle to travel as far as would an equal volume of gasoline. For hydrogen, electricity, and CNG, the decrease in range is at least fourfold; for methanol, ethanol, and LNG, the difference is two to one or less. Other differences that can affect consumer acceptance include, for some but not all fuels, slower refueling, different handling requirements, and lower availability for several years after introduction. Consumer response to any of these differences, or to the design changes necessary to overcome them (for example, larger fuel tanks to overcome reduced range), is uncertain.

SUMMARY AND CONCLUSIONS

During the oil crises of the 1970s, Federal policymakers initiated a variety of programs designed to enhance U.S. energy security, mainly by supplementing or replacing gasoline with alternative fuels produced from domestic coal and oil shale. These programs generally were not viewed as successful, and they were largely abandoned with the perceived end of the oil crisis in the early 1980s.

During the past year, the debate on reauthorizing the Clean Air Act caused a resurgence of interest in alternative transportation fuels as an option for reducing ozone levels in urban areas that cannot otherwise meet air quality standards. In addition, the original concerns about energy security and the mounting trade deficit have reemerged as oil imports have grown rapidly over the past few years and as petroleum-driven conflict louves in the Middle East. A third concern—the possibility of greenhouse climate change—has increased interest in those alternative fuels that do not rely on fossil fuel feedstocks or that can otherwise offer a net reduction in greenhouse emissions.

The alternative fuels of primary interest for the U.S. fleet of automobiles and light trucks are:

- the alcohols methanol and ethanol, either alone or blended with gasoline;
- compressed or liquefied natural gas (CNG or LNG);
- liquefied petroleum gas (LPG) and propane;
- hydrogen; and
- electricity.

In addition, gasoline that has been reblended to reduce emissions, so-called ''reformulated gasoline,' is a recent addition to the list of new fuels. The fuels and their basic characteristics are described in box A.

This report provides abroad overview of the costs and benefits of introducing methanol, ethanol, natural gas, electricity, hydrogen, and reformulated

Box A—Alternative Transportation Fuels

gasoline-a motor vehicle fuel that is a complex blend of hydrocarbons and additives, produced primarily from the products of petroleum and natural gas. Typical octane (R+M/2[1]) level is 89.

methanol--commonly known as wood alcohol (CH_3OH), a light, volatile, flammable alcohol commonly made from natural gas. Volumetric energy content is about half that of gasoline (implies range for the same fuel volume is about half that for gasoline, unless higher efficiency is obtained), Octane level of 101.5, which allows use in a high compression engine. Much lower vapor pressure than gasoline (low evaporative emissions, but poor starting at low temperatures).

natural gas-a gas formed naturally from buried organic material, composed of a mixture of hydrocarbons, with methane (CH_4) being the dominant component. Octane level of 120 to 130. Volumetric energy content at 3,000 psi is about one-quarter that of gasoline.

liquid petroleum gas, LPG--a fuel consisting mostly of propane, derived from the liquid components of natural gas stripped out before the gas enters the pipeline, and the lightest hydrocarbons produced during petroleum refining.

ethanol—grain alcohol ($C_{25}OH$), generally produced by fermenting starch or sugar crops. Volumetric energy content is about two-thirds of gasoline. Octane level is 101.5. Much lower vapor pressure than gasoline.

hydrogen—H_2, the lightest gas. Very low energy density even as a cryogenic liquid, less than that of compressed natural gas. Combustion will produce no pollution except NO_x. Can be used in a fuel cell, as well as in an internal combustion engine.

electricity-would be used to run electric motors, with batteries as a storage medium. Currently available batteries do not attain a high energy density, creating range problems.

reformulated gasoline-gasoline that has been reblended specifically to reduce exhaust and evaporative emissions and/m to reduce the photochemical reactivity of these emissions (to avoid smog formation). Lower vapor pressure than standard gasoline (which reduces evaporative emissions), obtained by reducing quantities of the more volatile hydrocarbon components of gasoline. Addition of oxygenates to reduce carbon monoxide levels.

[1]The average of research octane (R) and motor octane (M), which is the value found on the retail pump.

gasoline[1] **into the** U.S. light-duty fleet, and additionally provides more detailed analysis of a few particularly contentious issues such as the air quality impacts and costs of methanol use. This report is an interim product of an ongoing OTA assessment of *Technological Risks and Opportunities for Future U.S. Energy Supply and Demand. The* focus of the assessment and this report is the next 25 years in the U.S. energy system. While 25 years seems a long time period for projection purposes, it is short in terms of major transitions in energy sources, greenhouse warming strategies, and other similar concerns. Consequently, some of the longer term greenhouse options, such as using wood and other lignocellulose materials to produce methanol or ethanol, and the longer term greenhouse concerns such as the potential for an eventual turn to coal as a liquid fuel feedstock, are not addressed in detail in the report. However, policymakers addressing decisions for the short-term should recognize that decisions ranging from establishing research priorities to constructing new fuel infrastructures affect prospects for the longer term options.

A recent report from the National Research Council, *Fuels to Drive Our Future,*[2] discusses in detail the potential for producing motor fuels from domestic sources such as coal, oil shale, and biomass. Similarly, hydrogen as a potential motor fuel is addressed in a recent World Resources Institute report entitled *Solar Hydrogen: Moving Beyond Fossil Fuels.*[3]

The Perceived Benefits of Alternative Fuels

Ozone Control

Ozone control has become a primary driving force behind the push to alternative fuels because, 15 years after the passage of the original Clean Air Act, ozone pollution remains a serious national concern. About 100 cities, housing about half of the American population, do not meet the standard for ozone, the principal component of urban smog. At concentrations above the standard, ozone can cause coughing, painful breathing, and temporary loss of some lung function in healthy children and adults after exercising for about an hour or two. Medical concern centers as much-or even more-on possible chronic damage from long-term exposure as on short-term effects, although research on chronic risks is limited and inconclusive.

Ozone is produced when volatile organic compounds (VOCs) and nitrogen oxides (NO,) combine in sunlight. VOCs, a broad class of air pollutants that includes hundreds of specific compounds, come primarily from such manmade sources as automobile and truck exhaust, evaporation of solvents and gasoline, chemical manufacturing and petroleum refining (in some rural areas, however, natural emissions sources can dominate). NO_x arises from fossil fuel combustion. Major sources of NO_x include highway vehicles and utility and industrial boilers.

In a recent OTA study, *Catching Our Breath,*[4] *we* concluded that much of the Nation will still not be able to meet the goals of the Clean Air Act even by 2000. Over the next 5 to 7 years, available technology can lower summertime manmade VOC emissions by 35 percent (3.8 million tons/yr) compared to 1985 levels, bringing into compliance about half of all areas that now fail to attain the standard for ozone. Existing control methods can substantially improve the air quality of the other half of the areas, but meeting the ozone standard in these areas will require new, innovative, and nontraditional control methods.

The Nation has already failed several times to meet the deadlines set by Congress--first in 1975 and again in 1982 and 1987. In *Catching* ***Our*** *Breath, we* stated that when amending the Act, Congress must include *both* measures to achieve near-term emissions reductions using today's control methods and measures to insure that the Nation can continue to make progress after 2000. We view alternative fuels as one of several promising longer term measures.

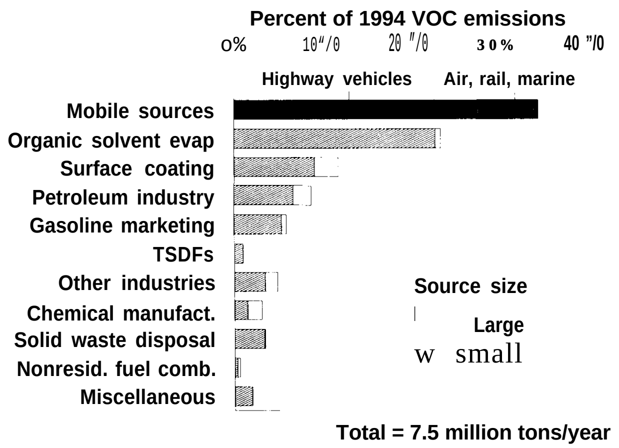
[1] LPG is not addressed because its supply limitations prevent it from playing a major long-term energy security role. Were alternative fuels use to be confined to the primary ozone nonattainment cities, LPG would be a viable option.

[2] Committee on Production Technologies for Liquid Transportation Fuels, National Research Council, *Fuels to Dive Our Future* (Washington, DC: National Academy Press, 1990).

[3] J.M. Ogden and R.H. Williams, *Solar Hydrogen: Moving Beyond Fossil Fuels* (Washington, DC: World Resources Institute, October 1989).

[4] U.S. Congress, Office of Technology Assessment, *Catching Our Breath: Next Steps in Reducing Urban Ozone*, OTA-O-412 (Washington, DC: U.S. Government Printing Office, July 1989).

Figure I—Volatile Organic Compound (VOC) Emissions in Nonattainment Cities in 1994, by Source Category, After All Additional Control Methods Are Applied



Stationary sources that emit more than 50 tons per year of VOC are included in the "Large" categories. (See figure 2-3 for 1985 emissions in nonattainment cities before additional controls applied.)

SOURCE: Office of Technology Assessment, 1989.

Ozone control efforts have traditionally focused on reducing VOC emissions. As shown in figure 1, about 25 to 30 percent of VOC emissions remaining after today's controls are applied will come from cars and trucks. Programs to introduce cleaner, alternatively fueled vehicles by using, for example, methanol or compressed natural gas (CNG) instead of gasoline, should lower emissions further, as would measures to reduce the Nation's use of cars.

Another quarter of the remaining VOC emissions will come from solvents used in a wide variety of industrial, commercial, and home uses, from painting and cleaning heavy equipment to washing paintbrushes. Further control of these sources is possible. And for some areas, controlling NO, emissions in addition to VOCs maybe an important ozone control measure, both locally and in areas upwind of certain nonattainment cities.

How do alternative fuels fit into the Nation's ozone control requirements? All of the fuels discussed here have the *potential* to reduce either (or both) the mass emissions of VOCs from highway vehicles or the reactivity of the VOCs, that is, their likely contribution to ozone formation per gram of gas emitted. The attractiveness of using alternative fuels as an ozone control measure clearly depends on the costs and effectiveness of such use relative to the costs and effectiveness of competing measures. As discussed below, the costs of alternative fuel use are as yet quite uncertain, while the effectiveness is reasonably well known only for some of the fuels.

An additional uncertainty is the extent to which further improvements maybe achieved in emission controls for gasoline-fueled vehicles. If highway vehicles' share of urban VOC emissions is reduced even below the projected 25 to 30 percent level representing the frost round of emission requirements expected from the new Clean Air Act, the emissions reduction benefits of moving to the alternative fuels will be reduced.

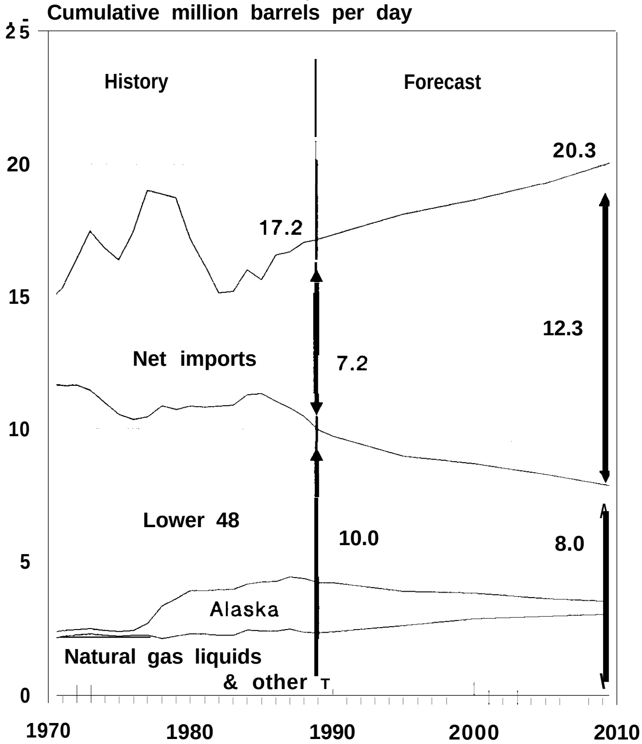
Aside from controlling ozone, alternative fuels should help to reduce the emissions of toxic pollutants associated with gasoline use. These include benzene, gasoline vapors, l,3-butadiene, and polycyclic organic matter. With the exception of methanol vehicles' increased emissions of formaldehyde, use of the alternative fuels is not likely to produce any counterbalancing emissions of similar toxicity. And with methanol vehicles, their higher direct emissions of formaldehyde are partly offset in the ambient air by the shift in VOC emissions associated with methanol use. Some of the VOCs are chemically transformed in the atmosphere into formaldehyde, and a methanol vehicle is a smaller "indirect" source of formaldehyde than a comparable gasoline vehicle.

Energy Security

After a few years of quiescence, energy security has again become a major U.S. concern. The key statistic driving that concern is the annual level of net U.S. oil imports, which had dropped to 27 percent of requirements by 1985 but rose to 46 percent in 1989, and continues to rise steadily as U.S. oil production drops. As illustrated by figure 2, which displays the Energy Information Administration's latest forecast, U.S. oil imports are expected to grow rapidly over the next few decades, to nearly 61 percent of demand by 2010 in the base cases The United States paid $44.7 billion for its 1989 oil imports, representing nearly half of its merchandise trade deficit of$111 billion, and expenditures would

[5] Energy Information Administration, *Annual Energy Outlook 1990*, DOE/EIA-0383(90), January 1990.

Figure 2—EIA Projections of Petroleum Supply, Consumption, and Import Requirements to 2010, Base Case



SOURCE: Energy Information Administration, *Annual Energy Outlook, 1990.*

rise with expected increases in import volumes and oil price. As in the 1970s, four basic elements underlie the concern: the near-total dependence of the U.S. transportation sector on petroleum; the United States' limited potential to increase oil production; the preponderance of oil reserves in the Middle East/Persian Gulf area; and the political instability and hostility to the United States existing in parts of that area.

In some ways, the first two of these elements have grown more severe since the energy crises of the 1970s. During the past 10 years, the share of total U.S. petroleum use by the transportation sector—whose prospects for fuel switching in an emergency are virtually zero-has grown from 54 to 64 percent. In addition, the prospects for a rapid rebound of U.S. petroleum production in the event of a price rise seem weaker than in the 1970s. The boom and bust oil price cycle of the post-boycott period, and especially the price drop of 1985-86, has created a wariness in the oil industry that would substantially delay any major boost in drilling activity in response to another price surge. And, with the passage of time, the industry's infrastructure, including skilled labor, that would be needed for a drilling rebound is eroding.

Despite these problems, OTA concludes that, on balance, the United States' energy supply is somewhat more secure today than in the 1970s. Shifts in the oil market that we consider to be supportive of increased short- to medium-term energy security include:

- the existence of the Strategic Petroleum Reserve and increased levels of strategic storage in Europe and Japan;
- increased diversification of world oil production since the 1970s, with OPEC losing 17 percentage points of world market share from 1979-89;
- the end of U.S. price controls on oil and most natural gas, allowing quicker market adjustment to price and supply swings;
- the increasing role of the spot market, adding flexibility to oil trade;
- the major investments of OPEC producers in the economies of the Western oil-importing nations, especially in their oil-refining and marketing sectors;
- the lessening importance of the Strait of Hormuz as a potential bottleneck due to the construction of new pipelines out of the Persian Gulf; and
- the recent political changes in the Eastern Bloc nations and lowering of East-West tensions.

Nevertheless, energy security concerns remain an important policy driver, and their importance could grow over time if current trends in U.S. oil supply and production continue and, as expected by many analysts, OPEC market power continues to grow. Futher, important and unsettling shifts in military power balances in the Middle East, in particular the greatly increased military capability of Iraq, introduce an important uncertainty into energy security assessments.

The development of alternative transportation fuels can have a positive effect on energy security, by:

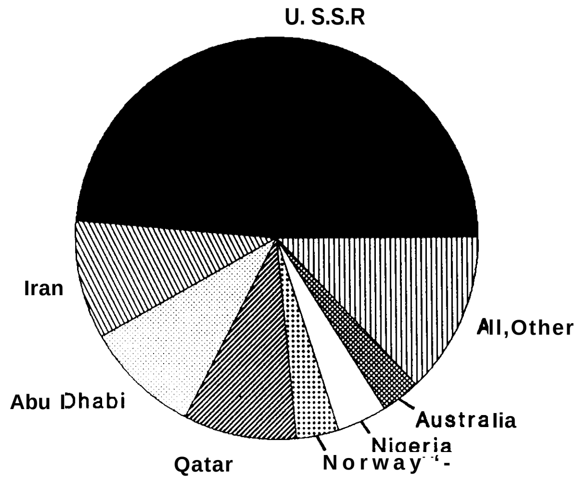
- diversifying fuel supply sources and/or getting supplies from domestic or more secure foreign sources,
- easing pressure on oil supplies through reduced demand for gasoline, and

. reducing the impact of an oil price shock.

The magnitude of the effect will depend on such factors as the feedstock used for the fuel and strategic arrangements for obtaining the feedstock or fuel, the volume of alternative fuel use, and the selection of dedicated vehicles or flexible fuel vehicles. The effect on energy security could be negative, however, if any Federal subsidies of the price of "secure" energy sources are too high, or regulatory requirements for their use too costly. The availability of ample foreign exchange is a powerful weapon in an energy emergency, so that the financial impact of an alternative fuels program that had a large negative net impact on the overall U.S. trade balance and/or on the Federal deficit conceivably could outweigh the positive value of reduced oil imports.

Although the security benefits of some fuels are indisputable, analysts disagree about others. Fuels such as electricity, hydrogen, and ethanol are likely to be domestically produced and thus unambiguously advantageous to energy security (if they can be produced cheaply enough). Corn-based ethanol's dependence on intensive agriculture, which may suffer on occasion from drought, may make it less secure than the others, however. Methanol or natural gas, on the other hand, will be imported from countries with large gas reserves (though a moderate level of natural gas vehicle use, perhaps up to several hundred thousand barrels per day of oil substitution, could be supported using North American gas sources), and their effect on energy security will depend on which countries enter the market, the type of financial arrangements made between producers and suppliers (the large capital requirements of a methanol or LNG supply system could enhance the stability of supply, but only if the producer nations are large equity holders), the worldwide price relationship between natural gas and oil (that is, will a large oil price rise automatically raise gas—and methanol-prices?), and other factors. Because two-thirds of the world's gas reserves, and a higher estimated share of the world's exportable gas surpluses (figure 3), reside in the Middle East and Eastern Bloc, some analysts deny that the United States would receive any security benefit from turning to natural gas-based methanol. OTA concludes that the Nation *can* derive a security benefit because large-scale methanol use will reduce pressures on world oil supplies; also, strategies such as

Figure 3--World Exportable Gas Surplus as of Dec. 31,1987



SOURCE: Jensen Associates, Inc., ***Natural Gas Supply, Demand, and Price,*** **February 1989.**

establishing long-term trade pacts with secure methanol sources could enhance the potential benefits.

Another way to enhance energy security maybe to produce alternative fuels from domestic coal-an option not explored in this report. Problems with the use of coal include its adverse impact on greenhouse warming (unless the CO_2 produced can be captured and stored, which seems unlikely) and its high costs, though these may be lowered over time. Similarly, alternative fuels can be made from wood and other lignocellulosic materials, with substantial greenhouse benefits if the use of agricultural chemicals is minimized and the feedstock is managed in a truly renewable fashion.

The availability of a domestic feedstock is not confined to the alternative fuels; *gasoline* can be made from coal and wood. In fact, gasoline can be made from natural gas as well. Clearly, the energy security benefits associated with a particular fuel have little to do with that fuel's chemical makeup, and much to do with its feedstock materials.

Global Warming

The potential need to slow and reverse the growth of worldwide emissions of carbon dioxide ($C0_2$) and other greenhouse gases has altered thinking about energy supply sources, enhancing the perceived value of sources that do not use fossil fuels or that use fuels low in carbon.

The greenhouse effect is a warming of the Earth and atmosphere as the result of the thermal trapping of incoming solar radiating by CO_2, water vapor, methane, nitrous oxide, chlorofluorocarbons, and other gases, both natural and manmade. Past and ongoing increases in energy use and other anthropogenic (man-caused) emissions sources are pushing up atmospheric concentrations of these gases; CO_2 concentrations, for example, have increased by about 25 percent since the mid- 1800s. Scientists believe that these growing concentrations will lead to significant global temperature increases: a global average of 3 to 8 'F (1.5 to 4.5 'C) from a doubling of CO_2 concentrations or the equivalent.[7] Other effects of the warming include an expected rise in sea level, drastic changes in rainfall patterns, and increased incidence and severity of major storms.

Despite a substantial scientific consensus about the likely long-term change in average global temperatures, there is much disagreement and uncertainty associated with the rapidity of the changes, the effects of various temperature feedback mechanisms such as clouds, the role of the ocean, the relative greenhouse effect of the various gases, regional impacts, and other factors. These uncertainties affect arguments about the value of alternative fuels; for example, uncertainties about the differential role of the various greenhouse gases complicate analyses of the relative impact on warming of the various fuels, because each fuel emits, over its fuel cycle, a different mix of gases.

To what extent are the potential users of alternative fuels-in this case, light-duty vehicles-a major source of greenhouse gases, and thus a good target for action to reduce emissions? The U.S. light-duty fleet accounts for about 63 percent of U.S. transport emissions of CO_2, 3 percent of world CO_2 emissions, and about 1.5 percent of the total greenhouse problem. This latter value has been variously interpreted as being a significant percentage of the greenhouse problem, or as proving that focusing on the U.S. fleet to gain significant greenhouse benefits is a mistake. In OTA's view, few if any sectors of the U.S. economy are large enough, *by themselves*, to significantly alter the course of greenhouse warming; ignoring all emissions sources as small as the light-duty fleet would eliminate most options to curb the greenhouse effect. Further, U.S. adoption of alternative fuels will increase the likelihood that other nations will do the same. The U.S. fleet's emissions thus understate the potential benefit of U.S. action.[8] To successfully combat global warming, nations must be prepared to take actions that will have an important effect only over the course of decades and in concert with similar actions taken on a global scale.

Alternative fuels for light-duty vehicles are of concern for global warming for the following reasons:

1. *The fuels generate, over their fuel cycle, different amounts and mixes of greenhouse gases than does gasoline. In* general, however, the fuels and feedstock choices most likely for the near term-in particular, methanol from natural gas and natural gas itself-have the potential for only modest benefits over gasoline in their overall greenhouse effect; and reformulated gasoline would offer no benefits. Methanol and ethanol made from wood, which might become practical with further development of gasifiers (methanol) and enzyme-based conversion processes (ethanol), would yield significant greenhouse benefits. The longer term choices, e.g., hydrogen and electricity based on nonfossil sources, can yield very significant benefits. In contrast, fuels derived from coal-including gasoline-from-coal-would yield substantial increases in greenhouse gases over ordinary gasoline.
2. *Current choices about alternative fuels may influence future fuel choices with significant greenhouse effects.* For example, turning to natural gas as a feedstock for transportation fuels might conceivably have the effect of delaying a transition to nonfossil fuels, by holding down oil prices, providing additional fossil supplies, and, perhaps, by being more attractive than gasoline in some regards. As

[6] That is, the incoming solar energy is reradiated by the Earth as heat (thermal energy) and then absorbed or 'trapped" in the atmosphere rather than radiating out to space.

[7] That is, other gases have a warming effect that is some multiple of CO_2's effect, so a combination of increases of various gases can be translated into an effective CO_2 increase by appropriately weighting the increased concentration of each gas.

[8] OTA's Oceans and Environment Program currently is conducting a study on policy options to curb U.S. greenhouse emissions, ***Climate Change: Ozone Depletion and the Greenhouse Effect.***

another example, building an EV system will generate electricity load growth that, by flattening the daily demand curve, could encourage utilities to consider nuclear plants (with zero CO_2 emissions) for their new generation capacity, since nuclear is most economical serving this type of demand pattern. Further, building of new infrastructures for near-term alternative fuels may affect our ability to move to longer term fuels, e.g., a natural gas system might possibly ease the way for hydrogen, another gaseous fuel, whereas the construction of a new infrastructure for methanol may hinder the later adoption of a system using gaseous fuels. And finally, premature introduction of any technology can have sharply negative effects on future consumer acceptance of that technology. The importance of these effects is extremely sensitive to the timing of technology development and other uncertain factors and, as shown by the example of natural gas, there may be plausible greenhouse arguments both for promoting the commercialization of a particular fuel, and for opposing such commercialization.

Introducing Alternative Fuels Into the Light-Duty Fleet

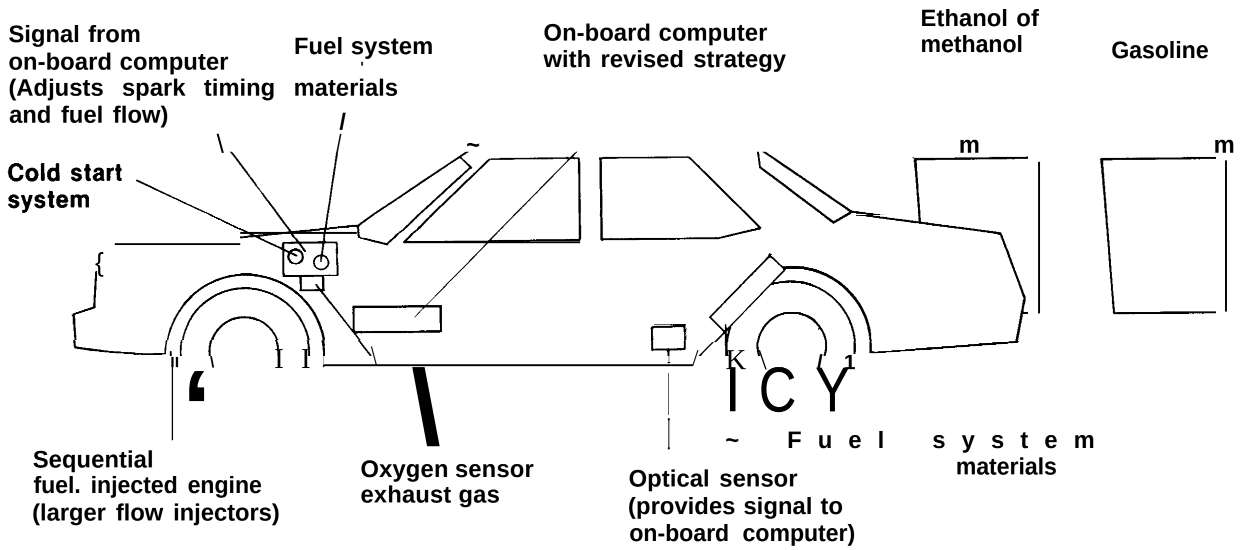
Although the physical characteristics of the alternative fuels are in some ways superior to that of gasoline, there are substantial barriers to introducing such fuels into transportation markets. Aside from the potential that the alternative fuels will cost more to produce than gasoline, these fuels have limited or no established transportation markets or infrastructure, whereas gasoline has both. The physical system for producing, storing, and distributing gasoline is in place and operating smoothly; massive amounts of capital and engineering time have been invested in engine modifications to optimize performance for gasoline; the regulatory system for controlling the safety and environmental impacts of light-duty vehicles is designed specifically for gasoline; and most consumers have a close familiarity with and acceptance of gasoline and its capabilities and dangers. In contrast, important facets of the infrastructure for the alternative fuels will have to be built virtually from scratch, the fuels will alter vehicle performance, in some ways for the worse (particularly with regard to range), and they will introduce new dangers, though possibly easing old ones associated with gasoline. It is difficult to predict how consumers will react to these differences in fuel characteristics.

With a few exceptions (electric and CNG vehicles designed to be recharged at home), the fuel distribution network will be severely limited geographically in the early years of an alternative fuels program. Consequently, early vehicles will either be limited in operation to those areas with available fuel supplies or, more likely, will be designed to operate as multifuel vehicles. For example, prototype flexible fuel vehicles (FFVs) can operate on any blend of gasoline and either methanol or ethanol up to about 85 percent alcohol (at higher concentrations, cold starting is a problem). As shown in figure 4, several vehicle systems must be modified to allow the vehicle to operate in this mode. Commercially available dual-fuel vehicles can operate on either gasoline or natural gas by the flip of a switch. And hybrid electric vehicles (EVs) would combine a battery/electric motor combination with a fuel tank and either a small internal combustion engine or a fuel cell.

To gain increased travel flexibility over single-fuel vehicles, multifuel vehicles must sacrifice some potential advantages afforded by the alternative fuels' special characteristics. For example, methanol, ethanol, and natural gas are high octane fuels; a vehicle dedicated to their use, which did not have to operate well on gasoline, could use a high compression engine with improved efficiency and power. To retain operability with gasoline, engines in multifuel vehicles must stay at lower compression levels. Consequently, as fuel availability for the alternative fuels improves over time, manufacturers are likely to shift their production lines towards vehicles dedicated to these fuels, with significantly improved performance and efficiency.

The large barrier to commercialization of alternative fuels caused by gasoline's entrenchment in the market, coupled with the likelihood that, *at least in the beginning,* alternative fuels will be more costly than gasoline, implies that alternative fuels may get a decent chance for market share only if government gives them a strong push. The primary dilemma for government policymakers is, then, is it worthwhile to do so? The alternative fuels certainly do have some intriguing potential, as discussed below, but they also have disadvantages and risks. A reasoned decision concerning government incentives for these

Figure 4—Technical Difference Between Flexible-Fuel and Conventional Automobiles



SOURCE: Ford Motor Co.

fuels requires a dispassionate analysis of these fuels' pros and cons relative to gasoline.

Conclusions about the costs, problems, and likely performance of the alternative fuels are based on a variety of evidence. First, their long use in nonvehicular applications has yielded considerable experience with distributing and handling the fuels. Second, many of the fuels have been used in vehicles for years, and although these vehicles perform less well than advanced vehicles are expected to, much of this experience still is relevant to projections of future, wider use. Third, limited testing of advanced vehicle prototypes has begun to clarify the potential of the fuels, as well as their problems. And fourth, unlike gasoline, which is a complex and nonuniform blend of hydrocarbons, most of the suggested alternative fuels have simple chemical structures and are relatively uniform in quality, which should help improve the accuracy of performance projections.

Despite this evidence, participants in the alternative fuels debate disagree sharply about virtually all aspects of fuel performance and cost. Part of these disagreements undoubtedly are due to the usual hyperbole associated with strong and opposing commercial interests and environmental values. There also are strong *technical* reasons, however, why the disagreements exist. In particular:

1. Changing technology. The technology for producing alternative fuels is still developing and changing, with the outcome of development and problem-solving programs highly uncertain. For example, full success of ongoing research on low-cost manufacture of ethanol from lignocellulose materials (e.g., wood waste) would radically improve ethanol's environmental and economic attractiveness. Similarly, successful development of catalysts that can reliably control exhaust formaldehyde levels over a vehicle lifetime would enhance significantly the standing of methanol as an option for ozone control.
2. Moving from lab to marketplace. The transition from successful research project to commercial, mass-produced product is a complex process involving massive scaleups and design and performance trade-offs. The unpredictability of this process limits the reliability of projections based only on laboratory or vehicle prototype testing. In particular, consumer reactions to differences in vehicle and fuel distribution characteristics (shorter range or less luggage space, slow refueling, less or more power, etc.) will profoundly influence system design, yet these reactions will become clear only as the fuels are introduced, and they might still change over time.
3. Effects of program size. The scale of alternative fuels development is a key determinant of the costs and characteristics of fuel supply systems and vehicles, yet there is little possi-

bility of predicting how large a program would be, or if it were likely to spread worldwide. For example, domestic gas sources or pipeline imports from Canada or Mexico could supply a moderate-sized program of natural gas vehicles, but larger scale development would require LNG imports from abroad—with different costs and energy security implications.

4. Continued evolution of the gasoline system. The relative benefits of any new alternative fuel depend on its comparison with the gasoline system, and this system may change markedly within the next decade. For example, there is some evidence that improved catalytic converters will reduce the photochemical reactivity of exhaust emissions from gasoline-fueled vehicles and thus reduce ozone formation from these vehicles. If confirmed, this would reduce the *relative* benefits of alternative fuels.

Although it may be impossible to rank the alternative fuels in a reamer that is relatively impervious to shifting assumptions and conditions, it *is* possible to describe the major advantages and disadvantages of the alternatives and to show the kinds of conditions that would tend to favor or discourage them.

Methanol's major advantages in vehicular use are that it is a convenient, familiar liquid fuel that can readily be produced from natural gas using well-proven technology; and as a blend of 85 percent methanol/15 percent gasoline (M85), it is a fuel for which vehicle manufacturers can, with relative ease, design either a dedicated or flexible fuel vehicle (FFV) that will outperform an equivalent gasoline vehicle and obtain an advantage in some combination of emissions reduction and efficiency improvement. The availability of a ''transition vehicle"--the M85 FFV--with few drawbacks from, and some advantages over, a gasoline-fueled vehicle is particularly important because it greatly eases the difficulties of introducing methanol into the fleet. Another important advantage of methanol is that world resources of natural gas, its primary feedstock, are plentiful.

Methanol can also be made from coal, though at higher costs and environmental impacts than from natural gas. As noted earlier, this does not represent an advantage over gasoline because gasoline too can be made from coal. Methanol also can be made from wood and other lignocellulose materials, though at still higher costs with current technology. Substantial improvements in wood gasifiers appear likely with further research.

Major disadvantages of methanol are the likelihood that it will cost more than gasoline, especially during the early years of a methanol fuels program; loss of as much as half of the driving range without a larger fuel tank; the loss of some of the air pollution benefits if FFV users frequently select gasoline instead of M85; and the need for a separate fuel delivery infrastructure. Methanol is more toxic than gasoline, and there is concern that accidental poisonings could increase with development of methanol fuels programs. However, methanol's lower flammability would likely lead to substantial reductions in injuries and fatalities from vehicle frees, probably more than offsetting any rise in poisonings.

The use of methanol made from natural gas is unlikely to provide a large greenhouse benefit, no more than a 10 percent reduction in net emissions with quite optimistic assumptions. Methanol from coal would be a large net greenhouse loser without some way of disposing of the CO_2; methanol produced from woody biomass could be a strong greenhouse net winner, though it would introduce other environmental concerns.[9]

Although methanol would likely be imported,[10] it could play a positive security role because of the nature of the suppliers or differences between the oil and methanol markets. There are enough potential suppliers of methanol in relatively secure areas that a concerted effort at promoting specific preferred supply sources-through trade agreements or other means[11]--could bring the United States significant benefits over dependence on Middle Eastern oil. Several South American nations as well as Trinidad and Australia have sufficient reserves and locational advantages to be viable methanol suppliers (figure 5 shows the locations of gas-rich areas that could

[9] Especially about the *long-term* renewability of the wood feedstock.

[10] The North Slope of Alaska does contain enough reserves of natural gas to be a technically viable methanol supplier to the lower 48 States, but North Slope methanol would not be competitive economically with methanol from other sources. However, the United States does, of course, retain the option of subsidizing North Slope methanol production (or forcing industry to subsidize it via legislative mandate) for energy security purposes.

[11] There may, however, be difficulties with fair trade agreements were the United States to attempt to establish such a closed fuel market relationship.

Figure 5—Potential Low-Cost Suppliers of Methanol

SOURCE: Energy and Environmental Analysis, Inc., 1988.

become low-cost suppliers of methano1[12]). And because natural gas development is decades behind oil development, with a much greater proportion of gas reserves still undeveloped, entry into the market of new suppliers is much easier for methanol than it is for oil-adding to market stability. And finally, the high capital investments necessary to develop methanol supplies bring further stability to markets, by increasing the financial costs to the supplier of a trade cutoff.

Under certain circumstances, the energy security of developing methanol as a transportation fuel might last only for a few decades. After a period of rapid resource development, if large new reserves of natural gas are not found, market power could evolve towards the holders of the largest blocks of resources-the Middle Eastern OPEC countries and the Eastern Bloc. At this time, security advantages of these alternative fuels could fade. Of course, if the current positive shift in the strategic relationship between the West and the Eastern Bloc continues, reliance on these nations might seem quite acceptable from a security standpoint.

Proposals for introducing methanol into ozone nonattainment areas have been extremely controversial, because competing claims about its expected costs and air quality benefits have varied over an unusually wide range.

Claims for the "per vehicle" reduction in ozone forming potential available by substituting M85 for gasoline range from 30 percent or higher (Environmental Protection Agency, California Air Resources Board) to little or none (some industry and consultant studies). Although considerable effort has been expended to estimate the ozone impacts of introducing M85 vehicles, especially for the Los Angeles Basin, a number of factors confound the estimates and lead OTA to conclude that M85 has significant *but poorly quantified and highly variable* potential to reduce urban ozone. In particular, there have been few tests of M85 vehicles that have measured the individual compounds in their emissions, even though such ''speciation' of emissions is important in accurately determining their photochemical reactivity. Other confounding factors include the essentially prototype nature of available methanol vehicles, potential future changes in the reactivity of *gasoline* exhausts (altering the trade-off between methanol and gasoline), and uncertainty about future progress in controlling formaldehyde emissions. And whatever net emissions changes are caused by using methanol vehicles, the effect of these changes on levels of urban ozone will vary with location and meteorological conditions. Ozone benefits from reduced organic emissions will occur only in urban areas where ambient concentrations of volatile organic compounds are low enough, relative to NO_x concentrations, that reducing organic emissions is an effective ozone strategy. In a few urban areas—Atlanta, for example-and in many rural areas, controlling NO_x, is a more promising ozone control strategy, and methanol use would provide little or no ozone benefits. To conclude, we do not reject the 30 percent reduction as a possible *average* effect, but some of the available data suggest smaller benefits, and whatever the average effect, the actual outcome would vary widely around that average.

Claims about the expected costs of methanol similarly have ranged from "competitive with and possibly below gasoline costs" to "much higher than gasoline. " Much of the range can be accounted for by legitimate differences in assumptions about the scale of a methanol program, likely gas feedstock sources, capital risk factors, and so forth. The extremes of the range, however, tend to assemble several low probability assumptions (either all optimistic or all pessimistic) together at once, and in a few instances choose values for key parameters that seem unlikely. OTA concludes that methanol will most likely be more expensive than gasoline (at current prices) in the early stages of an alternative fuels program. There may, however, be a few countries willing to subsidize some methanol production to obtain hard currency or for other reasons, making available a modest supply at low cost. Without government guarantees, the methanol's gasoline-equivalent price is likely to be at least $1.50/gallon during this period; government guarantees could bring it down as low as $1.20 if natural gas feedstock costs were very low. If the program were to grow quite large over time and were perceived to be stable, scale economies and lower costs of capital would significantly lower methanol costs relative to gasoline, with the lower end of the range dipping below $1.00/equivalent gallon. However, the uncertainty of the costs, and their sensitivity to various government decisions and other factors, remains

12Some areas, especially the Alaskan North Slope and Canadian frontier, would require technological advances to become low-cost suppliers.

Table 2—Two Scenarios of Methanol Costs, $/Gallon (Base Cases: $l.OO/mmBtu[a] natural gas cost)

	Scenario	
Part of fuel cycle	Transition period, free market scenario few guarantees, flex fuel vehicles (cost, $/gallon)	Established market, some government guarantees, dedicated vehicles (cost,$/gallon)
Production	0.55-0.65	0.28-0.30
Shipping	0.03-0.08	0.02-0.03
Distribution	0.03	0.05-0.06
Markup	0.09-0.12	0.06-0.09
Taxes	0.12-0.13	0.12
Retail price	0.82-1.01	0.53-0.60
Midrange price	0.85-0.95	0.53-0.60
Efficiency factor	1.9	1.67-1.82
Gasoline equivalent price	1.61-1.81	0.89-1.09
Gasoline equivalent prices if natural gas costs change		
$0.50/mmBtu gas	1.51-1.71	0.81-1.06
$1.50/mmBtu gas	1.71-1.81	0.96-1.15

a mmBtu = millions of British thermal units

SOURCE: Office of Technology Assessment.

very high. Table 2 illustrates the components to two cost ''scenarios" that represent relative extremes in methanol/gasoline competitiveness.

Methanol prospects for market success would benefit from the following:

- commercialization of direct oxidation methods of methanol production from natural gas (see figure 6),
- development of a world trade in methanol produced from remote sources of natural gas,
- freer evidence of major air quality benefits, particularly in cities other than Los Angeles,
- development of practical cold-starting methods for M1OO, and
- development of improved controls for formaldehyde emissions.

Ethanol is, like methanol, a familiar liquid fuel that can be quite readily used, with few problems, in vehicles competitive in performance with gasoline-fueled vehicles. Important advantages are its ease of use as a fuel component of gasoline suitable for existing vehicles and its attractiveness as a stimulus to the farm economy, since its primary feedstock is corn.

Ethanol made from food crops appears to be the most expensive of the major alternative fuels. Current ethanol production is profitable only because of a $0.60/gallon subsidy provided by the Federal Government through exemption of "gasohol," a 10 percent blend of ethanol with gasoline, from $0.06/gallon of Federal gasoline taxes. Some farm States allow gasohol a further exemption from State taxes.

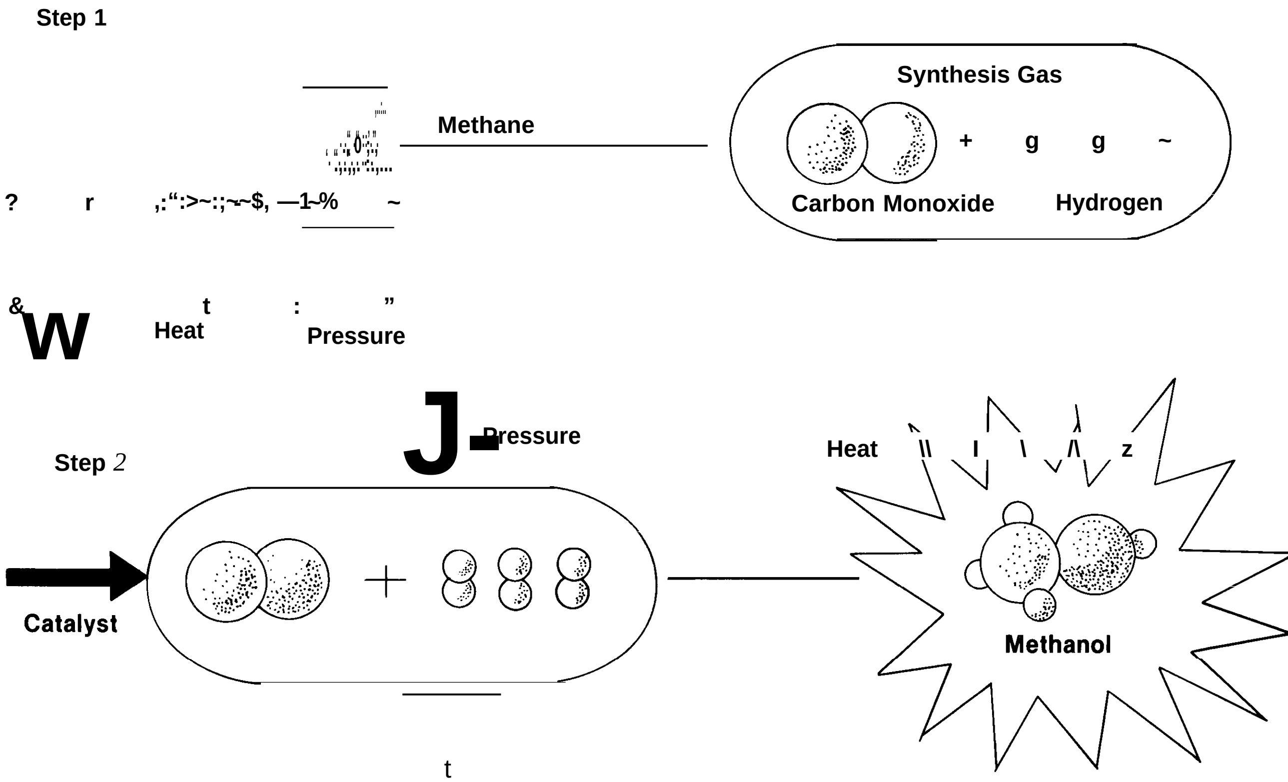
Under certain grain market conditions, ethanol production may generate reductions in required Federal crop subsidies and other significant secondary economic benefits to the Nation (aside from the benefits generated by *any* reduction in oil use). Under other conditions, however, it may generate large secondary costs. In particular, a major expansion of ethanol use might raise the Nation's food bill by billions of dollars.

The environmental effects of increasing corn production for ethanol manufacture are a matter of concern, because corn is an energy-intensive, agricultural-chemical-intensive, and erosive crop (see table 3). The net environmental impacts of ethanol use will be highly dependent on the overall adjustment of the agricultural system to large-scale ethanol production. The stillage byproduct of ethanol production is a high protein cattle feed that can displace soybean production. As long as this displacement occurs, the net agricultural impacts such as soil erosion and pesticide use are reduced; if byproduct markets become saturated, net environmental impacts may increase sharply. The level of ethanol production that would saturate the byproduct market is uncertain.

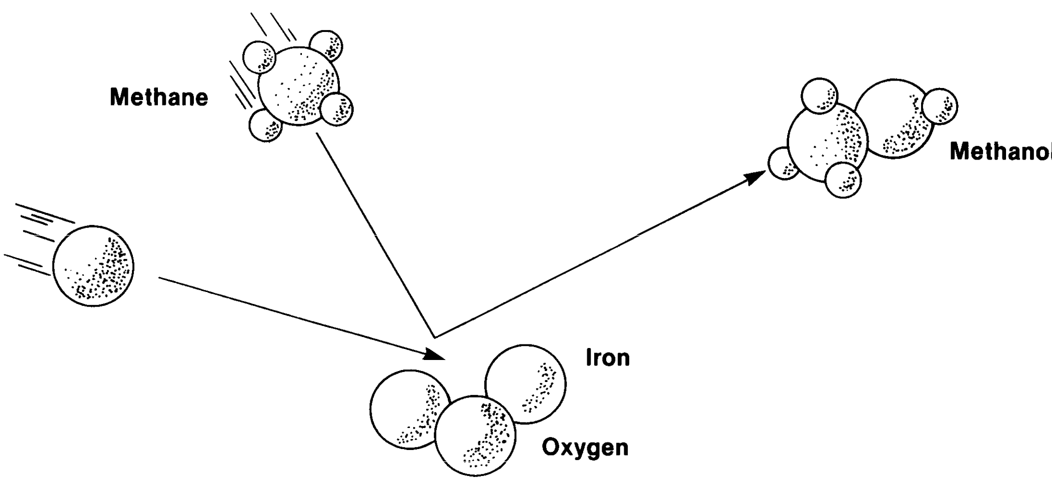
An important claim made for crop-based ethanol is that it will generate significant greenhouse bene-

Figure 6-Converting Methane to Methanol

Making methanol from methane with today's technology generally involves a two-step process. The methane is first reacted with water and heat to form carbon monoxide and hydrogen—together called synthesis gas. The synthesis gas is then catalytically converted to methanol. The second reaction unleashes a lot of heat, which must be removed from the reactor to preserve the activity of the temperature-sensitive catalyst. Efforts to improve methanol synthesis technology focus on sustaining catalyst life and increasing reactor productivity.



In a novel alternative to the two-step method, chemical catalysts are being developed that mimic the biological conversion of methane by enzymes. The iron-based catalyst captures a methane molecule, adds oxygen to it, and ejects it as a molecule of methanol. If this type of conversion could be performed on a commercial scale, it would eliminate the need to first reform methane into synthesis gas, a costly, energy-intensive step.



SOURCE: *EPRI Journal*, "Methanol: A Fuel for the Future?" October/November 1989.

Table 3-Environmental Impacts of Agriculture

Water
- Water use (irrigated only) that can conflict with other uses or cause ground water mining.
- Leaching of salts and nutrients into surface and ground waters, (and runoff into surface waters) which can cause pollution of drinking water supplies for animals and humans, excessive algae growth in streams and ponds, damage to aquatic habitats, and odors.
- Flow of sediments into surface waters, causing increased turbidity, obstruction of streams, filling of reservoirs, destruction of aquatic habitat, increase of flood potential.
- Flow of pesticides into surface and ground waters, potential buildup in food chain causing both aquatic and terrestrial effects such as thinning of egg shells of birds.
- Thermal pollution of streams caused by land clearing on stream banks, loss of shade, and thus greater solar heating.

Air
- Dust from decreased cover on land, operation of heavy farm machinery.
- Pesticides from aerial spraying or as a component of dust.
- Changed pollen count, human health effects.
- Exhaust emissions from farm machinery.

Land
- Erosion and loss of topsoil decreased cover, plowing, increased water flow because of lower retention; degrading of productivity.
- Displacement of alternative land uses-wilderness, wildlife, esthetics, etc.
- Change in water retention capabilities of land, increased flooding potential.
- Buildup of pesticide residues in soil, potential damage to soil microbial populations.
- Increase in soil salinity (especially from irrigated agriculture), degrading of soil productivity.
- Depletion of nutrients and organic matter from soil.

Other
- Promotion of plant diseases by monoculture cropping practices.
- Occupational health and safety problems associated with operation of heavy machinery, close contact with pesticide residues and involvement in spraying operations.

SOURCE: Office of Technology Assessment, 1990.

fits, with the regrowth of its feedstock corn crop compensating for much of the CO_2 produced by its combustion in vehicles. As with its other environmental impacts, the greenhouse impact also depends on factors such as avoidance of byproduct market saturation. Even under the best circumstances, however, substantial amounts of CO_2 will be produced by corn growing and harvesting, ethanol distillation, and other parts of the ethanol fuel cycle. OTA concludes that it is unlikely that ethanol production and use *with current technology and fuel use patterns will* create any significant greenhouse benefits.

Both ethanol costs and environmental consequences would improve significantly if technologies for ethanol production from wood and lignocellulosic materials materials are substantially reduced in cost—a goal of current research programs at the Solar Energy Research Institute and elsewhere. In particular, ethanol from these sources should provide a significant greenhouse benefit in addition to the elimination of the food/fuel competition problem inherent in a corn-to-ethanol production system.

Ethanol's likely contribution to improved air quality has been another area of some contention. Recent testing and air quality modeling indicate that use of gasohol, a 10 percent ethanol blend in gasoline, reduces carbon monoxide emissions even in newer vehicles (previously it was thought that newer vehicles would not benefit). Also, although addition of ethanol to gasoline increases its vapor pressure and thus its evaporative emissions, this negative effect is compensated for by the emissions' lower photochemical reactivity and a reduction in ozone formation caused by the lower CO emissions. Thus, the use of blends is unlikely to increase ozone concentrations even if fuel vapor pressure is not adjusted back to the original level.

The ability of high concentration ethanol fuels to reduce ozone levels is essentially untested with modern U.S. vehicles, and this potential remains a source of contention. Assumming that emissions of acetaldehydes (which are high for ethanol fuels, low for gasoline) can be satisfactorily controlled, it seems likely that ethanol use *will* offer an ozone reduction benefit, given ethanol's physical characteristics—but this remains untested. Recent testing should offer needed evidence on this potential.

Introduction of ethanol as a transportation fuel would benefit from:

- testing of its emissions performance as a neat fuel in catalyst-equipped vehicles;
- development of low-cost production systems using woody biomass as a feedstock;
- indications that other markets for American corn will remain depressed for the long term;
- improvements in distillation technology, or commercialization of membrane or other advanced separation technologies; and
- development of an international market in the fermentation byproducts from ethanol production.

[13]The total consumer cost may be higher once vehicle costs are factored in.

Natural gas may be cheaper *as a fuel* than gasoline[13]; the net cost to the consumer depends on the precise parameters of the distribution system. It can fuel a dedicated vehicle of equal performance to gasoline-powered vehicles, with generally lower emissions (except for potentially higher NO_x emissions) and equal or higher efficiency. In particular, natural gas' ability to yield large ozone benefits is much clearer than is the case with M85. Other important advantages include the availability of the United States' extensive pipeline network and extensive U.S. experience in gas handling. The use of natural gas may also confer some moderate greenhouse benefits, because of natural gas' low carbon/hydrogen ratio (yielding low CO_2 emissions per unit of energy), but the effect is highly sensitive to several system variables that can vary over a wide range. Because methane, the principal constituent of natural gas, is itself a powerful greenhouse gas, high tailpipe methane emissions coupled with distribution system leakage conceivably could cause a net greenhouse loss.

The use of natural gas could confer energy security benefits, though these will depend on the nature of the market structure. Suppliers of natural gas will not necessarily be the same as supplers of methanol; methanol's natural gas feedstock *must* be very low in cost to be competitive, whereas natural gas suppliers can use a higher priced feedstock so long as transportation costs to market are not too high. If a natural gas program were to grow very large, however, eventually the marginal suppliers would be the same countries that could serve as methanol suppliers.

Potential natural gas suppliers for a U.S. transportation market are, in order of probability, Canada, Mexico, and then a variety of nations shipping gas in the form of LNG. According to the Department of Energy, likely LNG suppliers for the United States are Algeria, Norway, Nigeria, and Indonesia, which may be viewed as a group as reliable suppliers. And, as with methanol, factors such as high capital costs of the supply system, the early stage of development of world gas resources, and ongoing changes in U.S./Eastern Bloc relationships are all positive factors for improved energy security.

Natural gas in the form currently used in vehicles—as compressed natural gas, CNG—has some important drawbacks as a transportation fuel, primarily limited range (CNG at 3,000 psi has one-fourth the volumetric energy density of gasoline), higher vehicle cost, slow refueling, and a limited base of technology development for gas-powered vehicles. Also, the transition vehicles that must establish the market would likely be dual-fueled vehicles, which have high first costs and some performance penalties when using gas.[14] Some of these disadvantages, particularly the range limitations, may be ameliorated by using gas in its denser liquefied form, LNG. New storage technology for LNG, which must be kept at –258 'F, appears to offer the potential for practical vehicular use.

Electricity as a vehicular "fuel" has the important advantages of having an available supply infrastructure (except for home charging stations[15] or an alternative recharging mechanism) that is adequate now—if refueling takes place at night—to fuel several tens of million vehicles, and of generating no vehicular air emissions. The latter attribute is particularly attractive to cities with severe ozone problems. Also, with the exception of some imports from Canada, the electricity needed to run a fleet of electric vehicles would be domestically produced. Recent improvements in ac converters have improved the prospects for successful electric vehicles. Because current commercial batteries simply cannot compete in range and performance with gasoline-powered vehicles, however, the primary determinant of the future of EV's is the success of ongoing battery research and engineering development, and/or the willingness of the driving public to accept substantial changes in vehicle performance and refueling characteristics. The outlook for significant improvement in commercial battery technology—especially regarding energy density and power—now appears promising, but there remain substantial uncertainties about the costs and, in most cases, the durability of advanced batteries, and previous confident predictions about imminent breakthroughs in battery technology have repeatedly proved incorrect. The market prospects are further limited by the cost and difficulty of rapid recharge.

[14] However, these penalties need not be as substantial as might appear from the performance of most current dual-fueled vehicles, which do not incorporate timing and other adjustments that will improve performance with gas.

[15] If the vehicle has an onboard charger, the recharging station will be simply an electric socket (probably with 220-volt capacity) with ground-fault protection. Adding this type of socket to an existing house can cost several hundred dollars, however.

Despite virtually zero vehicular emissions, EVs will have air emissions impacts because of the emissions from the electricity production needed for their recharging. Although EV fleets in different parts of the country would be recharged from quite different mixes of powerplants, in general, for at least the next decade or two, much of the power would likely come from coal-fired baseload steam-electric plants. Although nuclear and hydroelectric sources would be more desirable as recharging sources from the perspective of air emissions (including greenhouse emissions), they are less likely than coal-fired plants to be cycled down at night and to have excess capacity to contribute. Consequently, the use of EVs to replace gasoline vehicles trades off a reduction in urban hydrocarbon, carbon monoxide, and NO_x emissions (from the removal of the gasoline vehicles) against an increase in regional emissions and long range transport of NO_x and $S0_x$, (from the increase in power generation). The quantitative trade-off depends on the fuel burned and controls used; uncontrolled coal-fried powerplants burning high sulfur coal (typical of plants in the Ohio River Basin) can easily produce 10 or 20 times more SO_x than a modern plant with scrubbers burning low or medium sulfur coal. New Clean Air Act regulations governing acid rain emissions will likely narrow the environmental trade-offs among powerplants by imposing new emission controls on the worst polluters.

Some recent EV designs, in particular the General Motors Impact, may overcome some of the shortcomings generally associated with electric vehicles. The Impact achieves a substantial boost in range by attaining extremely high levels of vehicle efficiency, incorporating an extraordinarily effective aerodynamic design (drag coefficient of 0.19 v. 0.29 for the most efficient commercial gasoline vehicle) and ultra-low-friction tires among other measures. (Achieving high vehicle efficiencies is an important strategy for all alternative fuels because of their low energy content per unit volume. It is particularly critical for EVs and hydrogen powered vehicles, with the lowest densities of all the fuels.) However, the Impact and other vehicles remain much more expensive to operate than gasoline-powered vehicles, primarily because of the need for frequent battery replacement, and they have critical development needs that must be met before they can be successfully commercialized.

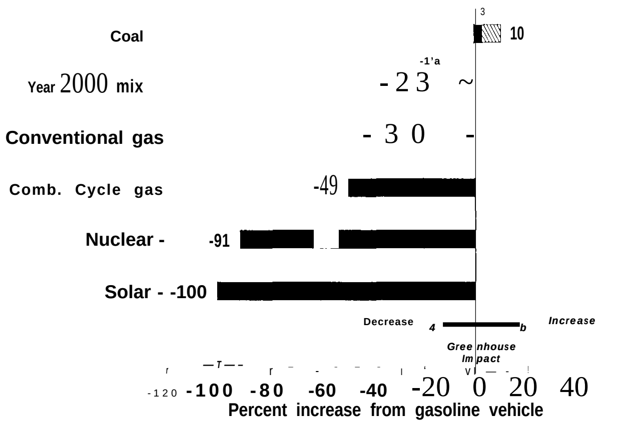
EVs, along with hydrogen vehicles, are often characterized as a primary means of reducing greenhouse emissions because nonfossil means of generating large quantities of electricity (e.g., nuclear, hydro) are in common use, while nonfossil means of creating large quantities of liquid and gaseous fuels are not. The greenhouse potential of EVs is obviously quite real, and could be realized with a resurgence in nuclear power and/or the large-scale commercialization of other nonfossil technologies. For generating plants based on renewable energy, plants using biomass are more likely to be used for recharging EVs than those using direct solar energy, because the latter are more suitable for providing daytime peak power. Development of new electricity storage systems would, of course, broaden the potential uses of solar electric powerplants.

In the near future, the greenhouse impact of an EV system is most likely to be small. The impact will depend on the mix of power generation facilities available to recharge the vehicles and the efficiency of both the EVs and the vehicles they replace. As noted above, except in the few areas where excess nuclear or hydro capacity is available, EV recharging will come from fossil-fueled plants, primarily coal-powered, with negative greenhouse implications. Also, the net impact depends on the vehicles actually replaced, not on some ‘‘average’ vehicle. The modest performance of likely EVs most resembles that characteristic of highly fuel-efficient vehicles; if the most efficient vehicles in the gasoline fleet are those being replaced, the net greenhouse advantage will be smaller than generally estimated. One analysis by researchers at the University of California at Davis of the net effect of using coal-fired power to charge EVs calculates that greenhouse emissions would increase 3 to 10 percent over gasoline vehicles. If new, efficient gas-fueled combined cycle powerplants can be used to recharge EVs over the next few decades, however, such a system would gain significant greenhouse benefits, up to 50 percent where such powerplants were the sole electricity source. Figure 7 illustrates the effect on net greenhouse emissions of changing the electricity recharging source.

Hydrogen's primary appeal is its cleanliness-its use in vehicles will generate very low emissions of hydrocarbons and particulate (from lubricating oil consumption), virtually no emissions of sulfur oxides, carbon dioxide, or carbon monoxide, and only moderate emissions of NOx. Primary draw-

Figure 7—Effect of Electricity Source on Greenhouse Impact of Electric Vehicles

(Total fuel cycle considered except construction materials manufacture)



Vehicle: EV powered by sodium sulfur batteries, ac powertrain, 150-mile range, 650-pound weight penalty v. competing gasoline car.

SOURCE: D. Sperling and M.A. DeLuchi, *Transportation Fuels and Air Pollution*, prepared for Environment Directorate, OECD, March 1990, draft.

backs are high cost fuel, limited range (liquid hydrogen has one-sixth the energy density of gasoline), and difficult and expensive onboard storage--either in heavy and bulky hydride systems that will adversely affect range and performance, or in bulky cryogenic systems that will reduce available space onboard the vehicle. In several ways, hydrogen vehicles share many pollution and performance characteristics with EVs, but with the potential for rapid refueling, countered by more difficult fuel handling. As noted above, the development of vehicle efficiency technology is critically important for successful introduction of hydrogen vehicles (as it is for EVs) because of hydrogen's extremely low energy density.

At the moment, the least expensive source of large quantities of hydrogen (but still at substantially higher system costs than gasoline) is from fossil fuels, either from natural gas reforming or coal gasification, the latter of which would exacerbate problems with greenhouse gas emissions. Production of hydrogen from photovoltaic (PV) systems (using the electricity to electrolyte water) would yield an overall fuel supply system that generated virtually no greenhouse gases, but costs will be prohibitively high without major success in cost reductions such as those associated with improvements in PV module efficiency and longevity. Even the most optimistic projections about cost reductions have photovoltaic hydrogen systems competing with gasoline only when gasoline prices rise by about 50 percent. Many might consider this added cost to be quite acceptable, however, given hydrogen's potential value to reducing urban ozone and greenhouse emissions.

Reformulated gasoline is especially appealing as a potential fuel because it requires no vehicle adjustments (though these might be desirable under some circumstances to maximize performance) or new infrastructure, aside from modifications to existing refineries. Of particular value is the potential to use reformulated gasoline to reduce emissions from *existing* vehicles; market penetration-and the air quality benefits associated with such penetration—require only providing adequate fuel supplies, unlike the other fuels that must wait for fleet turnover. However, with the exception of a small quantity of supply available in southern California and a few other cities, reformulated gasoline is primarily a concept; formulas for fuel constitution, and likely costs, await the results of a just-started testing program being sponsored by the oil and automobile industries, and the ultimate ability of reformulated gasoline to lower emissions is unclear at this time. Further, it is impossible at this time to predict how much reformulated gasoline the petroleum industry will be capable of producing. And reformulated gasoline offers lesser benefits in energy security (except, possibly, to the extent that its use prevents refinery closures from competition with alternative, imported fuels) or greenhouse emissions. than other fuels, because it is primarily oil-based and may increase refinery energy use somewhat. The oxygenate component of reformulated gasoline may offer some energy security benefits since it will likely be produced from natural gas-based methanol or domestically produced ethanol.

Chapter 1
Introduction

Substituting alternative fuels for gasoline in highway vehicles is being promoted by the U.S. Environmental Protection Agency, the California Energy Commission, and others as a way to combat urban air pollution as well as a means of slowing the growth of oil imports to the United States and—for some of the longer term alternatives---of delaying global climate change. The primary suggested alternative fuels include the alcohols ethanol and methanol, either 'neat' (alone) or as blends with gasoline; compressed or liquefied natural gas (CNG or LNG); liquefied petroleum gas (LPG), which is largely propane; hydrogen; and electricity. Each of the suggested liquid and gaseous fuels has one or more features-high octane, wide flammability limits, and so forth-that imply some important advantage over gasoline in powering highway vehicles. Electric vehicles (EVs) may be particularly attractive to urban areas because they operate virtually without air emissions. (However, the emissions from the powerplants providing the electricity are an important concern, even though these plants may be separated geographically from the area of vehicular use.) Similarly, hydrogen-fueled vehicles would emit only NO_x in significant quantities, and even the NO_x emissions could be eliminated if the hydrogen was used in a fuel-cell-powered EV.[1]

Not surprisingly, each of the suggested fuels has disadvantageous as well as advantageous features. Methanol is more toxic than gasoline, for example, and natural gas engines may have difficulty in achieving hoped-for large reductions in vehicular nitrogen oxides emissions; ethanol production may require crop expansion onto vulnerable, erosive lands; and so forth. Decisions about promoting the introduction of alternative fuels should carefully consider the full range of effects likely to accompany such an action.

Some experience has already been gained with each of the fuels. Hundreds of thousands of CNG-fueled vehicles operate worldwide, particularly in Italy, Australia, and New Zealand; about 30,000 CNG vehicles operate in the United States. Over 300,000 vehicles in the United States, primarily in fleets, are fueled by LPG. Nearly a billion gallons/year of ethanol are used in the U.S. fleet today in ''gasohol, ' a 10 percent blend with gasoline. Methanol serves as the feedstock for methyl tertiary butyl ether (MTBE), a widely used octane-enhancing agent for gasoline. Currently, about 25 percent of the United States' total annual methanol use of 1.7 billion gallons is devoted to MTBE manufacture, and about a billion gallons/year of ethanol are blended with gasoline. Brazil (and related auto manufacturers, including the U.S. "Big Three") has extensive experience with ethanol-fueled vehicles. And experience has been and continues to be gained with several small fleets of methanol-powered vehicles built for test purposes. Commercial (as well as experimental) electricity-driven light-duty vehicles exist today, both in the United States and overseas, and experimental hydrogen-fueled vehicles have been developed in Germany and Japan. Table 1-1 displays the volumes of alternative fuels used in several countries.

Other than fuel cost, the major barrier that most alternative fuels must overcome is the need to compete with the highly developed technology and massive infrastructure' that exists to support the production, distribution, and use of gasoline as the primary fleet fuel. Any new fuel must compete with the ready availability of gasoline throughout the country, the massive amounts of capital and engineering time that have been invested in continuing engine modifications to optimize performance for gasoline, and consumers' lifetime acceptance of gasoline. This competition will be an especially formidable problem if the fuel requires a totally new production and/or distribution network or if it significantly reduces vehicle performance and/or range.

In particular, the introduction of vehicles using alternative fuels creates a difficult transition problem because fuel availability is likely to be limited geographically during the first years following introduction of the fuel. This problem will likely be

[1] The magnitude of air emissions and other environmental impacts of *producing* the hydrogen depend on the technology used. At one limit, coal gasification would generate relatively large impacts; at the other, electrolytic production from water using solar energy as a power source would generate relatively low impacts aside from land coverage.

Table I-l—Major Users of Alternative Fuels (thousands of barrels/day of gasoline equivalent-estimated)

Country	Total	LPG	Ethanol	CNG	Synthetic gasoline	Methanol	Electricity
Brazil	110	—	110	—	—	—	—
Japan	79	79	—	—	—	—	—
United States	62	18	34	1	—	9	—
Italy	57	42	—	15	—	—	—
New Zealand	45	3	—	9	33	—	—
Holland	27	27	—	—	—	—	—
Europe	18	9	—	—	—	9	—
Canada	8	7	—	1	—	—	—
U. K.	2	—	—	—	—	—	2
Australia	2	2	—	—	—	—	—
All others	37	15	8	14	—	—	—
Total	447	202	152	40	33	18	2

World gasoline -15,700 thousand bbl/day (for comparison)
U.S. gasoline -6,800 thousand bbl/day (for comparison)
Ethanol and Methanol estimates are based on fuel production data. All others are based on the simplified assumption that vehicles use the equivalent of 800 gallons of gasoline per year.

SOURCE: U.S. Department of Energy, *Assessment of Costs & Benefits of Flexible and Alternative Fuel Use in the US Transportation Sector Progress Report Two:* The International *Experience,* DOWPE-0085, August 1988.

aggravated by the limited range of alternative fuel vehicles, caused by the low volumetric energy density (compared to gasoline) of the alternative fuels (or of the batteries in EVs). To counter this problem, some plans for the introduction of alternative fuels call for vehicles capable of using both gasoline and alternative fuels either one-at-a-time ("dual-fueled vehicles") or mixed together in varying proportions (flexible-fueled vehicles, or FFVs); for EVs, the equivalent is a so-called hybrid vehicle combining electric motors with small internal combustion engines or fuel cells to allow extended range. Unfortunately, the multifuel vehicles generally will be more costly than dedicated vehicles and inferior to them in fuel efficiency, emission characteristics, and performance,[2] reducing the benefits for which the alternative fuels are being vigorously promoted. Other measures for coping with range problems include a strong emphasis on vehicle fuel efficiency;[3] introduction of higher pressure storage tanks and cryogenic or hydride storage for gaseous fuels; and accepting the weight and space penalties associated with larger storage tanks.

The barriers to introduction and acceptance are not identical for the different, competing alternative fuels. For ethanol and methanol, the major barriers are potentially high fuel costs and the lack of pipelines, filling stations, and other pieces of a supply infrastructure; some nagging problems with vehicle performance need to be solved, but these seem likely to be of lesser importance than the cost and infrastructure problems. In contrast, aside from the need to establish large numbers of home charging stations, fuel cost and the fuel supply infrastructure do not appear to represent major barriers to electric vehicles; instead, the primary barriers are the high first costs, short battery life (of current batteries) and inferior range, performance, and refueling capabilities of EVs compared to existing gasoline-powered vehicles (though hybrid vehicles combining electric and gasoline propulsion and energy storage systems can overcome the range and performance barriers, at additional cost).

For vehicles powered by compressed natural gas, range is an important barrier, as is the lack of a retail sales infrastructure; on the other hand, long-range distribution, a problem for ethanol and methanol, is not a problem for gas because gas services currently can reach 90 percent of the U.S. population through its extensive pipeline network.[4] (Given the extensive

[2] In particular, the need to operate on gasoline compromises the ability to redesign engines to take advantage of the favorable properties of the alternative fuels.

[3] For example, General Motors' prototype "Impact" electric vehicle has an unusually low aerodynamic drag coefficient of 0.19 and high pressure tires that cut rolling resistance in half. SOURCE: General Motors Technical Center, "Impact Technical HighLights, press release of Jan. 3,1990, Warren, Mr.

[4] U.S. Department of Energy, *Assessment of Costs and Benefits of Flexible and Alternative Fuel Use in the US. Transportation Sector, Technical Report Five, Vehicle and Fuel Distribution Requirements,* January 1990, Draft.

Photo cmo'it: Ford Motor Co.

This Ford Flexible Fuel vehicle, an adaptation from a regular production Taurus, will operate on methanol, ethanol, gasoline, or any combination of those fuels. Similar prototypes or limited production vehicles have been introduced by a number of other vehicle manufacturers.

use of gas in residential applications, use of home compressors might help overcome the retail infrastructure barrier-though at considerable cost.) In addition, CNG/gasoline dual-fueled vehicles are expensive and of somewhat lower power than competing gasoline vehicles, which may make the transition to dedicated vehicles somewhat harder than for some competing fuels. For hydrogen-powered vehicles, the comparative lack of technology development, high fuel costs, lack of a supply infrastructure, and high vehicle cost, low range, and high fuel storage space requirements are major barriers. For natural gas, use of liquefied rather than compressed gas would help to overcome range problems, although at the loss of the option for home refueling and with losses in thermal efficiency during liquefaction.

Introducing alternative fuels will likely require large capital investments, government interference in markets, increased consumer expenditures on transportation, and, for most fuels, some decrease in consumer satisfaction. Undertaking such an introduction is justified only if the rewards, in terms of reduced pollution or increased energy security, are valued very highly and if other, less expensive measures are not available to achieve the same ends. Given the substantial differences in the importance that various policymakers attach to the potential benefits, and differences in their willingness to impose monetary and convenience costs, there would be substantial disagreement about the urgency of introducing alternative fuels, the appropriate policy measures to accomplish this introduction, and the appropriate ranking of fuels *even if the many uncertainties about fuel costs, pollution effects, and other characteristics were resolved.*

This report makes it clear that there are substantial uncertainties and remaining concerns about all aspects of the fuels; that costs will be high, especially during the transition from gasoline to the alternatives; and, for most of the fuels, that consumers would have to make substantial adjustments to allow successful entry of the fuels into the marketplace. The report also makes clear that alternative fuels can provide substantial levels of transportation service at costs to consumers that are similar to or lower than costs already being paid in Europe,[5] that some of the fuels have *long-term* potential to drastically reduce greenhouse gas emissions, and that there are ample supplies of natural gas and other nonrenewable feedstocks to provide at least several additional decades of fuel supply as a bridge to renewable sources of transportation fuel.

Existing analyses of the costs and benefits of the alternative fuels are based on a variety of evidence. As noted above, many of the fuels have been used in vehicles for years, and much of this experience is relevant to projections of future, wider use. Also, aside from their vehicular use, most of the fuels have been in commerce for decades, and the experience with producing and handling the fuels will also aid the projections. Finally, unlike gasoline, which is a complex *and nonuniform* blend of hydrocarbons, most of the suggested alternative fuels have simple chemical structures and are relatively uniform in quality-which should improve the accuracy of extrapolations of their performance in vehicles.

Nevertheless, evaluation of the costs and benefits of the various alternative fuels relative to gasoline and to each other is an exercise handicapped by four primary areas of uncertainty. First, *the technology for producing and using alternative fuels is still developing and changing.* Ongoing research programs are attempting to overcome or ameliorate the technical problems listed above and reduce the overall system costs for the competing alternative fuels. The *short-term* problems associating with bringing the *first generation* of alternative fuel vehicles to market are, for most of the fuels, relatively minor, and solving the remaining problems for these vehicles introduces only moderate uncertainty into projections of cost, performance, and system characteristics. For the longer term, though, bringing to market advanced technology, optimized vehicles, perhaps dedicated to a single fuel (and perhaps with a neat fuel rather than a blend), with a fuel supply obtained from large-scale, advanced-technology production plants, involves major uncertainties. The outcome of development programs for these technologies is essentially unpredictable, but the fact that most of the fuels are in an early stage of development for transportation use[6] makes it likely that at least some of the characteristics of future technologies available for supply and vehicle systems—and conclusions about their relative costs and benefits-will be considerably different from the characteristics of the technologies available today. For example, ethanol currently is one of the most expensive of the alternative highway fuels, and the fact that its primary source of feedstock materials in the United States is corn (it is sugar cane in Brazil) creates some potential problems for any attempt to greatly increase ethanol production. Ongoing research on manufacturing ethanol cheaply from wood conceivably could drastically improve ethanol's attractiveness as a transportation fuel, by lowering costs and by reducing or eliminating the potential for competition between society's food and fuel requirements. Similar "technological breakthrough" potential exists for the other fuels. Analysts and policymakers should be wary, however, of confident predictions that the potential benefits of such breakthroughs will actually occur-there are few guarantees in the research and development process.

Second, *uncertainty is introduced by the vagaries of the transition from successful research project to real world system. The* process of moving from promising laboratory experiments and technology prototypes to establishment of large vehicle fleets and an elaborate supply infrastructure involves

[5] Although today's fuel-cost differential between the United States and Europe is in the form of taxes, which benefits government services, as opposed to differential costs in raw materials, processing, and the other factors of production.

[6] Natural gas is an exception, since hundreds of thousands of vehicles are in use worldwide. These vehicles are retrofit from gasoline vehicles, however, and do not attain the performance likely to be required to break out of niche markets in the United States. Similarly, ethanol is widely used in Brazil, but the Brazilian experience is not encouraging for U.S. ethanol use.

massive scaleups, design trade-offs (and, often, acceptance of lower performance in exchange for cost reductions or improved marketability) to allow for mass production and practical vehicle maintenance, improvements in design as information is gained, and other factors that diminish the value of preliminary estimates of costs and performance. At the current time, without much actual experience to temper judgments, analysts with optimistic views see primarily the numerous potential opportunities for reducing emissions, increasing efficiency and power, and lowering costs associated with the alternative fuels; and analysts with pessimistic views instead see primarily the numerous problems—higher emissions of aldehydes with alcohol fuels, materials problems, and so forth-associated with the same fuels. Although the growing experience with small fleets of alternative fuel vehicles-for example, the highway fleet of several hundred methanol-fueled vehicles—will settle some of the ongoing controversies, others may remain until mass production places many thousands of such vehicles on the road and several years of driving experience are amassed.

Third, *it is difficult to predict in advance what the scale of alternative fuels development will be* (though the scale of development will, of course, depend strongly on government policy), *and whether such development in the United States would stimulate similar development in other countries . . . yet the scale of development of the fuels will affect the costs and characteristics of their supply systems.* For example, a moderate-sized shift to natural gas vehicles[7] could readily be supplied by domestic gas sources or pipeline imports from North America, but larger scale development would require LNG imports from overseas, at different costs and implications for national security. Similarly, vehicular methanol development, especially if it were confined to the United States, might first be accommodated by methanol produced from gas found in remote areas, which may be cheap and, by providing some additional diversity to transportation fuel supply sources, could be beneficial to national security concerns about OPEC dominance of the liquid fuels market. A large worldwide shift to methanol might, however, have distinctly different costs and security implications, because the geographical preponderance of world gas reserves and resources in the Middle East and Eastern Bloc nations could become important in such a scenario. The security implications of a major Eastern Bloc role in methanol production—and, indeed, the overall significance of energy security concerns—may, of course, need to be rethought in light of recent political developments in that part of the world.

The scale of a U.S. Government-backed alternative fuels program will depend on whether the program is principally an air quality control measure aimed at the few nonattainment areas that cannot satisfy ozone standards by conventional means, or instead is an energy security measure, which would demand a much larger market share for the fuels. The Federal Government might also envision the program as two-phased, with the first phase a smaller program aimed principally at air quality and designed as well to work out ‘‘bugs’ in the system, with a follow-on phase designed more for energy security and aimed at spreading fuel use throughout the country.

Fourth, *the gasoline-based system that alternative fuels will be judged against is a moving and movable target. The* prospects for conversion to alternative fuels are putting enormous pressure on the petroleum industry to devise *petroleum-based* solutions to the problems alternative fuels are designed to address. Although revisions to gasoline composition and modifications to gasoline-fueled vehicles are unlikely to address the problem of growing oil imports, it is air pollution more than oil import growth that is driving the current push towards alternative fuels--and further changes to fuels and vehicles *can* reduce air pollution. ARCO’s August 1989 announcement of a reformulated, pollution-reducing gasoline as an alternative to leaded gasoline in the California market[8] is likely only the opening salvo in an industry effort to defuse current interest in alternative fuels. Furthermore, State and Federal recognition of the potential for improving air quality by changing gasoline composition—stimulated by the ARCO announcement-is likely to lead to increased *regulatory* pressures towards reformulation. Similarly, Federal and some State governments are likely to exert continuing pressure

[7] The U.S. light-duty highway fleet consumed nearly 7 million barrels per day (mmbd) of gasoline in 1989 (U.S. Energy Information Administration data). If 5 percent of this demand were shifted to natural gas, this would add about 0.7 trillion cubic feet per year to U.S. gas consumption.

[8] M.L. Wald, ‘‘ARCO Offers New Gasoline to Cut Up to 15% of Old Cars’ Pollution,’’ New *York* Times, Aug. 16, 1989.

on vehicle manufacturers to improve gasoline-based emissions control systems.

The remaining questions about performance and costs of the alternative fuels create a policy dilemma for Congress. First and foremost, Congress must decide whether or not to support alternative fuels in the face of substantial uncertainty and controversy. Although alternative fuels are likely to have some important advantages over gasoline, these advantages are not easily quantified and must be balanced against significant but similarly uncertain costs (as well as some disadvantages).

Second, if Congress does wish to promote alternative fuels, it must choose between selecting one or two fuels and providing specific incentives for these, or providing more general market and/or regulatory incentives that do not favor one fuel but rather focus on air quality or other goals. Selecting one or two fuels-or selecting particular fuels for different market niches—may provide higher market certainty and larger scale, both of which are important cost determinants.[9] On the other hand, early selection of "winners" increases technological risk and opens up the very real possibility that the "best" fuel will not be selected. Providing a more general incentive reduces some of these risks, but may force higher costs because market uncertainty will lead to higher required capital return rates and higher markups, and smaller volumes of each fuel will tend to lower the economies of scale otherwise available.

A critical corollary to this decision is the need to consider whether to incorporate longer term goals into any alternative fuel program designed initially to meet short-term problems. In making decisions about alternative fuels, Congress must recognize that it maybe launching this Nation down a path that will have long-term consequences for the U.S. energy system—including, by building a new and expensive infrastructure, the enhancement or discouragement of the future adoption of certain energy technologies or fuels not currently economic or practical. Those concerned about global warming are concerned, in particular, about the likelihood that a turn to fuels such as methanol might lead inexorably to a dependence on coal as a feedstock—with potentially strong negative consequences for attempts to reduce emissions of CO_2 and other greenhouse gases (since gasoline can itself be made from coal, a *no change* strategy may have the same consequences). Others believe that even methanol produced only from natural gas is harmful to greenhouse control strategies because its use—by reducing stress on oil markets, keeping oil prices lower, and reducing strategic concerns—will reduce pressures on the industrial nations to move away from fossil fuels. And some scientists believe that a turn to natural gas could have the effect of paving the way for hydrogen produced from renewable sources. Because the short-term options for alternative fuels—methanol, ethanol, and natural gas—are unlikely to have a strong effect on greenhouse emissions, there may be a temptation for policymakers to ignore greenhouse problems in dealing with these fuels.

Third, Congress must choose a timetable for a program that finds an appropriate balance between testing and experimentation, and moving forward with mass production of vehicles and fuels. In deciding to act now or wait, Congress must judge whether the new information likely from a test program will add sufficiently to the selection process to offset the benefits lost by waiting.

In this report, OTA reviews the major factors affecting the commercial and societal acceptability of methanol, ethanol, CNG and LNG, electricity, and hydrogen,[10] as compared to gasoline and to each other (see box 1-A for a brief discussion of a key problem involved in making the alternative fuels/ gasoline comparison). In many of the discussions, especially in those involving energy security, we focus on the issues and effects of alternative fuel programs of a large-scale, nationwide nature. Programs restricted to helping solve the air quality problems of a limited group of ozone nonattainment areas would create much lesser impacts and have different costs. Where feasible, we try to separate the effects of the two program scales. We identify key

[9] Higher market certainty reduces the capital return rates demanded by developers, and larger scale allows scale economies to be realized. On the other hand, artificially stimulating higher demand for a single fuel can raise some costs by forcing reliance on more expensive sources of feedstock material, or by eliminating some incentives for cost reduction that would come with competition from other fuels.

[10] Propane and LPG were not addressed in this study. Use of these fuels should have air quality benefits similar to those obtainable with natural gas; in particular, effective hydrocarbon emissions (taking into account both changes in mass rates and changes in the reactivity of the emissions) should be cut substantially, providing ozone reductions in areas where hydrocarbon emissions area controlling factor in ozone concentrations. Enough supply of these fuels should be available for gasoline replacement in a few million vehicles, sufficient for an air-quality-based strategy aimed at critical ozone non-attainment areas.

Box I-A-Comparing Vehicles Fueled With Gasoline and Alternative Fuels

A source of confusion in examining the results of various studies of alternative fuels is a divergence in the nature of the gasoline/alternative fuels comparisons that are made. In particular, different studies may choose different baseline vehicles from which to compare vehicles fueled with alternative fuels.

It has been our experience that many studies choose a kind of "average" gasoline vehicle from which to compare vehicles powered by alternative fuels. This vehicle will have range, performance, and efficiency characteristics that are representative of the automobile fleet as a whole, or the new car fleet, during the time period in question-for example, 350 mile range, 2,500 to 3,000 pound curb weight, 30 to 35 mpg fuel economy, O to 60 mph time of 11 seconds, and so forth. Generally, these studies demand that the alternatively fueled vehicles satisfy minimum performance requirements, e.g. 200 mile range, though these requirements may be inferior to the baseline characteristics.

Using a baseline vehicle of this sort is the same as asking the question, "Is it possible to market an alternatively fueled vehicle that can compete economically (or in another critical characteristic) with a gasoline-fueled vehicle, even if it may be inferior in one or more other characteristics?" From a policy standpoint, framing the question this way implicitly assumes that the policymakers will be ready to force the market entry of alternative fuel vehicles as long as they are an effective way of achieving a policy goal (e.g., improving air quality), don't cost too much, and don't perform insufferably badly.

A manufacturing organization that is not counting on a government-mandated market will compare gasoline and alternative fuels differently. They will either demand that the alternative fuel vehicle perform up to the standards of the gasoline vehicle--e.g., by using very large fuel tanks to increase range--or they will select a baseline gasoline vehicle that matches some of the performance inferiority of the alternative fuel vehicle, trading off this loss by lowering costs and/or improving fuel economy. For example, the organization may consider that, if there is a market (e.g., as a commuter car) for an electric vehicle with limited cargo space, range, and performance, there may also be a market for a competing gasoline vehicle with similar characteristics but with the low cost and extremely high fuel economy made possible by accepting these characteristics. If such a vehicle could undercut the market for EVs, then it maybe too risky to build an EV even if the EV could compete *economically with an* "average" car.

Selecting different baselines will drastically alter the results of a "side-by-side comparison" of gasoline and alternative fuel vehicles. Properly interpreting the results of such comparisons demands an understandingof what baselines were chosen, and thus, what policy question is being addressed.

SOURCE: Office of Technology Assessment, 1990.

uncertainties and place the fuels in a time context, that is, identify how long they might take to become practical alternatives to gasoline. We also discuss the option of reformulating gasoline to reduce emissions, because reformulation is a likely strategy to be adopted by the oil industry to hold market share in the transportation fuels supply market.

Because available studies of the costs and benefits of the alternative fuels often have widely diverging results and conclusions, we have attempted to present and explain the source of the more important of these differences. In several instances, we could not resolve conflicting conclusions or even narrow significantly the range of appropriate views, partly because further testing and development is required, and partly because we could not evaluate each issue to the extent necessary to accomplish this. And because methanol has attracted the most policy interest, we discuss it in more detail than the other fuels. The discussions are not strictly parallel in structure because the issues affecting the acceptability of the fuels are different for each fuel, and because the states of knowledge for each fuel are not identical.

A **final note:** Although this report focuses on alternative fuel use in light-duty vehicles, readers should be aware that these fuels are suitable for heavy-duty vehicles, and in some cases their benefits are greater and liabilities less in these applications. In particular, heavy-duty vehicles have fewer space constraints than light-duty vehicles, and generally can accommodate more fuel storage, reducing the range constraint of alternative fuels. Also, many heavy-duty vehicle fleets, particularly bus fleets, are centrally fueled and maintained, greatly reducing infrastructure constraints. Finally, heavy-duty vehicles often use diesel engines that create difficult pollution problems in urban areas. These engines can be adapted to run on methanol, ethanol, or natural gas instead of diesel, with a corresponding improvement in emissions of particulate and other harmful pollutants.

Chapter 2
Why Support Alternative Fuels?

During the oil crises of the 1970s, support for alternative highway fuels focused primarily on the issue of energy security and the United States' growing dependence on imported crude oil and petroleum products. Recent support for alternative fuels has centered around efforts to attain urban air quality goals and the automobile's central role as a source of air emissions. Achievement of air quality goals have been frustrated by steadily growing demand for travel and the increasing difficulty of squeezing further emission reductions from gasoline vehicles already subject to stringent controls. Environmental officials and legislators—lead especially by State and local organizations in California and recently joined by the Bush Administration-view the use of 'clean fuels' as a promising way to begin a new cycle of atmospheric cleanup. They also foresee a secondary benefit from potential reductions in toxic air emissions from fuel production and distribution.

In addition, the old concerns about energy security are still with us and are increasing, and a new problem—global warming from increases in atmospheric concentrations of so-called "greenhouse gases" —has surged to the front of concern for the environment. Concern about both of these problems has played a role in the debate over alternative fuels.

This chapter reviews briefly each of these three concerns, to lay the foundation for judging the need for alternative fuels and the attractiveness of a strong government role in introducing these fuels. Readers familiar with these concerns may wish to skip this chapter and move to the chapters on the individual fuels.

OZONE CONTROL IN PERSPECTIVE

Within the next year, Congress must reauthorize--and, some believe, rethink-the Clean Air Act. The mechanism established in 1970 to assure the Nation's air quality has failed notably to reach health-based standards for a major pollutant, ozone, in much of the country. Today, almost two decades after the Act's original passage, about 70 to 100 urban areas (depending on weather conditions) still violate the ozone standard; indeed, the intense heat of summer 1988 added an estimated 28 new names to the list of "nonattainment" cities. Currently available control methods are not adequate to bring all of these cities into compliance. This third attempt to craft an ozone control program thus raises several controversial issues: how great a threat ozone poses to human health, agricultural production, and environmental welfare; what technical measures to take against this hard-to-control pollutant; how to alter deadlines, sanctions, and planning mechanisms; how to deal with the cities that cannot meet the standard with any existing or near-term means; and finally, how to encourage development of new control methods so that continued progress can be made.

Since 1970, a Federal-State partnership has been in place to handle ozone control, with the Environmental Protection Agency (EPA) setting nationally uniform ambient air quality standards and the States, with the Agency's help and approval, working to meet them. Based on ozone's known health effects, the standard is currently set at a peak, l-hour average ozone concentration of 0.12 parts per million (ppm). Any area experiencing concentrations exceeding the standard more than once per year, on average, is declared a nonattainment area. EPA updates the nonattainment list annually, as data become available. The list in 1988 included cities housing well over half of the American population.

One suggested strategy for reducing urban ozone is the substitution of alternative fuels for gasoline in the highway vehicle fleet. Each of the suggested alternative fuels--methanol, ethanol, natural gas, hydrogen, electricity, and reformulated gasoline--have, to a differing degree, the potential to reduce either the emissions of the volatile organic compounds that are the precursors of ozone, or the reactivity of these emissions (that is, their likely contribution to ozone formation per unit of mass). The Administration's ozone control strategy relies heavily on alternative fuel use by highway vehicles,

[1]This section is adapted from the summary chapter, U.S. Congress, Office of Technology Assessment, *Catching Our Breath: Next Steps in Reducing Urban Ozone, OTA-O-412* (Washington, DC: U.S. Government Printing Office, July 1989).

and the State of California, whose ozone problems are the United States' most severe, also supports alternative fuels, though its latest control strategy does so indirectly by mandating the sale of ultra-low-emission vehicles. Under the Administration's proposal, EPA must promulgate performance standards for alternatively fueled vehicles 18 months after enactment. EPA has stated that the initial standards are likely to be equivalent to the benefits achieved by flexibly fueled vehicles burning M85[2] (according to EPA, their benefit is equivalent in ozone forming potential to a 30 percent reduction in hydrocarbon emissions from vehicles meeting proposed hydrocarbon standards and operating on low volatility gasoline, with Reid Vapor Pressure of 9.0[3]). EPA anticipates that performance standards by the year 2000 or so can be set equivalent to the benefits achieved by dedicated M100[4] vehicles (which EPA believes are equivalent to about an 80 percent reduction in passenger car hydrocarbon emissions, relative to the proposed standards and low volatility gasoline). The proposal requires that 8.75 million alternatively fueled vehicles must be sold in the nine worst nonattainment areas (those with peak ozone concentrations of 0.18 ppm or higher) between 1995 and 2004. The proposal also gives EPA the authority to mandate adequate supplies of fuel to operate the vehicles and requires that the State make the sale of the fuel "economic." In California, both the South Coast Air Quality Management District (covering the Los Angeles area) and the California Air Resources Board have stated their intent to adopt an emissions control program likely to force large-scale use of alternatively fueled vehicles. The purpose of this section is to place these proposed measures into perspective, by describing ozone's impact on U.S. air quality and the available range of options for reducing ozone concentrations.

Why Control Ozone?

The 0.12 ppm national standard for ozone derives from solid evidence of the health effects of short-term exposure above that level, as illustrated in figure 2-1. Excessive ozone is harmful to people. Some healthy adults and children experience coughing, painful breathing, and temporary loss of some lung function after about an hour or two of exercise at the peak concentrations found in nonattainment cities.

Does the current standard adequately protect people who are exposed for long periods or at high exercise levels? Experts are unsure. Several studies over the past 5 years have shown temporary loss of some lung function after an hour or two of exposure at concentrations between 0.12 and 0.16 ppm, among moderately to heavily exercising children and adults. And despite the current standard's emphasis on a l-hour peak, real-life exposures to near daily maximum levels can last much longer; ozone levels can stay high from mid-morning through late afternoon. With exposure during 6 hours of heavy exercise, temporary loss of some lung function can appear with ozone levels as low as 0.08 ppm.

Potentially more troubling and less well-understood are the effects of long-term, chronic exposure to summertime ozone concentrations found in many cities. Regular out-of-doors work or play during the hot, sunny summer months in the most polluted cities might, some medical experts believe, cause biochemical and structural changes in the lung, paving the way for chronic respiratory diseases. To date, though, evidence of a possible connection between irreversible lung damage and repeated exposure to summertime ozone levels remains inconclusive.

Clear evidence shows that ozone damages economically, ecologically, and aesthetically important plants. When exposed to ozone, major annual crops produce reduced yields. Some tree species suffer injury to needles or leaves, lowered productivity, and in severe cases, individual trees can die. Important tree species are seriously affected in large areas of the country. In the most heavily affected forested areas, such as the San Bernardino National Forest in California, ozone has begun altering the natural ecological balance of species.

Whether or not the current standard is adequate, many areas of the country have failed to meet it. About half of all Americans live in areas that exceed

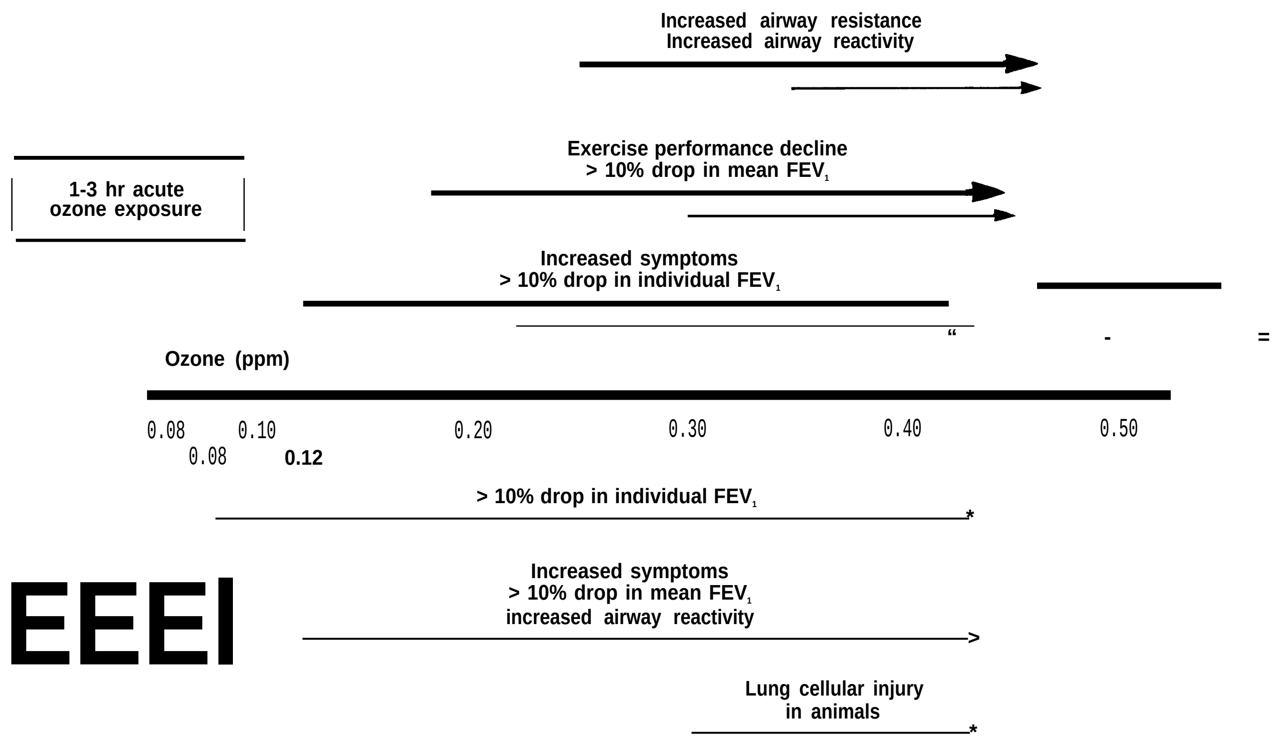
[2] M85: a mixture of 85 percent methanol and 15 percent gasoline.

[3] U.S. Environmental Protection Agency, *Analysis of the Economic and Environmental Effects of Methanol as an Automotive Fuel*, Special Report, Office of Mobile Sources, September 1989.

[4] M100: 100 percent methanol fuel.

[5] Ibid.

Figure 2-l—Acute Effects of Ozone Exposure



Effects above the ozone concentration line are from 1 to 3 hour exposures to ozone. Effects below the line are from 4 to 8 hour exposures. FEV, (forced expiatory volume in 1 second) is a measure of lung function. The bolder arrows indicate the range of concentrations at which effects occur from exposure while exercising heavily; the lighter arrows indicate the concentrations at which effects occur while exercising moderately. Effects begin at the concentration indicated by the tail (left side) of the arrow.

SOURCE: Office of Technology Assessment, 1989.

the standard at least once a year. About 100 " nonattainment areas" dot the country from coast to coast, with ‘‘design values” —a measure of peak ozone concentrations-ranging from 0.13 ppm to as high as 0.36 ppm. Half the areas are fairly close to attainment, with design values up to 0.14 or 0.15 ppm; for these areas, reaching the standard is probably feasible with existing technologies. However, the remaining areas, including the Nation’s worst violator, Los Angeles, present much more serious and challenging problems, with design values in excess of 0.16 ppm. Sixty of the 317 urban and rural areas for which we have data had at least 6 days/year between 1983 and 1985 with ozone levels exceeding 0.12 ppm for 1 or more hours. A number of areas topped the standard for 20 or more days, with the worst—Los Angeles-averaging 275 days per year.

Ozone in a city’s air, however, does not necessarily equal ozone in people’s lungs. Concentrations vary with time of day and exact location. People vary in the amount of time they spend indoors, where concentrations are lower. And the more actively someone exercises, the more ozone he or she inhales. Each year, nationwide, an estimated 34 million people are actually exposed to ozone above 0.12 ppm at low exercise levels, and about 21 million are exposed during moderate exercise, on average about 9 hours per year. About 13 million people are exposed to ozone above 0.12 ppm during heavy exercise, each of them for about 6 hours each year, on average. At each exercise level, one-quarter of these people live in the Los Angeles area.

Ozone and Its Precursors

Ozone is produced when its precursors, volatile organic compounds (VOCs) and nitrogen oxides (NO_x), react in the presence of sunlight. VOCs, a broad class of pollutants encompassing hundreds of specific compounds, come from manmade sources including automobile and truck exhaust, evaporation of solvents and gasoline, chemical manufacturing, and petroleum refining. In most urban areas, such manmade sources account for the great majority of VOC emissions, but in the summer in some regions, natural vegetation may produce an almost equal quantity. NO_x arises primarily from fossil fuel combustion. Major sources include highway vehicles, and utility and industrial boilers.

Ozone control efforts have traditionally focused on reducing local VOC emissions, partly because the relevant technologies were thought to be cheaper and more readily available. In addition, under some conditions at some locations, reducing NO_x can have the counterproductive impact of increasing ozone concentrations above what they would be if VOCs were controlled alone.[6]

Local controls on VOC emissions cannot completely solve the Nation's ozone problem, however. In many places, even those with good control of their local emissions, reducing ozone is complicated by the 'transport' of pollutants, as ozone or precursors originating elsewhere are carried in by the wind. "Plumes' of elevated ozone have been tracked 100 miles or more downwind of some cities: the Greater New York area's plume, for example, can extend all the way to Boston. Over half of the metropolitan areas that failed to attain the ozone standard between 1983 and 1985 lie within 100 miles downwind of other nonattainment cities. In such cases, VOC (and sometimes NO_x) reductions in the upwind cities could probably improve air quality in their downwind neighbors. Indeed, reductions in certain areas that are themselves already meeting the standard might also aid certain downwind nonattainment areas.

The significance of transported pollutants varies substantially from region to region and day to day. During severe pollution episodes lasting for several days, for example, industrial or urban NO_x, or ozone pollution can contribute to high ozone levels hundreds of miles away. In certain heavily populated parts of the country, pollution transport is a significant and very complex problem. The northeast corridor, from Maine to Virginia, contains 21 nonattainment areas in close proximity; California, 8; the gulf coast of Texas and Louisiana, 7; and the Lake Michigan area, 5. Figure 2-2 shows the location of nonattainment areas.

Aside from pollution transport, the balance of VOCs and NO_x in the atmosphere is another complicating factor in controlling urban ozone levels. The precise local balance of VOCs and NO_x varies from place to place, even within the same metropolitan area, and from day to day. Where the concentration of NO_x is high relative to VOCs, for example, in urban or industrial centers with high NO_x emissions, reducing VOC emissions can effectively cut ozone because production is limited by the quantity of available VOCs. In these cases, focusing primarily on control of VOC emissions is the correct strategy for reducing ozone concentrations.

On the other hand, where the relative concentration of VOCs is high and the level of ozone is thus "NO_x-limited," NO_x reductions must be a critical part of an ozone reduction strategy. NO_x-limited conditions occur in some cities and in most rural areas. As an air mass moves away from industrial districts and out over suburban or rural areas downwind of pollutant emission centers, conditions tend to become more NO_x-limited because NO_x disappears from the air through chemical and physical processes more rapidly than do VOCs.

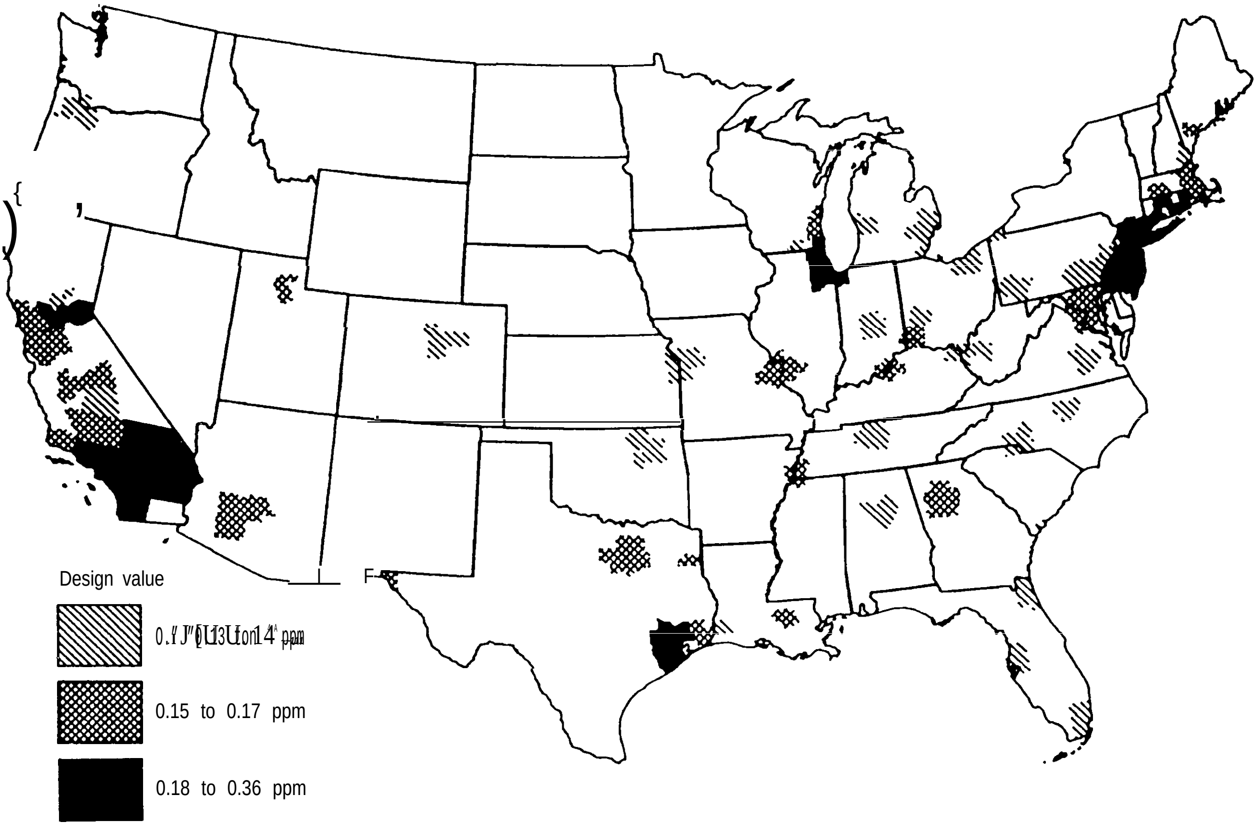
Controlling Volatile Organic Compounds

Since 1970, reducing VOC emissions has been the backbone of our national ozone control strategy, and the Nation has made substantial progress, at least in slowing further degradation from preexisting conditions. According to EPA estimates, while VOC emissions have remained relatively constant over the last decade, they are about 40 percent lower than they would have been without existing controls. Despite this progress, however, large areas of the country have missed each of several 5- and 10-year deadlines set by Congress-first the original deadline of 1975, and again in 1982 and 1987.

Additional progress is still possible in this area. Total manmade VOC emissions, according to OTA estimates, will remain about the same for about a decade. Substantially lower emissions from cars and trucks should offset sizable increases from stationary sources. But total emissions will begin rising again by around 1995 to 2000, assuming that State and EPA regulations remain unchanged.

[6] Although NO_x is an ozone precursor, it also can destroy ozone when NO_x/VOC ratios are high.

Figure 2-2—Areas Classified as Nonattainment for Ozone Based on 1983-85 Data



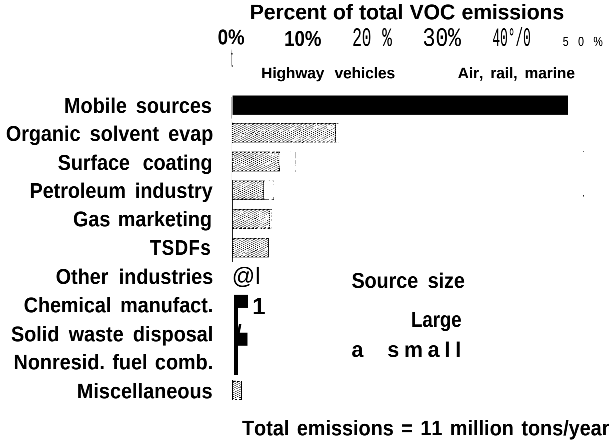
The shading indicates the fourth highest daily maximum 1-hour average ozone concentration, or "design value," for each area.

SOURCE: Office of Technology Assessment, 1989.

Today, as shown in figure 2-3, emissions from mobile sources, surface coating such as paints, and other organic solvent evaporation together account for about two-thirds of all manmade VOCs. Highway vehicles alone contribute about 40 to 45 percent of the total. The next largest category of emissions, evaporation of organic solvents, involves such diverse activities as decreasing metal parts and drycleaning, and products such as insecticides. Next come surface coatings, which include inks, paints, and various similar materials used in painting cars, finishing furniture, and other products. These sources vary in size from huge industrial installations to a person painting a chair. About 45 percent of all manmade VOC emissions originate in small stationary sources producing less than 50 tons per year; they include vapors from solvents and paints, gasoline evaporating while being pumped, emissions from printing shops and autobody repair shops, and the like.

All of the alternative fuels examined in this report have the potential to lower effective VOC emissions (either by lowering mass emissions or by producing less reactive emissions) from mobile sources by a substantial degree-on a "per vehicle basis,' some can eliminate all or virtually all of these emissions (though there may be VOC emissions from fuel production and delivery). Of course, the actual reductions in urban emissions will take place slowly, as new, alternative fuel vehicles gradually replace gasoline-fueled vehicles. Because introducing these fuels is expected to be expensive, policymakers should judge the potential costs and benefits of these fuels as compared to the potential costs and benefits of alternative methods of reducing VOC emissions.

Figure 2-3—VOC Emissions in Nonattainment Cities, by Source Category, in 1985



Stationary sources that emit more than 50 tons per year of VOC are included in the "Large" categories.
SOURCE: Office of Technology Assessment, 1989.

In its recent study *Catching Our Breath: Next Steps for Controlling Urban Ozone,* OTA analyzed about 60 currently available control methods that together deal with sources producing about 85 percent of current manmade VOC emissions (included among these methods is methanol in fleet use; methanol in general use and the other fuels examined in this report were not considered ''currently available" in *Catching Our Breath).* We believe that the potential exists, using these various controls, to lower summertime manmade VOC emissions in nonattainment cities in the year 1994 by about 35 percent compared to the 1985 level. A reduction of this size would equal approximately two-thirds of all the reductions needed, on average, to allow nonattainment cities to meet the standard. According to our analysis, if all currently available controls are applied, total VOC emissions in the nonattainment cities will fall by about 3.8 million tons per year by 1994; the exact figure could be as low as 1.5 million tons or as high as 5.0 million tons, depending on the accuracy of our assumptions.

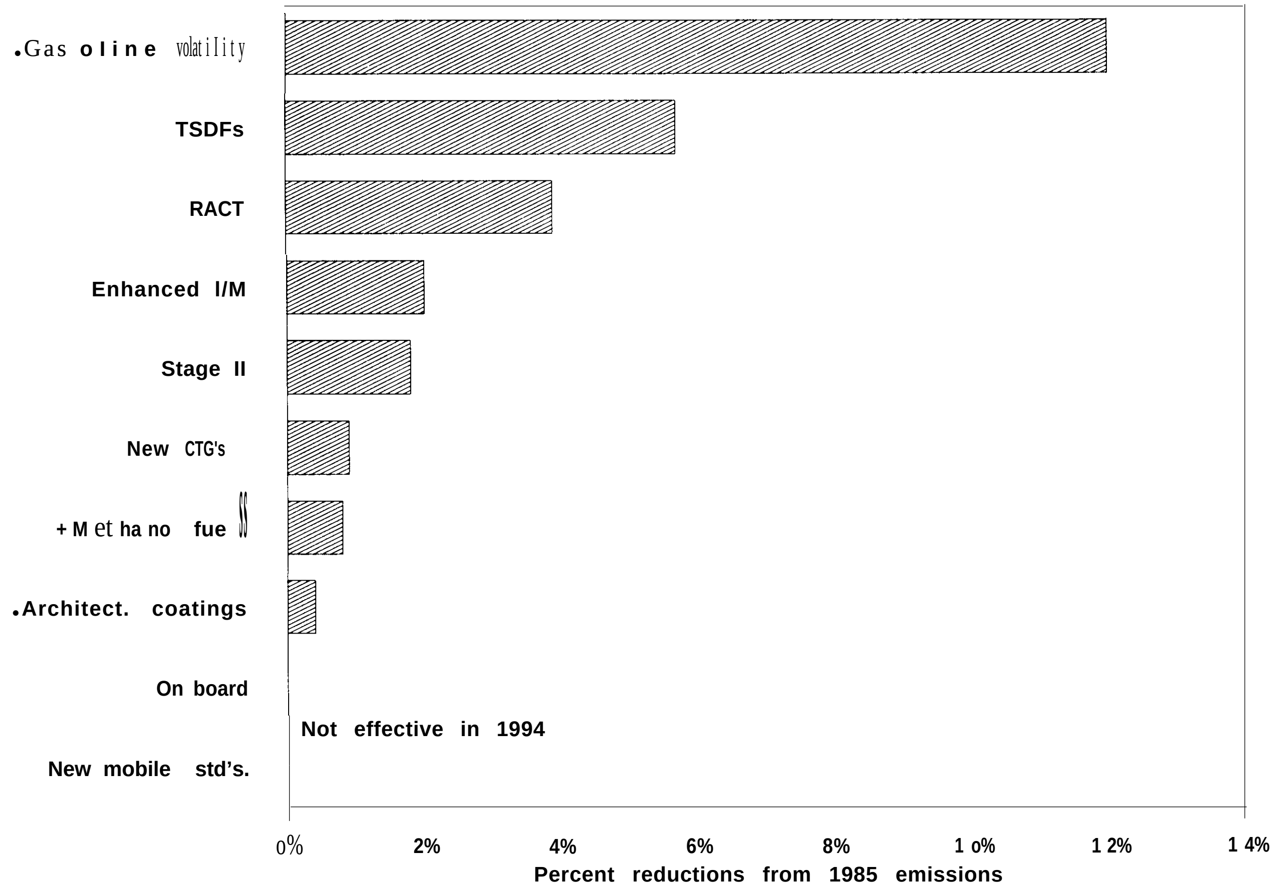
All cities, however, would not benefit equally from these reductions. If those with current design values (peak ozone concentrations) of 0.14 ppm were to implement all the VOC control methods we analyzed, most could achieve ozone levels at, or even below the standard. Cities with current design values of 0.16 ppm or higher would likely fall short, and in some cases far short, of the needed reductions.

Each of the 60 control methods analyzed contributes to the 35-percent reduction from 1985 levels that we foresee happening in nonattainment cities, as shown in figure 2-4. The most productive method, yielding 12 percent in reductions (about one-third of the total) on a hotsummer day, requires reducing the volatility of the Nation's motor fuels. Less volatile gasoline[7] would curtail evaporation emissions (including so-called ''running losses' while the vehicle is moving) and would lower exhaust emissions. An additional 6 percent in reductions could come from stricter controls on facilities that store, treat, and dispose of hazardous wastes. Another 4 percent could come from applying all 'reasonably available control technology' (RACT-level) controls now found in *any* State's ozone control plan to *all* nonattainment areas' sources larger than 25 tons. About 40 types of sources, such as petroleum refineries, chemical manufacturers, print shops, and drycleaners, would be included.

A 2-percent reduction would come from enhanced programs to inspect cars and trucks and require maintenance of faulty pollution controls. This is over and above the reductions achieved by the inspection and maintenance programs in operation today. Modifying the nozzles of gas station pumps to trap escaping vapors (installing 'Stage II gasoline vapor recovery systems") would yield another 2-percent reduction. Installing devices to do the same job on individual vehicles as they fuel up ("onboard technology") would produce about the same reductions 8 to 10 years later, as newer cars that have the devices replace older ones that do not. (The two methods together would yield only slightly greater reductions than either method alone.) Adopting new ''control technique guidelines' for smaller (but still larger than 25 tons) categories of stationary sources not already controlled in some ozone control plans, such as autobody refinishing and wood furniture coating shops, coke oven byproduct plants, bakeries, and the like, would account for an additional 1 percent. Another 0.5-percent reduction can be had in the worst nonattainment areas by requiring businesses that operate fleets of 10 or more vehicles

[7] In our analysis, we assume that gasoline volatility is reduced to 9 pounds per square inch (psi) Reid Vapor Pressure (RVP), nationwide, during the 5-month summertime period when ozone concentrations most often exceed the standard.

Figure 2-4—VOC Emissions Reductions in 1994 Compared to 1985 Emissions, by Control Method



•Emissions reductions also achieved in attainment areas.

+ Percent reductions only in those cities in which it is adopted.

Strategy Descriptions

Gasoline volatility controls which limit the rate of gasoline evaporation.
TSDF = controls on hazardous waste treatment, storage, and disposal facilities.
RACT = "Reasonable Available Control Technology" on all existing stationary sources that emit more than 25 tons per year of VOC.
Enhanced inspection and maintenance (i/M) programs for cars and light-duty trucks.
Stage ii control devices on gas pumps to capture gasoline vapor during motor vehicle refueling.
New CTGs = new Control Technique Guidelines for several categories of existing stationary sources for which no current regulations exist.
Methanol fuels as a substitute for gasoline as a motor vehicle fuel.
Federal Controls on architectural surface coatings.
Onboard controls on motor vehicles to capture gasoline vapor during refueling.
New **highway-vehicle emission standards** for passenger cars and light-duty gasoline trucks.

SOURCE: Office of Technology Assessment, 1989.

in those areas to substitute methanol for gasoline. Limits on the solvent content in architectural coatings such as paints and stains would lower emissions by 0.5 percent. Finally, more stringent standards for tailpipe emissions from gasoline-powered cars and light-duty trucks[8] would lower emissions by 1.5

[8] The emission standards used in our analysis are as follows:
(in grams of pollutant emitted per mile traveled (g/mile) for non-methane hydrocarbons (NMHC) and NO_X)
Passenger cars—NMHC: 0.25 g/mile; NO_X: 0.4 g/mile
Light-duty gasoline trucks (by truck weight>
(up to 3,750 lbs) NMHC: 0.34 g/mile; NO_X: 0.46 g/mile
(3,751 to 6,000 lbs) NMHC: 0.43 g/mile; NO_X: 0.80 g/mile
(6,001 to 8,500 lbs) NMHC: 0.55 g/mile; NO_X: 1.15 g/mile
We assume that these standards can be met during 50,000 miles of *controlled test driving* (certification testing) for passenger cars, and 120,000 miles for light-duty trucks; however, VOC emission rates after 50,000 miles (for cars) and 120,000 miles (for trucks) of *actual* use by vehicle owners would likely exceed these standards. We assume that new standards go into effect in 1994 for both passenger cars and light-duty trucks.

percent by 2004 as new cars and trucks enter the Nation's vehicle fleet. Some of these and the other options can be implemented by the States in nonattainment areas alone, others are better suited to Federal implementation nationwide. Table 2-1 summarizes the options for implementing currently available control methods that may be most appropriately considered by Congress.

We can estimate the cost of applying all these controls in all nonattainment cities, bringing about half of the cities into compliance and substantially improving the air quality of the rest: between $4.3 and $7.2 billion per year in 1994 and between $6.6 and $10 billion annually by 2004, assuming the current state of technology. Because some controls would apply nationwide, rather than just in nonattainment areas, the *national* price tag would total about $8.8 to $13 billion in 2004.

Some of these controls simultaneously reduce other air pollutants in addition to VOCs. Enhanced motor vehicle inspection and maintenance programs also reduce nitrogen oxides and carbon monoxide. More stringent highway vehicle standards apply to nitrogen oxides, too. About $2.5 billion of the total cost in 2004 can be assigned to nitrogen oxide control, the benefit of which will be discussed later. About $1.5 billion per year can be assigned to control of carbon monoxide.

Depending on the method used, the cost of eliminating a ton of VOC emissions varies considerably. By far the cheapest is limiting fuel volatility, at about $120 to $750 per ton of VOC reduction; replacing gasoline with methanol or some other alternative fuel could be far more expensive than this, but the potential to lower fuel costs *in the long term* might eventually bring the "per ton" costs down to a range competitive with the other methods. The cheaper methods of reducing VOCs can provide reductions equal to about 25 to 30 percent of the 1985 emissions levels at total costs of $2 to $3 billion. As more reductions are required, though, more and more expensive methods must come into play, and the cost of additional reductions rises steeply.

Most of the control methods we analyzed cost between $1,000 and $5,000 per ton of VOC reductions obtained. We estimate that in 1994, if controls costing more than $5,000 per ton of reductions were excluded from consideration, total annual costs for the nonattainment areas would drop to about $2.7 to $5.1 billion per year, a drop of about 30 to 35 percent. There would be a corresponding loss in reductions of about 2 percent of 1985 emissions.

Table 2-l—Options for Amending the Clean Air Act: Currently Available Control Methods

Federally implemented, nationwide control requirements:
- Option 1: Limits on gasoline votality.
- Option 2: More stringent tailpipe exhaust standards for cars and trucks.
- Option 3: "Onboard" technology for cars and trucks to control refueling emissions.
- Option 4: Federal solvent regulations for example, for architectural coatings.

Control requirements to be implemented by States in nonattainment areas:
- Option 1: Lowered source-size cutoff for requiring "reasonably available control technology" (RACT).
- Option 2: Require EPA to define RACT for additional source categories.
- Option 3: More stringent requirements for motor vehicle inspection and maintenance programs.
- Option 4: Required use of alternative fuels by centrally owned fleets.
- Option 5: Transportation control measures.
- Option 6: Tax on gasoline.

Managing growth:
- Option 1: Lower the cutoff for new source control requirements
- Option 2: Eliminate "netting" out of new source control requirements.
- Option 3: Areawide emission ceilings.

SOURCE: Office of Technology Assessment, 1989.

All of the above costs could change if engineering advances reduce the costs of applying existing technologies, or if alternative methods and new technologies can achieve the same reductions using alternative, less costly means.

To summarize, if we are willing to use and pay for currently available technology, we can make significant advances over the next 5 to 10 years, achieving about two-thirds of the emissions reductions in nonattainment areas that we need. This should bring about half of the current nonattainment areas into compliance. But we cannot, by the year 2000, get the entire Nation to the goal that Congress established in 1970. In the worst areas, even the most costly and stringent of available measures will not lower emission levels sufficiently to meet the standard. Achieving that goal is a long-range project, well beyond the 5- and 10-year horizons of existing law. It will require both new technologies and lifestyle changes in the most affected communities, including changes in transportation, work, and housing patterns. In other, less polluted nonattainment areas, the standard can be met with less cost and disruption.

To meet the ozone standards in all cities, we must turn to new, nontraditional controls, with uncertain costs. With application of all of the traditional controls discussed above, by 1994, about 60 percent of the remaining manmade VOC emissions will come from small stationary sources that individually emit less than 25 tons per year. Over half of this latter category will come from surface coatings and other organic solvent evaporation.[9] In addition, between 25 and 30 percent of the remaining emissions will come from highway vehicles. Efforts to further reduce VOC emissions must focus on these sources. Table 2-2 summarizes the nontraditional VOC controls as well as other new options for controlling levels of urban ozone.

Regulators will face difficult problems in trying to control emissions from these sources. For example, to further reduce solvent emissions, regulators face the challenge of encouraging development of an enormous variety of new products, manufacturing processes, and control methods. One possible approach is applying existing controls to smaller sized commercial and industrial sources. This is no easy task for regulators, however, because hundreds of thousands of firms in nonattainment areas individually use small quantities of solvents. Another approach is to place limits on the permissible VOC content of certain products and processes; those that exceed the limit after a specified date would be banned from sale. These two strategies are variations on established 'engineering' techniques of regulating users. Also, market-based approaches could be used. For example, emission fees or marketable emission permits could be established to discourage use of products high in VOCs by making it more profitable to use substitutes. And in areas where consumer environmental interest and activism is strong, product labeling designed to identify "low emission" products could be a useful strategy.

Cutting the use of motor vehicles, especially private cars, is another way to lower VOC emissions. Although technologically simple, it is politically difficult. The 1977 Amendments to the Clean Air Act required urban areas to implement transportation control measures (TCMs) necessary to meet ozone and carbon monoxide standards. Experience shows, though, that TCMs require considerable local initiative and political will because they aim to change the everyday habits and private decisions of hundreds of thousands of people. Involuntary TCMs have proven politically infeasible and voluntary programs difficult to sustain. Success requires long lead times, high priority in urban transportation and land-use planning, a high degree of public support and participation and, in some cases such as mass transit development, major capital expenditures. Possible tactics include requiring staggered work hours; encouraging carpools through inducements like priority parking places, dedicated highway lanes and reduced tolls; constructing attractive and economical mass transit systems; limiting available

Table 2-2—Options for Amending the Clean Air Act: New Directions

Controls on emissions of nitrogen oxides in nonattainment areas:
- **Option 1: Congressionally mandated NO_x controls.**
- **Option 2: Presumptive NO_x controls on stationary sources, with EPA authority to exempt areas under specified situations.**
- **Option 3: Requirements to analyze NO_x controls under certain situations.**

Long-term control VOC strategies:
- **Option 1: Lowering emissions from solvents, either through traditional "engineering" approaches or through market-based mechanisms.**
- **Option 2: Transportation control measures.**
- **Option 3: Requirements for widespread use of alternative fuels in nonattainment areas that are far from meeting the standard.**

Controls in upwind areas:
- **Option 1: Enlarge nonattainment areas to include the entire extended metropolitan area.**
- **Option 2: Congressionally specified NO_x controls in designated "transport regions" or nationwide.**
- **Option 3: Strengthen the interstate transport provisions of the Clean Air Act.**
- **Option 4: Provide EPA with clear authority to develop regional control strategies based on regional-scale modeling.**

Reducing ozone in attainment (rural) areas:
- **Option 1. Specify a deadline for EPA reconsideration of the ozone secondary standard and a schedule for options by the States.**
- **Option 2. Congressionally specified NO_x controls.**

Research:

Decision 1: What areas of research deserve increased funding?
- **Improving the planning process, developing new control methods, and further evaluating the risks from ozone.**

Decision 2: Who pays for the research?
- **Option 1: General revenues.**
- **Option 2: User fees.**

SOURCE: Office of Technology Assessment, 1989.

[9] Solvents are used in a wide variety of industrial, commercial, and home uses, from cleaning and decreasing heavy equipment to washing paintbrushes and removing spots from garments. They appear in thousands of commercial and consumer products such as personal-care products, adhesives, paints, and cleaners used daily throughout the country. They are used by manufacturers to paint or otherwise coat cars, appliances, furniture, and many other products in facilities that range from the huge to the tiny.

parking places; and encouraging employers to locate closer to residential areas, which would cut distances workers have to travel.

Controlling Nitrogen Oxides

Historically, ozone control efforts have concentrated on VOC emission reductions both because methods were thought to be cheaper and more available and because in some cases reducing NO_x may actually be counterproductive. As mentioned earlier, however, many areas of the country, especially rural areas but some cities as well, have mixtures of high atmospheric levels of VOCs in relation to NO_x levels, creating conditions where ozone concentrations are limited by NO_x rather than VOC. In these areas, successful reduction in ozone concentrations requires control of NO_x emissions beyond current requirements.

Two types of sources, highway vehicles and electric utility boilers, account for two-thirds of NO_x emissions. Highway vehicles contribute about a third of the national total, led by passenger cars with 17 percent and heavy-duty diesel trucks with 9 percent. In the southern California cities with design values above 0.26, highway vehicles account for about two-thirds of local NO_x emissions; in most nonattainment cities, they contribute about 30 to 45 percent.

Under current regulations, total NO_x emissions will increase steadily between 1985 and 2004, rising by about 5 percent by 1994 and by about 25 percent by 2004. (See figure 2-5.) As newer, cleaner cars replace older ones, highway emissions will decline until the mid- 1990s, only to rise again as miles traveled increase. Stationary sources, however, will increase their emissions steadily.

The impacts of controlling NO_x emissions in nonattainment areas will vary from city to city. preliminary analyses indicate that in most southern cities (from Texas east), NO_x reductions would help reduce ozone concentrations; in most isolated Midwestern cities, however, they might have the opposite effect. Recent results from EPA's Regional Oxidant Model (ROM) simulating ozone formation and transport throughout the Northeast over a 2-week period, indicate that in this region, results will be mixed. Overall, a one-third cut in NO_x emissions on top of a 50-percent reduction in regionwide VOC emissions resulted in modest ozone benefits for most nonattainment cities, compared to a case where VOC emissions were controlled alone. A detailed examination, however, shows considerable variation among cities. Adding NO_x controls *increased* population exposure to ozone at concentrations above the standard in some cities (e.g., Pittsburgh), decreased population exposure in some (e.g., Hartford), and resulted in negligible changes in others (e.g., New York). Further regional and city-by-city modeling is necessary to verify these conclusions.

NO_x emissions affect more than just nonattainment area ozone concentrations, complicating the decision about whether to mandate controls. NO_x emissions contribute to acid deposition and are a major determinant of elevated ozone concentrations in agricultural and forested regions. Though NO_x reductions can have either a beneficial or detrimental effect on peak ozone concentrations in nonattainment areas,[10] they will most likely lower both acid deposition and regional ozone concentrations.

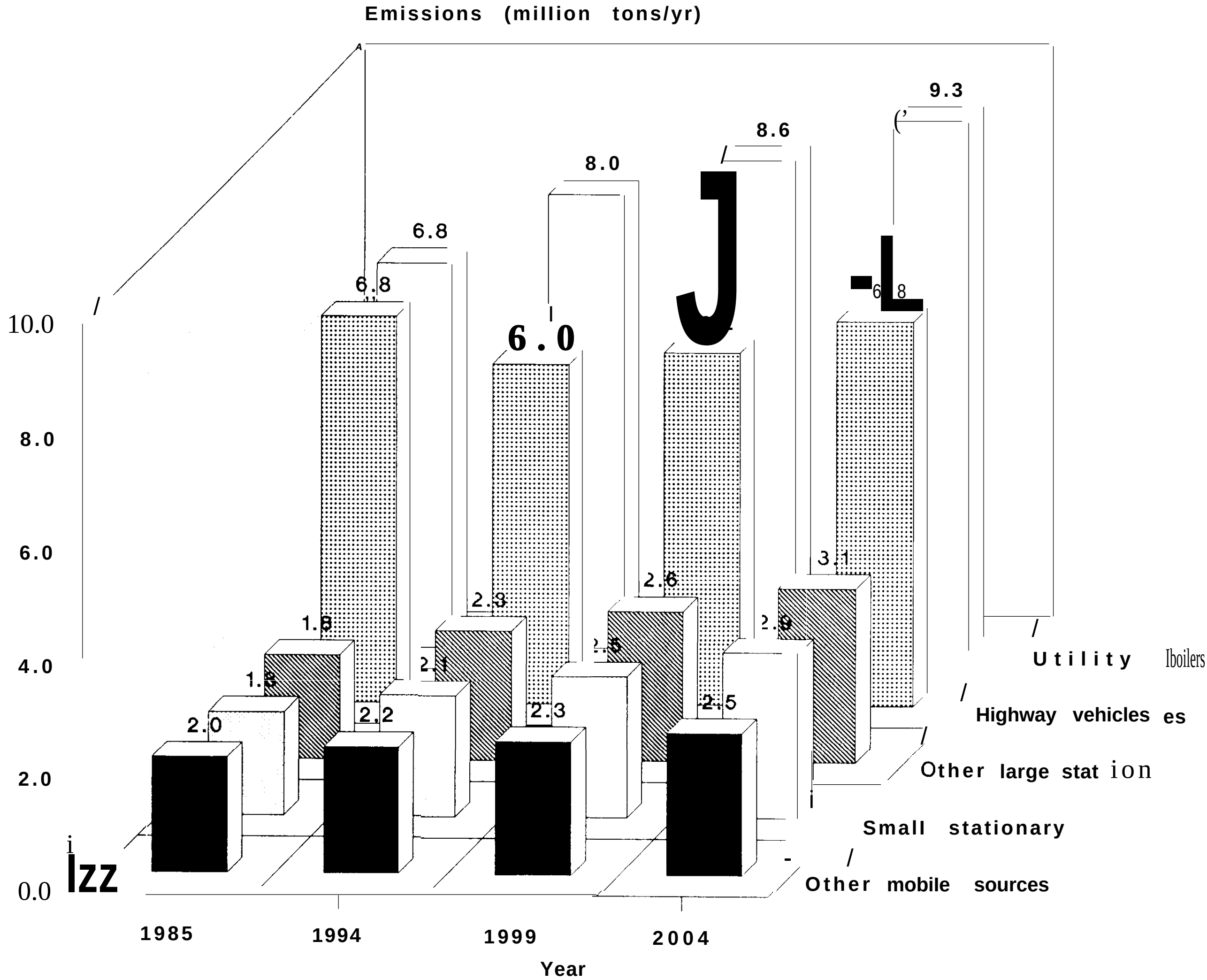
The Role of Alternative Fuels

Recent promotion of alternative fuels has been based on their potential to reduce urban ozone, through reductions in "effective" VOC emissions, that is, reductions in actual VOC emissions by weight and/or reductions in the reactivity of the VOCs that are emitted. In addition, EPA and others view a major benefit of alternative fuels to be their elimination or reduction of toxic emissions of benzene, gasoline refueling vapors, 1,3-butadiene, and polycyclic organic matter.[11] All of the fuels examined in this report have, to differing degrees, some potential to yield reductions in effective emissions of VOCs if used appropriately, and all should reduce toxic emissions (except for aldehydes) as well. On the other hand, most of the fuels do *not* automatically yield reductions in NO_x, and some may add to NO_x emissions under certain conditions. The emissions characteristics of the fuels are examined in the chapters that follow.

[10] The detrimental effect occurs at certain conditions with high atmospheric ratios of NO_x to VOCs.

[11] Environmental Protection Agency, *Analysis of the Economic and Environmental Effects of Methanol as an Automotive Fuel*, Special Report, Office of Mobile Sources, September 1989.

Figure 2-5-Summary of Estimated Nationwide Nitrogen Oxides (NO_x) Emissions by Source Category, by Year



The numbers directly above the boxes are the total emissions within the source category. For example, emissions from highway vehicles in 1994 are 6.0 million tons per year, nationwide. Assumes no new laws or regulations.

SOURCE: Office of Technology Assessment, based on work by E.H. Pechan and Associates.

The complexity of the relationship between urban ozone, local VOC concentrations, local NO_x concentrations, and long-range transport of ozone froms other areas implies that the use of alternative fuels will have substantially different impacts on urban ozone concentrations from city to city and area to area. In cities such as Los Angeles, with high NO_x concentrations and ozone levels limited primarily by VOC levels, the reduction in effective VOC levels likely to accompany large-scale use of alternative fuels should yield a significant reduction in ozone levels.

In areas with high background levels of VOC and lower NO_x levels, reductions in effective VOC emissions will be less successful in reducing ozone concentrations. In cities such as Houston and Chicago, and in most rural areas, the widespread use of alternative fuels is likely to have far less effect on ozone levels than similar use would have in VOC-limited areas. In fact, under some circumstances, attempts to gain maximum efficiency from vehicles using alcohol fuels or natural gas might interfere with stringent control of NO_x emissions from these vehicles, and ozone reduction efforts actually might suffer slightly from use of such fuels.

ENERGY SECURITY IN PERSPECTIVE

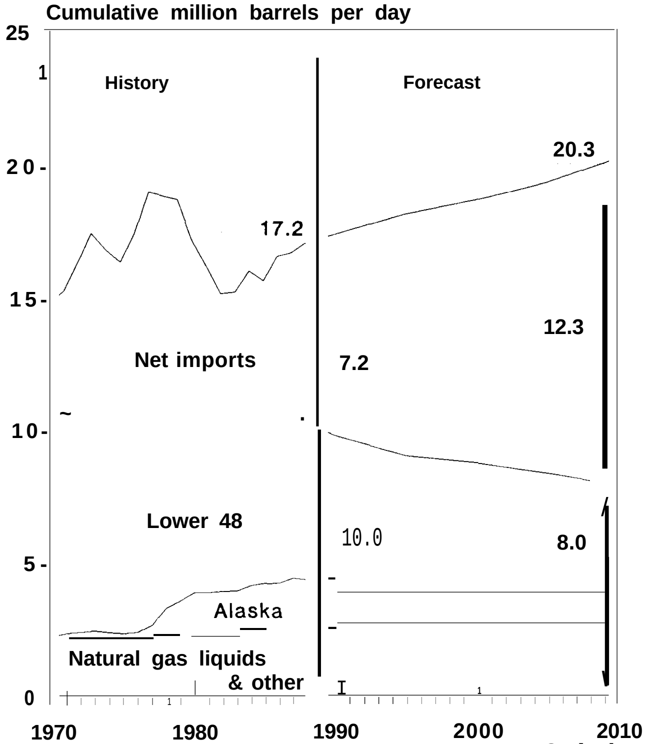
Many supporters of alternative fuels programs argue that introduction of such fuels to the highway fleet would provide substantial positive benefits to U.S. energy security, breaking oil's monopoly on highway transportation and providing an expandable new source of fuel in case of an oil supply disruption. Whether energy security benefits provide a powerful motive for government support of alternative fuels depends on the security risks actually faced by the United States, and the ability of alternative fuels to combat these risks.

Should Energy Security Be a Major Concern for U.S. Policymakers?

To the extent that projections of continued reductions in domestic oil production and continued increases in U.S. and worldwide oil demand are correct-and we believe they *are* correct[12]--the United States has already resumed relatively high levels of oil imports from politically insecure sources (figure 2-6 shows the Energy Information Administration projections for future U.S. oil import levels). Congress clearly viewed the high levels of oil imports of the 1970s as a threat and responded with extensive legislation, including programs to promote synfuels development, tax incentives for energy conservation and alternative energy sources, an extensive energy R&D program, and the establishment of the Strategic Petroleum Reserve (SPR). In addition, Congress appropriated funds to establish military forces specifically designed to deal with threats far from established U.S. military bases, and, in particular, the Middle Eastern oilfields.

Industry supporters of congressional measures to fight increases in U.S. oil imports-such as opening environmentally sensitive areas to oil development, establishing tax incentives for increased domestic production, shifting from gasoline to nonpetroleum fuels, and so forth-have portrayed the potential increases in precisely the same manner, i.e., as a serious threat to the security and long-term economic interests of the United States. These supporters have pointed to the United States' large expenditures during the Iran/Iraq war in protecting U.S. flagged tankers in the Persian Gulf as one cost of growing U.S. oil import dependency. The fact that the United States is now deeply embroiled in a mideast conflict is another ''cost' that can be attributed to the United States' import dependency.

Figure 2-6--EIA Projections of Petroleum Supply, Consumption, and Import Requirements to 2010, Base Case



SOURCE: Energy Information Administration, *Annual Energy Outlook, 1990.*

It is important to recognize, however, that there are important differences between oil *dependency* and oil *vulnerability*. Dependence is simply the portion of total U.S. oil supplies that must be imported. Vulnerability, on the other hand, is not nearly so well-defined, but clearly is associated with the kind of damage that the United States would incur in the event of an oil shortage or price shock, and the risk of such an event.[13] The United States is vulnerable to economic and military disruptions

[12] We do believe, however, that there are available policy measures that could slow, but not stop, the oil production decline and reverse the trend of increasing U.S. oil demand.

[13] See R.L. Bamberger and C.E. Behrens, "World Oil and the ANWR Potential,' Congressional Research Service Report 87-438 ENR, May 21, 1987, for more discussion on this theme. Also, OTA has evaluated the U.S. oil replacement capability in the event of an oil supply shortfall of indefinite duration; see U.S. Congress, Office of Technology Assessment, ***U.S. Vulnerability to an Oil Import Curtailment; The Oil Replacement Capability, OTA-E-243*** (Springfield, VA: National Technical Information Service, September 1984).

associated with Persian Gulf instability whether it is importing 30 percent of its oil or 70 percent, because any price increases attributable to that instability will affect all world oil supplies simultaneously and because U.S. agreements with its allies require sharing the effects of any widespread shortages.

This is not to say that the two import levels are identical in their implications. In particular, lower imports would reduce pressures on worldwide oil supply, lowering the probability of a disruption in supplies and/or a rapid price increase. Also, higher oil prices would likely damage a U.S. economy importing 70 percent of its oil more than the economy importing 30 percent, because more of the added energy expenditures would remain inside U.S. borders in the latter case. And if a percentage of U.S. highway travel relied on fuels whose prices were somewhat buffered from world oil prices-which is possible under certain circumstances[14]--the economic impact of an oil price shock would be still less.

Policymakers should also avoid attributing to U.S. oil vulnerability all costs of actions such as those of the United States in the Persian Gulf. Clearly, other geopolitical considerations were at stake here, including a desire to avoid allowing the Soviet Union the primary role in defending Kuwaiti shipping interests.

Furthermore, the United States' balance between domestic and imported energy is enviable compared to most of the developed world. Whereas U.S. oil imports for 1989 were about 46 percent of oil consumption (and less than 20 percent of total energy consumption), the European Organization for Economic Cooperation and Development (OECD) nations import about two-thirds of their oil, and Japan imports all of its oil and most of its energy. However, this difference might be interpreted in the opposite fashion: that it illustrates further the United States' dilemma, because of our close economic and military ties to the OECD nations.

Regardless of these arguments, what direct economic costs would the United States incur in the event of another oil price ''shock"? There appears to be a general consensus among U.S. energy policy analysts that the costs the United States actually incurred as a result of the earlier oil disruptions of 1973 and 1979 were very large, in terms of both inflationary impacts and the recessions that followed, and that these costs were caused by the rapid oil price rises that accompanied the disruptions. Although we are not prepared to dispute this point, we note that studies at Resources for the Future (RfF) of the relationship between the oil price shocks of the 1970s and the recessions that followed concluded that the shocks themselves had essentially no important adverse effects on output and employment in the United States and other industrial countries, and that the most likely cause of the worldwide recessions that followed the shocks were the very monetary and fiscal policies adopted to fight the effects of the shocks.[15] Because this alternative view of the danger of future price shocks leads to drastically different conclusions about energy policy than implied by the more conventional view, we hope that the RfF report will generate a vigorous, open-minded debate about the vulnerability of the U.S. economy.

If we, for prudence's sake, take the more conventional view of the danger of future oil price shocks, there is little doubt that an oil security threat to the United States still exists. The four basic elements to this threat-the dependence of the U.S. transportation sector on petroleum; the United States' limited potential to increase oil production; the preponderance of oil reserves in the Middle East/Persian Gulf (see figure 2-7); and the basic political instability and considerable hostility to the United States existing there-are as true today as they were in the early 1970s at the time of the Arab oil boycott.

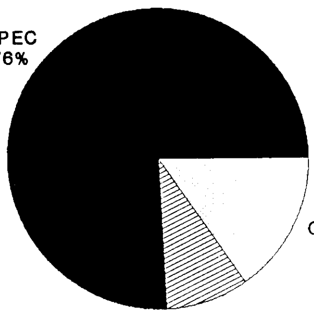
In fact, in some ways these elements have grown more severe. For example, during the past 10 years, the transportation sector's share of total U.S. petroleum use has grown from 54 to 64 percent.[16] This is particularly important because the sector's prospects for fuel switching in an emergency are virtually zero. In addition, the boom and bust oil price cycle of the post-boycott period, and especially the price drop of 1985-86, may have created a wariness in the oil

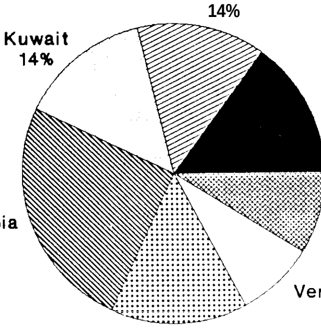
[14]For example, if feedstocks for producing the fuel had few other competitive uses, and if the vehicles using this fuel were dedicated rather tin flexible fuel.

[15]D.R. Bohi, *Energy Price Shocks and Macroeconomic Performance* (Washington, DC: Resources for the Future, 1989).

[16]Energy Information Administration, *Annual Energy Review 1985*, DOE/EIA-0384(85), May 1986, and *Annual Energy Outlook 1990*, DOE/EIA-0383(90), January 1990.

Figure 2-7—Distribution of World Oil Reserves, 1988





SOURCE: Arthur Anderson & Co./Cambridge Energy Research Associates.

industry that would substantially delay any major boost in drilling activity in response to another price surge. And, with the passage of time, the industry's infrastructure, including skilled labor, that would be needed for a drilling rebound is being eroded.[17]

Thus, if the United States is moving towards an energy situation similar to the one it faced in the 1970s, it may be facing severe economic risks. Therefore, an examination of any differences between the U.S. and world energy situation in the '70s and the situation today is an important element of evaluating U.S. vulnerability. There are several areas in which important differences may exist.[18]

Petroleum Stocks

First, the United States now has a Strategic Petroleum Reserve containing in excess of 580 million barrels of crude oil,[19] the equivalent of about 81 days of oil imports at 1989 levels.[20] Similarly, Europe and Japan have also added to their strategic storage; the International Energy Agency countries, excluding the United States, had accumulated government owned and controlled stocks of about 360 million barrels by 1986.

Private stocks are also important. Currently, private stock levels in the United States are similar to levels in the early 1970s—a bit over 1 billion barrels.[21] Because stock levels were higher in the middle to late 1970s, averaging over 1.3 billion barrels in 1977, 10-year comparisons imply that private stocks have declined, nullifying some of the benefit of the SPR. Oil company analysts claim that the stock "decline" is due to the rationalizations of refining capacity and markets that have occurred during this time period, and that the minimum working stock needed in the supply system has declined. This explanation appears logical; however, a detailed analysis of private petroleum stock changes during the past decade and a half might be useful.

The value of substantial oil stockpiles in mediating the adverse effects of an oil disruption will be determined by the actual strategy used during a crisis. Ideally, stockholders will gradually release

[17] For a discussion of the problems faced by the U.S. oil industry in the face of low world oil prices, and the effects on production, see U.S. Congress, Office of Technology Assessment. *U.S. Oil Production: The Effect of Low Oil Prices-Special Report, OTA-E-348* (Washington DC: U.S. Government Printing Office, September 1987).

[18] For a more detailed discussion of shifts in world oil markets, we recommend the General Accounting Office's report Energy *Security: An Overview of Changes in the World Oil Market,* August 1988.

[19] 580.2 million barrels as of January 1990. Energy Information Administration, *Weekly Petroleum Status Report,* data for week ended Jan. 26, 1990, DOE/EIA-0208(90-06).

[20] The average import rate for the first 11 months of 1989 was 7.16 mmbd. Ibid.

[21] Ibid.

their holdings to the market-ruse the stored oil as their supply source-in the aftermath of a decline in general oil availability. However, some stockholders may act to hold their stored oil-or even to increase the level of storage—if they perceive that oil prices will rise in the future. If hoarding is a widespread behavior, any adverse effects of an oil supply disruption will be magnified.

Diversification of Oil Production

Second, world oil production has become substantially more diversified since the '70s, with OPEC's share of the world oil export sales declining from 82 percent in 1979 to approximately 61 percent today,[22] and its share of total production dropping from 49 percent to 32 percent in the same time period.[23] For several years, at least, no single country or cohesive group of countries can control as large a share of the world market as was possible previously. Furthermore, there are new doubts about earlier assumptions that low oil prices would lead to contracting world oil supplies. In some of the higher cost oil producing areas, eased government taxes and royalties and extensive industry cost-cutting efforts have greatly reduced oil development costs, offsetting much of the damage to oilfield development prospects caused by falling prices.[24] Also, many analysts had previously assumed that the OPEC nations would not further expand their production capacities. It is now more widely recognized that the maintenance of excess capacity is important to retaining power within the OPEC organization, and OPEC nations may be likely to expand capacity rather than relinquish control. In addition, the cessation of hostilities between Iran and Iraq have given these countries the breathing space necessary to expand their production capabilities, with Iran having no outside source of income for rebuilding and thus turning to potential oil revenues as its primary source of capital, and both Iran and Iraq having added substantially to their reported proved reserves, which, combined, now rival those of Saudi Arabia.[25] If total OPEC production capacity grows rather than contracts, assumptions about the ' 'using up" of OPEC's excess production capacity and the return of market power to the Middle East—the centerpiece of "conventional wisdom' warnings about future price increases—may be inaccurate.

Published projections of short-term trends in world crude production capacity support this view. The Energy Information Administration (EIA), for example, expects non-OPEC crude production to grow by about 600,000 barrels/day in 1990 and remain steady through the early 1990s despite slippage in the United States' capacity.[26] EIA expects OPEC production capacity to grow by over 1 million barrels per day (mmbd) in 1990 and then continue to grow for the indefinite future.[27]

In counterpoint to this view is the expectation that the oil production rates of both the Soviet Union and Great Britain, in addition to the United States, will soon be in serious decline. In the early 1970s, prospects for these important regions were positive, in contrast. In addition, the number of areas that remain unexplored and unexploited is much lower now than it was in the early 1970s. This is a critical factor, because it implies that a future price increase would be less likely to stimulate new supplies than previously.

Reversibility of Demand

Third, there have been changes—both positive and negative—in the ability of the economies of both the United States and the remainder of the Free World to reverse a portion of any increase in oil consumption. On the negative side, as noted previously, the U.S. transportation sector's share of total oil use increased from 54 to 64 percent over the past 10 years. Because transportation fuel use is essentially locked into petroleum for all but the long term, this shift has hurt the economy's ability to switch from oil. On the positive side, in the U.S. industrial

[22] The Middle East's share of world trade was 58 and 42 percent, respectively.

[23] Arthur Andersen & Co. and Cambridge Energy Research Associates, *World Oil Trends, 1988-1989 Edition*, table 16.

[24] Areas where oilfield development originally thought to require $25/bbl oil has continued at prices well below $20/bbl include several North Sea fields and a number of development projects on the North Slope of Alaska.

[25] According t. *World Oil* Trends, *1989-1990* Edition , op. cit., footnote 23, table 21, Iran and Iraq essentially doubled their reported oil reserves between 1987 and 1988, from a combined 95.9 billion barrels to 192.9 billion barrels. By comparison, Saudi Arabia had 169.6 billion barrels of reserves in 1988, though it revised its estimated reserves upwards in January 1989, to 255.0 billion barrels (Energy Information Administration *International Energy Annual 1988, DOE/EIA-0219(88),* November 1989).

[26] Energy Information Administration, *International Energy Outlook 1990*, DOE/EIA-0484(90), March 1990, table A2.

[27] Ibid., table B3.

sector, shifts to oil for a boiler fuel can be readily reversed with a shift back to coal or natural gas. During the past decade, industry has made a vigorous effort to insure that its boiler capacity has rapid fuel-switching capability. Similarly, in the electric utility sector, a portion of increased oil use has involved the use of existing oil-fired generating capacity—removed from baseload service when oil prices rose in the 1970s—in place of coal, gas, or even nuclear plants. As long as the industry retains excess generating capacity, this use can also be reversed. The steady decline of the utility sector's excess capacity is diminishing the potential for reversal, however.

Another threat to reversibility is the potential for inadequate supplies of natural gas resulting from the same drilling slowdown acting to reduce oil production. A gas supply shortage is a realistic possibility only in the United States, as world gas reserves have expanded substantially and, generally, adequate supply seems assured. There is considerable controversy about U.S. gas supply adequacy for the future. Some analysts are projecting an imminent market tightening if gas prices stay low, followed by supply problems as domestic production capability continues to decline. Others claim, however, that significant gas shortages (excepting short-term seasonal shortages) are extremely unlikely, because additional large volumes of gas can be made available rapidly if markets tighten, by increasing import levels and by developing reserves now kept out of the market by low demand and inadequate price. Furthermore, even at reduced drilling rates, trends in gas reserve additions have rebounded this year, and continued progress in recovery of unconventional gas (such as coal-bed methane) is encouraging to long-term resource availability. OTA agrees that prospects for ample natural gas supplies, although still somewhat uncertain, have improved greatly during the past decade.

Experience

Fourth, the United States and its allies have undergone two major price shocks in the recent past, and this additional experience, as well as a series of international agreements on oil sharing, may assist them in a future supply crisis. Many oil experts are skeptical about the usefulness of these agreements, however. A special concern is the difficulty of defining the market conditions that constitute an actionable disruption; in particular, the relationship between the magnitude of supply reductions and the economic impact of those reductions has been difficult to specify.[28]

Balance of Trade

Fifth, in the 1970s some of the economic effects of oil imports, specifically those associated with the U.S. balance of trade, were offset by large trade surpluses in other sectors. The current absence of large balancing trade surpluses-in 1989, the United States ran a merchandise trade of $111 billion and paid $44.7 billion for its oil imports[29]--may change the relative importance of oil imports to the U.S. economy and may weaken the ability of the economy to absorb the effects of a large jump in the dollar value of imports, which would occur if oil prices were to rise rapidly.

Price Decontrol

Sixth, U.S. oil prices are no longer controlled as they were during the 1970s. For years following increases in world oil prices, the price of oil products were held artificially low in the U.S. market. The result was that the potential market responses—increased production activity and decreased oil demand—were stifled. In the event of a new increase in world oil price, the market forces that act to reduce demand and increase supply will be felt in full (assuming price controls are not resumed). Similarly, the wide recognition that the Federal Government's attempts to allocate gasoline during the earlier crises were counterproductive may help prevent misguided regulatory distortions in future crises.

Market Shifts

Seventh, most of the world's oil trade now operates on the spot market, in contrast to the long-term contracts of the 1970s (a spot market is a short-term market where prospective buyers can obtain bids for immediate shipment and timely delivery of crude and petroleum products). Coupled with an active futures market, this new oil trading situation makes single country embargoes, which could never be airtight even in the past, still less of a threat. Also, because world refinery capacity is

[28]See D.R. Bohi, *Evolution of the Oil Market and Energy Security Policy* (Washington, DC: Resources for the Future, 1986).

[29]*Economic Report of the President* (Washington DC: U.S. Government Printing Off@ February 1990).

considerably more flexible in terms of the crudes that can be expected, the ability of countries to switch oil suppliers is greater than during the 1970s.[30]

Economic Limits on Producers

Eighth, the ambitious and very expensive internal development programs of the OPEC nations and the financial difficulties most have encountered in the 1980s reduce their ability to absorb a large drop in their oil revenues, making oil boycotts less likely. The OPEC countries' current account balances, which reached a high of nearly $100 billion in 1980, have been negative between 1982-87.[31] Furthermore, during the past decade and a half, several OPEC countries have invested heavily in the economies of Western oil-importing nations, and particularly in their oil-refining and marketing sectors. For example, Kuwait has established an extensive gasoline marketing network in Europe under the trade name Q8, and Saudi Arabia has large investments in the U.S. refining sector. An oil embargo could severely damage these investments.

Flexibility of Oil Transportation

Ninth, the Strait of Hormuz has become less important as a critical potential bottleneck of Persian Gulf oil supply. The Iran Iraq war and its effects on tanker traffic in the Persian Gulf stimulated the diversification of oil transport routes out of the Gulf nations. In particular, pipeline capacity capable of taking Persian Gulf oil to ports outside of the Gulf grew from less than 1 mmbd in the late 1970s to between 4.5 and 4.8 mmbd in 1987.[32] Although pipelines are vulnerable to sabotage or direct attack, damage to most pipeline segments can generally be quickly repaired; the more difficult to repair pumping stations, being limited in number, are easier to defend. Also, most of the pipeline lengths are located in Saudi Arabia and Turkey. Conventional, direct attacks within these countries would encounter serious problems, although such attacks certainly cannot be ruled out.[33]

Changing Military Power Balance

Tenth, unsettling changes in military power have occurred in the Middle East since the early 1970s. Iraq, for example, has assembled military forces large and effective enough to make outside intervention extremely costly for Western forces, should such intervention become desirable. The rise in power of the three States of Iran, Iraq, and Syria has been disproportionate to that of the other Middle Eastern OPEC nations. Furthermore, these States, and in particular Iraq, now have access to chemical arms and to long distance capability to deliver munitions by missile, putting Israeli and Egyptian civilian populations at risk. Consequently, the threat to the weaker OPEC nations of blackmail or invasion by Iraq or others has grown since the 1970s. At the time of final editing of this report, Iraq had just invaded Kuwait, with unpredictable consequences for oil supply and prices.

Natural Gas

Eleventh, intensive exploration programs during the last decade and a half have uncovered very large resources of natural gas, spread in a somewhat more diversified reamer than oil resources. This gas provides an alternative fuel to oil used in boilers in many areas, and provides a potential longer term source of fuel suitable for transportation use, as methanol, synthetic gasoline, or LNG/CNG. Although the current world gas trade is small, and local use requires capital-intensive pipeline systems, gas use is growing and its potential provides a bargaining chip in dealings between oil users and suppliers.

This variety of changes in world oil markets can be summarized as a general shift to more flexible and responsive markets, with closer economic ties between oil producers and users, leading to lower risks of market disruptions and improved capability for effective *short-term* responses to such disruptions. There is a major counterpoint to this general improvement in worldwide and U.S. oil security: the likely reduction in long-term oil production responses to significant market disruptions. In particu-

[30] W.A. Johnson, The JOFFREE Corp., "Oil: A Future Crisis in the Making?" testimony at hearings before the House Subcommittee on Energy and Power, Committee on Energy and Commerce, Mar. 23, 1987.

[31] Arthur Andersen & Co. and Cambridge Energy Research Associates, op. cit., footnote 23.

[32] R.L. Bamberger and C.R. Mark, "Disruption of Oil Supply from the Persian Gulf: Near-Term U.S. Vulnerability (Winter 1987/88),' Congressional Research Service Report 87-863 ENR, Nov. 1, 1987. Although an additional 2.4 to 2.7 mmbd of capacity are theoretically available in nonoperational lines, it is unlikely that much of this capacity can be restored.

[33] Ibid.

lar, prospects for finding large new sources of oil supply appear to be considerably poorer than in the 1970s. In the United States, prospects for an oil production response to a price shock seem poorer than during the 1970s simply because many of the opportunities have been pursued during the interim. Although there have been improvements in oilfield technology and methods for enhanced oil recovery during the past decade and a half, few would argue that these improvements will fully compensate for the intensive oilfield development that has occurred during the same period.

In OTA's view, the overall effect of this complex series of changes and adjustments since the early 1970s has been a net improvement in U.S. and world energy security, at least for the short term. We believe that a substantial disruption of oil markets is now less likely than it was then, and that the industrial nations are now better equipped to handle a disruption were it to occur, especially over the short-term. Further, the recent political changes in the Soviet Union and its Eastern Bloc neighbors may redefine basic perceptions about the nature of U.S. national security problems. Nevertheless, it remains true now, as it did then, that the lion's share of the world's oil reserves lies in the Persian Gulf nations, that these nations have most of the world's excess oil production capacity, and that they remain politically shaky. As long as this is true, and as long as a sharp price shock would be disruptive to the U.S. economy—which it would, though the magnitude of the disruption is in dispute--policymakers must still count effects on energy security as an important factor in judging proposed energy policy measures. However, the relegation of energy security from the ''number one energy issue' status that it held in the 1970s, to the somewhat lower status that it has today, seems to be a reasonable response to both a reduced security risk and an elevation of concern about environmental issues.

Energy Security Effects of Alternative Fuels

Development of alternative fueled systems—vehicles, supply sources, and distribution networks—is viewed by supporters as both a means to reduce dependence on oil, lowering the economic and national security impact of a disruption and/or price rise, and as leverage against oil suppliers-' 'raise the price too high, or disrupt supply, and we will rapidly expand our use of competing fuels. ' OTA concludes that the use of alternative fuels does offer *the potential* to significantly enhance U.S. energy security, but the effect depends greatly on the fuel chosen, the scale of the program, and the specific circumstances of the supply and vehicle system used.

At a large enough scale, an alternative fuels program could reduce the United States' overall demand for oil and its level of oil import dependence. If the price of the fuels were not tied too tightly to world oil prices—a possibility under limited circumstances-use of alternatives could reduce the primary economic impact of an oil disruption, since any price rise associated with such a disruption would apply to a lower volume of oil. Even if alternative fuel prices *were* tied to world oil prices, a large-scale *worldwide* program would reduce pressures on world oil supplies, reduce OPEC market dominance, and lessen the potential for future market disruptions. Also, the threat of rapid expansion of the program would be far more credible after the basic distribution infrastructure was widely emplaced and economies of scale achieved.

On the other hand, unless it were simply "phase 1" of a larger program, a small-scale program—either a true experimental program, or one aimed only at ozone reduction in a limited number of cities—would likely have very small security benefits, though at moderate cost and risk. A limited program can serve as a laboratory to develop and free-tune technologies and marketing strategies, putting the United States a few years up the learning curve if it had to respond to a long-term crisis in oil supply. Given the slow turnover of the fleet and the significant infrastructure requirements for emplacing an alternative fuels system, however, this benefit, though useful, probably should be considered minor. A small-scale program could also serve as a symbol to OPEC, a reminder that an attempt to use their oil power as a weapon could backfire. However, current OPEC governments appear quite aware of the availability of longer term substitutes for oil, and future crises seem more likely to be created by radical governments that will not be readily swayed by considerations such as these. Finally, a small-scale program can serve as a first phase of a larger program, designed to work the "bugs" out of the technology and system design and to avoid large, expensive mistakes. In this role, a small program can have substantial advantages, though these must be traded off against the delay in emplacing a system large enough to affect energy security.

The efficacy of an alternative fuel program in providing security benefits, especially in the short term, will depend on whether the vehicles are dedicated to a single fuel or else are able to use multiple fuels. If the program relied on flexibly fueled vehicles (FFVs), this would allow the United States to play off the suppliers of oil against suppliers of alternative fuels, and would avoid the potential problem—inherent in a strategy favoring dedicated vehicles-of giving up one security problem (OPEC instability) for another (instability in whichever group of countries becomes our supplier of alternative fuels). However, a fleet of flexibly fueled vehicles attains important leverage against energy blackmail only if the supply and delivery infrastructure is available to allow them to be fueled exclusively with the alternative fuel, if this becomes necessary. FFVs don't *require* widespread availability of an alternative fuel supply network to be practical during normal times, so adoption of an FFV-based strategy will not guarantee full infrastructure development unless there are regulatory requirements for such development. In fact, because dedicated vehicles are likely to have performance and emissions advantages over FFVs, policymakers may view FFVs as only a stopgap measure on the way to a dedicated fleet.

Having a fuel be domestically available clearly is a net benefit for short-term energy security considerations,[34] but the necessity of importing the fuel does not negate all security benefits from an alternative fuel. If the potential supply sources are different from the primary suppliers of crude oil, or even if the supply markets are simply more open to competitive pressures, a turn to alternative fuels would have advantages to national security. As discussed in the chapters on individual fuels, there are wide differences in the likely supply sources for the various fuels.

There are also clear security differences between fuels that are "unique"—not used elsewhere in the economy—and those that are widely used. There are substantial energy security advantages in having vehicles powered by fuels-such as natural gas and electricity-that also power other important segments of the U.S. economy. In the event of a crisis, emergency measures to reduce demand for these energy sources throughout the economy might free up fuel supplies for the transportation sector. With the greatly reduced use of oil in the nontransportation segments of the economy, and with much of the remaining use in the form of residual oil-not easily transformed into transportation fuels (exception: production of electricity for electric vehicles or electrified mass transit systems)---there are few remaining opportunities to free up oil for transportation.

As a final point, we have assumed in our discussions that the marginal barrel of oil eliminated by an equivalent volume of alternative fuel used in the United States will be an imported barrel. This view has been disputed by some analysts,[35] who claim that alternative fuels will eliminate the higher cost supplies, e.g., domestic oil production. We note that it is the high *price* of imported oil, not its low cost, that is relevant to which barrel is eliminated. However, if a large alternative fuel program results in keeping world oil prices (and thus domestic oil prices) well below what they would have been without such a program, domestic oil production could decrease. This decrease would certainly not be on a one-to-one basis with alternative fuel use, but it would temper the energy security advantage of a given volume of fuel substitution. We note that this theoretical "disadvantage" of an alternative fuels program applies equally well to any measures, including energy conservation, that would reduce pressure on world oil supplies. We do not believe that this potential is a serious concern.

THE GREENHOUSE EFFECT IN PERSPECTIVE

Introduction

The "greenhouse" effect—a warming of the Earth and the atmosphere—is the result of certain atmospheric gases absorbing the thermal radiation given off by Earth's surface, and trapping some of

[34] Many in the environmental community have raised questions about the wisdom of 'draining America first,' which makes the issue of the long-term benefits and costs of increasing domestic oil and gas production somewhat more contentious. Discussions of this issue can quickly degenerate into ideological argument, and we have not presented an analysis and discussion here.

[35] For example, see M.A. DeLuchi, R.A. Johnston, and D. Sperling, "Methanol vs. Natural Gas Vehicles: A Comparison of Resource Supply, Performance, Emissions, Fuel Storage, Safety, Costs, and Transitions," Society of Automotive Engineers Technical Paper Series, #881656, 1988.

this radiation in the atmosphere.[36] The Earth's natural greenhouse effect is due primarily to water vapor, clouds, and carbon dioxide (CO_2), with small contributions from other trace gases that have natural sources, such as methane (CH_4) and nitrous oxide (N_2O). Without its natural atmospheric heat trap, Earth's surface temperatures would be about 60 OF cooler. than at preSent.[37]

The "heat trapping" property of greenhouse gases is essentially undisputed. What *is in* question is how the Earth's climate will respond to the accumulation of man-made emissions, and the resulting increase in heat trapping, over the last century and into the next. Carbon dioxide, chlorofluorocarbons, methane, and nitrous oxide are known to be increasing annually in the atmosphere due to man's activities (see box 2-A). The effect of the increases in concentrations of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), chlorofluorocarbons (CFCs), and other gases since the late 1800s is extra heat trapping equivalent to about a 1.4 'F (0.8 'C) equilibrium warming in global average surface temperatures.[38]

This "direct" heat trapping effect, or "radiative forcing' '[39] as it is often called, is the amount of warming expected to eventually occur at the Earth's surface if potential climate feedbacks—processes that amplify or diminish warming—are ignored. However, scientists expect that some climate feedbacks will operate; thus, **actual warming** cannot be neatly predicted.

In addition, while the human-induced component of the greenhouse effect increases in magnitude, other causes of climate changes remain important and make predicting future climate difficult. These include changes in the amount of energy emitted by the sun, changes in the atmospheric composition due to volcanic eruptions and man-made aerosols, incidences of El Ninos, and other unpredictable events.

Some regions of the globe will experience more than the average warming, and some regions less warming or even cooling, due to shifts in atmospheric and oceanic circulation patterns. Changes expected to accompany warming include arise in sea level and a more vigorous hydrological cycle, i.e., more precipitation and evaporation. Other predicted but less certain consequences include more drought in some regions; and more frequent and intense tropical storms. Scientists remain uncertain about the details of these impacts: what their magnitude will be; how fast they will develop; and which regions of the world they will affect.

Key Uncertainties

Most scientists agree that ***some warming will occur in the*** next century; instead, the controversy involves the geographical distribution of temperature changes—"where?"; the timing and rate of such changes—' 'when?' and the magnitude of the changes—' 'how much?

The frost issue—" where? ''—is likely to remain unresolved for many years. Scientists have significantly less confidence in temperature change predictions for specific regions than for global averages, beyond the general expectation that the greatest warming will occur at high latitudes in the Northern Hemisphere. Climate models are not expected to provide reliable guidance on regional variations in temperature and rainfall patterns due to increasing greenhouse gases for some time-research on the order of a decade may be needed before such refinement will be possible.

The second question-' when? '-depends a great deal on the role the ocean plays in temperature

[36] Greenhouse gases emit as well as absorb thermal radiation, but the net effect is absorption, because greenhouse gases absorb relatively intense radiation from the warmer Earth, and emit relatively weakly, at cooler atmospheric temperatures. Thermal radiation declines as the temperature of the emitting object declines.

[37] Differences in the concentrations of CO_2 in the atmospheres of Earth, Mars, and Venus help to explain the contrast in the average surface temperatures of the three planets-from roughly -600 F (–500 C) on Mars to 750° F (400° C) on Venus, compared to a global, annual average of about 600 F (15° C) on Earth.

[38] V. Ramanathan, R.J. Cicerone, H.B. Singh, and J.T. Kiehl, "Trace Gas Trends and Their Potential Role in Climate Change," *J. Geophysical Research* vol. 90, pp. 5547-5566, 1985; and R.E. Cicerone, "Future Global Warming from Atmospheric Trace Gases," *Nature* vol. 319, pp. 109-115, 1986.

[39] Radiative forcing or heat trapping is calculated with models of the energy balance of the Earth/atmosphere system. These models calculate surface temperature adjustments to increased greenhouse gas concentrations from information about the radiative absorption characteristics of the gas molecules, and globally averaged profiles of gas concentration versus height in the atmosphere. The models also require information about preexisting conditions, such as atmospheric temperature profiles; the amount of solar energy entering the atmosphere and the amount reflected from Earth's surface and from atmospheric aerosols and gases; and the rate at which heat is redistributed through mechanical mixing processes.

Box 2-A-Greenhouse Gases

Carbon dioxide (CO_2) concentrations in the atmosphere are estimated to have increased by about 25 percent since the mid-1800s, from around 280parts per million then to about 350 parts Per million now. Carbon dioxide concentrations have been measured at Mauna Loa since 1958; the record shows a steady increase from year-to-year superimposed on a clear seasonal cycle. The seasonal variation reflects winter-to-summer changes in photosynthesis ($C0_2$ storage) and respiration ($C0_2$ release) in live plants. Most of the increase is attributable to growth in fossil fuel use in the 20th century[1] unless current trends change, $C0_2$ concentrations in 2030 are typically projected to be about 450 Ppm, about 60 percent higher than preindustrial levels.[2] Carbon dioxide concentrations in air bubbles trapped in Antarctic ice indicate that present CO_2 levels are already higher than at arty time in the past 160,000 years. Over that period, $C0_2$ concentrations were correlated with temperature, and ranged from roughly 200 parts per million during glacial episodes to *270* parts per million during interglacial periods.[3] Currently, CO_2 contributes about 50 percent of the greenhouse effect.

Methane (CH_4) measurements made since 1978 indicate a steady rise of about 1 percent per year, from about 1.5 ppm in 1978 to about 1.7 ppm in 1987.[4] Primarily from its domestic animals, natural gas and coal production, and landfills, the United States apparently contributes about 10 percent of the methane emissions due to human activity? Per molecule, methane is about 25 times more effective in trapping heat than $C0_2$.[6] Currently, CH_4 contributes about 18 percent of the greenhouse effect.

Nitrous oxide (N_20) concentrations apparently began to rise rapidly in the 1940s, and increased about 0.2 to 0.3 percent per year during the mid-1980s. Sources of N_20 are primarily associated with soil nitrification and denitrification. N_20 is also produced during biomass and fossil fuel combustion; the magnitude of emissions from fossil fuel combustion is currently highly uncertain due to errors in sampling for N_20.[7] Per molecule, the w arming effect of nitrous oxide is about 200 times greater than that of $C0_2$.[8] Currently, N_20 contributes about 6 percent of the greenhouse effect.

Concentrations of the most widely used chlorofluorocarbons (CFCs), CFC-1 1 and CFC-12, were 0.2 and 0.4 parts per trillion, respectively, in 1986, increasing at a rate of about 4 percent per year.[9] Increases in CFC concentrations are unambiguously due to human activity, as they are synthetic chemicals that do not occur naturally. U.S. Environmental Protection Agency[10] projects that the rate of increase will be curtailed by the Montreal Protocol on Substances that Deplete the Ozone Layer, which was signed in September 1987; but that nevertheless, by 2030, concentrations of CFCs 11 and 12 will increase to 0.5 and 1.0 parts per billion, respectively. Use of CFC 11 in this country is dominated by production of synthetic foams for cushioning and insulation. The largest use of CFC 12 is in motor vehicle air conditioners. Outside of the United States, both CFCs 11 and 12 are commonly used in aerosol sprays. The warming effect of CFCs is on the order of 10,000 times greater, per molecule, than that of $C0_2$.[11] Currently, CFCs contribute about 15 percent of the greenhouse effect.

---

[1] C.D. Keeling, "Industrial Production of Carbon Dioxide From Fossil Fuels and Limestone," *Tellus*, vol. 28, pp. 174-198, 1973; R.M. Rotty and C.D. Masters, "CarbonDioxide From Fossil Fuel Combustion: Trends, Resources, and Technological Implications," in J.R. Trabalka (cd.), *Atmospheric Carbon Dioxide and the Global Carbon Cycle*, DOE/ER-0239 (Washington, DC: U.S. Department of Energy, December 1985); and A.M. Solomon, J.R. Trabalka, D.E. Reichle, and L.D. Voorhees, "The Global Cycle of Carbon," in J.R. Trabalka (cd.), *Atmospheric Carbon Dioxide and the Global Carbon Cycle*, U.S. Department of Energy, DOE/ER-0239, Washington DC, December 1985.

[2] U.S. Environmental Protection Agency, Office of Policy, Planning and Evaluation, *Policy Optionsfor Stabilizing Global Climate*, draft report to Congress, D.A. Lashof and D.A. Tirpak (eds.) (Washington DC: February 1989); V. Ramanathan, L.B. Callis, Jr., R.D. Cess, J.E. Hansen, I.S.A. Isaksen, W.R. Kuhn, A. Lacis, F.M. Luther, J.D. Mahlman, R.A. Reck, and M.E. Schlesinger, "Trace Gas Effects on Climate," in *Atmospheric Ozone 1985*, Global Ozone Research and Monitoring Project Report No, 16, World Meteorological Organization, National Aeronautics and Space Administration Washington DC, 1985; and J. Hansen, I. Fung, A. Lacis, S. Lebedeff, D. Rind, R. Ruedy, G. Russell, and P. Stone, "Global Climate changes as Forecast by the Goddard Institute for Space Studies Three-Dimensional Model," *Journal of Geophysical Research*, vol. 93, pp. 9341-9364, 1988.

[3] J.M. Barnola, D. Raynaud, Y.S. Korotkevich, and C. Lorius, "Vostok Ice Core Provides 160,000-year Record of Atmospheric CO_2," *Nature*, vol. 329, pp. 408414.

[4] See D.R. Blake and S.F. Rowland, "Continuing Worldwide Increase in Tropospheric Methane, 1978 to 1987," *science*, vol. 239, pp. 1129-1131, 1988.

[5] U.S. Environmental Protection Agency, 1989, op. cit., footnote 2.

[6] Ibid.

[7] L.J. Muzio and J.C. Kramlich, "An Artifact in the Measurement of N_2O From Combustion Sources," *Geophysical Research Letters*, vol. 15, pp. 1369-1372, 1988.

[8] U.S. Environmental Protection Agency, 1989, op. cit., footnote 2.

[9] Ibid.

[10] Ibid.

[11] V. Ramanathan et al., 1985, op. cit., footnote 2.

SOURCE: Office of Technology Assessment, 1990.

regulation, which is only partially understood and incorporated into current models. Oceans play important roles in the climatic response to changed temperatures because they emit and absorb both heat and CO_2 and because changing ocean circulation can change the distribution of energy throughout the entire climate system. The upper ocean (50 to 100 m) appears to respond relatively rapidly to temperature changes; if interactions with the deep ocean are important, time lags up to 100 years for equilibration with the atmosphere may be required. Such lags would greatly slow down the "appearance' of global warming. On the other hand, as oceans warm, they may absorb a smaller fraction of CO_2 put into the atmosphere each year, which would accelerate the warming.[40]

The third issue—''how much?' '-depends on the role of climate feedbacks. Feedbacks can either enhance (positive feedback) or diminish (negative feedback) the warming effect expected from simply increasing concentrations of the greenhouse gases. Physical feedback mechanisms include water vapor, snow and ice, and clouds. When the climate warms, the atmosphere can hold more water vapor. This enhances warming because water vapor itself is a greenhouse gas. Despite some recent controversy[41], most scientists believe the positive effect of water vapor on temperature dominates any regional negative feedbacks from water vapor (e.g., increased cloud cover near the equator).

When climate warms, snow and ice will melt, reducing the reflectivity of the Earth and increasing its absorbance of heat. The insulating property of the ice is also lost, allowing a transfer of heat to the atmosphere from the ocean. Thus, in general, snow and ice feedbacks also appear to increase warming. However, nine new studies presented at the American Geophysical Union's meeting last fall suggest the south polar ice sheet may actually get bigger due to a warmer atmosphere carrying more moisture and depositing more snow on Antarctica. This outcome has reduced estimates of projected sea level rise to about 14 inches (ranging from a drop in 2 inches to arise of *30* inches) from the earlier (1987) National Academy of Sciences estimate of *20* to *59* inches.[42] The projected net change in **sea** level is still positive because the melting of Greenland's ice sheet and expansion of ocean water as it warms up will outweigh the effect of the enlargement of the Antarctic ice cap.

Important uncertainties about cloud formation limit our understanding of how climate will respond to greenhouse forcing. Clouds play a dual role in Earth's energy balance: depending on their shape, altitude, and location, their dominant effect can either be to reflect solar radiation or absorb thermal radiation. Satellite data have recently been used to demonstrate that the dominant effect of clouds at present is to reflect solar radiation and hence help cool the earth.[43] However, as conditions change, whether cloud feedbacks will amplify or reduce greenhouse warming depends on whether the cooling effects of clouds increase compared to their warming effects, or vice versa. If all types of clouds simply increase in area, they will reflect more sunlight back into space and cool the earth. If, as some new research suggests, taller narrower clouds form, or thin cirrus clouds form, they will actually exacerbate the warming effect. Sensitivity analyses conducted recently on the current models suggest they are extremely sensitive to assumptions about cloud cover. A comparison of 14 General Circulation Models concluded that clouds can have either a strongly positive or strongly negative feedback effect on global warming.[44] They can halve the expected warmin[45] or double it.[46]

[40] D. Lashof, "TheDynamic Greenhouse: Feedback Processes that May Influence Future Concentrations of Greenhouse Gases and Climate,' *Climatic Change, in* press, 1989.

[41] R. Lindzen, unpublished paper, Massachusetts Institute Of Technology, 1990.

[42] National Academy of Sciences, *Responding* t. *Changes* i_n *Sea Level:* Engineering *Implications* (Washington, DC: National Academy of Sciences, 1987),

[43] V. Ramanathan, R.D. Cess, E.F. Harrison, P. Minnis, B.R. Barkstrom, E. Ahmad, and D. Hartmann, "Cloud-Radiative Forcing and Climate: Results From the Earth Radiation Budget Experiment" *Science,* vol. **243,** pp. 57-63, 1989.

[44] R. Cess, State University of New York, Stony Brook, as quoted by Richard Kerr, *Science,* vol. 243, PP. 28-29, 1989.

[45] J.F.B. Mitchell, *The Equilibrium Response to Doubling CO_2 in Greenhouse-Gas-Induced Climatic Change: A Critical Appraisal of Simulations and Observations,* Michael E. Schlesinger (cd.), (Elsevier) in press.

[46] V. Ramanathan, ' 'The Greenhouse Theory of Climate Change: A Test By an Inadvertent Global Experiment, ' *Science,* vo1. 240, pp. 293-299, 1988.

Benchmark Warming—The Effect of Doubled CO_2

Predictions of future warming due to greenhouse gases are highly uncertain, largely because of the uncertainties inherent in both the climate models themselves and in the forces driving climate to change. Future emissions will be tied to future population and economic growth, technological developments, and government policies, all of which are notoriously difficult to project. In order to avoid the pitfalls and complexity of trying to estimate future emissions, and to provide a common basis for comparing different models or assumptions, standard practice on the part of climate modelers has been to perform sensitivity analyses. Typically, this entails examining equilibrium climates associated with preindustrial $C0_2$ levels, and then comparing them to equilibrium climates associated with doubled atmospheric $C0_2$ concentrations. Although such calculations are unrealistic in that they *instantaneously* double CO_2 concentrations, rather than increasing them gradually over time, they provide a useful "benchmark" of the sensitivity of climate to rising greenhouse gas concentrations.

Reviews of doubled-$C0_2$ calculations generally agree on a range of 3 to 8 'F (1.5 to 4.5 'C) as bounding the equilibrium warming responses given by a wide variety of current models.[47] The uncertainty in this benchmark warming is primarily due to uncertainty about feedbacks. The lower end of the range roughly corresponds to the direct impact of heat trapping associated with doubled $C0_2$, with little amplification from feedbacks. At the upper end of the range, feedback processes more than double the direct heat trapping effect. Some scientists believe that even more than an 8 'F warming could occur, due to hypothesized geochemical feedbacks that would release extra methane and $C0_2$ into the atmosphere, but which are not presently included in any models.[48]

It is important to realize that the3to8'F warming cited above only caps model predictions of warming in response to doubled CO_2; higher CO_2 concentrations or a combination of greenhouse gas levels equivalent to more than a doubling of $C0_2$ could lead to greater warming. U.S. EPA[49] has projected that in the absence of policies to slow emissions growth, an 'effective' $C0_2$ doubling (i.e., accounting for increases in other trace gases as well as ***CO_2***) could occur as early as 2030, **assuming** high population and economic growth, or be delayed for about a decade, if low growth prevails. Beyond **that,** still higher trace gas concentrations and correspondingly more climate change would occur.

Reducing CO_2 Emissions in the Near-Term

$C0_2$ is responsible for about 50 percent of current warming in this decade, with CFCs, methane, and nitrous oxide combined, contributing the other 50 percent (see figure 2-8). With anticipated controls on CFC emissions due to the Montreal Protocol, however, carbon dioxide's comparative contribution is expected to increase in the future. A recent EPA analysis (1989) suggests that to stabilize atmospheric concentrations of the greenhouse gases at current levels would require world-wide emission reductions from *today's levels* of 50 to *80* percent for CO_2, 10 to 20 percent for CH_4, 80 to 85 percent for N_20, and 75 to 100 percent for CFCs, and a freeze on carbon monoxide and NO_x. If the less developed countries are to grow in energy use at all, the developed world would have to virtually phase-out fossil fuels to achieve such a goal. In lieu of such a possibility, the world will continue to increase emissions of greenhouse gases and will most likely experience some warming over the next few decades.

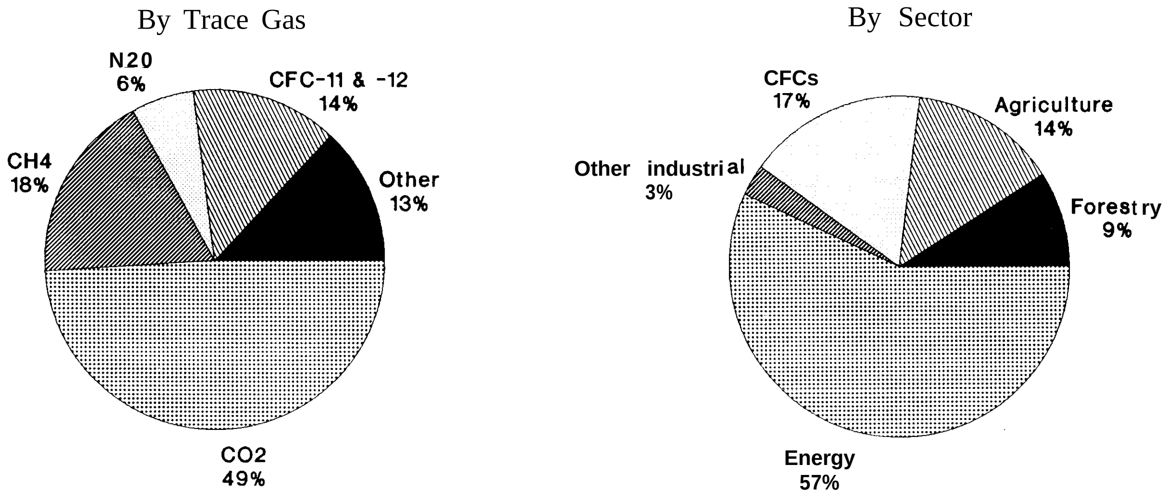
The United States is responsible for about 21 percent of current greenhouse warming. In the United States, fossil fuel $C0_2$ emissions are distributed roughly equally across the industrial, transportation, and buildings sectors. (See figure *2-9.)* Per unit of energy produced, $C0_2$ emissions from coal combustion are highest, followed by oil and then natural gas. Oil and coal combustion each account for roughly 40 percent of U.S. emissions, with natural gas contributing the other 20 percent. The

[47] National Academy of Sciences, Changing *Climate* (Washington DC: National Academy Press, 1983); and M.C. McCracken and F.M. Luther, ***Projecting the Climatic Effects of Increasing Carbon Dioxide,*** DOE/ER-0237, December 1985.

[48] Lashof, 1989, op. cit., footnote 40.

[49] U.S. Environmental Protection Agency, Office of Policy, Planning and Evaluation, *Policy Options for Stabilizing Global Climate*, draft report to Congress, D.A. Lashof and D.A. Tirpak (eds.) (Washington, DC: February 1989).

Figure 2-8-Current Contribution to Global Warming (percent)



SOURCE: U.S. Environmental Protection Agency.

U.S. Environmental Protection Agency[50] projects that annual world CO_2 emissions will increase from about 6 billion metric tons of carbon in 1985 to 9 to 12 billion metric tons of carbon in 2025, without new initiatives to reduce them. The U.S. contribution in 2025 is projected to be larger in absolute terms but smaller as a fraction of the world's total than at present.

In 1988, at the now famous "Toronto Conference,' scientists and policymakers from 47 countries called for a 20 percent reduction in carbon dioxide emissions from today's levels by early in the next century. Several groups are attempting to calculate the potential for such reductions on a country by country basis[51]. Preliminary results suggest that substantial emissions reductions can be attained by efficiency improvements in all sectors of the economy (buildings, transportation, industry, energy supply, and agriculture). However, achieving a 20 percent reduction from current levels would not be possible by that time from efficiency changes alone. Pursuing such a goal would require changes in energy usage patterns and fuels consumed as well. These would probably require extensive government intervention to accomplish. In the transportation sector, VMT (vehicle miles traveled) are expected to grow at 2 to 3 percent per year, and efficiency improvements to grow at a slower rate (if current trends continue); thus, CO_2 emissions will continue to grow. Emissions are expected to increase about 25 percent between now and 2010 despite the appearance of new, more-efficient cars, trucks, and planes. To achieve a 20 percent reduction from 1987 levels in this sector therefore, would require both offsetting expected growth *and* decreasing emissions by an additional 20 percent.

The Transportation Sector and Global Warming

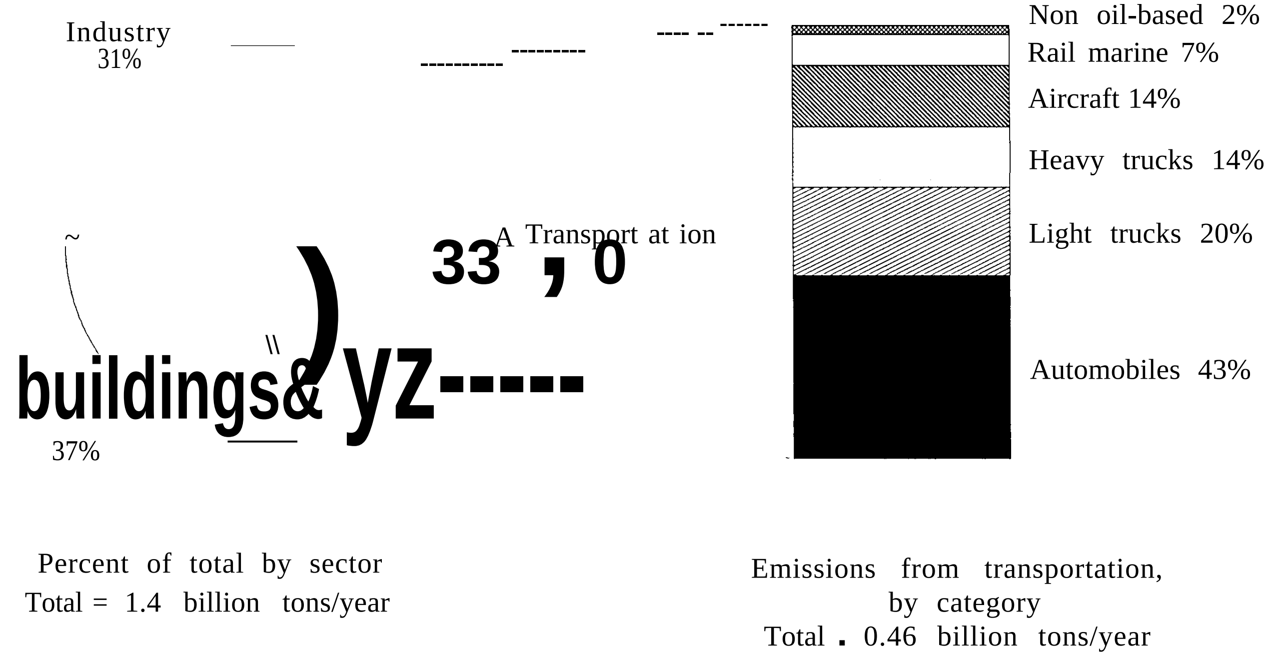
Transportation's impact on global warming comes principally from the CO_2 released by burning fuel. There are other contributions-refinery emissions and methane from tailpipes, for example-but these are much smaller than the warming contribution from CO_2.[52] Consequently, to a close approximation, studying transport's contribution to global

[50] U.S. Environmental Protection Agency, 1989, op. cit., footnote 49.

[51] Four U.S. studies are underway: by the U.S. Department of Energy, the U.S. Environmental Protection Agency, the Congressional Research Service, and the Office of Technology Assessment.

[52] If we consider U.S. highway vehicles, for example, DeLuchi et al. (M.A. DeLuchi, R.A. Johnston, and D. Sperling, "TransportationF uels and the Greenhouse Effect," UniversityWide Energy Research Group, University of California, UER-180, December 1987, p. 15) estimate the following shares of contribution to greenhouse emissions: 85 percent CO_2 from vehicle tailpipes, 11 percent CO_2 from production and nonhighway distribution of fuels, 3 percent from flaring and venting of natural gas, and 0.2 percent from tailpipe methane emissions.

Figure 2-9-Contribution of the Transportation Sector to CO_2 Emissions



SOURCE: Oak Ridge National Laboratory.

warming is the same as studying transport energy consumption. The actual ‘‘ warming contribution,” expressed as mass of carbon emitted, is calculated by multiplying energy consumption by an emission coefficient that is roughly constant for all petroleum-based transport.

There are three important exceptions to this rough equivalence of greenhouse emissions and energy consumption, though. First, chlorofluorocarbons (CFCs), used in transport as air conditioning working fluids and, in smaller quantities, as foam padding and insulation, will not vary proportionally with energy consumption. Second, if other fuels replace petroleum as the principal source of transport energy, then the constant of proportionality between CO_2 emissions and energy use will change. Finally, the secondary effects of other tailpipe emissions such as carbon monoxide and reactive hydrocarbons may be large, for they both contribute to the formation of tropospheric ozone (also a greenhouse gas) and reduce concentrations of the hydroxyl radical (OH), which scavenges many trace gases from the atmosphere.

Short of capturing and storing the CO_2 produced by fossil fuel combustion-a remote possibility—the only way to reduce CO_2 emissions is to consume less fossil fuel. This can be accomplished by burning the fuel more efficiently (e.g., higher mpg cars), reducing demand for transportation services (driving less, carpooling), or actually changing fuels. Emissions of CO_2 per passenger mile depend on the kind of fuel efficiency technology in a car, but also on how big and powerful the car is, how fast it is driven, road and signal design, and how many people are in the car.

U.S. Transportation Energy Use and CO_2 Emissions

The carbon emitted from the transport sector represents about 30 percent of total U.S. fossil fuel carbon emissions, and, as noted, the United States contributed 23 percent of world fossil fuel carbon emissions. Worldwide, fossil fuel combustion was about 75 to 80 percent of total carbon emissions (the rest came mostly from deforestation), and CO_2 represents about half of total current contributions to the greenhouse problem. Multiplying all these shares together indicates that the American transport sector contributes about 5 percent of total world CO_2 emissions, or about 2.5 percent of the total greenhouse problem. As figure 2 shows, the U.S. light-duty fleet-cars and light trucks-accounts for about 63 percent of U.S. transport emissions, or 3 percent of world CO_2 emissions, or 1.5 percent of the total greenhouse problem.

Future trends in transport greenhouse emissions will be determined by three factors: population growth, travel per person, and greenhouse emissions per unit of travel. Travel per person, and mode of travel, are determined by economic choices, many of which are constrained in the short run by existing patterns of settlement and available transportation infrastructure. Greenhouse emissions per unit of travel are largely determined by vehicle efficiency technology, including such market-determined factors as the average size and power of vehicles in the fleet. These factors are also constrained in the short run, due to the remaining lifetime of existing vehicles and the lead times required for introduction of substantial innovations in new vehicles.

Cars and light trucks are likely to continue to dominate U.S. transport. Consequently, the single most important factor determining future transport energy use and greenhouse emissions will be the rate of light vehicle efficiency gains. Although today's best production models and prototypes, surpass 50 mpg and 80 mpg respectively, fleet increases in efficiency to this level are unlikely. Consumer preference for larger and more powerful vehicles suggest that, under current conditions, efficiencies this high cannot be translated into production fleet performance.

Alternative Fuels

New transport fuels may also change the rate of greenhouse emissions per unit of travel. Fuels under development include methanol derived from natural gas or coal, ethanol derived from fermented plant feedstocks, natural gas in compressed (CNG) or liquefied (LNG) form, and hydrogen derived from electrolysis of water. Electric vehicles that run on rechargeable batteries are also being developed aggressively. To assess the greenhouse effects of new fuels, you must look beyond the tailpipe. In the present petroleum-based system, emissions of CO_2 from vehicles represent about 85 percent of total transport-associated greenhouse emissions; the other 15 percent comes from the production, refining, and transmission of the fuel, and venting and flaring of natural gas found with the petroleum. Changes in vehicle efficiency or travel patterns alone, without changes in the sources of transport fuel, will keep this relationship unchanged; if CO_2 from vehicles declined by 25 percent, greenhouse emissions from the transport system would decline by 25 percent. But new fuels will change the relationship, because their sources and manufacture will be different. Consequently, it is necessary to add up total greenhouse emissions from extraction, production, distribution, and use of new fuels to assess their net impact on emissions.

While other fuels could reduce greenhouse emissions, large movement to new transport fuels is blocked by two categories of obstacles: technical problems of cost, vehicle performance and fuel storage; and threshold problems related to fuel distribution and repair systems. The new power sources that offer the largest reductions in greenhouse emissions-hydrogen or electricity from nonfossil sources-are the furthest from large-scale technical viability, and the most difficult to move to from a gasoline system.

As discussed in the chapters that follow, although there are serious disagreements about details, there is a substantial consensus that those alternative fuels that are most ready for the marketplace will *not* substantially alter the effective volume of greenhouse gases produced by the transportation sector—assuming that feedstocks are selected based on market prices rather than national security considerations or global warming considerations (so that natural gas is likely to be the primary feedstock, rather than coal or biomass). This conclusion is reached not only because no new fuel, except possibly reformulated gasoline, will penetrate deeply into the marketplace by the end of this century, but also because the fuels most likely to *begin* to penetrate don't offer a substantial advantage over gasoline in their net greenhouse emissions.

Methanol and compressed or liquefied natural gas will rely, at least at first, on geologic deposits of natural gas as their primary feedstock. Although methane, the key constituent of natural gas, generates less CO_2 per unit of energy on combustion than does gasoline, methane is itself a potent greenhouse gas and will be a major component of the emissions from natural gas-fueled vehicles. This, coupled with certain energy inefficiencies in transporting and/or transforming the natural gas, approximately compensate for methane's advantage in combustion CO_2 emissions. *Reformulated gasoline* may gain or lose greenhouse emissions "advantages" by adding or subtracting various components of gasoline, but the net effect is highly uncertain (because the actual makeup of reformulated gasoline is highly uncertain) and unlikely to be large. We would guess that reformulated gasoline will create a small net increase in greenhouse emissions. And *ethanol is* theoretically attractive because its primary feedstocks, sugar and starch crops, are renewable, with plant growth reabsorbing the CO_2 lost to combustion. However, with current agricultural and fuel production technology, the energy used to grow the feedstocks and convert them to ethanol produces enough CO_2 to roughly negate the advantage gained by crop regrowth; without changes in the production system, ethanol use will generate about as much CO_2 as gasoline use.

Electricity and hydrogen are often cited as fuels that could yield substantially reduced greenhouse emissions. However, these reductions can be achieved only by using energy feedstocks—probably nuclear in the case of electricity, solar for hydrogen-that at present are either not available in large quantities or not economic. Both of these "fuels" probably are longer term alternatives, not likely to be the fuel of choice for any program seeking to put millions of vehicles on the road before the year 2000.

If the near-term options will not greatly affect greenhouse emissions, should we then *not* consider global warming implications in making decisions about promoting alternative fuels? Environmentalists are making the following arguments *for the* proposition that decisions about alternative fuels are a key factor in global warming strategies:

- *Some decisions about alternative fuels will foreclose future options.* Introducing particular alternative fuels may open or foreclose future fuel options that *do* have profound greenhouse implications. For example, introducing natural gas as an alternative may open the way for future use of hydrogen, by making gaseous fuels more familiar and by developing a gas-oriented infrastructure that is more convertible to hydrogen use than would be an infrastructure based on liquids. Alternatively, introducing new liquid fuels may make it far more difficult to switch to hydrogen later on, given the large investment made in new, liquids-oriented infrastructure.

  As a corollary to the above argument, introducing any new fuel using fossil materials, e.g., natural gas, will simply prolong the age of fossil-based transportation fuels and delay entry of renewable fuels. To fight global warming, we must begin to make a transition from fossil fuels as soon as possible. Moving from one fossil fuel (petroleum) to another (natural gas) is basically defeatist. We should instead move as quickly as possible to solar or biomass-based fuels.
- *Introduction of some fuels will lead inexorably to more coal use.* Introducing fuels that are dependent on fossil materials as feedstocks will inevitably lead to a dependence on coal as the feedstock. Such a dependence will have a profound greenhouse impact, so that consideration of the long-term feedstock sources for the alternative fuels must take place before setting us on a particular path.
- *Current estimates of greenhouse emissions don't consider future technology improvements.* The fact that several of the alternative fuels can *match* gasoline in greenhouse emissions should be viewed as encouraging rather than disappointing, given the current rudimentary state-of-the-art of much of the fuel cycle for the various alternatives. It is inevitable that commercial development of these fuels will stimulate substantial improvements to efficiency in production and utilization, and consequent reductions in greenhouse emissions. Although the current gasoline-based system can improve as well, it has less opportunity because of its maturity.

OTA agrees with some of these concerns, with caveats. We do believe that the near-term fuel choices will affect the potential for introducing other fuels in the future; we do not believe that these effects are necessarily very straightforward, however (as in the argument that introduction of near-term gaseous fuels will assist longer term hydrogen fuel development), nor necessarily so predictable that this concern should play a key role in selecting fuels. We agree that moving to methanol or natural gas will increase the chances of our eventually moving to coal as a transportation feedstock, and may even prolong our use of fossil transportation fuels, but *only* because these fuels are in some ways more attractive than gasoline and may make a fossil-based system more congenial. If we ran out of oil and had not turned to methanol or natural gas, this would *not* necessarily push us towards renewable, however; like methanol and natural gas, gasoline can also be made from coal (or natural gas).

Finally, we agree that technology improvements will improve the future net greenhouse balance of the alternative fuels, although resource depletion might eventually work in the other direction.

In the chapters on the individual fuels that follow, we have relied in large measure on the analyses of fuel cycle greenhouse emissions conducted by Mark DeLuchi, Daniel Sperling, and colleagues at the University of California at Davis. These analyses are comprehensive and superbly documented.

Chapter 3

Substituting Methanol for Gasoline in the Automobile Fleet

Much recent attention has been focused on the potential for using methanol as a primary vehicle fuel, either neat (100 percent methanol, or M1OO) or mixed with up to 15 percent gasoline (M85). Among its advantages as an automotive fuel are its familiar liquid form, its ease of manufacture from natural gas, and the availability of processes allowing its manufacture from coal and biomass,[1] its high octane level allowing higher engine power (at constant displacement), and its potential as a cleaner burning fuel than gasoline. The technology to use M85 as an automotive fuel has been demonstrated and could be commercially available within a few years, and development programs in the United States, Japan, Germany, and elsewhere are working to improve the efficiency, driveability, and emission characteristics of methanol-burning engines and to allow operation with M1OO (cold-starting is a problem with this fuel). Cities and States with vehicular air quality problems have expressed particular interest in methanol use, and California has had an active program to stimulate the development of a fleet of methanol-

Photo credit: General Motors Corp.

Chevrolet Lumina Flexfuel auto can use straight gasoline, M85, or any combination in between.

[1] Gasoline can also be produced from these feedstocks as well.

capable vehicles since 1978.[2] Also, Congress has passed measures to stimulate development and sales of methanol-capable vehicles, and is actively considering legislation to develop alternative-fuel fleets in cities suffering from ozone problems. The Alternative Motor Fuels Act of 1988, Public Law 100-494, allows manufacturers to use dedicated and flexible fuel vehicles to help meet Corporate Average Fuel Economy (CAFE) standards. The law allows the manufacturers to calculate fuel mileage by including only the petroleum portion of fuel usage with the vehicles operating with petroleum use at its minimum level.[3]

If Federal, State, or local governments restrict gasoline use in urban areas, methanol is in a good position to compete for a significant share of the highway vehicle fuel market. Without restrictions on gasoline sales, however, methanol must overcome a number of obstacles to compete successfully. These include a potentially high price in relation to current gasoline prices (particularly in the early years of a methanol program), lack of incentives to establish a supply and distribution infrastructure, and possible strategic problems associated with potential supply sources. Also, because methanol's potential air quality benefits have become a critical factor in its support, questions about the magnitude and nature of these benefits must be satisfactorily resolved.

EFFECTS ON AIR QUALITY

Support for measures to promote methanol has focused primarily on its potential to reduce urban ozone in areas with significant smog problems, e.g., Los Angeles and the Northeast corridor. Methanol's potential energy security benefits as well as its potential for improvements in automotive emissions of toxic pollutants and in fuel efficiency and performance are also important. Methanol has been presented as superior to gasoline as a vehicle fuel because of several favorable physical and chemical characteristics: the low photochemical reactivity of methanol vapors emitted in vehicle exhaust or fuel evaporation; high octane level; wide flammability limits; high flame speed; low volatility; and low combustion temperature. Methanol's low reactivity means that emissions of unburned methanol, the primary constituent of methanol vehicle exhaust and fuel evaporative emissions,[4] have less smog-forming potential than an equal weight of organic emissions from gasoline-fueled vehicles and infrastructure[5] (however, other, more reactive constituents of methanol vehicle emissions complicate the analysis of the overall smog benefit). The octane and flammability characteristics allow a methanol engine to be operated at higher (leaner) air-fuel ratios than similar gasoline vehicles, promoting higher fuel efficiency and lower carbon monoxide and exhaust organic emissions than with gasoline, though causing a potential problem with NO_x control. The low volatility should reduce evaporative emissions if the effectiveness of evaporative emissions controls is not compromised. The high octane level allows higher engine compression ratios to be used, promoting efficiency and power.[6] And methanol's relatively low combustion temperature should reduce "engine out" NO_x emissions (that is, emissions prior to the exhaust stream entering the catalytic converter) compared to emissions from gasoline engines, other things equal.

In general, then, the substitution of methanol vehicles for gasoline vehicles will affect emissions of smog-forming organic compounds and nitrogen oxides, toxics, and carbon monoxide. This section discusses each of these emissions, with the primary focus on organic compounds because their reduction

California is now also evaluating the use of propane, compressed natural gas, and electricity as alternative fuels.

[3] If a dedicated methanol vehicle uses M85, which is 85 percent methanol and 15 percent gasoline, the law allows the vehicle fuel economy to be calculated as if the 15 percent gasoline usage were its total fuel consumption. A flexible fuel vehicle would receive half the CAFE credit available to dedicated vehicles, based on the assumption that such vehicles will use methanol fuels 50 percent of the time. Each manufacturer is limited in the total alternative fuel credit it can claim to 1.2 mpg.

[4] J. Milford, "Relative Reactivities of M85 Versus Gasoline-Fueled Vehicle Emissions," contractor report prepared for Office of Technology Assessment, Jan. 18, 1990. In tests of M85 cars, methanol accounted for approximately 70 percent of total vehicle emissions by weight.

[5] J.A. Alson, J.M. Adler, and T.M. Baines, "Motor Vehicle Emission Characteristics and Air Quality Impacts of Methanol and Compressed Natural Gas," D. Sperling (cd.), *Alternative Transportation Fuels: An Energy and Environmental Solution* (Westport, CT: Quorum Books, Greenwood Press, 1989), pp. 109-144.

[6] Specifically, methanol's research octane number of 112, compared to 91 for regular gasoline, should allow the engine compression ratio to be raised from 8.5/9.0 in today's gasoline engines to over 10. There is dispute about how high a compression ratio can be reached. Energy and Environmental Analysis estimates the capability to reach 12.0 for an M1OO vehicle, with a potential 12 percent fuel benefit (Energy and Environmental Analysis, Inc., *Methanol' sPotential as a Fuel for Highway Vehicles*, contractor report prepared for the Office of Technology Assessment, October 1988). Ford Motors, however, projects an increase to only 10.5 to 11.1 (D.L. Kulp, Ford Motor Co., personal communication, Feb. 1, 1990).

is both the centerpiece of efforts to promote methanol use and one of the most controversial technical aspects of the debate over methanol use.

Organic Compounds and Ozone Reduction

Conclusions

There has been substantial controversy about how effective methanol fuels will be in reducing ozone levels. In OTA's view, although considerable effort has been expended to estimate the ozone impacts of introducing methanol vehicles, especially for the Los Angeles Basin, a number of factors confound the estimates and lead us to conclude that methanol has significant *but poorly quantified and highly variable* potential to reduce urban ozone. In particular, there are few examples of emissions tests of methanol vehicles that have measured the individual compounds in their emissions, even though such ''speciation' of emissions is important inaccurately determining their photochemical reactivity. Other confounding factors include the essentially prototype nature of available methanol vehicles, potential future changes in the reactivity of *gasoline* exhausts (altering the trade-off between methanol and gasoline), and uncertainty about future progress in controlling formaldehyde emissions. And whatever net emissions changes are caused by using methanol vehicles, the effect of these changes on levels of urban ozone will vary with location and meteorological conditions. Ozone benefits from reducing organic emissions will occur only in urban areas where ambient concentrations of volatile organic compounds are low enough, relative to NO_x concentrations, that reducing organic emissions is an effective ozone strategy. In some urban areas-Atlanta, for example-and in most rural areas, controlling NO_x is a more promising ozone control strategy, and methanol use will provide little or no ozone benefits.

Some of the more favorable data imply that use of M85 vehicles could yield an "effective" reduction in organic emissions (that is, taking into account both changes in the mass of organic emissions and changes in the reactivity of these emissions) in the range of 20 to 40 percent, assuming that formaldehyde is reasonably well controlled (e.g., in the vicinity of 30 mg/mile or so). On the other hand, some of the less favorable data imply a much lower benefit: no higher than about a 20 to 25 percent reduction even in the most favorable areas (e.g., the Northeast corridor) with good formaldehyde control, much less of a reduction and possibly even an *increase in* some areas such as the Los Angeles basin. And if formaldehyde control efforts are not successful, some of the benefits would be lost, particularly when vehicles age and catalyst effectiveness diminishes.

The prognosis for M1OO dedicated vehicles is more uncertain in some ways, given the scarcity of data and, for M1OO vehicles, the uncertainty associated with cold starting problems. However, the physical characteristics of a 100 percent methanol fuel, if not altered too radically by additives to aid cold starting and to provide taste and flame luminescence, do appear very promising for substantial ozone benefits. In particular, the absence of reactive hydrocarbon species in the fuel guarantees their absence from evaporative emissions and, further, should lead to low levels (compared to gasoline) of such species in the exhaust-reducing the reactivity of these emissions; and methanol's low vapor pressure, low molecular weight, and high boiling point should keep evaporative emissions, including running losses and refueling emissions, at much lower levels than for gasoline. The available emissions tests of M1OO vehicles, though few in number, appear to bolster these expectations.

Discussion

The range of claims about methanol's effectiveness as a means of reducing urban ozone is extremely wide. For example, the Environmental Protection Agency (EPA) claims that methanol vehicles operating with M85 and current engine technology can achieve reductions in "ozone-forming potential"—the net effect of changes in either or both mass emission rates and reactivity of the emissions of volatile organic compounds that are ozone precursors-of about 30 percent from future gasoline-fueled vehicles meeting the Administration's proposed emission standards and fueled with low volatility (9 psi) gasoline.[7] With optimized M85 vehicles—achieving reduced levels of hydrocarbons, methanol, and formaldehyde in their exhausts—the net emission benefit claimed is about 40

[7] U.S. Environmental Protection Agency, *Analysis of the Economic and Environmental Effects of Methanol as an Automotive Fuel,* Special Report, Office of Mobile Sources, September 1989.

Box 3-A—How Does EPA Arrive at Its Estimates for the Ozone-Reduction Impact of Methanol Vehicles?[1]

EPA has concluded that an "interim" M85 flexible fuel vehicle can obtain a 30 percent reduction in "gasoline VOC-equivalent"' emissions (or about a 40 percent reduction for a fully optimized vehicle), and that an optimized M1OO vehicle can obtain an 80 percent reduction compared to a gasoline vehicle satisfying the Administration's Clean Air Act proposal for hydrocarbons and operating on low volatility, 9 psi gasoline. EPA arrived at these values by the following method:

For M85 interim vehicle:

1. Evaporative emissions were assumed to equal gasoline emissions on a mass basis; emissions composition was calculated by basing the ratio of hydrocarbons to methanol on EPA test data.
2. Exhaust emissions were assumed to equal gasoline emissions on a *carbon* basis (the current standard for methanol vehicles demands that their exhaust emissions be no higher on an equivalent carbon basis than the standard for gasoline). Emissions were assumed to consist only of methanol, formaldehyde, and HC emissions, the latter identical in composition to gasoline emissions. The emissions breakdown was based on ' 'manufacturer's views. Formaldehyde emissions were assumed to be 60 mg/mile.[2]
3. Assigning the HC component of the emissions a relative reactivity of 1.00, reactivity factors were derived for methanol and formaldehyde using an air quality model. EPA calculated methanol's relative reactivity to be *0.19,* and formaldehyde's to be 2.2, on a mass basis.
4. The gasoline VOC-equivalent emissions were calculating by multiplying the mass of each component of the emissions by its reactivity factor, and totaling the results. The calculated VOC-equivalent emissions were 0.95 for gasoline vehicles complying with the Administration's proposed standards, and 0.66 for the M85 vehicles, or a 30 percent reduction.

For M85 optimized vehicles:

1. EPA assumed that evaporative emissions would be unchanged from the interim vehicle, but that exhaust NMHC emissions would drop by 20 percent, methanol emissions by nearly 30 percent, and formaldehyde emissions by 40 percent (to 35 mg/mi) in an optimized vehicle. Multiplying each new component by the same reactivity factors, EPA found that equivalent organic emissions fell by 43 percent from the baseline gasoline vehicle.

For M1OO optimized vehicles:

1. EPA assumed that M1OO vehicles would emit extremely low levels of non-methane hydrocarbons (.05 grams/mile versus 0.31 grams/mile for the optimized M85 vehicle) and formaldehyde (15 mg/mile, the California standard), with a moderate reduction in methanol emissions from the M85 vehicles. These emissions levels are in line with the small number of M1OO emissions tests available. Multiplying the emissions components by their respective reactivity factors gives a gasoline VOC-equivalent emissions rate of 0.19, or an 80 percent reduction from the baseline gasoline vehicle.

[1]The description of EPA's methodology is based on U.S. Environmental Protection Agency, Office of Mobile Sources Special Report, *Analysis of the Economic and Environmental Effects of Methanol as an Automotive Fuel,* September 1989.

[2]1bid., p. 50.

percent.[8] And with advanced vehicles using M1OO, EPA claims reductions of 80 percent.[9] EPA's estimates are explained in more detail in box 3-A. Critics have questioned the accuracy of the EPA claims; some have estimated that M85 will yield *no* net ozone advantage.[10]

In examining and attempting to understand and evaluate the alternative claims, we examined the literature and data on the emissions and air quality effects of methanol-fueled vehicles, and analyzed some existing emissions data for their ozone-producing implications.

[8]Ibid.

[9]Ibid.

[10]Sierra Research, Inc., *Potential Emissions and Air Quality Effects of Alternative Fuels—Final Report,* SR89-03-04, Mar. 28, 1989. Also, C.S. Weaver, T.C. Austin, and G.S. Rubenstein, Sierra Research, Inc., *Ozone Benefits of Alternative Fuels: A Reevaluation Based on Actual Emissions Data and Updated Reactivity Factors,* Apr. 13, 1990, Sacramento, CA.

The available literature shows a bewildering array of conclusions about methanol's potential as an ozone control measure. A wide range of numerical results and conclusions arises due to differences in:

- assumptions about the penetration of methanol-fueled vehicles into the fleet;
- assumptions about the rate and composition of vehicle emissions (including assumptions about the success of formaldehyde controls);
- choices about what to compare methanol to (e.g., current gasoline vehicles, future gasoline vehicles with advanced controls and low volatility gasoline, and so forth);
- assumptions about how effective future controls on gasoline emissions might be; and
- choices of geographical areas and types of meteorological episodes to examine.

These factors, and their implications for the potential effects of a methanol fuels program, are examined below.

In our separate analyses of available emissions data, we applied calculations of the incremental contributions of various organic compounds to ozone formation[11] to data on emissions of each compound from gasoline and M85-fueled vehicles. Estimates of the relative contributions of various organic compounds were available for seven sets of meteorologic conditions and initial pollution levels, which simulated different geographic areas and types of pollution episodes.

Across a range of pollution episode conditions, and differing estimates of the composition and magnitude of organic emissions from both M85 and gasoline vehicles, our analysis suggests that M85 use could yield as much as a 40 percent advantage over gasoline or, at the negative extreme, as much as a 20 percent increase in ozone potential over gasoline. We conclude that EPA's claim for M85 vehicles—a 30 percent reduction in per-vehicle "ozone-forming potential' '—is plausible for many situations but, even for these, is but a point in a range of possible outcomes.

The 30 percent claim fits well with some of the available vehicle emissions data (EPA's own test data, in particular), though even for these data the claim is applicable only to certain meteorological conditions and geographical areas for which controlling hydrocarbon emissions is an effective means of ozone control (in some areas, it is not). For other emissions test data (tests conducted by the California Air Resources Board, in particular), the 30 percent value appears too high even in the areas where methanol use is expected to be most beneficial. The results are sensitive to the level of formaldehyde in the exhaust, a factor that has been quite variable in tests and which could be affected significantly by ongoing development of catalytic controls. In other words, the existing data seem to support a wide range of possible outcomes.

The ozone benefits of optimized M85 and M1OO vehicles—according to EPA, about 40 and 80 percent reductions in ozone-forming potential, respectively— are even more uncertain than the benefits of current M85 vehicles because the former vehicles exist only in early prototypes. In all likelihood, these vehicles will achieve improvements in ozone reduction capability over current M85 vehicles, though cold starting problems with M1OO vehicles must be solved before such vehicles can be marketed.

The following discussion reviews the factors that affect methanol's ozone benefit relative to gasoline use, focusing in turn on methanol vehicle emissions, gasoline vehicle emissions, geographical area and type of episode, and other concerns. The discussion focuses primarily on M85, with a brief discussion of M1OO.

Methanol Vehicle Emissions—The air quality effects of using methanol vehicles depend on both the magnitude and the composition of the vehicle emissions compared to the gasoline vehicles they replace. Each of these factors has shown wide divergences among the various studies of air quality effects.

Emissions Magnitude-Analysts have used a range of assumptions about the relative magnitude of M85 emissions. Current EPA emissions standards for methanol-fueled vehicles demand that the total mass of carbon in their exhaust emissions be no higher than the total mass of carbon allowed from gasoline vehicles' exhaust.[12] Because M85 emissions consist in large part of methanol, which has a

[11] W.P.L. Carter and R. Atkinson, ' 'Computer Modeling Study of Incremental Hydrocarbon Reactivity, " *Environmental Science and Technology,* vol. *23, pp. 864-880, 1989.*

[12] "Standards for Emissions From Methanol-Fueled Motor Vehicle Engines," Final Rulemaking, *Federal Register 54,* FR14426, Apr. 11, 1989.

Table 3-I—Organic Emissions Levels for Gasoline and Methanol-Fueled Vehicles

	Exhaust			Evaporative		Total
Emission Test	Methanol (mg/mi)	TNMHC (mg/mi)	HCHO (mg/mi)	Methanol (mg/mi)	TNMHC (mg/mi)	TNMOC (mg/mi)
CARB: gasoline	0.0	330	7.7	0	45	380
M85	160	65	22	55	36	340
Gabele:						
gasoline	0	320	4.8	0	47	370
M85	290	80	27	19	20	440
Williams et al.:						
gasoline	1	230	7.2	0	120	360
M85	220	51	37	85	25	420

KEY:
HCHO=formaldehyde
TNMHC=total non-methane hydrocarbons
NOTE: does not include running losses.

SOURCE: J. Milford, "Relative Reactivities of M85 Versus Gasoline-Fueled Vehicle Emissions," contractor report prepared for the Office of Technology Assessment, Jan. 18, 1990.

high oxygen content and thus a lower carbon/mass ratio than most hydrocarbons, this standard allows M85 emissions of carbon-based compounds (methanol, hydrocarbons, and formaldehyde) to be significantly higher than gasoline emissions on a *total mass* basis. With the likelihood that manufacturers of both M85 and gasoline vehicles will tailor their control systems to Federal standards, some analysts have assumed that M85 and gasoline vehicles will have equivalent emissions on a carbon basis.[13] However, in emission tests of current vehicles, M85 vehicles tend to have lower organic emissions on a carbon basis than the gasoline vehicles. As shown in table 3-1, emissions tests of flexfuel vehicles operating on M85 and gasoline conducted by the California Air Resources Board (CARB), Environmental Protection Agency, and General Motors reported exhaust plus evaporative nonmethane organic emissions rates (excluding running losses, which were not measured) for M85 equal to 89, 119, and 117 percent by total mass of the gasoline emissions,[14] well below gasoline carbon equivalent rates.[15] These and other measured emission rates suggest that it might be reasonable to assume that M85 emissions may range as low as a *total mass* equivalence with gasoline emissions. EPA has chosen a midpoint between these assumptions-exhaust emissions equivalent on a carbon basis (reflecting the standard), evaporative emissions equivalent on a mass basis—which seems reasonably consistent with at least some of the available emissions data. Given the substantial difference in actual emission rates between mass equivalence and carbon equivalence (for the balance of individual emissions components measured in the EPA emissions tests, "carbon equivalent" total M85 emissions would be about 80 percent higher than "mass equivalent" emissions), the range between the two represents a wide range of consequences with respect to ozone reduction.

Emissions Reactivity-The primary basis for most claims of M85's and M 100's ozone reduction capability is the low photochemical reactivity of methanol, itself-that is, its low propensity to form ozone in the atmosphere--compared to gasoline emissions. However, emissions from M85 (and M1OO, as well) consist of more than just methanol; formaldehyde and a range of hydrocarbons similar to those produced by gasoline-fueled vehicles are also present. In particular, methanol vehicles produce highly reactive formaldehyde in larger quantities

[13]For example, this is the assumption used in T.Y. Chang et al., "Impact of Methanol Vehicles on Ozone Air Quality, " *Atmospheric Environment*, vol. *23, No, 8, pp. 1629-1644, 1989.*

[14]California Air Resources Board, Mobile Sources Division, "Definition of a Low-Emission Motor Vehicle in Compliance with the Mandates Of Health and Safety Code Section *39037 .05,' May 1989;* P.A. Gabele, "Characterization of Emissions from a Variable Gasoline/Methanol Fueled Car," personal communication, October 1989; and R.L. Williams, F. Lipari, and R.A. Potter, "Formaldehyde, Methanol, and Hydrocarbon Emissions from Methanol-Fueled Cars," General Motors Advanced Engineering Staff, Warren MI, 1989; J. Milford, op. cit., footnote 4.

[15]If the M85 and gasoline vehicles had carbon equivalent emission rates, the M85 vehicles would typically have mass emission rates well OVer 150 percent of the gasoline rates. J. Milford, op. cit., footnote 4.

than gasoline vehicles do.[16] The balance of the various reactive emissions compounds determines the overall reactivity of the emissions, and thus determines the effectiveness of methanol in reducing ozone levels.

Accurate estimates of M85 emissions reactivity require emissions measurements that are speciated, i.e., measure the amounts of each reactive compound in the emissions. Unfortunately, most emissions tests of methanol vehicles provide, at best, only limited breakdowns of organic compounds, e.g., unburned methanol, formaldehyde, and nonmethane hydrocarbons. Although such breakdowns are useful in gauging rough reactivity differences, they are of limited use in establishing reliable measures of ozone reduction potential. OTA identi.tied only three tests of methanol vehicle emissions, involving four vehicles, in which the data had been speciated in detail.[17] Using the data from these tests, we estimated the incremental contribution to ozone formation that each compound found in the emissions would make (i.e., the compound's "incremental reactivity' using results from a computer modeling study .18 We then combined these estimates with assumptions about the total mass of each type of emissions to estimate the relative reactivities of the M85 emissions compared to gasoline emissions.

The most significant finding of our analysis is that the test-to-test variability of the composition of exhaust nonmethane hydrocarbons from both M85 and gasoline *and thus their reactivity* is quite high. Particularly striking is the difference in composition and reactivity between the EPA and CARB tests, because both use the same fuel—indolene--yet the reactivity of the exhaust NMHC generated in the EPA tests is over 50 percent higher than the exhaust NMHC in the CARB tests. *This difference in NMHC reactivity drastically affects the estimated ozone benefits achievable by M85; using EPA's estimates of total mass emissions, we arrive at much more favorable (M85) results using the EPA test data than we do using the CARB data.* Figure ***3-1*** displays the relative reactivities of emissions from M85 versus gasoline-fueled vehicles using the EPA and CARB data. As shown, the EPA-based M85 ozone benefits range from 6 to 34 percent (that is, the M85 relative reactivities range from 0.94 to 0.66) for the 7 episode cases simulated, whereas the CARB-based benefits range from –20 (that is, an estimated *increase in* ozone formation)to+21 percent (reactivities range from 1.20 to 0.79).

An important source of controversy about the overall reactivity of both M85 and M1OO emissions is the likelihood of achieving long-term, effective control of formaldehyde. If formaldehyde emissions of the methanol vehicles increase from assumed levels, e.g., with catalyst aging, the reactivity benefits of shifting to methanol will decrease as well. For example, formaldehyde emissions for the emissions tests included in OTA's reactivity analysis ranged from 22 to 37 mg/mile, compared to about 5 to 8 mg/mile with straight gasoline.[19] These levels are low compared to other studies, which have reported formaldehyde emissions ranging to in excess of 100 mg/mi,[20] but higher than the proposed California standard of 15 mg/mile. It is possible that the low levels of formaldehyde were due to the relatively low miles accumulated by the vehicles: the CARB vehicles, for example, had 11,000 and 22,000 miles,[21] for example. As shown in figure 3-2, at formaldehyde emissions rates of 100 mg/mile, the reactivity benefits of M85 are largely lost when compared to advanced technology gasoline vehicles, and are reduced substantially compared to current technology vehicles.[22] Because catalyst aging does reduce formaldehyde control effectiveness with currently available catalyst technology, the potential loss of benefits is a real concern, and will remain so until improved catalysts are developed.

A final point here is that existing M85 (and the few M1OO) vehicles are prototypes, not production vehicles, and policymakers should be wary of

16Environmental Protection Agency, Office of Mobile Sources, op. cit., footnote 7. EPA's formaldehyde reactivity factor is 2.2 (compared to gasoline hydrocarbons) on an equal mass basis; its methanol reactivity factor is 0.19.

17These are the CARB, EPA, and GM tests discussed above, J. Milford, op. cit., footnote 4.

18W.P.L. Carter and R. Atkinson, op. cit., footnote 11.

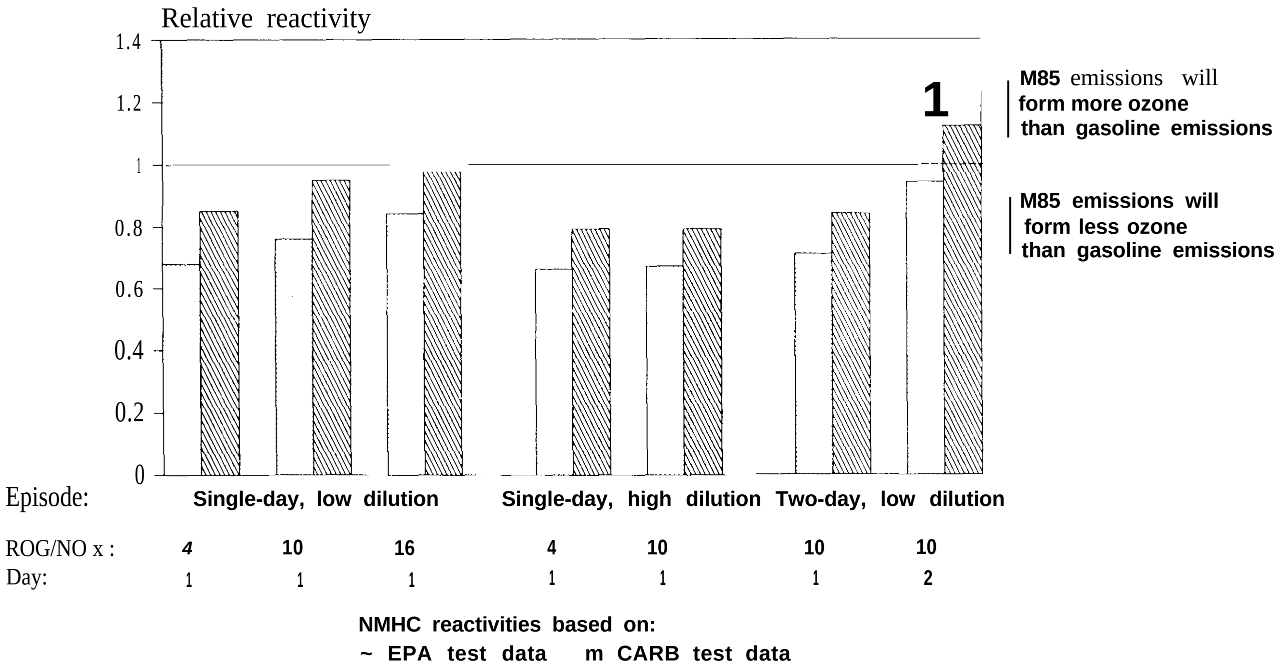
19J. Milford, op. cit., footnote 4.

20R. Snow et al., "Characterization of Emissions from a Methanol Fueled Motor Vehicle," *Journal of the Air Pollution Control Association (JAPCA)*, vol. *39, pp. 48-54, 1989.*

21California Air Resources Board, May 1989, op. cit., footnote 14.

22Ibid.

Figure 3-l—"Relative Reactivity" (Ozone-Forming Capability) of Emissions From M85-Fueled Vehicles v. Gasoline-Fueled Vehicles



Assumptions: 1. gasoline NMHC emissions rate based on proposed standards.
2. M85 mass emissions rate and breakdown into NMHC, formaldehyde, and methanol based on EPA analysis. Assumes M85 and gasoline exhaust emissions equal on a carbon basis, evaporative emissions equal on a mass basis.

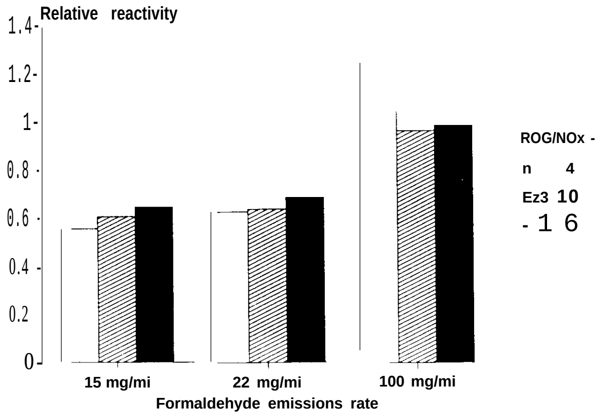
SOURCE: J. Milford, "Relative Reactivities of M85 Versus Gasoline-Fueled Vehicle Emissions," contractor report prepared for the Office of Technology Assessment, 1990.

extrapolations from their tested performance to the expected performance of a commercial fleet. Most of the vehicles have relatively low mileage and thus low degradation of catalysts and other equipment[23]. Further, in the process of moving from prototypes to mass-produced vehicles designed to satisfy consumers for at least 10 years, vehicle manufacturers will make important trade-offs among emissions, efficiency, durability, and performance; some methanol advantages could diminish in the process unless prevented by regulation. For example, though vehicle designers may be capable of holding total organic emissions well below those of gasoline vehicles on a carbon basis, they may choose not do so in order to reduce cost or enhance performance. On the other hand, most of the existing vehicles have engines and pollution control systems that are relatively minor adaptations of gasoline-fueled systems and not representative of systems optimized for methanol. Also, most vehicles were not designed or set up to attain minimum emissions levels, and most are multifueled rather than dedicated vehicles. Thus, existing vehicles cannot take full advantage of methanol's physical properties and do not perform as well as methanol proponents expect an optimized methanol vehicle would.

Gasoline Vehicle Emissions-Gauging the relative benefits of introducing methanol fuels involves comparing the emissions and air quality impacts of adding a number of methanol vehicles to the impacts of adding the same number of gasoline vehicles. Since the methanol vehicles would be added at some time in the future, analysts should compare them to future, not current, gasoline vehicles and fuel quality. The problem here is that we cannot predict with accuracy how well *either* a future methanol or a future gasoline vehicle is going to perform, or how

[23]According to Sierra Research (1989, op. cit., footnote 10), first generation M85-fueled methanol vehicles have experienced severe deterioration of emissions control equipment with increasing mileage. Acurex Corp., contractor to the State of California Advisory Board on Air Quality and Fuels, did not find this type of deterioration in their evaluation for the Board. Personal communication Michael Jackson, Acurex Corp.

Figure 3-2—Sensitivity of Relative Reactivities of M85 Emissions to Formaldehyde Emissions Levels



NOTES: M85 reactivitv is compared to future gasoline vehicles; M85 vehicle as tested by California Air Resources Board.

SOURCE: J. Milford, "Relative Reactivities of M85 Versus Gasoline-Fueled Vehicle Emissions," contractor report prepared for the Office of Technology Assessment, 1990.

changes in gasoline composition may affect emission levels or reactivity.

Future gasoline vehicles will likely have lower mass emissions of hydrocarbons (and NO_x, another ozone precursor) than today's vehicles, in response to more stringent emissions standards. The magnitude of the standards for the next few years are not certain at this time, and it is not known whether a second, more stringent round of standards will be required in the future. And the effect of uncertainty about the magnitude of future gasoline emissions is compounded by uncertainty about the reactivity of these emissions. Because catalytic converters will tend to work best on the most reactive substances, future increases in catalyst effectiveness might tend to reduce exhaust reactivity by selectively removing the most reactive substances left in the exhaust. In support of this hypothesis, available tests of the reactivity of the emissions from gasoline-fueled vehicles, conducted by General Motors, have shown reductions in reactivity in moving from current models to models with advanced catalytic converters.[24] If future gasoline-fueled vehicles have exhaust emissions that are lower in reactivity than today's vehicles, then the level of ozone produced by future vehicles will be lower than projected by existing modeling studies,[25] and this will reduce the relative benefits of methanol substitution.

Unfortunately, the cause of the reactivity changes observed in the GM tests is obscured by differences in vehicle mileages and in the gasolines used in the ''current' and ''advanced' vehicles tested. For example, the current vehicles were fueled with regular gasoline that may have had a higher fraction of extremely reactive alkenes and lower fraction of less reactive alkanes than the indolene used in the advanced vehicles; conceivably, this may explain part of the differential reactivities.[26] If the fuel differences, rather than differences in catalyst efficiency, were the primary cause of the differences in reactivity, then the results of these tests suggest a strong future role for gasoline reformulation as a strategy for reducing urban ozone. With such a strategy, however, the relative benefits of methanol substitution would be reduced. Further tests of gasoline and methanol-fueled vehicles, with better controls on fuel quality and vehicle mileage, are needed to clarify the effects on exhaust emission reactivity of improved emission controls and altered fuel composition.[27]

Geographical Area and Type of Episode—The effectiveness of methanol fuels as an ozone control measure will vary considerably from area to area, with some areas benefiting significantly and some not benefiting at all. In particular, methanol's effectiveness will tend to be high in areas that characteristically have low ratios of reactive organic gas (ROG) levels to NO_x levels, such as Baltimore or Philadelphia, and will tend to be low in areas with high ratios, such as Houston.[28] Other area variables affecting methanol effectiveness include average temperatures and mixing heights of the atmosphere. Low mixing heights (low dilution) are most characteristic of ozone episodes in California cities; high

24A.M. Dunker, ''The Relative Reactivity of Emissions from Methanol Fueled and Gasoline-Fueled Vehicles in Forming ozone," General Motors Research Laboratories, Warren MI, 1989.

25These studies typically account for lower per-vehicle mass emissions in future years but assume that the hydrocarbon component of vehicle exhausts is identical in composition to that of current vehicles.

26Ibid.

27Presumably, the research program on alternative fuels begun by the auto and oil industries—see ch. 8 discussion on reformulated gasoline—will add significantly to the database.

28J. Milford, op. cit., footnote 4.

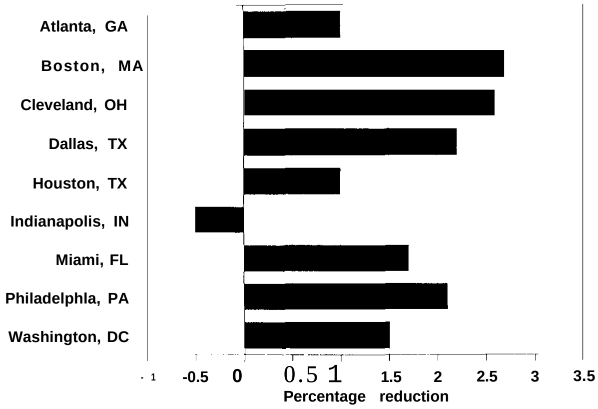
mixing heights (high dilution) are characteristic of summertime conditions in the Eastern United States.[29] In our analyses, methanol was more effective in the high dilution cases.[30] Figure 3-3, based on a Ford Motor Co. analysis, shows the strong differences among various cities in changes to peak l-hour ozone concentrations caused by the introduction of large numbers of M85 vehicles. City -specific changes in ozone range from an 0.5 percent *increase in* peak l-hour concentrations to a 2.7 percent decrease.[31] The changes in ozone concentration shown in figure 3-3 are small because, by the year 2000, automobiles will produce less than a quarter of total urban organic emissions (see ch. 2), so even a total elimination of vehicles would not cause a massive reduction in ozone concentrations in most cities. Also, the Ford analysis assumes that total gasoline and methanol emissions will be the same on a carbon basis, an assumption that will tend to minimize the estimated ozone benefit of methanol.

Methanol effectiveness will also tend to diminish in the later days of multiday episodes, which are common in the Los Angeles area and Northeast. The cause of this effect is a shift towards higher ROG/NO_x ratios, and lower methanol effectiveness, over the course of the episode, because NO_x is shorter lived in the atmosphere than most ROG species and thus tends to become depleted overtime.

Finally, methanol's effect on organic emissions will likely yield little or no benefit in many rural areas, because ozone production in these areas tends to be NOX-limited, i.e., there is an excess of organic gases in the atmosphere and reducing them somewhat does little good.[32]

Other Ozone Concerns—Although flexible fuel M85 vehicles allay some worries about fuel supply and vehicle resale value,[33] they raise concerns about the effect of methanol/gasoline mixtures other than M85. Unless government regulations *require* methanol use in ozone nonattainment areas, flexible fuel vehicles allow vehicle owners to shift back and forth from M85 to gasoline depending on fuel price and

Figure 3-3—Year 2000 Reductions in Peak l-Hour Ozone Concentrations From M85 Use



SOURCE: T.Y. Chang, S.J. Rudy, G. Kuutasal, and R.A. Gorse, Jr., "Impact of Methanol Vehicles on Ozone Air Quality," *Atmospheric Environment, vol. 23, No. 8,* pp. 1629-1644, 1989.

availability, mixing the two fuels in their tanks and diluting or negating potential air quality benefits associated with methanol use. In fact, significant use of gasoline in flexible fuel vehicles could potentially yield an *increase in* ozone-causing emissions because gasoline/methanol mixes that are preponderantly gasoline, aside from offering little benefit in exhaust emissions, have higher volatility than straight gasoline, and thus higher evaporative emissions.

M1OO Vehicles and Organic Emissions— Quantitative predictions of the ozone reduction benefit obtainable from M1OO seem somewhat premature, given the limited data and remaining uncertainty about the nature of additives and cold starting characteristics. There are few M1OO vehicles in existence and sparse emissions data. However, these data are less variable than existing M85 data,[34] perhaps implying that the absence of a gasoline component in the fuel makes the emissions benefits more robust than with M85. EPA believes that M1OO will produce very low evaporative emissions based on their experience with an M1OO Toyota Carina and

[29] Ibid.

[30] Ibid.

[31] T.Y. Chang et al., op. cit., footnote 13.

[32] S. Sillman and P.J. Samson, "Impact of Methanol Fueled Vehicles on Rural and Urban Ozone Concentration During a Region-wide Ozone Episode in the Midwest," conference on Methanol as an Alternative Fuel Choice: An Assessment, Johns Hopkins University, Dec. 4-5, 1989, Washington DC.

[33] That is, they can be used, and thus sold, in areas where an extensive fuel supply network has not Yet been built.

[34] P.A. Lorang, "Emissions From Gasoline-Fueled and Methanol Vehicles,' Conference on Methanol as an Alternative Fuel Choice: An Assessment Johns Hopkins Foreign Policy Institute, Washington DC, Dec. 4-5, 1989, Draft.

their evaluation of the effects of M1OO's physical characteristics, and about two-thirds lower exhaust NMHCs than even optimized M85 vehicles.[35] The expectations for lower evaporative emissions—including running losses and refueling emissions—appear reasonable given M1OO's low volatility and molecular weight and high boiling point. Similarly, because unburned fuel provides much of the organic emissions in vehicle exhausts, M1OO's chemical makeup is consistent with low exhaust NMHCs. However, mass emissions rates can increase substantially if the vehicles experience cold start problems. Also, assumptions of low mass emissions rates presume that the use of additives, to assist cold starting and add flame luminescence and taste to the fuel, will not affect evaporation rates and engine-out emissions, and that M1OO use will not affect control system effectiveness. These assumptions cannot be tested with available data. Reliable emissions estimates must await considerable testing for confirmation.

EPA also believes that the *reactivity* of M1OO emissions will be much lower than M85 reactivity because, as noted above, they expect M1OO's emissions of reactive NMHC emissions to be substantially lower than M85 levels, and formaldehyde levels to be better controlled.[36] Although it is certain that formaldehyde control levels will improve from today's capabilities, it is not possible to predict how successful current efforts will be. However, given the certainty that the evaporative emissions will have substantially lower reactivity than gasoline evaporative emissions (since the M1OO emissions consist only of methanol vapors), and the high probability that the M1OO vehicles will have fewer reactive NMHCs than M85 vehicles, the expectation of lower overall ozone-forming potential seems quite reasonable.

OTA concludes from the available evidence that there is good reason to consider methanol as offering likely long-term improvements to urban air quality, but less justification for confident predictions of up to 90 percent reductions in (effective) ozone precursor emissions. The quantitative effect on air quality, and specifically on levels of urban ozone, of shifting to methanol vehicles is uncertain, because of remaining questions about the magnitude, composition, and reactivity of organic emissions from optimized vehicles. Also, the effect will depend on the fuel chosen (pure methanol or a methanol/gasoline mix) and on whether the vehicles are flexible fuel or dedicated to a single fuel, as noted above. Finally, the effect will be dependent on the atmospheric conditions in the area. For example, in areas where the atmosphere contains a high ratio of reactive hydrocarbons to nitrogen oxides (for example, Atlanta), ozone formation will be limited by NO_x rather than by hydrocarbon concentrations; under these conditions, hydrocarbon reductions obtained from methanol may yield little reduction in ozone.

If current assumptions about methanol vehicles' organic emission characteristics-that is, a 30 percent reduction (compared to low volatility gasoline in current vehicles) in *effective* emissions[37] with M85 and current technology, an upper bound of 90 percent reduction with M1OO and advanced technology—prove correct, moderate but important reductions in total area-wide emissions of volatile organic compounds can be achieved if significant numbers of vehicles are converted. OTA estimates that if 25 percent of the light-duty vehicles in the 38 worst ozone nonattainment areas (areas with design values[38] of 0.15 ppm or higher) are switched to methanol by 2004, the areas will achieve average reductions in effective emissions of volatile organic compounds of 1.3 percent for M85/current technology vehicles and up to 4.1 percent for M1OO/advanced technology vehicles.[39] The reason these reductions are small is that, by the year 2004, light-duty vehicles will produce less than one-fifth of the organic emissions in most urban areas; in other words, complete elimination of the light-duty fleet could not eliminate more than one-fifth of the organic emissions.

[35]U.S. Environmental Protection Agency, op. Cit., footnote 7.

[36]Ibid.

[37]That is, measured in terms of the emissions' actual ozone-forming potential.

[38]The design value is the fourth highest of all of the daily peak 1-hour ozone concentrations observed within the area over the most recent 3-year period.

[39]Office of Technology Assessment, *Catching Our Breath: Next Steps for Reducing Urban Ozone*, OTA-O-412 (Washington DC: U.S. Government Printing Office, July 1989), table 7-10.

Nitrogen Oxides (NO_x)

Another concern about the potential ozone benefits of methanol use is methanol's effect on NO_x, emissions. NO_x is a crucial ozone precursor, so that any changes in its emissions can have consequences on ozone levels. Methanol's physical characteristics work in both directions with respect to NO_x emissions: for example, the higher compression ratio (compared to that possible in gasoline engines) made possible with methanol use tends to increase NO_x, emissions, the lower flame temperature and latent heat of vaporization tend to decrease emissions. Available tests of M85 vehicles have found NO_x emissions levels to be uniformly lower with M85 than with gasoline for dual-fuel vehicles,[40] probably because these vehicles do not have increased compression ratios; on the other hand, tests with dedicated vehicles show a mixed performance (some had higher NO_x emissions, some lower) with regard to comparable gasoline vehicles,[41] presumably because of the higher compression ratios in methanol vehicles. It appears reasonable to assume that methanol vehicles using three-way catalysts will be able to achieve the same levels of $NO_=$ emissions, on average, as comparable gasoline-fueled vehicles. However, some economic analyses favorable to methanol have assumed that methanol engines will achieve high efficiency by operating lean, i.e, by increasing the air/fuel ratio.[42] In this, designers may face a conflict between maximizing fuel efficiency and minimizing NO_x. Increasing the air/fuel ratio-operating lean—would likely reduce *engine-out* $NO_=$ levels (because the excess air keeps engine temperatures down) but would interfere with use of NO_x reduction catalysts, potentially increasing *controlled* levels of NO_x.[43] In some areas, an increase in NO_x emissions could have a significant deleterious impact on ozone concentrations.

Carbon Monoxide

Aside from organic emissions and NO_x, methanol use will affect emissions of carbon monoxide (CO). If the engines are run with high air/fuel ratios to maximize efficiency, they should produce lower CO than comparable gasoline vehicles if they can start well; because much of gasoline CO emissions are produced during cold start, starting problems could increase methanol CO emissions. If the vehicles are run with air/fuel ratios at stochiometric levels, as with gasoline, CO emissions should be similar to levels achieved by comparable gasoline vehicles, and perhaps a bit higher.[44]

Toxic Emissions

Methanol use will also reduce significantly (or nearly eliminate, for M1OO) emissions of some toxic substances, primarily benzene, 1,3-butadiene, polycyclic organic material, and gasoline fumes. This reduction has been cited by supporters of methanol as a critical benefit of methanol use.[45] Methanol use will, however, increase direct emissions of formaldehyde, a highly toxic substance, and this has raised concerns. Whereas gasoline engines generally emit formaldehyde at rates considerably less than 10 mg/mile,[46] methanol vehicles typically emit formaldehyde at rates several times this much.[47] As noted above, the M85 vehicles considered in our analysis[48] emitted 22 to 37 mg/mi of formaldehyde, and these rates were comparatively low compared to other tests. On the other hand, EPA has measured much lower formaldehyde rates, but for relatively new vehicles.[49] Automakers have expressed concern that long-term catalytic control of formaldehyde, over a

40M.A. DeLuchi et. al., 'Methanol vs. Natural Gas Vehicles: A Comparison of Resource Supply, Performance, Emissions, Fuel Storage, Safety, Costs, and Transition,'' Society of Automotive Engineers Technical Paper 881656, October 1988.

41Ibid.

42U.S. Environmental Protection Agency, op. cit., footnote 7.

43Reduction catalysts require stoichiometric (or richer) mixtures of air and fuel (a stochiometric mixture has just enough air to fully burn the fuel) to operate properly. They cannot operate with significant levels of excess oxygen, which would occur with "lean' '-excess air-air/fuel mixtures.

44DeLuchi, op. cit., footnote 37.

45U.S. Environmental Protection Agency, op. Cit., footnote 7.

%1 the three sets of tests reported in J. Milford, op. cit., footnote 4, the *highest rate* was 7.7 mg/mile.

47M. DeLuchi, op. cit., footnote 37, reports that EPA estimates that in-use methanol vehicles emit about 106 mg/mile over their life.

48J. Milford, op. cit., footnote 4.

49U.S. Environmental Protection Agency, op. cit., footnote 7, and M. DeLuchi, op. cit., footnote 37.

vehicle lifetime, represents a serious challenge to the industry .50

Formaldehyde emissions are a concern in enclosed places such as parking garages and tunnels (or areas where diffusion is restricted, e.g., urban "canyons"), where levels of any pollutant can rise to much higher levels than in ambient air, as well as in ambient air, where the primary concern is longer term exposure of large populations. The former situation is definitely an important concern, especially with occasional malfunctioning vehicles, but similar concerns about gasoline emissions may be equally important. Concerns about ambient exposures to formaldehyde are made ambiguous by the substantial quantities of ambient formaldehyde caused by emissions of hydrocarbon precursors—more than half of atmospheric formaldehyde appears to be due to this "indirect" source.[51] Because methanol use will cause a decrease in emissions of some formaldehyde precursors, the net effect of methanol on ambient formaldehyde may actually be a reduction in concentrations.[52] Studies by Carnegie Mellon University estimated an increase in *peak* formaldehyde but little change in average levels with methanol substitution.[53] However, this and other estimates are extremely sensitive to assumptions about formaldehyde emission rates, and these remain uncertain.

Greenhouse Emissions

Methanol use is expected to provide, at best, only a small greenhouse gas benefit over gasoline, and then only if the vehicles are significantly more efficient than gasoline vehicles. According to Sperling and DeLuchi,[54] use of flexible fuel vehicles with M85 will yield essentially no benefit, assuming a 5 percent efficiency increase and current methanol production technology. At the optimistic extreme, use of M 100 with a 25 percent efficiency gain (in our view, an unrealistically high value) and advanced methanol conversion technology will yield a 12 percent gain.[55] The primary uncertain factors in the ''net greenhouse gas emission' calculation are vehicle efficiency, methanol production efficiency, the effect of increased methanol production on natural gas leakage and on venting and flaring, and the potential for use of coal as a methanol feedstock.

Production efficiency is somewhat uncertain primarily because some of the natural gas that might be available for methanol production is cheap enough to create interesting trade-offs between high efficiency/high capital cost and lower efficiency/lower capital cost facility designs.

As for venting and flaring, some proponents of methanol as a transportation fuel have noted that considerable amounts of natural gas are today either vented to the atmosphere or flared, producing greenhouse gases (both carbon dioxide and methane itself are greenhouse gases, with methane by far the more potent of the two) with no corresponding energy benefit. To the extent that development of a methanol economy would capture and convert this gas, net greenhouse emissions would be reduced. However, the extent of venting and flaring is likely to be reduced with or without methanol demand because of gas' growing use as a chemical feedstock and as a clean-burning combustion fuel. It seems unrealistic to award methanol with this potential environmental benefit. (There is further discussion of this issue in app. 3A.)

Because coal may eventually become the raw material source for a U.S. methanol-fueled highway fleet, many in the environmental community have concerns about the long term impact of methanol use on emissions of greenhouse gases. Methanol from coal will produce substantially higher emissions of greenhouse gases than the current gasoline-based system, primarily because coal has a high carbon-to-hydrogen ratio and because the current processes of producing methanol from coal are inefficient.

Although these concerns appear realistic, world natural gas supplies appear capable of fueling even

---

[50] David Kulp, Manager of Fuel Economy and Compliance, Ford Motor Co., personal communication.

[51] T. Russell, Carnegie Mellon University, presentation on Methanol Impacts on Urban Ozone and Other Air Toxics, conference on Methanol as an Alternative Fuel Choice, Johns Hopkins University, Washington, DC, Dec. 4-5, 1989.

[52] Ibid.

[53] J.N. Harris, A.R. Russell, and J.B. Milford, "Air Quality Implications of Methanol Fuel Utilization,'' Society of Automotive Engineers Technical Paper 881198, 1988.

[54] D. Sperling and M.A. DeLuchi, *Alternative Fuels and Air Pollution*, draft report prepared for Environment Directorate, Organization for Economic Cooperation and Development, March 1990.

[55] Ibid.

a large methanol program for several decades at least, and future process changes to improve coal-based production efficiency and to sequester the CO_2 produced during methanol conversion could allay these concerns. On the other hand, if energy security concerns become paramount-certainly a possibility given recent history-producing methanol from domestic coal might suddenly appear much more attractive. However, because *gasoline* can be made from natural gas and coal, avoiding methanol or other alternative fuels that can be manufactured from coal in no way guarantees that coal will not eventually become the feedstock source for our transportation fuels.

OTHER ENVIRONMENTAL/ SAFETY EFFECTS[56]

Aside from air quality changes, a broad shift to methanol vehicles will create environmental changes because methanol's characteristics are substantially different from those of gasoline. From an overall safety and human health perspective, methanol represents some new dangers but probably not a net increase in risk.

Both methanol and gasoline are harmful if inhaled, absorbed through the skin, or ingested. Because minute quantities of methanol occur naturally in the body, ingestion or absorption of small quantities—i.e., a few drops-would be relatively harmless. However, methanol is more likely than gasoline to be fatal if swallowed, and an amount equal to only about 10 teaspoonful can be a fatal dose to an adult (In contrast, a full mouthful of gasoline will generally be less than a fatal dose). A 3-year-old child could be killed by a dose little more than a tablespoon full.[57] For this reason, and because methanol is tasteless, some analysts are very concerned about the potential for accidental ingestion. In all likelihood, a bad-tasting additive would be used to guard against this danger. Further protection could be offered by required antisiphoning screens in methanol fuel tanks, and a ban on methanol use in small engines.[58] And, unlike gasoline, methanol is not an effective solvent for oils and grease and will not be stored in and around the house for such purposes. This should decrease exposure considerably. Finally, remedies for methanol ingestion are more effective in preventing damage than those for gasoline.

Methanol is absorbed through the skin more quickly than gasoline.[59] Such absorption could be a problem if methanol is handled as badly as gasoline currently is handled, especially in self-service stations. Gasoline spills from overfilling of tanks, from expansion when fuel is introduced into warm tanks during the summer, and from improperly set fuel cutoff valves are common,[60] and would presumably remain common with methanol if additional precautions are not taken. However, prolonged or frequent contact are necessary for acute symptoms, and methanol's inadequacy as a solvent should help reduce such contact.[61] Also, straightforward technical solutions to this problem are available, including tank redesign to reduce potential for spillage, cutoff valves set to prevent continued filling after initial cutoff, and so forth. Although technical solutions can be overridden, they could still provide a substantial reduction in methanol exposure risk.

Methanol should present less of an open-air fire and explosion hazard than gasoline because it ignites much less readily and, once ignited, burns with considerably lower intensity. A methanol fire is easier to fight because the methanol is soluble in water and thus can be diluted, whereas gasoline will float on top of water and continue to burn. M1OO's invisible flame (M85's flame is visible) is an important drawback, however; chemists are looking for a trace additive that would make the flames

[56] Material from P.A. Machiele, "Flyability and Toxicity Tradeoffs With Methanol Fuels,' Society of Automotive Engineering Technical Series 872064, 1987, unless otherwise referenced.

[57] T. Lotovitz, "Acute Exposure to Methanol in Fuels: A Prediction of Ingestion Incidence and Toxicity, " National Capital Poison Center, Oct. 31, 1988.

[58] Fuel used for lawnmowers and other small engines often is stored in households, in small containers, with significant incidence of accidental ingestion.

[59] B. Bayeart et al., "An Overview of Methanol Fuel Environmental, Health and Safety Issues," American Institute of Chemical Engineers 1989 Summer Meeting, Symposium on Alternative Transportation Fuels for the 1990's and Beyond, Aug. 22, 1989, Philadelphia PA.

[60] Gasoline spillage will likely be reduced significantly when Stage II vapor recovery controls (with automatic fuel cutoffs) are adopted fOr gasoline station pumps.

[61] P.A. Machiele, ' 'Perspective on the Flammability, Toxicity, and Environmental Safety Distinctions Between Methanol and Conventional Fuels," AIChE 1989 Summer National Meeting, Philadelphia, PA, Aug. 22, 1989.

visible. Nevertheless, the potential reduction in both incidence and intensity of fires will be an important safety issue, because gasoline fires associated with vehicle accidents are a major cause of injury and death in the United States.

A potential disadvantage of neat methanol, M1OO--but not of M85—is that methanol vapors in an enclosed space, such as a half-full gas tank, form a combustible mixture and thus can present a fire or explosion hazard. Bladder-type fuel tanks, which avoid creating an air space as the tank empties, may be necessary for M1OO vehicles.[62] An alternative or additional safety precaution would be flame arrestors at the mouth of the fuel tank. These could serve double duty as anti-siphoning devices, to prevent accidental ingestion. Flame arrestors are now used in all flexible and variable fueled vehicles.[63]

Methanol's volubility also will greatly affect its impacts in the event of a spill. In open waters, methanol would disperse rapidly and decompose rapidly as well. The major problem would be severe toxicity in the immediate vicinity of a spill, with large spills in enclosed harbors or similar areas being a particular problem. If methanol were spilled on land, its volubility and low viscosity would allow it to penetrate porous ground and enter aquifers more readily than gasoline. Methanol would be likely to disperse rapidly throughout an aquifer, limited only by the slow movement of the water. For shallow aquifers with high oxygen contents, the methanol would be decomposed by natural processes fairly quickly; where oxygen contents were low, however, decomposition would be slow. Toxicity problems in drinking water aquifers would occur where the spill was in close proximity to wells, where the water flow in the aquifer moved 'plumes" of methanol to the wellbores, or simply where the volume of the spill was large in comparison to the volume of the aquifer. In contrast, a gasoline spill of similar magnitude would disperse less quickly into and through an aquifer, but its failure to degrade could cause the aquifer water to become unpalatable and remain so for years. If bad-tasting additives were added to methanol (for consumer safety), however, the potential for palatability problems from spills would exist for methanol as well.

Methanol's advantages over gasoline in a spill situation might be partially nullified if chemicals are added to methanol to provide taste (as a safety precaution to reduce incidence of accidental ingestion), flame color, or improved cold starting capability. Selection of such chemicals should account for the desirability of compounds that can be neutralized easily or that are biodegradable to less harmful components.

COST COMPETITIVENESS

The economic competitiveness of methanol used as a gasoline substitute is a source of intense and ongoing controversy, with alternative positions ranging from claims that methanol will eventually be less expensive than gasoline, on a $/vehicle mile basis, at *current gasoline and world oil prices*[64] to claims that methanol will remain noncompetitive until gasoline prices reach $1.50/gallon (in 1989 dollars) or even higher.[65] Price estimates for neat methanol delivered to the United States have ranged from as low as $0.25/gallon to as high as $0.75/gallon for methanol produced from natural gas, and higher for methanol produced from coal (distribution costs, service station markup, and taxes would be added to these prices). This wide range stems from different assumptions about natural gas prices, technological selections, required rates of return, infrastructure requirements, required chemical purity,[66] and other factors, and the substantial variability of plant costs in remote locations. And estimates for the appropriate conversion factor between methanol and gasoline prices (that is, the multiplier of methanol price to make it comparable to gasoline price), to account for differences in energy content and efficiency between the two fuels, range from 1.5 or 1.6 (assuming that methanol vehicles will be 25 to 30

[62] M.A. DeLuchi et al., op. cit., footnote 37.

[63] Alan Lloyd, South Coast Air Quatity Management District, personal communication.

[64] Office of Mobile Sources, U.S. Environmental Protection Agency, "Analysis of the Economic and Environmental Effects of Methanol as an Automotive Fuel," September 1989.

[65] W.J. Schumacher, ''The Economics of Alternative Fuels and Conventional Fuels, " SRI International presentation to the Economics Workshop, California Advisory Board on Air Quality and Fuels, Feb. 2, 1989, San Francisco, CA.

[66] Methanol sold in today's market generally is ' 'chemical grade'' methanol, which is quite pure. It has been suggested that a lower purity methanol, producible with some cost savings, might be satisfactory as a motor fuel.

percent more efficient than equivalent gasoline vehicles) to 2.0 (assuming that methanol and gasoline vehicles will be equally efficient). Because the extremes of the ranges imply such different prospects for methanol, it is important for policymakers to understand the bases for the various positions and to be able to judge their reliability.

One thing is quite certain about future methanol prices—if methanol is to emerge as a major transportation fuel, expected prices must be high enough to stimulate major new capacity additions. Although some countries might be willing to build new capacity to operate at a loss, to obtain foreign exchange or to pursue social policy, only expectations of profit are likely to bring forth enough new capacity to allow a significant shift to methanol for transportation use. And although substantial shut-in capacity exists today, perhaps as much as a billion gallons/yr, it is a small fraction of the methanol volume that would be necessary to fuel even a small percentage of the U.S. auto fleet. For example: Were 10 percent of U.S. commercial fleet vehicles amenable to fueling from dedicated stations converted to methanol, an additional methanol demand of 2.7 billion gallons per year would be created;[67] and, were California somehow to convert its automobile fleet entirely to methanol, that State alone would demand 25 billion gallons of methanol per year—four times current world capacity.[68]

Assuming that natural gas-currently the most economic feedstock for methanol-remains the primary feedstock, we discuss in appendix 3A (See end of chapter) the factors that are critical in determining methanol's cost and competitiveness with gasoline. As noted in the appendix, various analysts have selected a wide range of assumptions about most of the factors. Aside from differences that may arise from vested interests (oil industry analysts may tend to prefer pessimistic assumptions, analysts working for chemical plant manufacturers—potential methanol producers—may tend to choose optimistic assumptions), differences stem from technical uncertainties as well as uncertainties about market reactions and government policies.

Given the large number of 'optimistic/pessimistic' selections possible, it is difficult to define a reasonable maximum/minimum range for methanol costs. Nor can we readily define a' 'most likely' cost. We can, however, attempt to put possible methanol costs into perspective by examining a few scenarios and defining cost ranges for them. In the scenarios that follow, production and shipping costs are based on the Department of Energy (DOE) analysis prepared by Chem Systems, Inc.[69] *Rates of return (RORs) are real (corrected for inflation), after tax rates.*

1. Transition period. In the early years of a methanol program, new plants will likely be of moderate scale (2,500 metric tons per day, or MTPD) and use standard technology (steam reforming). Required rates of return will tend to be high because of high market risk, though somewhat restrained by low *technical* risk. Likely RORs will be perhaps 15 to 20 percent unless there are strong nonmarket guarantees that methanol demand will keep growing; even with such guarantees, plant developers must be wary of overbuilding unless they can sign long-term contracts with distributors. With strong assurances, possibly including take-or-pay contracts,[70] required ROR might be as low as 10 percent. Shipping will likely be in tankers of about 40,000 dead weight tons (DWT) scale, but larger tankers might be feasible a few years into the program if producers are given strong market guarantees[71] and the lack of suitable ports can be overcome[72] (presumably, this cannot occur for several years). If the vehicles are fuel flexible and if methanol supply is constrained at first to port cities, distribution costs will be low;[73]

[67] D.A. Dreyfus and A.B. Ashby, "The Prospects for Gas Fuels In International and Interfuel Competition%" International Energy Workshop, IIASA, Luxemburg, Austria, June 16-18, 1987. These fleet vehicles and equipment account for about 15 percent of U.S. gasoline demand.

[68] Energy and Environmental Analysis, op. Cit., footnote 6.

[69] U.S. Department of Energy, Office of policy, Planning, and Analysis, *Assessment of Costs and Benefits of Flexible and Alternative Fuel Use in the U.S. Transportation Sector. Technical Report Three: Methanol Production and Transportation Costs,* DOE/PE-0093, November 1989.

[70] A take-or-pay contract is one where fuel buyers agree to pay for a fixed volume of fuel each period whether they accept the fuel or not. Previous experience with such contracts in the natural gas industry does not, however, offer much assurance to developers-these contracts were routinely broken.

[71] If large tankers can be readily converted to carry gasoline or other products and if there is a demand for such vessels, the risk associated with building larger tankers may be reduced.

[72] It may also be possible to simply transfer the methanol to smaller ships offshore, though this option maybe limited by weather conditions.

[73] Although distribution costs for gasoline should be low as well, lowering the retail price with which methanol price must be compared.

Table 3-2—Component and Total Methanol Supply Costs During a Transition Phase

Part of fuel cycle	Strong market guarantees	Free market, few guarantees
Production[a]	0.42	0.55-0.65[d]
Shipping	0.02-0.03 or 0.04-0.08[b]	0.03-0.08
Distribution	0.03	0.03
Markup	0.06-0.09	0.09-0.12
Taxes	0.12	0.12-0.13
Retail Price	0.65-0.69 or 0.67-0.74	0.82-1.01
Midrange Price[c]	0.68-0.72	0.85-0.95
Efficiency Factor	1.9	1.9
Gasoline Equivalent Price, $/Gallon	1.29-1.37	1.61-1.81
Low gas cost case (gas at $.50/MMBtu for many sites) $/Gallon	1.19-1.27	1.51-1.71

Higher cost gas cases: each increase of $O.50/MMBtu yields a methanol price increase of about $O.05/gallon of methanol, or about $0.10/gallon increase in the gasoline equivalent price.
a Natural gas cost is $l.O0/MMBtu.
b Two to three Cents represents very large tankers shipping over moderate to long distances; 4 t0 8 cents represents smaller tankers. Import duty for chemical-grade methanol assumed to be dropped.
c Range reduced to avoid extremes with little probability.
d Range represents 15 to 20 percent required Rate of Return (ROR).

SOURCE: Office of Technology Assessment, 1990.

however, fuel flexibility and guaranteed markets may be incompatible unless methanol prices are artificially maintained lower than equivalent gasoline prices or flexible fuel vehicles are required to refuel with methanol within market areas around ozone nonattainment cities. Similarly, retail markups will be high unless there are market guarantees or government regulations requiring minimum levels of methanol sales from each station. Taxes would likely be based on methanol's energy content in a ''market guarantees scenario," to promote methanol use; in a free market scenario, taxes might instead be set to reflect miles driven, to avoid a tax loss (because of methanol's potentially higher efficiency in use) and to require methanol vehicles to pay their share of road services.[74] Finally, vehicles are most likely to be fuel flexible, and would likely have a modest (e.g., 4 to 7 percent) efficiency gain over gasoline.

Table 3-2 presents the component and total costs of methanol supplies during the transition period, for both "market guarantees" and "free market" scenarios.

2. Established methanol supply and demand, low shipping costs, dedicated vehicles. Assuming that methanol demand becomes strongly established in the United States, eventually producers should be willing to build larger, advanced technology plants,[75] and vehicle manufacturers may move to dedicated vehicles to achieve improved air quality benefits and higher efficiencies. With a larger program, the potential for equivalent programs in other countries, and other worldwide increases in gas use, there is an increased potential for higher gas feedstock costs—unless continued exploration turns up large new reserves, which is quite possible. Average distribution costs should increase because of greater distances associated with wider distribution of methanol, including availability in many inland areas. Whether the fleet moves from flexible fuel to dedicated vehicles depends on government air quality regulations and security interests (flexible fuel vehicles have certain energy security advantages over dedicated vehicles). In this scenario, there should be a stronger possibility that large, dedicated tankers (250,000 DWT) will become the primary methanol

[74] It may not be likely that governments would tax methanol this way, but taxing methanol strictly on a Btu basis could be construed as a subsidy of methanol vehicle use.

[75] Assumes use of catalytic or noncatalytic partial oxidation for the synthesis gas generation section, at considerable savings in Capital costs. Improvements are also assumed for the methanol synthesis section, e.g., Davy McKee mixed flow reactor, or Mitsubishi fluidized bed rector. U.S. Department of Energy, op. cit., footnote 69.

Table 3-3—Component and Total Methanol Supply Costs in an Established Market Environment

Part of fuel cycle	Some continued guarantees	Free market, few guarantees
Production[a]	0.28-0.30	o.34-o.39[b]
Shipping	0.02-0.03	0.02-0.03
Distribution	0.05-0.06	0.05-0.06
Markup	0.06-0.09	0.06-0.09
Taxes	0.12	0.13-0.14
Retail price	0.53-0.60	0.60-0.71
Efficiency factor	1.67-1.82	1.67-1.82
Gasoline equivalent price, $/Gallon	0.89-1.09	1.02-1.27’
Low gas cost case (gas at $0.50/MMBtu for many sites) $/Gallon	0.81-1.06	0.91-1.24
Higher gas cost cases: Each increase of $0.50/MMBtu yields increased methanol costs of $0.04-$0.05/gallon, or about $0.07-$0.1 O/gallon of gasoline equivalent.		
Flex-fue/ *case* (all vehicles are flexibly fueled) $/Gallon	1.01-1.14	1.14-1.35
Higher capita/ cost case (required rate of return (ROR) without government guarantees assumed to be 20 percent) $/Gallon	NA	1.08-1.42

a Natural gas cost is $1 .00/MMBtu

b Free market ROR is assumed to be 15 percent; market guarantee case assumes 10 percent.

c The factor of 1.67 is applied to 61 cents, not 60 cents, and the factor of 1.82 is applied to 70, not 71 cents, because the 13 cent taxis appropriate only if the efficiency factor is 1.82, and the 14 cent tax applies only to the factor of 1.67.

SOURCE: Office of Technology Assessment, 1990.

transporters, significantly reducing shipment costs. With lower risks, required rates of return should be lower (in this scenario, we assume a free market required rate of return of 15 percent; this may be considered low for many sites, but capital should be available at such rates in several Middle Eastern sites with large gas reserves, assuming a stable political climate), and retail markups may come down even without government sales requirements. For the “market guarantees” case, the measures needed to keep RORs at 10 percent presumably will not need to be as strong as those required in the short term. If retailers move to dedicated vehicles, methanol vehicles could be significantly more efficient than gasoline vehicles; a likely value for the efficiency increase is about 15 percent, but there is a wide range of uncertainty. Note that a move to dedicated vehicles is most likely if distribution is wide; in that case, distribution costs must go up.

Table 3-3 presents the component and total methanol supply costs for this case.

These scenarios imply that on a cost basis methanol will be difficult at the outset to introduce as a gasoline substitute, but that its prospects for economic competitiveness should improve substantially once a market is established and economies of scale can be achieved. In the short term, high risks, inability to achieve scale economies, and the need to start out with proven, and nonoptimal technology is likely to make methanol a rather expensive fuel compared to gasoline. In the longer term, fuel and other costs can come down and fuel use efficiencies rise to lessen the economic gap between methanol and gasoline. However, there remain significant uncertainties and disagreements about just how expensive methanol will be in the long term, with key uncertainties associated with feedstock costs, vehicle efficiency, shipping and distribution system costs, financial risks and required rates of return, and other factors. At the same time, there is some uncertainty associated with the future price of gasoline even *at stable oil prices.* Changing crude oil quality, new government requirements to reduce volatility and otherwise improve gasoline’s environmental performance, and refiner pressure for price increases to correct historically low rates of return all may work to raise prices.

How long will a “transition period” last? Neglecting development of natural gas feedstocks, which will likely become more expensive with time, we would guess that the methanol fuel cycle might reach the lower cost, ''stable market' phase within 8 to 12 years from the beginning of commercial production of fuel and vehicles.

We do not envision a well-defined period that ends at a single point, with lower cost, larger scale systems then taking over essentially all at once. Instead, there will be a transition period associated with high cost factors of production, followed by a gradual shift of the various factors of production towards lower cost, larger scale units, and eventually a period of established, lower cost methanol supply. For example, some higher "transition" costs, e.g., high service station markups, could be reduced quickly, essentially as soon as it became clear that a stable market for methanol fuel was developing and capital improvements would be paid off with little risk. On the other hand, planning, financing, and building a fleet of large methanol-dedicated tankers would not be likely to even begin for a few years, and then would require a few more years before the first tankers began to haul methanol. And building larger scale production plants would also take a number of years. Presumably, the first of these lower-unit-cost factors of production would not affect market costs until they controlled enough of the market to begin competing among themselves (unless they were overbuilt, with excess supply of that factor requiring the new factors to bid low for market share). Until then, their owners would obtain higher profits because of the price structure established by the predominant, smaller scale, higher cost tankers, production plants, or other factors. In contrast to the other factors of production, feedstock costs would likely start at low costs because of the current availability of sites with abundant gas reserves, low development costs, and lack of alternative markets, and eventually move to higher costs as methanol demand outgrows the availability of the lower cost reserves.

The scenarios apply to methanol manufactured in locations that combine low natural gas prices with moderate construction costs. Generally, locations that offer low construction costs because of a well-developed infrastructure also have prohibitively high natural gas costs; and locations with virtually free gas (because they are so isolated that the gas has no other possible markets) also have very high construction costs because they lack infrastructure and have poor availability of both trained workers and critical supplies. This implies that essentially all methanol used for transportation in the United States would be imported, probably from areas that are at least partially developed at this time.

Despite the apparent economic advantages of imported methanol, some support for a shift to methanol has come from policymakers who desire to see the United States supply more of its own transportation fuel. One option for U.S.-produced methanol is to manufacture it on the North Slope and ship it to the lower 48, primarily because the North Slope has gas reserves of at least 37 trillion cubic feet (TCF) and no ready markets.[76] North Slope methanol may have difficulty competing with other sources because of higher cost, however. The California Energy Commission has estimated that the delivered (wholesale) cost of North Slope methanol to Los Angeles would be roughly $1.00/gallon of methanol,[77] as much as triple the cost of competing sources. Similarly, a recent study by SRI International estimated North Slope methanol production costs at about $0.40/gallon of methanol assuming a $0.51/mmBtu gas price. Even with the high transportation costs associated with transporting the fuel by pipeline to Valdez and shipping it to the lower 48 States, the delivered cost would still be under $ 1.00/gallon of methanol.[78] The level of uncertainty associated with these estimates is high, however, with delivered methanol cost dependent on the "value" of the gas resource as reflected in its price, the availability and practicality of the Trans Alaskan Pipeline as part of the delivery system, and capital costs of modular methanol plants delivered and installed on the North Slope. Some analysts believe the cost of methanol can be less than these estimates.[79] In particular, shipping costs may not be

[76] Currently, gas that is produced with North Slope oil is either reinfected to maintain reservoir pressure or is used as part of enhanced oil recovery operations in the Prudhoe Bay Field.

[77] California Energy Commission *AB234 Report: Cost and Availability of Low-Emission Motor Vehicles and Fuels. Volume II: Appendix*, August *1989.* The price ranges from $0.90 to $1.1 I/gallon with natural gas costs ranging from $0.33 to $2.00/mmBtu.

[78] W.J. Schumacher, op. cit., footnote 65.

[79] David L. Ku@, Manager, Fuel Economy Pl arming and Compliance, Ford Motor Co., personal communication. It is worth noting that the charge for using the Alaskan pipeline is due to be reduced substantially; further, because oil throughput in the pipeline is expected to decline during the coming decade, there is substantial incentive to give methanol an attractive rate if this will keep the pipeline operating at full capacity.

high if, as expected, North Slope oil production declines and substantial excess capacity is available on the Trans Alaskan Pipeline System. Even with low pipeline tariffs, however, it appears that North Slope methanol would be priced, at retail, at least $0.15 to $0.20 more per gasoline gallon equivalent than low cost imported methanol. Of course, a "premium" of this magnitude might seem a reasonable price to pay for a secure, domestic source of transportation fuel if energy security concerns were to escalate.

Methanol can also be made from coal, which the United States has in abundance, but the total production costs are likely to be considerably higher than costs for gas-based methanol. Amoco reports probable manufacturing costs for methanol from coal as approximately $ 1.00/gallon.80 A recent report by the National Research Council estimates methanol-from-coal's crude oil equivalent price to be over $50/barrel.[81] As with North Slope methanol, the level of uncertainty associated with the cost estimates is high and the potential exists to reduce costs substantially with advanced technology. For example, advocates of coal-based systems that produce methanol in conjunction with electricity in a gasification/combined cycle unit claim methanol costs comparable to those of natural gas-based systems.[82] DOE's evaluation of this type of system implies that it could achieve significant cost reductions from other coal-to-methanol processes, producing methanol at costs of about $0.58/gallon using $35/ton midwestern coal and assuming a 10 percent (real) rate of return.[83] This is still significantly higher than methanol produced from natural gas, unless the latter proves to be a higher risk source and requires a higher rate of return. Also, because gasification/combined cycle plants of this type are primarily power producers,[84] the potential methanol supply from this source would be limited by the growth of electricity demand and by U.S. willingness to satisfy increased demand primarily with coal plants.

Similarly, methanol can be made from wood and other biomass materials, at highly uncertain costs because of the extreme variability of the cost of the biomass materials. The National Research Council's estimate for the crude oil equivalent price of methanol produced from wood using demonstrated (but not commercial) technology is over $70/barrel.[85] Because biomass gasifiers suitable for producing synthesis gas (these are either pyrolysis or oxygen blown gasifiers) have not gotten the development attention that coal-fed gasifiers have, some researchers believe that methanol produced from biomass could eventually be competitive with coal-based methanol.[86] Such an outcome would require improvements in both conversion technology and in all aspects of the growing and harvesting cycle for biomass-to-methanol production.

If oil prices-and thus gasoline prices-rise, the relationship between gasoline and methanol prices may change, and methanol may become more competitive. Under some circumstances, methanol prices need not rise in lockstep with gasoline prices. For example, if methanol producers were using natural gas feedstocks that had few or no other markets, gas prices in these areas might not be tied closely to oil prices. For such a scenario, rising oil prices probably would lead to improved methanol competitiveness.[87] Other causes of likely different rates of gasoline/methanol price escalation include the different proportion of feedstock conversion costs embodied in each fuel, the differences in current market conditions for natural gas and oil (gas is in oversupply), and the differing role that shipping costs play in oil and natural gas prices.

[80] J. Levine, Amoco Corp., personal communication.

[81] Committee on Production Technologies for Liquid Transportation Fuels, National Research Council, *Fuels to Drive Our Future* (Washington, DC: National Academy Press), 1990.

[82] G.W. Roberts, "Methanol as an Alternative Fuel," testimony before the Subcommittee on Energy Research and Development, Committee On Energy and Natural Resources, United States Senate, June 8, 1989.

[83] U.S. Department of Energy, Office of Policy, Planning, and Analysis, op. cit., foomote 69, assuming 20 percent capital recovery rate. In this analysis, the derived methanol price is particularly sensitive to the assumed value of the electricity produced.

[84] Ibid.

[85] Committee on production Technologies for Liquid Transportation Fuels, op. cit., footnote 81.

[86] T.E. Bull, "Liquid and Gaseous Fuels from Biomass," D. Hafemeister et al. (eds.), *Energy Sources: Conservation and Renewables*, American Institute of Physics, New York, NY, 1985. Suitable gasifiers would probably be small units that could be prefabricated in a factory and simply assembled in the field.

[87] Similarly, the prices of coal and biomass should not rise as fast as oil prices, and methanol from these sources may eventually become competitive.

On the other hand, there are counterarguments to the proposition that methanol and gasoline prices need not be closely linked. In particular, if the fuels are readily interchanged by the driver (that is, if flexible fuel vehicles are used), gasoline and methanol prices would tend to be locked into an "equivalent price/mile" relationship. Also, feedstock costs may be linked to world oil prices through liquefied natural gas trade and competition between natural gas and middle distillates for utility and other markets.

Just as methanol competitiveness might improve with rising oil prices, it might suffer if oil prices fall. This leaves methanol-and *any* alternative to gasoline-vulnerable to Organization of Petroleum Exporting Countries (OPEC) production increases designed to depress world oil prices and win back lost market shares. Such a price drop would have beneficial side effects, however, in particular the economic stimulation provided by lower energy prices, but the longevity of such effects would depend on the willingness and ability of alternative fuel suppliers to maintain a market presence. Of course, the U.S. Government, if it wished, could protect methanol market share with tariffs and other mechanisms.

INFRASTRUCTURE

Transforming a significant portion of the vehicle fleet to methanol use would be a major undertaking. Aside from the obvious "chicken and egg" problem--neither methanol suppliers nor vehicle manufacturers wish to take the first step without the other segment of the market in place—methanol distribution is likely to require a substantial investment in new equipment. Methanol is hydroscopic (it attracts and absorbs water) and corrosive to some materials now used in gasoline vehicles and distribution systems. It may prove to be incompatible with materials in much of the existing infrastructure-gas station pumps and storage tanks, pipelines, tanker trucks, ocean going tankers, etc.,[88] and thus may require significant quantities of equipment to be duplicated or modified.8g It will require new vehicles, because conversion of existing vehicles will be too expensive because of the materials compatibility problems and the need for changes in onboard computers and other components. And, because of methanol's low volumetric energy density, more trucks, ships, and pipeline capacity will be needed to move an amount of fuel equivalent to the gasoline replaced.

In gauging infrastructure costs for a shift to methanol or other alternative fuels, it is important to factor in potential *gasoline* infrastructure investments that might be avoided if methanol or other fuels absorb some of gasoline's market share. This potential exists because many analysts expect U.S. gasoline consumption to grow significantly over the next two decades; the Energy Information Administration, for example, projects a 0.6 percent/year increase, from 7.34 mmbd in 1989 to 8.38 mmbd by 2010.[90] This growth, and interregional shifts in gasoline consumption, are likely to require building significant amounts of new pipeline capacity, truck transport capacity, and other infrastructure elements unless use of alternative fuels offsets the requirements.

The *pace* of introduction of the alternative fuels will be a critical factor in determining the extent to which infrastructure costs for the new fuels will be offset by reductions in gasoline infrastructure requirements. Similarly, government actions to slow the growth in fuel consumption, in response to air pollution, global warming, and energy security issues, can alter the potential for infrastructure offsets. Congress currently is discussing the imposition of new fuel economy regulations for automobiles and light trucks, in response to global warming and energy security concerns. And some of the nonattainment areas where much new alternative fuel infrastructure would be built have been experimenting with transportation control plans to hold driving down below forecasted levels. Success for either or both strategies could hold down the growth in vehicle miles traveled and improve the efficiency of travel, reducing gasoline demand and thus reducing the potential for infrastructure offsets. On the

[88] Chem Systems, Inc., "A Briefing Paper on Methanol Supply/Demand for the United States and the Impact of the Use of Methanol as a Transportation Fuel," prepared for the American Gas Association September 1987.

[89] Several companies in the United States are now offering EPA-approved in situ lining technology so that existing *gasoline* storage tanks can be made methanol-compatible for about .$4,000/tank. G.D. Short, ICI Products, personal communication, January 1990.

[90] Energy Information Administration, *Annual Energy Outlook 1990, DOE/EIA-0383(90),* January 1990, table A.3.

other hand, if gasoline demand stabilizes, there may be some potential for modifying gasoline equipment, such as storage tanks, to accommodate methanol at lower cost than building new facilities. Generally, the *incremental* costs of alternative fuels infrastructure, over and above what would have been spent anyway for gasoline infrastructure, will be lower if alternative fuels reduce the *growth in* gasoline demand rather than actually reducing gasoline demand from current levels.

The Department of Energy has estimated the U.S. infrastructure requirements (that is, excluding overseas production facilities and shipping infrastructure) for methanol displacement of 1 mmbd of gasoline. The analysis assumes that a fleet of flexible fuel vehicles (FFVs) using M85 will accomplish the displacement.[91] DOE estimates that total costs for storage tanks, loading and other equipment at existing marine-based petroleum product terminals, tank trucks, and approximately 91,000 service station conversions will be $4.8 billion, $4.1 billion of which is used for the service stations.[92] At a $275/vehicle incremental cost for mass-producing FFVs, the total additional cost for the vehicle fleet is $16.6 billion. As discussed above, distribution costs would change somewhat if all new tankage and other equipment were required (because of increasing total fuels demand) rather than being able to convert existing facilities from gasoline use to satisfy part of the infrastructure demand. In its study, DOE implicitly assumed that gasoline demand would have been stable without the introduction of alternative fuels, in contrast to the Energy Information Administration projection. Also, the estimate for infrastructure costs is extremely sensitive to the assumptions made about vehicle costs. Unforeseen problems with excess wear, formaldehyde control, and so forth could easily push costs higher; cost savings obtained from engine downsizing and associated vehicle weight savings, if efficiency and power gains are at the high end of the potential range, might just as easily push costs downwards.

ENERGY SECURITY IMPLICATIONS

With relatively generous worldwide reserves of crude oil available, current interest in gasoline substitutes is based not on the threat of actual physical scarcity of oil but on the potential for supply disruptions and large and sudden increases in price. This concern is heightened by the concentration of oil reserves in the volatile Middle East and the expectations of many analysts that OPEC will regain its former large market power in the 1990s. Development of alternative fueled systems—vehicles, supply sources, and distribution networks—is viewed as both a means to reduce dependence on oil, lowering the economic impact of a disruption and/or price rise, and as leverage against oil suppliers—"raise the price too high, or disrupt supply, and we will rapidly expand our use of competing fuels."

Analysts have argued both for and against the proposition that a U.S. turn to methanol would provide an important strategic advantage. OTA concludes that, under some circumstances, the addition of methanol to the U.S. transportation fuel inventory could improve U.S. energy security for at least a few decades, even though most or all of the methanol would be imported. (The major security benefit would be to reduce U.S. exposure to economic damages from a future oil supply disruption and/or price shock.) Longer term prospects depend on the scale of worldwide natural gas demand and the course of future gas discoveries. The degree of security benefit will depend primarily on the scale of the program and the nature of the vehicles, with flexibly fueled vehicles coupled with an extensive methanol distribution network offering maximum benefits. The benefit may also depend on the extent that the United States acts to promote the entry of more secure suppliers into emerging methanol markets. Because the transition to methanol fuels will be expensive, and because methanol could remain more expensive than gasoline for many years, its energy security and other potential benefits, in relation to its costs, should be weighed carefully against alternative means to achieve the same benefits.

[91] U.S. Department of Energy, *Assessment of Costs and Benefits of Flexible and Alternative Fuel Use in the U.S. Transportation Sector. Technical Report Five. Vehicle and Fuel Distribution Requirements (Draft), Office* of Policy, Planning, and Analysis, January 1990.

[92] Ibid. The analysis assumes that all delivery is by tanker truck, which can service 75 percent of the U.S. population from the terminals. Achieving 100 percent access to methanol would require pipeline transport and additional cost. Part of the infrastructure is converted from gasoline, part new—for example, half of the tankage needed is assumed to be converted.

Table 3-4—Market Shares of Oil and Gas Production and Reserves by Region in 1985
(percent)

	Total natural gas production	Total natural gas reserves	Total oil production	Total oil reserves
Canada	5.2	2.9	3.1	1.0
United States	26.1	5.7	18.9	3.8
OPEC	14.6	31.6	29.2	67.9
Central/South America	4.1	3.7	8.8	9.1
Western Europe	10.1	6.5	7.4	3.1
Eastern Europe & U.S.S.R.	34.1	43.5	20.8	8.7
Africa	0.6	0.6	3.0	1.3
Far East & Oceania	4.4	4.8	7.8	4.7
Other	0.8	0.6	0.9	0.9
Total	100.0	100.0	100.0	100.0

SOURCE: U.S. Energy Information Administration, International Energy Annual 1986, DOE/EIA-0219(86), Oct. 13, 1987.

As discussed in chapter 2, the scale of a methanol program is critical to its national security benefits because the benefits of a small-scale program may be correspondingly small-unless, of course, such a program **was** merely a first phase in a larger effort.

At a larger scale, a methanol fuels program could reduce the United States' overall demand for oil and its level of oil import dependence. Under certain restricted circumstances,[93] this could reduce the primary economic impact of an oil disruption if the prices of methanol did not rise in lockstep with oil prices. Also, **a** large-scale methanol fuels program—perhaps coupled with similar programs in other countries--could reduce pressures on world oil supplies, reduce OPEC market dominance, and lessen the potential for future market disruptions. Further, the threat of rapid expansion of the program would be far more credible after the basic distribution infrastructure was widely emplaced and economies of scale achieved.

Even if it is used in large quantities, methanol is strategically attractive as a gasoline substitute only to the extent that the potential supply sources are different from the primary suppliers of crude oil, and/or to the extent that natural gas markets remain more open than oil markets to competitive pressures. Table 3-4 compares the market shares of oil and gas production and reserves by region in 1985. The primary difference between the distribution of oil **reserves** and gas reserves is that Eastern Europe and the Soviet Union hold a dominant position in gas but not in oil, and OPEC holds an important position in gas but not nearly to the same extent as in oil. A recent study of potential methanol supply sources concludes that, assuming widespread methanol-for-gasoline substitution, OPEC and the Eastern Bloc nations would likely capture at least 75 percent of the supply market.[94]

Table 3-5 shows the proven reserves and estimated exportable surplus gas[95] of the nations holding large gas reserves. This distribution of potential methanol suppliers does imply a diversification of market share in liquid fuels away from OPEC and the Middle East. However, policymakers may be wary of the potential shift in market power towards the Eastern Bloc. On the other hand, the addition of new sources of transportation fuels, even if they are not major market powers, would add somewhat to the stability of the world market for transportation fuels. Also, the changing political status of Eastern Europe could radically alter the U.S. strategic view of the effect of the development of economic ties between the Eastern Bloc and western energy markets, from sharply negative to sharply positive. Finally, widespread use of methanol as a transportation fuel in Eastern Europe would remove an important source of supply pressure on world oil markets.

There is some question about how to interpret the estimates in table 3-5. Even if the distribution of methanol suppliers evolved in proportion to exportable surplus reserves, the market power associated

[93] The bulk of methanol vehicles would have t. be dedicated vehicles, creating basically a separate market for methanol, and feedstock gas prices would also have to be separated from oil prices. See the discussion in app. 3A.

[94] Chem Systems, Inc., op. cit., footnote 88.

[95] Estimates of exportable surplus account for commitments to domestic markets, including existing and planned chemical plants.

Table 3-5—Proved Gas Reserves and Exportable Surpluses

	As of Dec. 31, 1987 (Tcf)	
	Proved reserves	Exportable surplus
U.S.S.R.	1,450	809
Iran	489	158
United States	187	0
Abu Dhabi	184	155
Qatar	157	152
Saudi Arabia	140	0
Algeria	106	40
Canada	95	12
Venezuela	95	14
Norway	89	56
Nigeria	84	67
Australia	79	53
Mexico	76	0
Indonesia	73	46
Netherlands	64	10
Malaysia	52	29
Other Middle East	122	0
Other Asia Pacific	113	25
Other Europe	77	3
Other Latin America	61	31
Other Africa	56	6
Total world	3,849	1.666

SOURCE: Jensen Associates, Inc. National Gas *Supply, Demand and* Price, February 1989.

with this distribution maybe considerably different than in the oil market. Because the degree of development of known resources is much lower for gas than for oil,new gas production capacity may be obtained from many more sources than can new oil production capacity, at least for the next several decades. For the foreseeable future, therefore, any concerted effort on the part of a group of nations to manipulate natural gas supplies and prices would likely elicit a quick supply response from new sources. This should weaken the market power of the Middle Eastern and Eastern Bloc nations even though they hold the preponderance of gas reserves. Also, the substantial number of undeveloped gasfields around the world gives the United States the opportunity to promote development of secure methanol sources by targeting investment to selected areas. Such a strategy would be a departure from past trade policy but would respond to existing national security concerns. Finally, because current world natural gas reserves are largely the outcome of oil exploration, it is quite possible that intensive exploration aimed at locating natural gas would both add substantially to total reserves and shift the proportion of reserves away from the current imbalance illustrated in the table.[96]

An important factor in determining the national security implications of a substantial shift to methanol use in transportation is the *magnitude* of worldwide development of gas resources. At moderate levels of development, there will always be available potential sources of incremental supply to block market manipulation; high levels of development might eventually tighten supplies, giving market power to the remaining holders of large reserves. The magnitude of development will in turn depend on the scale of any shift to methanol in the United States, the extent to which the shift becomes a worldwide phenomenon, and the development of other uses of natural gas in the world market. A worldwide surge in natural gas development seems quite possible given concerns about the greenhouse effect and urban air pollution,[97] growing recognition that natural gas is a cleaner fuel than its fossil competitors, and recent improvements in gas combustion technologies (for example, more efficient gas turbines for electricity generation). Even if such a surge accelerated a trend towards market tightening, however, this would not occur for several decades at the earliest, and might not occur for far longer if new gas production technologies open up new, large gas resources to development.

The capital-intensive nature of methanol production will also play a role in the relative energy security of methanol supplies (compared to gasoline). Because the country-of-origin must invest in facilities similar to those required for crude oil export (e.g., drilling pads, pipelines, docks) *plus* a methanol production facility that may approach a billion dollars in capital costs (for a 10,000 million-ton-per-day (MTPD) facility),[98] it will have a greater

96The potential for finding large new gas reserves is a controversial issue. The group at the United States Geological Survey working on world oil and gas resources generally does not believe that enough new giant gasfields will be found to greatly affect the current distribution of world gas reserves and projected resources (Charles Masters, USGS, personal communication, Mar. 3, 1990).

97As noted elsewhere, combustion of natural gas produces less carbon dioxide than competing fossil fuels *per unit Of energy.* Consequently, substituting natural gas for coal or oil will tend to yield greenhouse benefits unless increased gas development creates significantly higher gas leakage to the atmosphere. Because methane-the key constituent of natural gas—is a far more potent greenhouse gas than is CO_2, increased leakage can null@ the combustion benefit.

98U.S. Department of Energy, op. cit., footnote 69.

financial stake in maintaining stable fuel shipments than a crude oil exporter. This possible advantage must be tempered, however, by the growing tendency of oil suppliers to invest in refinery capacity and ship petroleum products, including gasoline, instead of lower value crude. To the extent that this trend continues, there may be little difference in this regard between gasoline and methanol. Also, the security advantage offered by the increased financial stake of the suppliers maybe offset somewhat by the possibility that a methanol production facility or refinery may be more vulnerable to terrorism or internal disorder than a simpler crude oil supply system. The trade-off between physical security disadvantage versus financial security advantage is not particularly obvious.

The potential advantage to supply security stemming from the capital intensity of the methanol supply system can be weakened if methanol purchasers agree to financial arrangements that shift plant ownership--and financial risk-to them. Although U.S. ownership of manufacturing facilities in other countries may be attractive in other circumstance, this is not likely to be the case here. Because a methanol plant will be tied to its local gas supply, a supplier country does not have to control the methanol plant to control methanol supply.

Aside from questions about methanol supply, the nature of methanol fuel development in the United States will decide methanol's energy security benefits. For example, there are substantial security differences between a strategy favoring dedicated vehicles and one favoring flexibly fueled vehicles. A commitment to FFVs would allow the United States to play off the suppliers of oil against methanol suppliers, and would avoid the potential problem—inherent in a strategy favoring dedicated vehicles—of trading, for a portion of the fleet, one security problem (OPEC instability) for another (instability in whichever group of countries becomes our methanol suppliers). However, a fleet of FFV's attains important leverage against energy blackmail only if the supply and delivery infrastructure is available to allow them to be fueled exclusively with methanol, if this becomes necessary. Because FFVs don't *require* widespread availability of an alternative fuel supply network to be practical during normal times, adoption of an FFV-based strategy may not include full infrastructure development unless this is demanded by government edict. In fact, because dedicated vehicles are likely to have performance and emissions advantages over FFVs, most policymakers are likely to view FFVs as only a stopgap measure on the way to a dedicated fleet. Here, energy security considerations appear to conflict with air quality goals.

If methanol is eventually produced from coal, the energy security benefits would clearly be substantial—assuming that production costs at that time were reasonably competitive with methanol from natural gas. The previous discussion on methanol cost competitiveness concludes that coal-based methanol would be substantially more expensive than gas-based methanol at current prices and technology. A future shift to coal will depend on future natural gas availability and prices as well as further development in methanol-from-coal production systems that appear to offer substantial cost reductions. Unless security pressures grow strong enough to compel large government subsidization of methanol-from-coal production, a shift to coal seems unlikely for several decades at least.

METHANOL OUTLOOK AND TIMING

The difficulties of providing an infrastructure and the uncertain economics of methanol as a vehicle fuel-especially in the early stages of its introduction when economies of scale cannot be achieved—imply that its widespread use in the general vehicle population is unlikely to progress without government promotion or substantial and lasting increases in oil prices. There is now considerable interest in methanol at the State and local level, primarily as a means to cut urban air pollution, and methanol use in certain dedicated fleets, especially in urban bus transit systems, seems quite possible. At the Federal level, Public Law 100-494 now allows vehicle manufacturers to use methanol vehicles as a means to reduce their measured fleet CAFE (corporate average fuel economy), making it easier to comply with Federal regulations. This would tend to promote the availability of methanol vehicles if manufacturers expect difficulty in complying with fuel economy requirements. Also, recently announced Administration policy towards urban air quality problems favors use of alternative fuels.

Research programs in the United States and elsewhere are working to improve the attractiveness of methanol-fueled vehicles; progress in these programs will increase the likelihood of methanol introduction. And success in reducing the costs and raising the efficiency of methanol production would have important implications for its eventual commercial success (as well as its value as a component of a strategy to lower the concentration of greenhouse gases). On the other hand, improvements in fuel use efficiency and engine control in today's gasoline-fueled light-vehicle fleet, coupled with indications that refiners can restructure the composition of gasoline to help reduce emissions, imply that policymakers may be able to tighten vehicular pollution standards somewhat. Such an action might remove some of the pressure for an urban switch to methanol-fueled vehicles.[99] Also, as discussed above, the magnitude of pollution benefits from a shift to methanol are somewhat uncertain. For M85, the most likely methanol fuel for the first generation of vehicles, available data on organic emissions is variable enough to support conclusions about the fuel's potential ozone benefits ranging from quite optimistic (a 20 to 40 percent 'per vehicle' benefit) to pessimistic (at best about a 20-percent benefit, to possibly an ozone increase). Although M1OO--straight methanol-would likely give clearer, and larger, ozone benefits, remaining questions about cold starting problems, formaldehyde controls, and the nature of any additives that might be used must be answered before benefits can be assured. Given the uncertainties associated with methanol costs and benefits and the advantage in existing infrastructure held by gasoline, the near-term future of methanol use in the U.S. vehicle fleet seems captive to government policy.

If methanol *were* given a' 'push' by government financial and/or regulatory incentives, it should be able to begin to play a significant role in automobile use within a decade. Methanol is among the most "ready' of the alternative fuels because: methanol for chemical use has been produced in quantity for many decades, and thus the production technology is well known; vehicular technology capable of burning M85 is readily available, and could be produced within a few years; methanol vehicles should perform as well as or better than existing gasoline vehicles, so market acceptance problems should be mild-the sole drawback is range, and larger but not excessive fuel tanks should solve this; infrastructure necessary to operate a methanol system is considerable, but the technology is commercially available; enough of its primary feedstock, natural gas, is readily available to support a major methanol system; and methanol costs, though uncertain and probably considerably higher than gasoline on a "per mile" basis (at least for the short term), still appear to be more favorable *with em-sting technology* than the other alternative fuel candidates aside from natural gas. The major uncertainties concerning methanol technology are the practicality of vehicles optimized for pure methanol, especially regarding their cold starting ability, and the prospects for long-term formaldehyde control. OTA's best guess is that these problems will not be 'show stoppers," but we recognize that the size of the roadblock represented by these remaining problems is an area of vigorous dispute within the alternative fuels community.

Over the long term--certainly beyond the year 2000, quite possibly considerably longer--methanol-from-coal or methanol-from biomass systems may become competitive. Given the interesting potential of coal hybrid systems, producing both methanol and electric power from one gasification unit, and of advanced biomass gasifiers, research into these areas appears well worth pursuing.

APPENDIX 3A: FACTORS AFFECTING METHANOL COSTS

The gasoline-equivalent costs of methanol at the retail pump are affected by a variety of factors at each stage of the fuel cycle, beginning with the gathering and other costs of the natural gas feedstock and ending with the efficiency of methanol-fueled vehicles relative to their gasoline-fueled counterparts. This appendix discusses some of the key factors affecting these costs, by stepping through the methanol fuel cycle, and presents likely cost (or performance) ranges for each factor. Costs at each fuel cycle stage will be affected by government policy, which affects risk and may affect other critical factors such as vehicle design, available subsidies, location of markets, and so forth; technological development and trade-offs made; timing (technology costs should decrease over time; feed-

[99] Although increased costs associated with such standards might improve methanol's economic competitiveness. In particular, gasoline restructuring may cost $0.10/gallon or more, depending on the severity of the changes.

stock costs may increase); magnitude of development; and a variety of other factors.

Feedstock Costs

Natural gas feedstock costs are an important component of methanol cost. For efficiencies typical of steam reforming--one of the primary methods of creating the synthesis gas from which methanol is formed--every 10 cent/MMBtu of gas costs contributes about 1 cent/gallon to methanol cost at the plantgate. Although advanced methanol production technologies are more efficient than current commercial technologies, the efficiency increase is not so strong as to markedly alter this relationship.

Consequently, assuming natural gas costs of $1.00/MMBtu implies that the feedstock represents about $0. 10/gallon in the cost of methanol. For each increase (or decrease) in gas costs of $0.50/MMBtu, methanol cost will rise (or fall) by $0.05/gallon.

Gas prices in the United States average about $1.80/MMBtu at the wellhead and about $2.50/MMBtu delivered to electric utilities,[100] the sector able to command the best prices. However, domestic natural gas has been in surplus for several years, holding down prices,[101] it is widely believed that U.S. gas prices will rise substantially over the next decade. Generally, lower 48 gas supplies are not considered an economically viable feedstock for significant increments of new methanol production.

Instead, most analysts believe that the most likely suppliers of gas for methanol will be either 'remote gas"—gas that has no pipeline markets because of its location---or the very large reserves of gas located in several Middle Eastern nations, the Eastern Bloc, and a few other sites.

Some supporters of methanol use as a transportation fuel have speculated that natural gas that currently is flared or vented could serve as a feedstock for methanol production. The claimed advantages for using such gas are that it would be extremely inexpensive, having no other use, and that its diversion to methanol production would yield a strong environmental benefit. Gas that is flared adds to the atmosphere's burden of carbon dioxide without providing useful energy services; gas that is vented adds to atmospheric concentrations of methane, a far more potent greenhouse gas than carbon dioxide.

On further examination, it seems unlikely that flared/vented gas can provide a viable feedstock supply for methanol production. First, there is not a great deal of such gas. The worldwide volume of flared/vented gas in 1988 was about 3.3 trillion cubic feet (TCF) spread out among dozens of countries and hundreds of fields.[102] A single 10,000 metric tons per day (MTPD) methanol plant requires a gas supply of 100 billion cubic feet (Bcf)/year, and only a dozen countries exceeded that level in their entire national production of flared/vented gas.[103] Furthermore, there are ongoing efforts to drastically reduce this volume of wasted gas, so that volumes available in future years should be significantly smaller.

Second, a world-class methanol plant is highly capital intensive[104] and will demand reliable, high quality, long-lived gas reserves. Flared/vented gas—which is associated with oil production-generally is not highly reliable, nor is it particularly cheap. Variations over time in oil production levels and in gas/oil ratios can cause significant variations in gas production levels. And gathering and compression costs often are high.[105] Current experience with liquefied natural gas (LNG) facilities, of which only 1 of 11 is based solely on associated gas, confirm that developers prefer more reliable nonassociated gas supply for such projects.[106]

[100] Energy Information Administration, *Natural Gas Monthly,* DOE/EIA-0130(89/05), May 1989, table 4.

[101] The United States *does* import substantial quantities of Canadian gas—over a TCF in 1989—but this was due largely to this gas' price advantage in certain regional markets, not to the unavailability of domestic supplies.

[102] Cedigaz, *Natural* Gas *in the World in 1988.*

[103] Ibid.

[104] According to DOE (U.S. Department of Energy, Office Of Policy, Planning, and Analysis, ***Assessment of Costs and Benefits of Flexible and Alternative Fuel Use in the U.S. Transportation Sector. Technical Report Three: Methanol Production and Transportation Costs,*** DOE/PE-0093, November 1989), an advanced scheme, fuel grade, 10,000 metric ton per day methanol plant will cost from 588 to 1,323 million dollars (1987 dollars), including infrastructure, depending on site location.

[105] Jensen Associates, Inc., "Natural Gas Supply, Demand and Price," Economics Workshop, Advisory Board on Air Quality and Fuels, State of California, February 1989.

[106] Jensen Associates, Inc., "Comment on the California Energy Commission Staff Draft 234 Report," May 3, 1989.

Assuming that either remote nonassociated gas or gas in large, established fields in the Middle East or Eastern Bloc will be the primary methanol feedstocks, what will be the likely price of such gas to the methanol producer? The *minimum* price, over the long term, will generally be the sum of the "cost of service," that is, the actual costs of producing and gathering the gas, and some bonus to compensate for resource depletion (although market vagaries can temporarily force prices below this, eventually they must rise to this price or supply will drop). The actual price, however, will depend on negotiations between the gas purchaser (the methanol producer) and gas owner (generally the government). Some governments will demand prices higher than the minimum, to reflect the lack of competition (there may be no competing supply sources with costs of service this low or with a similar competitive advantage, for example, easy access to markets or availability of skilled labor for methanol plant construction), high methanol or LNG prices that can sustain higher-than-cost-based gas prices (in trade jargon, the netbacks from product prices are higher than gas production costs), higher gas costs elsewhere, or simply an attitude that the gas is a valuable national treasure that should not be sold cheaply.

In this analysis, we seek to learn if methanol prices can be low enough to compete with gasoline or, if not, what the minimum subsidy would have to be to provide the supply desired. We have little interest in the outcome of negotiations about who receives the added profits from methanol prices that are higher than necessary to provide sufficient supply. Also, we do not believe that gas pricing will be based on "national treasure' '-type valuation by governments. In the past, governments as varied as Canada's, Algeria's, and Iran's *have* demanded such higher-than-market prices, but in each case they lost market share as a result. Given this history and what we perceive as a general worldwide movement towards acceptance of market realities, we suspect that gas supplies *will* be available at prices reflecting either supply costs or netbacks from product prices. Consequently, we believe that estimates of gas supply costs, coupled with an examination of potential netback gas prices obtainable from high LNG prices, provide an adequate measure of methanol feedstock costs for our analysis.

Based on available estimates of costs of service for various sites around the world, we conclude that gas prices of $1.00 to $1.50/MMBtu should be sufficient to obtain large volumes of gas for methanol production. Table 3A-1 presents estimated cost of service for a variety of sites. Some of the lower estimates-in particular, the Qatar and Australian NW Shelf estimates-reflect large credits for extracting natural gas liquids from the gas before sale. These credits are limited to portions of fields with particularly "wet" gas, and estimated cost of

Table 3A-l—Estimated 1987 Gas Costs and Prices (1988 dollars)

	cost of investment $/MMBtu/yr	service[a] $/MMBtu	Price $/MMBtu
North America			
Gulf Coast	[b]	b	1.42
Alberta	[b]	b	0.95
Prudhoe Bay	[b]	b	0.33
Asia Pacific			
Australia			
NW Shelf	4.34	0.62	0.94
Indonesia			
Sumatra	3.01	0.69	0.93
Kalimantan	2.00	0.46	0.93
Natuna	[b]	b	0.93
Malaysia			
Sarawak	3.87	0.84	1.17
Peninsula Offshore	4.39	1.01	1.17
Thailand	5.94	1.37	1.67
Bangladesh	[b]	.67	.82
U.S.S.R.			
Sakhalin/Yakutsk	[b]	b	1.69
Middle East			
Qatar	4.45	0.14	0.45
Abu Dhabi	2.85	0.66	0.80
Iran	[b]	b	1.00
Latin America			
Trinidad	4.40	1.01	1.06
Venezuela			
Gulf of Paria	6.52	1.50	1.83
Mexico			
Chiapas/Tabasco	[b]	b	0.74
Argentina			
Neuquen	[b]	b	0.97
Tierra Del Fuego	2.75	0.27	0.49
Chile			
Tierra Del Fuego	3.30	0.40	0.57
Atlantic Basin			
Norway			
North Sea	6.91	1.33	1.67
Troms	7.24	1.30	1.66
Nigeria			
Associated	[b]	0.89'	1.08
Nonassociated	[b]	0.48[c]	0.58
Cameroon	[b]	1.95[c]	2.37
Algeria	[b]		0.50
U.S.S.R.			
W Siberia (in Europe)	[b]	b	2.35

[a]Excluding tax
b No valid basis for estimate
World Bank estimate

SOURCE: Jensen Associates, Inc., *Natural Gas Supply, Demand and Price,* February 1989.

service for future projects will generally be higher. Additional cost-of-service estimates for 13 similar sites show that 11 of the sites have costs between $0.65 and $1.30/MMBtu (the other two are much higher).[107]

Although the amount of gas theoretically available at these prices is large, we do not know how large a methanol market can be supplied by these less-expensive gas sources. Aside from the sheer lack of data about costs of gas service at more than a few sites, it is not clear how much competition there may be for the gas during the next few decades. If developing nations' economies grow substantially during this period, some of the gas will be used locally. Similarly, if world LNG trade grows rapidly, LNG will compete with methanol for some of this gas. The extent of this competition will depend not only on the size of the LNG trade but also on the value of the delivered gas, the value of the methanol, and the costs of methanol production and shipping.

If the worldwide demand for methanol grows large enough, and substantial quantities of low-cost gas find local or export markets, methanol gas supply sources will need to expand to higher cost gas. This possibility is critical because minimum methanol prices are likely to be set according to production and shipping costs for the highest cost marginal supplier rather than the average-cost supplier-at least when methanol is not in substantial oversupply.[108] Consequently, analyses of methanol costs for ''typical" supply situations are relevant to expected methanol prices only so long as the demand for methanol does not force higher cost methanol onto the market. When demand outstrips low-cost production capacity, prices must rise to allow higher cost suppliers to enter the market.

Production Costs

Aside from natural gas feedstock costs, key factors affecting production costs are the production technology, the size of the production facility, and the nature of the site. Current methanol plants produce chemical grade (highly purified) methanol using technology whose basic design is about 20 years old.[109] Large new fuel grade methanol plants could achieve substantial savings because of the economies of scale available if the size of the market allows plants as large as 10,000 MTPD capacity to be built, and because of the increased feedstock utilization efficiency and lower capital costs of advanced designs. The nature of the site is important because it strongly affects the capital costs—necessary infrastructure may or may not be available, labor and materials may have to be imported at high cost, working conditions will affect schedules, etc.—and affects the risk involved in building and operating the plant, which in turn affects the cost of capital (discussed below).

Although a 2,500 MTPD methanol plant is a large plant indeed, most analyses of future methanol costs focus on fuel grade methanol from plants sized at 10,000 MTPD. Increasing plant size gains modest but important scale economies; for example, doubling plant size from 2,500 to 5,000 MTPD reduces capital costs *per unit of methanol produced* by about 1O percent.[110] However, a single 1O,OOO MTPDplant produces over 3 million gallons of methanol each day, or over a billion gallons per year-enough methanol to fuel well over a million alternative fuel vehicles, and over 10 percent of current world methanol production capacity. Consequently, plants this large can only be built if many millions of methanol vehicles are in service or if there is an assured market based on a prior trade agreement.

Aside from increasing plant size, methanol producers can reduce costs by shifting to advanced technologies that cut capital costs, decrease total energy use, and increase plant efficiency. A variety of technologies are available that can reduce costs both in the production of synthesis gas, the first step of the methanol production process, and the catalytic transformation of the synthesis gas into methanol.

The Department of Energy (DOE) has calculated methanol production and delivered costs for large (10,000 MTPD), "advanced scheme" plants producing fuel-grade methanol. For relatively remote sites (e.g., Australia, Indonesia, Malaysia) with no or only partial current infrastructure, and gas costs of

---

107The estimates are confidential.

108If methanol is in oversupply—e.g., if methanol demand declines, or methanol production capacity is overbuilt-prices may drop below total production costs to the marginal costs of production, *i.e.*, operating costs plus gas and shipping costs, with no allowance for capital recovery.

109G.D. Short, ICI Americas, personal communication September 1989.

110U.S. Department of Energy, Office of policy, Planning, and Analysis, *Assessment of Costs and Benefits of Flexible and Alternative Fuel Use in the U.S. Transportation Sector. Technical Report Three: Methanol Production and Transportation Costs*, DOE/PE-0093, November 1989.

$1.00/MMBtu, methanol production costs range from $0.33 to $0.41/gallon for a 20 percent capital recovery rate (CRR). If some of the more developed nations with large gas supplies, e.g., Saudi Arabia, Algeria, and Iran, chose to price their gas equally low, they could produce methanol at closer to $0.30/gallon or even a bit lower for the same CRR.[111]

The advanced plant design selected for this analysis achieves an estimated 25 percent reduction in plant capital costs over a standard scheme plant of the same capacity (10,000 MTPD),[112] as well as a 10 percent savings in feedstock costs because of its higher efficiency. Translated into costs per gallon of methanol produced, moving from current to advanced technology saves $0.06 to $0.07/gallon at a CRR of 20 percent, and $0.09 to $0.10/gallon at a 30 percent CRR.

The *overall* savings associated with building at a very large scale, producing fuel-grade rather than chemical grade methanol (this allows fewer distillation steps to be used), and using advanced technology are very substantial. According to the DOE analysis, moving from a current technology, chemical-grade, 2,500 MTPD facility to an advanced technology, fuel-grade, 10,000 MTPD facility saves $0.12 to $0.22 for each gallon of methanol produced, depending on the site chosen, assuming 20 percent CRR. This implies that production costs are likely to drop sharply as a methanol fuel program matures—as early plants using standard technology at 2,500 MTPD scale eventually give way to much larger plants using advanced technology. The time frame over which this process will occur depends on the confidence of developers in the new technologies, the rapidity of the movement of methanol vehicles into the fleet, the vehicle technology (fuel flexible or dedicated) chosen, and developer confidence in continued growth of methanol demand.

Production costs could be further reduced over the long term, though uncertainty is very high because some of the most promising new processes have not gone beyond bench-scale application. In particular, current research in the field aims to catalytically convert methane directly to methanol without producing an intermediate synthesis gas.[113] Successful development of such a process would likely reduce production costs substantially, as well as raising the conversion efficiency of the process—adding to methanol's attractiveness because improved efficiency would reduce the net production of CO_2 from the methanol fuel cycle. Lawrence Berkeley Laboratory currently is exploring the use of catalysts that mimic the enzyme produced by bacteria that ingest methane and convert it to methanol. Thus far, the researchers have managed only to produce methanol in very small quantities.[114]

A less radical approach to improved methanol production, under investigation at Brookhaven National Laboratory, uses a new catalyst suspended in a liquid[115] that will convert synthesis gas to methanol at low temperatures and pressures--lOO °C and 100 psi compared to 250‘C and 750 psi required by conventional catalysts.[116] This catalyst also converts a high percentage of the synthesis gas on the first pass, reducing the need for recycling, and tolerates normal catalyst poisons, reducing gas cleaning requirements.[117] If perfected, the process should be both cheaper and more energy efficient than current production processes.

Significant uncertainty exists as well about production costs over the shorter term, even if uncertainties in feedstock costs and required capital recovery rates are ignored. Two important sources of uncertainty are, frost, the large variability in building costs at remote sites, and, second, uncertainty about the extent of savings that may be obtained by moving to emerging production technologies such as liquid-phase reactors.

[111] Ibid, table 1.14. In its analysis, DOE chose different values than $1.00/MMBtu for feedstock costs, and we have adjusted their production cost estimates to account for the difference in fuel costs.

[112] Ibid, figure I-4.

[113] J. Haggin, "Alternative Fuels to Petroleum Gain Increased Attention," *Chemical and Engineering News*, Aug. 14, 1989.

[114] Electric Power Research Institute, "Methanol: A Fuel for the Future," *EPRI Journal*, vol. 14, No. 7, October/November 1989.

[115] So-called "liquid-phase catalysts" are not new, and would likely be used in advanced scheme production plants built to satisfy anew transportation market for methanol.

[116] Electric Power Research Institute, Op. cit., footnote 114.

[117] Ibid.

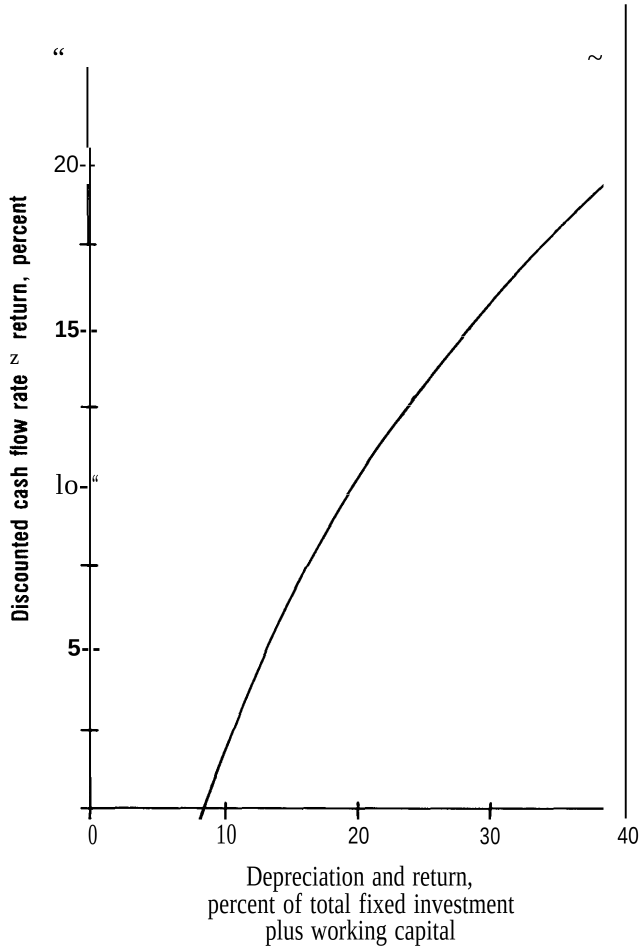
Capital Charges

Even if two competing analyses of methanol costs assume identical capital costs for plants with identical production capacity and output, the role that these costs play in total methanol costs—the capital charge, expressed in $/gallon of methanol produced—can still be quite different if the two analyses assume different returns on investment. In fact, available analyses of methanol costs *have* assumed substantially different rates of return, and these differences play an important role in explaining why the range of methanol costs appearing in the literature is so wide.

The capital costs of a methanol production plant can be translated into a capital charge assigned to each gallon of methanol by breaking down the cost into capital debt and investor equity, estimating the amount of annual earnings needed to both service the debt and provide a return on equity, and dividing these earnings by the number of gallons produced annually. Most analyses of methanol costs have simplified this calculation by assuming a discounted cash flow rate of return (ROR), which in turn defines a capital recovery rate (CRR)--the percentage of total capital costs, net of operating expenses, earned back each year-and applying either parameter to total capital costs. Figure 3A-1 provides a means of translating RORs into CRRs and vice versa.[118] As in the rest of the discussion, the RORs in the figure are real, after tax rates.

A number of studies have examined the sensitivity of methanol costs to assumptions about CRR and ROR, and these studies illustrate clearly that the costs are highly sensitive to these assumptions. For example, Acurex has examined changes in capital charges for methanol produced in 10,000 MTPD plants with differing assumed ROR. For a Texas-based methanol plant, capital charges range from $0.08/gallon for an assumed ROR of 10 percent, to $0.14/gallon for a 17 percent ROR, to $0.25/gallon for a 25 percent ROR.[119] Similarly, the Department of Energy has calculated that capital charges would vary from $0. 17/gallon with a CRR of 20 percent to

Figure 3A-l—Comparison of Discounted Cash Flow Rates of Return With Capital Charges Based on a Percentage of Total Fixed Investment Plus Working Capital



Basis: Natural gas reforming, site has well-developed infrastructure in an established industrial environment.

SOURCE: U.S. Department of Energy, Assessment *of Costs and Benefits of Flexible and Alternative Fuel Use in the U.S. Transportation Sector. Technical Report thru: Methanol Production and Transportation* Costs, DOE/PE-2093, November 1989.

$0.26/gallon for a CRR of ***30*** percent, for **a** 10,000 MTPD plant located in a developing nation with only partial infrastructure available.[120] For a lower CRR of 16.2—which is the baseline assumption used by the Environmental Protection Agency in

[118] U.S. Department of Energy, *Assessment of Costs and Benefits of Flexible and Alternative Fuel Use in the U.S. Transportation Sector. Technical Report Three: Methanol Production and Transportation Costs*, DOE/FE-0093, November 1989. The figure applies to a particular set of plant conditions: 3 years for construction 15 years of operation, 37 percent income tax rate.

[119] State of California Advisory Bored on Air Quality and Fuels, *Economics Report: Volume IV*, report to California Advisory Board on Air Quality and Fuels, Aug. 4, 1989 (Acurex Corp., primary contractor).

[120] Department of Energy, Technical Report Three, 1989, op. cit., footnote 110.

recent presentations[121]--capital charges would be $0.14/gallon for this plant.

As noted above, alternative calculations of methanol prices have used an extremely wide range of assumed CRRs and RORs for production plants at the same or similar sites, and this has led to both substantial divergence in estimated prices-as well as confusion among policymakers. At least a portion of this range can be traced to differences in technical judgments about the most likely return to be attained or demanded in specific circumstances. However, more of the range is attributable to differences in the basic assumptions underlying the price calculation. Differences include:

- *Timeframe.* Because the risks associated with methanol production are likely to change with time, the ROR or CRR required will change as well. In a free market scenario, for example, building a large methanol plant in the first decade or two after a fuel methanol market is established may be viewed by investors as quite risky. A single plant would represent a significant percentage of world methanol production capacity-as noted, a 10,000 MTPD plant would represent well over 10 percent of current world capacity—so that alternative markets for the plant's output would not be readily available, and overbuilding would be a significant risk. Later, when millions of vehicles are on-the-road and the overall market is much larger and more mature, the risks associated with a single plant might be greatly reduced. For these reasons, early plants will likely be of smaller capacity, i.e., 2,500 MTPD, and carry a high required ROR unless governments provide strong guarantees. Methanol RORs and capital charges will tend to go down with time, if other factors do not change. Analyses of methanol costs for the long term timeframe must not ignore the problem associated with the potentially expensive transition to a mature market.
- Is *the analysis calculating a probable price after the investment is made, or the price necessary to encourage that investment?* Some price calculations seek the most likely price of methanol assuming that some type of methanol-fueled system has been established; other calculations seek the price of methanol necessary to encourage investment in a methanol system, for example, the wholesale price necessary to encourage investors to build production plants. "What is the most likely price?" may be the appropriate question to ask when examining a scenario where government has required methanol plants to be built; "What is the necessary price?' is more appropriate when the analyst is questioning whether the plants will be built at all.
- *Do the capital cost estimates already incorporate risk?* Many business managers require higher earnings on proposed investments than seem justified by the underlying economics of the investment. This may result from their expectation that their engineers estimated project costs based on so-called "most likely costs,' that is, the costs that would occur most often if many identical plants were built. Managers demand high rates of return based on these cost estimates because there is comparatively little chance of costs being very much below the "most likely' level (savings of 10 or 20 percent might be considered unusual), whereas there are a number of circumstances—in particular, long construction delays—that could force costs to levels double or triple the most likely value. . and investors will demand higher returns to compensate for this risk. On the other hand, some engineers already have incorporated the risks in their estimate by calculating an "expected value" for capital costs, which averages the possible outcomes—including the potential for large cost overruns—and generally produces an estimate higher than the most likely cost.
- *What policy scenario is assumed? The risks* associated with a capital project—and thus the rate of return demanded--obviously depend on the vision of the future assumed by the analyst. An assumption of a free market without government interference might demand a high rate of return to compensate for a high perceived risk; however, there are free market situations that manage risk well, e.g., an explicit contractual agreement to share risks with pricing

121C.L. Gray, Director, Emission Control Technology Division, U.S. Environmental Protection Agency, letter of June 8, 1989 to R. Friedman, Office of Technology Assessment. Also, U.S. Environmental Protection Agency, ***Analysis of the Economic and Environmental Effects of Methanol as an Automotive Fuel,*** Office of Mobile Sources Special Report, September, 1989.

formulas and other mechanisms. Government requirements for methanol vehicles, on the other hand, might lower risks by assuring the existence of market demand—although investors have been burned before by shifts in political support, and may be wary of assigning a low risk to a project dependent on government incentives or regulations. If government support is assumed, the nature of that support is critical to risk—a government requirement for dual-fueled vehicles without a requirement that methanol actually be used might do little to reduce risk; a trade agreement with price guarantees for a plant's output, on the other hand, could reduce the required rate of return to utility levels. Even with a trade guarantee, however, developers may recall the poor experience of natural gas producers in enforcing take-or-pay contracts with pipelines and still demand high rates of return. Also, policymakers should note that if the government provides market guarantees or establishes regulatory requirements for methanol use, the risk has not really been reduced, but instead it has been transferred, from producers to the government itself, to consumers, or to the regulated indus-Q .

. *Where is the methanol assumed to be coming from? As* discussed earlier, a number of countries, with differing physical, political, and social conditions, are available to provide methanol to U.S. markets. Factors such as the potential for political instability or natural disasters greatly affect capital risk.

Capital charges for methanol production can thus legitimately vary over a wide range depending on assumptions about the timing of the investment, government policies, and other factors. For example, in estimating the likely price of methanol after the system is in place, analysts may examine historical capital recovery rates of similar investments and apply these to methanol CRRs. On the other hand, for estimating the methanol price necessary to encourage investment, analysts may instead examine the industry decisionmaking process to establish the minimum "hurdle rate' for ROR, that is, the minimum estimated value of ROR necessary for eliciting a positive investment decision. Surveys of oil and chemical firms conducted by Bechtel Financing Services indicate that capital recovery rates and rates of return required by investors for new methanol plants will be much higher than historical rates of return for the industry. In particular, building such plants in developing countries would add substantially to required returns: risk premiums added to required aftertax rates of return for building in developing countries would be in the range of about 5 percent. Bechtel concluded that minimum rates of return for the sites they surveyed (Texas, Canada, Trinidad, Alaska, Saudi Arabia, and Australia) ranged from 14 to 19 percent.[122] Also, the firms indicated that assumptions of long project investment life, e.g., 20 years of full operations, are unrealistic, with perhaps 10 years of full operations being an acceptable assumption. Shortening assumed project lifetime has a major impact on estimates of the product costs needed to support the investment.[123] These rates and shortened plant lifetimes imply capital recovery rates ranging from *30* percent for even low-risk sites (Texas, Canada, Western Australia) to 40 percent or higher for the highest risk sites (Trinidad and Saudi Arabia). These rates seem astonishingly high compared to the 16.2 percent CRR assumed by EPA.

Changes in the perception of risk, and thus changes in required CRR, may change the order of preference for alternative sites. As capital risk increases, sites with high feedstock costs and high operating costs but low capital costs—in particular, sites in developed areas with considerable available infrastructure--become more attractive, and more remote sites, with low gas costs but high capital costs, become less attractive. Of course, estimates of breakeven methanol costs are not the only factor influencing site decisions. Plants with high capital costs and low operating costs may be judged more favorably than their breakeven costs seem to dictate, because these plants can at least maintain a positive cash flow if methanol prices plunge, whereas a less capital intensive plant with high operating costs may be forced to shut down in similar circumstances. And to make things even more complicated, it is

[122] Assumptions of analysis: aftertax return on investment, current dollars assuming 5 percent inflation. William E. Stevenson Bechtel Financial Services, Inc., letter of May 17, 1989 to Mr. Charles R. Imbrecht, Chairman, California Energy Commission. ROR values in the text are real, adjusted for the assumed inflation. Nominal RORs were 20 to 25 percent.

[123] For example, Bechtel computed methanol costs for a plant in Saudi Arabia to be 24 percent higher (36 cents v. 29 cents/gallon) when assumed years of operations were shortened from 20 years to 3 years of partial and 10 years of full operations.

highly unlikely that a site-by-site comparison of the same technology will represent a true decision, because plant designers will add capital cost to maximize efficiency at sites with high gas costs, but choose less efficient, but cheaper, designs at sites with low gas costs.

A further, crucial point is that some of the areas that may produce methanol are the same, or quite similar to, the areas where new petroleum refineries will be built to satisfy growing world demand for gasoline and other petroleum products. Some of the arguments for projecting high rates of return on new methanol facilities may apply quite well to projections of the rates of return that may be required for the new refineries.[124] If so, methanol priced high to reflect high investment hurdle rates may be competing with gasoline whose price has also risen, reflecting the same forces that drove up the methanol prices. On the other hand, if volatility in oil prices is considered a key source of uncertainty in future energy markets, it is worth noting that refineries have a built-in buffer from the effects of this uncertainty, because a reduction in product prices—e.g., gasoline prices--caused by a drop in oil prices will be accompanied by a corresponding drop in refinery feedstock costs; the methanol price drop that would likely accompany an oil price drop (assuming methanol were competing with gasoline for market share) might *not* be accompanied by a corresponding drop in natural gas feedstock costs. The resulting volatility in methanol profit margins may make anew methanol plant a riskier investment than a new refinery.

Long-Distance Shipping

Long-distance shipping costs are dependent on the type of carriers used. Although methanol currently is shipped at high cost in multicompartment chemical tankers, a large-scale expansion of methanol production and shipping would require the use of large, dedicated carriers. DOE calculates the costs of long-range transport by large, 40,000 deadweight ton (DWT) carriers to be about $0.06/gallon for a *6,000 mile* (one-way) distance and about $0.09/gal for a 9,000 mile distance.

Much larger tankers would be considerably more economical-about a third as much per gallon for 250,000 DWT, according to DOE.[125] There are questions about when such tankers could be deployed, however. Only one U.S. port (Louisiana) can handle tankers this large, and only a few ports (none currently on the East or Gulf coasts) can handle even 120,000 DWT tankers, Thus, either new port facilities would have to be built; or methanol could be transported to smaller carriers at a nearby port, perhaps in the Carribean (at additional cost), or at an offshore terminal; or offshore docking facilities with pipelines leading to onshore terminals would be necessary. Also, 40,000 DWT tankers can use the Suez and Panama Canals, and the larger tankers cannot. Furthermore, the amount of methanol embodied by one tanker load of 200,000 DWT--about 68 million gallons, or about enough methanol to fuel a fleet of 5 million vehicles for a week—implies that tankers of this size will become practical only when methanol demand has grown both large and stable--perhaps implying dedicated rather than flexible fuel vehicles (unless market stability is obtained by government regulations requiring methanol purchase within nonattainment areas or, less likely, by methanol prices consistently lower than gasoline equivalent prices. Thus, assumptions of very low long-distance shipping costs based on extremely large carriers are problematic, at least for a considerable time after any transition to methanol transportation fuels has begun.

Distribution Costs

Both gasoline and methanol will have differential distribution costs depending on location, and both fuels will be more expensive when their distribution costs are higher. Methanol has lower energy density than gasoline, however, so that methanol should be less competitive in areas with high "per gallon" distribution costs.

124That is, the risks associated with the plants are largely associated with their location rather than with the nature of their technology or the markets for their products. Location-specific risks include risks of gas supply contract abrogation; force majeure events; exchange rate changes; currency inconvertibility; unfavorable tax law changes; forced sale without full compensation and expropriation (W.E. Stevenson, Bechtel Financing Services, Inc., "Capital Servicing Costs of Fuel Methanol Plants," presentation to California Energy Commission, May 3, 1989).

125On the other hand, Energy and Environmental Analysis estimates shipping costs for 200,000 to 300,000 DWT carriers at $0.04 to $0.06/gallon, about twice DOE's estimate. Energy and Environmental Analysis, Inc., *Methanol's Potential as a Fuel for Highway Vehicles,* contractor report prepared for the Office of Technology Assessment October 1988.

126U.S. Environmental Protection Agency, op. cit., footnote 121.

In its analysis of methanol costs, EPA has assumed that distribution costs will be $0.03/ gallon,[126] assuming that methanol will be delivered primarily to cities with ozone control problems, and these are primarily coastal port cities. EPA's distribution costs appear reasonable for large port cities. For inland cities with waterway access (e.g., St. Louis, Detroit), costs might be somewhat higher. For inland cities with no waterway access, distribution costs could be considerably higher than EPA's estimates, conceivably $0.05/gallon or more higher.

With one exception (Chicago), the worst (top 10 in highest l-hour concentrations) ozone nonattainment cities are coastal, port cities.[127] If methanol were used only in these cities, distribution costs would be low. However, many cities currently in nonattainment are inland, and some have no waterway access. Also, if methanol is introduced more generally as part of a strategy to lower oil imports, it will need to be available in areas with high fuel distribution costs. Because of its low energy density, methanol will be less competitive with gasoline in such areas.

Retail Markup

Markups of $0.09 to $0.12/gallon are common for gasoline.[128] If the financial risk in retailing methanol is similar to that of retailing gasoline, methanol's "per gallon" markups should be no higher than this, and indeed may be lower, given the potential to pump methanol more quickly than gasoline (because of its low volatility), the possibility that methanol vehicles will carry larger storage capacity than gasoline vehicles (to compensate for methanol's lower energy density) and thus purchase more fuel per fillup, and the significant portion of station costs that are dependent on the number of fillups rather than the actual pumping volume per fillup.[129] Some analyses (e.g., EPA's) have assumed retail markups for methanol as low as $0.05/gallon, which implies that service stations' operating costs, and thus their markup, will depend more on energy content than on actual fuel volume sold.

Under certain circumstances, however, methanol's markup could be as high or higher than gasolines. For example, if methanol vehicles do not have additional storage, they will have shorter range than gasoline vehicles and will buy fewer Btu's of fuel at each fillup. In that case, retail markups for methanol would be expected to be similar to gasoline markups even if the market risk in retailing methanol is low. And if market risk is high, e.g., during the transition period when demand is growing, retailers are likely to demand a higher markup for methanol to compensate for the higher risks involved in installing methanol-compatible equipment and maintaining retail space during a time of uncertain demand for methanol. If flexible fuel vehicles are the primary users of methanol, unless these vehicles are *required* to use methanol within the service areas, both conditions—high market risk, and methanol and gasoline vehicles buying about the same volume of fuel per fillup--are likely, and retail markups for methanol should be higher than gasoline's $0.09 to $0.12/gallon. The original Administration plan for alternative fuels *did* contemplate a methanol refueling requirement.

Another part of markup is the taxes charged to methanol. Gasoline taxes average about $0.24/ gallon. If methanol is taxed strictly on a Btu basis, taxes should be about $0.12/gallon. With higher efficiency vehicles, this will reduce total tax revenues somewhat. If fuel tax revenues are viewed by government as a user fee for highways and traffic services, methanol taxes conceivably could be raised to equalize taxes between methanol and gasoline on a "per mile" basis. Given the likelihood that Federal and State Governments will be actively promoting methanol use, however, it seems likely that these governments will adopt a "per million Btu" rather than a "per mile" basis for taxation.

Methanol/Gasoline Conversion Factor

Gasoline and methanol are not compared directly on a "gallon v. gallon" basis, because a gallon of methanol has only about half the energy content of

127 U.S. Congress, Mice of Technology Assessment, *Catching Our Breath: Next Steps for Reducing Urban Ozone*, OTA-O-412 (Washington, DC: U.S. Government Printing Office, July 1989), table 3-2.

128 M.A. DeLuchi, R.A. Johnston, and D. Sperling, "Methanol vs. Natural Gas Vehicles: A Comparison of Resource Supply, Performance, Emissions, Fuel Storage, Safety, Costs, and Transitions,' SAE TechnicalPaper # 881656, 1988.

129 For example, the size requirement of the station is dependent on the total time needed per fillup. Even if pumping takes longer, the time needed to park, remove and replace the filler cap, and pay for the fillup is independent of fuel volume.

a gallon of gasoline.[130] To compare the prices of the two fuels, the methanol price must be multiplied by a factor that reflects both the difference in energy contents and any differences in the fuel efficiency of equivalent gasoline and methanol vehicles.

Factors for converting an M1OO cost into a ''gasoline equivalent' cost range from about 1.5 to 2.0, the latter reflecting methanol's actual volumetric energy content compared to gasoline's, the former reflecting a most optimistic view of the efficiency potential of a mass-produced dedicated M100 vehicle.[131] The lower conversion factors are based on the ability of methanol engines to run at a higher compression ratio (because of methanol's high octane level) and higher ("leaner") air/fuel ratio (allowed by methanol's higher combustion flame speed and other attributes) than equivalent gasoline engines, as well as on the cooling of the air/fuel mixture caused by methanol's high latent heat of vaporization.[132] The higher conversion factors are based on an assumed methanol vehicle weight penalty of up to 100 pounds for added fuel and a larger fuel tank (causing a 2 to 4 percent fuel economy penalty[133]), and the need for manufacturers to trade off fuel efficiency against other factors such as emissions and performance.[134] The emissions trade-off is especially important because methanol is being promoted largely as a means to reduce urban air pollution.

Assuming that the focus on emissions reduction will continue and that manufacturers will make numerous design trade-offs in the process of moving from laboratory and vehicle prototypes to mass production, OTA believes that a reasonable range for the methanol/gasoline conversion factor is about 1.67 to 1.82 (10 to 20 percent efficiency improvement) for the long term assuming optimized vehicles dedicated to M100, with both extremes of the 1.5 to 2.0 range appearing to be much less likely. Vehicles dedicated to M85 may have a range of conversion factors shifted slightly higher, e.g., towards lower efficiency, though the shift should be small. Flexible fuel vehicles are likely to achieve still smaller efficiency gains; a methanol/gasoline conversion factor of about 1.9[135] (equivalent to an M85/gasoline conversion factor of 1.7) appears reasonable. There is, however, some possibility that FFVs may attain higher efficiency running on methanol, but this would likely come at the expense of the vehicle's general performance running on gasoline; that is, the vehicles could be designed to run optimally on M85 or M100, with the ability to run on gasoline (although not as well as with a gasoline vehicle) retained for an emergency.

The fairly wide ranges of 'reasonable' costs for different segments of the fuel cycle, discussed above, lead to a wider range of potential methanol costs in comparison to gasoline costs, in equivalent terms. However, the cost ranges derived in the body of this report are actually narrower than the true range of costs presented in the ongoing debate about the wisdom of supporting methanol's entry into the transportation sector. It seems to us that some of the differences in the cost estimates presented in this debate—in particular, the tendency of some price estimates to range up to very high values-stem from a basic analytical misunderstanding exhibited by some analysts. In surveying a variety of potential plant sites, production technologies, and plant builders and operators, analysts have gathered a wide range of expected plant capital and construction costs, required investment hurdle rates, and other factors affecting methanol costs. This range will, in turn, lead to a very wide range of potential methanol costs and prices. *It is rarely appropriate to display this full range as "the range of likely methanol costs and prices." In* reality, those sites that lead to high infrastructure or raw material costs, those companies demanding very high hurdle rates, and those tech-

[130] Methanol contains about 56,600 Btu per gallon (lower heating value) versus 115,400 to 117,000 Btu per gallon (lower heating value) for gasoline. Source: S.C. Davis et al, *Transportation Energy Data Book: Edition 10*, Oak Ridge National Laboratory report ORNL-6565, September 1989; and David Kulp, Ford Motor Co., personal communication.

[131] A 1.5 conversion factor reflects a greater than 30 percent improvement in efficiency compared to the efficiency achieved by a comparable gasoline-powered vehicle. EPA has based its economic analysis of methanol on a 30 percent efficiency advantage (EPA, Office of Mobile Sources, *Analysis of the Economic and Environmental Effects of Methanol as an Automotive Fuel,* September 1988).

[132] Energy and Environmental Analysis, Inc., op. cit., footnote 125.

[133] Ibid.

[134] For example, hi@ compression engines tend to produce more NO_x, and very lean air/fuel mixtures, while reducing engine-out NO_x levels, will interfere with the performance of reduction catalysts designed to reduce tailpipe NO_x emissions.

[135] Industry analysts believe that FFVs will have a 4 to 7 percent efficiency advantage at equal performance, implying methanol/gasoline conversion factors of 1.87 to 1.92.

nologies with high expected capital costs or operating costs will not play a role in a realistic methanol supply scenario *unless the* sites, companies, and technologies that will produce lower cost methanol cannot produce enough supply to satisfy methanol requirements. For example, the construction industry may require anywhere from 20 to 30 percent hurdle rates for methanol investments. It is not appropriate, however, to use 20 to 30 percent as the appropriate hurdle rates in cost analysis (or 25 percent, the arithmetic average, or whatever the weighted average is) unless the companies requiring the lower end of the hurdle rates represent only a small fraction of industry construction capacity. The group of companies actually willing to bid on methanol construction is likely to be restricted to those that will accept perhaps 20 to 25 percent rates; the "30-percenters" probably won't bid.

This suggestion to ignore the high end of the cost range applies *only* when the range reflects differences in known quantities-that is, different companies' actual hurdle rates, or known differences in construction costs between alternative technologies—rather than differences due to uncertainty, e.g., a cost range that reflects the lack of experience in building a particular technology under untried circumstances.

Chapter 4
Natural Gas as a Vehicle Fuel

Although most attention has been directed to methanol produced from natural gas, natural gas itself, either compressed (CNG) or in liquid (low temperature) form (LNG), also can serve as an alternative fuel for vehicles, with the vehicles either equipped to use both gasoline and natural gas or optimized to serve in a single-fuel mode. There are currently nearly 700,000 CNG-powered vehicles worldwide, mostly in Italy (300,000), Australia (over 100,000), and New Zealand (130,000), with the United States (30,000) and Canada (15,000) having moderate numbers as well.[1] The primary attraction of these vehicles outside of the United States is their not using an oil-based fuel and, for New Zealand, their use of a domestic fuel that may otherwise have limited markets.

VEHICLES

Existing natural gas-powered vehicles generally are gasoline vehicles modified by after-market retrofitters and retain dual-fuel capability, i.e., they are able to use either gasoline or gas. Despite the low cost of the natural gas fuel, dual-fueled gasoline/gas-powered vehicles generally are not cost-competitive with gasoline-powered vehicles at current energy prices under most usage circumstances, and they will likely remain noncompetitive unless gasoline becomes heavily burdened with taxes or prices for oil rise sharply while gas prices remain low. Previous studies have shown that only heavily used vehicles (e.g., commercial fleet vehicles) can save enough money from lower fuel prices to compensate for higher vehicle costs and the costs for a compressor station (a natural gas retrofit costs $ 1,600/vehicle or more, and a factory built vehicle will cost $800 or more extra, to pay for the extra fuel tank, gas-air mixer, pressure regulators, and other components). In addition, most currently available dual-fueled vehicles have significantly less power and some driveability problems under heavy load when operated on natural gas (and slightly less power when operated on gasoline, because of the weight of the extra fuel tanks), and lose much of their storage space to fuel storage. Much of the power loss and probably all of the drivability problems are due to the design and/or installation of the retrofit packages; significant improvements in power and driveability can be realized with more-sophisticated retrofit kits, or in factory-built, dual-fueled vehicles.[3] Nevertheless, given the remaining problems, dual-fueled vehicles will have a difficult time competing with gasoline vehicles or vehicles fueled with other, higher-energy-density fuels except in high-mileage fleets or other specialized applications.

Single-fueled vehicles optimized for natural gas use are likely to be considerably more attractive in terms of performance, and somewhat more attractive in terms of cost—though firm conclusions must await considerable vehicle development and testing. The cost of pressurized storage will make the vehicles more expensive than a similar gasoline-powered vehicle, but probably by no more than $700 or $800,[4] not the $750 to $1,600+ differential posed by a dual-fuel vehicle. A natural gas-powered,

[1] U.S. Department of *Energy, Assessment of Costs and Benefits of Flexible and Alternative Fuel Use in the U.S. Transportation Sector. Progress Report One: Context and Analytical Framework,* January 1988.

[2] U.S. Department of Energy, *Assessment of Costs and Benefits of Flexible and Alternative Fuel Use in the U.S. Transportation Sector. Technical Report Five. Vehicle and Fuel Distribution Requirements (Draft),* January, 1990.

[3] The improvements are obtained primarily from enriching the fuel mix during cold starts and during high power requirements, easing driveability problems, and advancing spark timing during operation with gas, to increase power. Most current retrofit kits aim for low cost and are not designed for specific vehicles, sacrificing power and driveability for cost. K.G. Duleep, Energy and Environmental Analysis, Inc., personal communication Mar. 15, 1990.

[4] That is the approximate cost of CNG cylinders storing about 0.8 mmBtu of gas. If the cylinders have a high salvage value (because they can last for several vehicle lifetimes), their net cost will be lower. If the vehicle does not need an NO_x reduction catalyst, its cost will be a few hundred dollars lower. M.A. DeLuchi, R.A. Johnston, and D. Sperling, "Methanol vs. Natural Gas Vehicles: A Comparison of Resource Supply, Performance, Emissions, Fuel Storage, Safety, Costs, and Transitions," Society of Automotive Engineers Technical Paper 881656, 1988.

Photo credit: Ford Motor Co.

The Ford compressed natural gas Ranger has a driving range of 225 miles with four compressed natural gas (CNG) tanks. Major component changes from a gasoline-powered Ranger include modifications to the exhaust valve seats, pistons, and piston rings and addition of a fuel mixer, pressure regulator, and CNG tanks.

single-fuel vehicle should be capable of similar power,[5] similar or higher efficiency, and substantially lower emissions (except for nitrogen oxides (NO_x)) than an equivalent gasoline-powered vehicle. Such a vehicle would have a much shorter driving range-due to the lower energy density of CNG versus gasoline[6]--unless the fuel tanks are made quite large, which would then entail a further penalty in weight, space, performance, and cost, and which could increase greenhouse emissions as well. Advanced storage containers made of fiber-reinforced steel and aluminum, and of composites, have been developed. These containers are lighter in weight than existing steel containers and, because of their greater strength, could reduce storage volume somewhat because they allow increased storage pressures. Fiberglass-wrapped aluminum is the most affordable option among the newer materials; a tank

[5]Designing the engine specifically for natural gas allows increasing the compression ratio and advancing the spark timing, which will approximately compensate for the power-depressing effect of the greater displacement and lower flame speed of gas versus gasoline and the vehicle's greater weight, though at some cost in higher NO_x emissions. Source: DeLuchi et al., op. cit., footnote 4. Because some further optimization of *gasoline* engines will likely occur during the period in which natural gas engines could be perfected, speculation over the precise final outcome of any gas vs. gasoline power competition seems fruitless.

[6]CNG at 3,000 psi occupies about 4 times more volume than gasoline of equal energy content,

of this material would add about 150 pounds to the vehicle (over a gasoline system), assuming 3,000 psi tanks and 300-mile range.[7] Another, longer term option for storage may be the use of absorbents that allow high density storage at lower pressure.

CNG vehicles' range limitations would be eased considerably if LNG were substituted as the fuel. Rather than CNG's 4:1 volume disadvantage (at 3,000 psi) with gasoline, LNG has only a 1.3:1 disadvantage.[8] Even with their required insulation, and the added bulk it causes, advanced LNG fuel tanks should be only about twice as bulky as gasoline tanks holding the same energy,[9] and possibly less than twice as bulky to achieve the same range if the vehicle can attain an efficiency gain over gasoline vehicles. Further, unlike CNG vehicles, the added weight of the storage tanks should be modest. And the extremely low temperature of the fuel can add an additional power boost to that obtainable with compression ratio and spark timing,[10] so the LNG vehicle will have a power advantage over a CNG vehicle.

LNG storage tanks have been demonstrated that allow vehicles to remain idle for a week without the need to vent gas.[11] Retrofit costs to convert a gasoline vehicle to LNG have been estimated at $2,780 per vehicle;[12] a factory-built dedicated vehicle would presumably have a considerably smaller cost penalty.

EFFECTS ON AIR QUALITY

The magnitude and character of emissions from natural gas vehicles, like emissions from methanol vehicles, will vary depending on trade-offs made between performance, fuel efficiency, emissions, and other factors. However, the physical makeup of natural gas tends to make it a basically low emission fuel. Natural gas contains virtually no nitrogen or sulfur and does not mix with oil; thus, it will not foul engine combustion chambers, engine oils, and spark plugs as readily as gasoline, and may help to avoid the deterioration of emissions control performance common in gasoline-powered automobiles. Fuel losses due to leaks will not add appreciably to ozone formation because methane-natural gas' key component—is not (photochemically) very reactive (however, as discussed later, methane is a powerful greenhouse gas, so leaks, as well as high concentrations of methane in vehicle exhausts, would be harmful from the standpoint of global warming). And because it is gaseous and does not require vaporization before combustion, its use will lessen the cold start problems—with the need to run 'rich' (air/fuel ratio lower than normal) before warmup is achieved—responsible for much of the hydrocarbon and carbon monoxide emissions of today's gasoline engines. With these advantages, natural gas is likely to be considered at least as good as methanol as a clean fuel so long as NO_x, emissions can be held down. In fact, as far as ozone effects are concerned, there is a general consensus that natural gas use will provide a strongly beneficial effect, in contrast to the controversy about methanol's impact (see ch. 3).

A key determinant of emissions will be the decision to run the vehicle either "lean" (with excess air) or stoichiometric (with just enough air to theoretically achieve complete combustion). However, no optimized, dedicated, natural gas vehicles running stoichiometric, and very few running lean, have ever been built or tested,[13] so any discussion of emissions effects must be based largely on theory and extrapolation.

Running the engine lean will optimize efficiency and lead to low engine-out levels of CO and

7DeLuchi et al., op. cit., footnote 4.

8LNG's lower heating value is about 87,600 Btu/gallon versus gasoline's 115,400. S.C. Davis et al., *Transportation Energy Data Book: Edition 10, Oak* Ridge National Laboratory report ORNL-6565, September 1989, table B.1.

9DeLuchi et al., op. cit., footnote 4.

10DeLuchi et al., op. Cit., footnote 4.

11F.L. Fischer, "Introduction of a Commercial System for Liquid Methane Vehicles," *Nonpetroleum VehicularFuelsIII, Symposium Papers*, Institute of Gas Technology, Chicago, 1983, and R.J. Nichols, "Ford's CNG Vehicle Research," 10th Energy Technology Conference, Washington DC, Mar. 1, 1983, both cited in M.A. DeLuchi, op. cit., footnote 4.

12R.E. Adkins, "An Alternative Transportation Fuel—"The Lng Option," paper presented for American Gas Association September 1989, Adkins is the president of a firm that is marketing LNG systems.

13C.S. Weaver, "Natural Gas Vehicles-A Review of the State of the Art," Society of Automotive Engineers paper 892133, presented Sept. 25-28, 1989, SAE International Fuels and Lubricants Meeting and Exposition, Baltimore, MD.

nonmethane hydrocarbons.[14] Major drawbacks of running lean include drivability problems and low power, both of which would adversely affect consumer acceptance. Also, an NO_x reduction catalyst will be ineffective under excess air (lean) conditions, and NO_x tailpipe emissions may increase over gasoline-based emissions with catalytic control. Because NO_x formation is dependent on the duration of the fuel combustion process, some analysts hope that so-called "fast burn" designs, probably coupled with high levels of exhaust gas recirculation, will be capable of keeping NO_x emissions down to or below the levels of the best current gasoline engines.[15]

CO emissions under lean burn conditions should be considerably lower than those of a competing gasoline engine equipped with similar controls; running the engine in a lean burn mode with an oxidation catalyst could virtually eliminate CO emissions.[16] Because manufacturers may be able to satisfy Federal CO standards without a catalyst, however, theoretically they might choose to forego catalytic control to reduce vehicle cost. In this event, CO emissions would be comparable to those from gasoline-fueled vehicles.

If gas engines are run stoichiometric (at significant loss in efficiency), the emissions result will be somewhat different. CO emissions during most of the driving cycle will generally be similar to emissions from gasoline engines. However, the reduction in cold start fuel enrichment allowed by natural gas should reduce sharply the relative emissions during the vehicle warmup period which, for newer cars, is when the bulk of CO emissions are produced. During the winter, when CO air quality problems tend to occur, the warmup period is longer and the emissions benefit more pronounced. Nonmethane hydrocarbon emissions will be higher than with lean burn, but probably still lower than gasoline-fueled engines, again because of gas' low cold-start emissions. Also, as with all gas-fueled vehicles, much of the total exhaust hydrocarbons will be methane, which is essentially nonreactive and will not contribute to ozone formation (though methane is a powerful greenhouse gas). Consequently, the overall ozone-producing impact of the hydrocarbon emissions should remain very low even without running the engine lean.

The ability to use a reduction catalyst under stoichiometric conditions should allow NO_x emissions to be kept low—to the level of the best gasoline vehicles—for these engines,[17] though perhaps not as low as with similar methanol engines.[18] Such emissions probably could be made still lower by using fast burn technology with exhaust gas recirculation, as with the lean burning engines.[19] Unfortunately, this type of emission control strategy may have driveability and low power/weight problems.

All natural gas vehicles will emit aldehydes, primarily in the form of formaldehyde. Relatively high formaldehyde emissions (compared to gasoline engines) from methanol vehicles are considered a key uncertainty in determining methanol's net effect on ozone formation. Limited testing of natural gas vehicles indicates that uncontrolled aldehyde emissions may be considerably lower than those from methanol vehicles, approximately comparable to uncontrolled emissions from gasoline engines,[20] and should be of less concern than emissions from methanol vehicles.

Natural gas vehicles are expected to produce moderately lower net emissions (including all fuel cycle emissions) of greenhouse gases than gasoline-fueled vehicles, though the use of different but plausible assumptions yields a range spanning about a 25 percent decrease in greenhouse emissions to an 11 percent increase for domestic natural gas,[21] and lower benefits for overseas gas.[22] The overall effect

[14] Methane often is not counted as part of hydrocarbon emissions because its atmospheric reactivity is so low that it plays little role in ozone formation. Its low reactivity also means that it is not efficiently controlled by catalytic converters, however, so that exhaust levels of methane maybe fairly high, depending on engine operating conditions. DeLuchi et al., op. cit., footnote 4.

[15] C.S. Weaver, op. cit., footnote 13.

[16] DeLuchi et al., op. Cit., footnote 4.

[17] C.S. Weaver, op. cit., footnote 13.

[18] DeLuchi et al., op. Cit., footnote 4.

[19] Ibid.

[20] DeLuchi et al., op. cit., footnote 4.

[21] D. Sperling and M.A. DeLuchi, *Alternative Fuels and Air Pollution*, draft report prepared for Environment Directorate, OECD, March, 1990.

[22] Overseas shipment as LNG extracts a significant energy penalty.

is complicated by several factors, including methane's potency as a greenhouse gas—it is many times as effective as CO_2, pound for pound, though the precise effect is in some dispute[23]—and the role that CO plays in destroying hydroxyl radicals in the atmosphere and possibly preventing these radicals from scavenging methane out of the atmosphere.[24] Of special concern is the amount of additional methane that might leak into the atmosphere if a significant shift to natural gas vehicles were to occur; measurements of current leakage in the natural gas production and distribution systems are highly variable and of suspect accuracy. The greenhouse estimate is also sensitive to assumptions about gas engine efficiency, methane emissions from the tailpipe, and vehicle range. Sperling and DeLuchi's "base case," which assumes the use of domestic CNG with a 10 percent efficiency gain and an assumed range equal to that of a gasoline vehicle, estimates the greenhouse benefit to be 3 to 17 percent depending on methane's assumed potency as a greenhouse gas.[25]

SAFETY

Natural gas should be a safer fuel than gasoline. It is neither toxic, carcinogenic, nor caustic, whereas gasoline is all three. A gas leak into an enclosed area can be an extreme explosion hazard, implying the need for strict control of refueling operations (particularly if home refueling becomes popular). However, a leak into open air will not detonate because gas disperses quickly and the concentration in air required for detonation is high, 5.3 percent (versus 1.1 percent for gasoline vapors, which can represent a strong detonation hazard[26]). Also, the temperature required for natural gas ignition is higher than gasoline's, about 1,000 'F versus 440 to 880'F.[27]

An important safety concern associated with natural gas vehicles has been the integrity of the pressurized or cryogenic storage tanks carried onboard the vehicles. Because they are designed to withstand high pressure, CNG pressurized tanks are extremely strong and have no record of problems in collisions despite extensive use on vehicles.[28] LNG tanks, while not as strong, do not carry material under high pressure, and thus represent a situation somewhat similar to gasoline tanks, though with less fire and explosion hazard but with some danger of frostbite were the tanks to rupture and the fuel contact vehicle occupants or passersby.

COST COMPETITIVENESS

A fleet of natural gas-powered vehicles might be competitive economically with gasoline-powered vehicles, but there are significant uncertainties. Most important are the uncertain future prices of natural gas and gasoline, and the uncertain cost penalty of the gas-powered vehicles. The latter uncertainty is due to the relative lack of interest of auto manufacturers in this fuel, and thus the limited research and development effort that has been devoted to single-fueled natural gas vehicles. A recent analysis assumed that mass-produced, dedicated, optimized CNG-powered vehicles would cost $700 to $8OO/vehicle more than comparable gasoline vehicles, with most of the cost difference attributed to the high pressure storage, and would be 10 to 25 percent more thermally efficient[29] (the higher end of this efficiency range appears overly optimistic). Assuming $7.50 to $9.00/mmBtu gas delivered to the compression station, the analysis concluded that a single-fueled CNG vehicle would break even with a gasoline-fueled vehicle when gasoline cost between $0.75 to $2.14/gallon. A parallel analysis for LNG-fueled vehicles arrived at a virtually identical gasoline breakeven cost range, $0.75 to $2.23/gallon.[30] Uncertainties in costs, performance, engine lifetimes, etc. will widen this range, but from a cost standpoint-as well as an environmental standpoint-natural gas-powered vehicles appear to deserve further attention for at least a portion of the vehicle fleet.

23 Sperling and DeLuchi, ibid., define the range as 10 to 40 times more effective than CO_2, pound for pound.

24 C.S. Weaver, op. cit., footnote 13.

25 D. Sperling and M.A. DeLuchi, Op. Cit., footnote 21.

26 DeLuchi et al., op. Cit., footnote 4.

27 Ibid.

28 Ibid.

29 Deluchi et al., op. cit., footnote 4.

30 Ibid.

SOURCES OF SUPPLY AND STRATEGIC CONSIDERATIONS

As with methanol-powered vehicles, natural gas vehicles have been promoted as a measure to enhance national security by shifting to supposedly more-secure natural gas. Unlike methanol, however, natural gas needs no expensive processing to become a viable vehicle fuel, so that higher priced gas can be a viable feedstock if transportation costs are not too high. Consequently, although relatively high-priced U.S. gas is not an economic feedstock for methanol, it might be a viable feedstock for a U.S. natural gas vehicle fleet if supplies hold out. U.S. natural gas supply currently is in surplus, and the United States has a substantial gas resource base, which has caused some analysts to predict that domestic gas production could fuel a major transportation shift to gas.[31]

This projection is correct for the short term-the next few years-but probably incorrect for the longer term. Although there is room for argument about the size of the current surplus, it probably is in excess of 1 trillion cubic feet (TCF) per year, which is enough gas to power about 25 million automobiles.[32] However, gas demand is likely to be increasing over the coming decade, while domestic gas production is unlikely to keep pace. Much of the new generating capacity expected to be added to the U.S. electricity supply system during this time is expected to be natural gas-fueled, and current acid rain control strategies appear likely to increase gas use in existing generating capacity as well. Essentially all major U.S. gas supply forecasts project growing gas imports during the 1990s and beyond *without* any movement of gas to vehicular use. And although none of these forecasts fully incorporate the potential increases in recoverable resources that might be available with advanced technology, OTA does not believe that such advances are likely to provide enough increased supply to simultaneously displace imports, power a growing segment of the electric utility sector, *and* fuel a substantial portion of the fleet.[33] Thus, *the natural gas necessary to power a large U.S. fleet of gas-fueled vehicles is likely to come from gas imports.*

A second potential source of natural gas for U.S. transportation needs is pipeline imports from Canada and Mexico. Although gas from these sources also will not be cheap at the wellhead and thus, like U.S. gas, is unlikely to be used to produce methanol, pipeline access for the gas is relatively inexpensive, except from the Canadian Arctic. Thus, a key to the magnitude of potential national security advantages from a shift to natural gas as a transportation fuel may be the magnitude of gas imports that the United States can obtain via pipeline from Canada and Mexico. Current projections generally include steady or rising imports from Canada, but little or no imports from Mexico. There is potential for increased gas imports from both sources, but little assurance that such imports can be obtained.

In 1988, the United States imported more than a TCF of natural gas from Canada, with existing pipelines close to maximurn capacity at peak gas demand periods.[34] Additional pipeline capacity, 1.2 TCF/yr if all proposed projects are built, could be ready by the 1990s.[35] Most U.S. supply projections foresee steady or gradual growing Canadian gas imports to the lower 48 during the next few decades, and there is little doubt that Canada has the resources to provide such imports-Canadian resources are comparatively undeveloped, with recent National Energy Board of Canada estimates of total recoverable resources at slightly above 400 TCF,[36] with 100 TCF in proved reserves, but with total production below 3 TCF/yr.

31Ibid.

32Assumptions: Average vehicle driven 10,000 miles/year, efficiency equivalent to 35 miles per gallon of gasoline.

33Several hundred additional TCF of gas are available in the United States in tight sands, Devonian Shales, and coal seams. Commercial production of these resources is possible with significant improvement in production technology, for example, with improved capability of fracturing tight (low permeability) reservoirs. The potential for such improvements is high but uncertain. Research efforts are maintained by the Gas Research Institute, but previous efforts by the Federal Government have been dropped or reduced, and current low prices are stifling private initiatives. The potential of developing the United States' unconventional resources is discussed in a previous OTA report, *U.S. Natural Gas Availability: Gas Supply Through the Year 2000*, OTA-E-245 (Washington DC: U.S. Government Printing Office, February 1985).

34The pipeline capacity exists t. sustain a theoretical flow of over 1.8 TCF/yr if sales could be sustained at peak levels, but seasonal changes in gas demand prevents this. Source: Arthur Andersen & Co. and Cambridge Energy Research Associates, *Natural Gas Trends, 1988 to 1989 Edition.*

35Energy Information Administration, *Annual Outlook for Oil and Gas 1989*, DOE/EIA-0517 (89), June, 1989.

36Reported in Energy Modeling Fore, Stanford University, *North American Natural Gas Markets*, EMF Report 9, vol. 2, February 1989.

In the past, the magnitude of Canadian exports to the United States was strongly constrained by the Canadian Government. Although export policies have been liberalized, future imports will still be constrained by Canadian perception of the adequacy of their resource base and their capacity to serve growing domestic needs, as well as by the price offered.

There also is little doubt that Mexico has the physical resources to provide large quantities of export gas for the U.S. market, but its recent energy policies have focused on expanding domestic use of gas and stressing oil development in its capital spending plans. With a resource base of at least 200 TCF, reserves of 60 TCF, and annual production of less than 1.0 TCF, Mexico could export substantial quantities of gas, especially if it began to develop its nonassociated resources.[37] However, it is highly uncertain whether it will do so without a substantial rise in U.S. gas prices. Aside from the Mexican Government's desire to boost internal use of gas, there is concern about public reaction to "cheap" gas sales-that is, sales at price levels below the $/Btu level of oil.

If imported LNG is the marginal supply source for a gas-powered fleet, the national security advantages of building a gas-fueled vehicle fleet probably will resemble somewhat the security advantages of a methanol fleet: probably still positive, but much less clear than the advantages of domestic and North American supplies. If a large worldwide gas trade has placed the Middle East and Eastern Bloc into the role of swing suppliers of LNG, the national security advantage of a gasoline-to-natural-gas shift will be reduced. However, because of the very large capital requirements for both suppliers (liquefaction plants) and buyers (expensive port and regasification facilities) in the LNG trade, LNG markets are more likely than oil markets to be based on long-term contracts, and the stability of the specific suppliers is likely to be a more important factor in overall security concerns in the LNG supply system than it is in the oil supply system. According to the Department of Energy, likely LNG suppliers for the United States are Algeria, Norway, Nigeria, and Indonesia,[38] which may be viewed as a group as reliable suppliers. LNG shipments from these countries earmarked for use as a transportation fuel thus may provide to U.S. policymakers a welcome offset to oil imports from the Persian Gulf.

LNG will have two major roadblocks to serving as a supply source for gas-powered vehicles. First, for imports greater than about 750 bcf/yr,[39] new LNG terminals would have to be built, and there is substantial environmental opposition to such construction. Second, LNG is expensive. Liquefying the gas costs between $1 and $3/mcf plus about 10 percent of the incoming gas stream (for energy and losses)[40]; transportation can add up to $1 or so per mcf,[41] and regasifying can add still more. All in all, the delivered price of LNG to the United States needs to be *at least $2* or so per mcf *plus the* wellhead price to make the operation profitable to the exporting country.

REFUELING AND INFRASTRUCTURE

Whatever their relative advantages or disadvantages in cost, performance, and emissions, the outlook for any substantial shift to natural gas as a vehicle fuel--especially for the general fleet-may ultimately rest on consumer acceptance of a new and different refueling system. For CNG vehicles used only in low-mileage applications, refueling conceivably could occur at low compression systems that would fill storage tanks overnight-in essence, the fossil fuel equivalent of recharging the batteries of an electric vehicle. Home systems currently are quite expensive, however, costing upwards of $1,000.[42] Providing "filling station"-type service may be a more formidable barrier. Assuming dedicated CNG

[37]Nonassociated gas resources are gas resources that are separate from oil resources and whose production generally is not tied to oil production.

[38]Energy Information Administration, op. cit., footnote 35.

[39]This is the capacity of the United States' four existing LNG terminals , at Cove Point, MD; Elba Island, GA; Lake Charles, LA; and Everett, MA, reported by the American Gas Association. Other sources (Arthur Andersen, the Energy Information Administration) report capacity at about 900 bcf/yr.

[40]U.S. Department of Energy, Office of Policy, Planning, and *Analysis, Assessment of Costs and Benefits of Flexible and Alternative Fuel Use in the U.S. Transportation Sector. Technical Report Three: Methanol Production and Transportation Costs, DOE/PE-0093,* November 1989.

[41]Ibid. DOE estimates transport costs from Trinidad to San Francisco at $0.67/Mcf, from Bahrain to either Baltimore or San Francisco at more than $1.00/Mcf.

[42]DeLuchi et al., op. cit., footnote 4. Current systems cost $2,000 and up (personal communication, David Kulp, Ford Motor CO.), but mass production should lower costs.

21-541 - 90 - 5 : QL 3

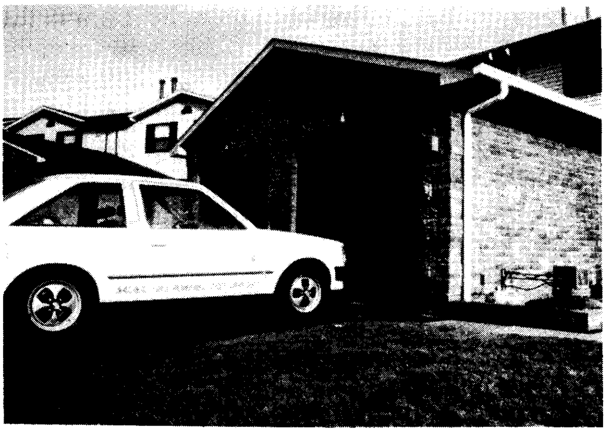


Photo credit: Natural Gas Vehicle Coalition

Natural gas commuter vehicle being filled by a home compressor.

vehicles, large numbers of such stations with rapid fill capability will be needed to maintain a practical system with large numbers of vehicles. Current rapid fill systems, with gas stored at high pressures, allow refilling times that are at least twice as long as refilling gasoline tanks[43]--an inconvenience but one that may be overcome by further equipment development. A further problem, however, is that the stations could share little else besides cashier and maintenance facilities with the gasoline distribution infrastructure. Otherwise they will need to be constructed essentially from scratch, an important hurdle in moving to a gas-based vehicle system. The Department of Energy projects the cost for a rapid-fill station designed to handle 300 vehicles/ day, with 8 minute fill time, peak capacity of 30 vehicles/hour, and four refilling stations, to be $320,000 plus land acquisition costs.[44] In the scenario constructed by DOE, the capital cost of sufficient public stations to displace 1 mmbd of gasoline would be $7.6 billion.[45]

An additional $1 to $2 billion would be needed to improve local gas distribution systems to accommodate the increased gas demand. DOE concluded that no additional long-range transmission expenditures would be required for the approximately 1.9 TCF/yr required to displace 1 mmbd of gasoline.[46]

To our knowledge, there are no studies of potential LNG distribution infrastructures similar to the DOE CNG analysis. An LNG filling station can be either purely a storage and dispensing facility, with LNG delivered to the station by truck from central liquefaction plants, or it can incorporate a small onsite prefabricated liquefaction plant.[47] Although there is some disagreement about whether or not LNG dispensers can be as safe and easy to use as gasoline pumps, firms marketing LNG dispensers claim that their products are comparable to gasoline pumps.[48] There is little reason to doubt that this type of performance is attainable, though presumably such dispensers would have to be maintained with considerable rigor.

NATURAL GAS OUTLOOK AND TIMING

A combination of factors will make natural gas a more difficult fuel than methanol to move into the automobile fleet. First, dual-fuel vehicles will not perform quite as well as competing gasoline vehicles, so that the first generation of vehicle buyers must be willing either to accept the limitations of these vehicles or to accept the risks-and travel limitations--of dedicated vehicles before an extensive infrastructure is built (Of course, operators of vehicle fleets with certain characteristics, e.g., central refueling, limited mileage/day/vehicle, will have an easier time accepting CNG vehicles). Second, range limitations or, conversely, the need for very bulky on-board fuel storage will continue to provide an unattractive comparison with gasoline vehicle characteristics. This is far more a problem with CNG than with LNG, however; the latter's range limitations are similar in scale to those of methanol. Third, the vehicle manufacturers have done comparatively little work on optimized light-duty natural gas

43Ibid.

44U.S. Department Of Energy, *Assessment of Costs and Benefits of Flexible and Alternative Fuel Use in the U.S. Transportation Sector. Technical Report Five. Vehicle and Fuel Distribution Requirements (Draft)*, Office of Policy, Planning, and Analysis, January 1990.

45The DOE scenario is not exclusively one of light-duty vehicles and public filling stations. Two-thirds of the oil displacement in the scenario is accomplished by light duty vehicles, one-third by heavy-duty vehicles. The capital costs were adjusted to represent a displacement of 1 mmbd by light-duty vehicles only.

46U.S. Department of Energy, Technical Report Five, Op.cit., footnote 44.

47Such plants are offered by Cryogas Engineering Ltd. and Cryopak, cited in DeLuchi et al., op. cit., footnote 4.

48Ibid.

engines (though appreciable work is presently being done on heavier duty engines), so that more time will be needed to develop a market-ready engine capable of competing with gasoline-fueled engines. And fourth, although the infrastructure for long range distribution of the fuel is in place, the infrastructure for retail distribution will be more expensive than a similar infrastructure for methanol fuels.

Despite these potential difficulties, natural gas is an attractive fuel that deserves careful consideration as an alternative to gasoline for the U.S. light-duty fleet. It appears likely to be a cleaner fuel than methanol, particularly so if M85 is the methanol fuel alternative. Although domestic supplies are limited, there is an excellent possibility that it can be obtained from our North American neighbors, or from quite secure sources as LNG (though building ports to handle the LNG could be an important hurdle) . . . in contrast to the possibility that a key methanol source would be the Middle East. It offers none of the toxicity and few of the explosion hazards of methanol (or gasoline),[49] and does not appear to offer a substantial engineering challenge to engine designers. And its short-term economics look good, though it is unlikely that gas prices from the likely sources could be uncoupled from oil prices the way methanol prices theoretically could be—if the methanol came from remote gas sources.

Given these characteristics, it seems likely that an effort to move natural gas into the light-duty fleet would lag behind a similar effort for methanol a few years, but could begin to play a significant role—especially in niche applications-well in advance of the other alternatives (aside from reformulated gasoline).

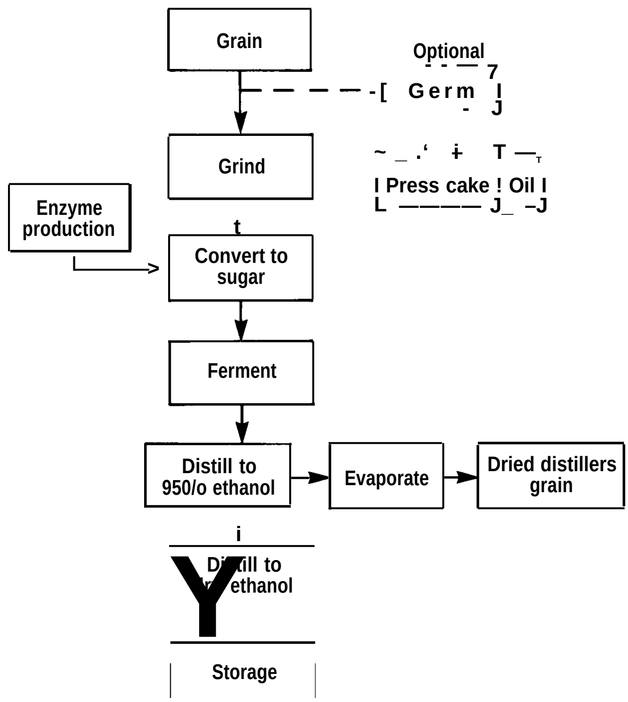
[49]Although indoor refueling could pose some hazards.

Chapter 5

Ethanol as a Gasoline Blending Agent or Neat Fuel in Highway Vehicles

Although methanol generally is acknowledged as the least expensive of the alcohol fuels, ethanol (ethyl alcohol) has gained support because of its potential contribution to the U.S. agricultural economy. Proponents of ethanol usage either as a blending agent or a neat fuel argue that its expanded use as an automotive fuel will displace imported oil, aid the farm economy by creating a stable new market for its agricultural feedstocks, and improve air quality by reducing emissions from vehicles using it. Ethanol's close tie to the U.S. agricultural system separates it from the other potential alternative fuels.

Figure 5-l—Process Diagram for the Production of Fuel Ethanol From Grain



SOURCE: Office of Technology Assessment, 1980.

As shown in figure 5-1, in making ethanol, the distiller produces a sugar solution from the feedstock (in the United States, usually corn, sometimes sugar crops), ferments the sugar to ethanol, and then separates the ethanol from the water through distillation. In distillation, the water-ethanol solution is boiled and the vapors pass through a column causing numerous evaporation-condensation cycles, each one of which further concentrates the ethanol.

Currently, nearly a billion gallons of ethanol per year are added to U.S. gasoline stocks to create "gasohol, ' a 90 percent gasoline/10 percent ethanol blend. The U.S. Government and about a third of the States subsidize ethanol use by partly exempting gasohol from gasoline taxes. The subsidy is critical to ethanol economics. For example, the exemption from the Federal tax alone yields a subsidy of $0.60/gallon of ethanol (at the pump, the tax exemption for gasohol is $0.06/gallon, and 1 gallon of ethanol is contained in 10 gallons of gasohol). Each additional penny of State tax exemption for gasohol is worth an additional $0.10/gallon subsidy to ethanol.

EFFECTS ON AIR QUALITY

In looking to ethanol use as an aid to reducing automotive air pollution, the sought-after benefits are quite different for blends and neat ethanol use. The addition of small quantities of ethanol to gasoline-as in gasohol—is viewed primarily as a means to reduce carbon monoxide emissions; use of neat ethanol is viewed primarily as a means to reduce concentrations of urban ozone, by reducing the reactivity of the organic component of vehicle emissions.

The use of ethanol blends has been demonstrated to reduce levels of carbon monoxide emissions from existing automobiles. This effect originates from the alcohol's causing engines to effectively run more "lean," that is, the air/fuel mixture will contain more oxygen (because the ethanol itself contains oxygen), and the availability of the oxygen assists in the combustion of CO to CO_2. It had, until recently, generally been thought that the extent of CO reduction would differ according to the vehicle's ability to adjust to changes in air/fuel oxygen content: for older vehicles that do not adjust at all, the effect was known to be large; for the most modern vehicles with systems that automatically compensate for changing air/fuel ratios, the effect was assumed to be small. Recent tests of vehicles with so-called "adaptive learning" have cast doubt on this assumption, however. The Environmental Protection Agency (EPA) now considers vehicles with adaptive learning to be likely to obtain average CO benefits from the use of ethanol and other oxygenated fuels "similar in magnitude to the benefits of closed-loop vehicles in general."[1] The greatest benefits occur during cold start operation, when vehicles produce the major part of total trip CO emissions, but some benefit continues even after warmup.[2] If these conclusions hold up, the use of ethanol and other oxygenates in gasoline blends will continue to be an effective strategy for CO reduction even after the fleet consists primarily of vehicles with modern pollution controls.

The effect of ethanol blends on ozone production has been a controversial issue. Ethanol/gasoline blends have higher volatility than the original gasoline, yielding an increase in net evaporative emissions of VOCs. Without counterbalancing changes, this increase would lead to aggravation of urban ozone problems. In fact, there has been substantial debate about requiring gasoline volatility to be adjusted downwards to compensate for the volatility increase caused by addition of the ethanol. Previous studies have concluded that use of ethanol blends *without a restriction on resulting fuel volatility* would likely yield an overall increase in ozone concentrations.[3]

It now appears that volatility adjustment is *not* necessary to prevent an increase in ozone formation from ethanol blend use. Carbon monoxide also plays a role in ozone formation, and the reduced carbon monoxide emissions associated with ethanol blend use will tend to reduce ozone formation. In addition, the incremental evaporative emissions will be somewhat less reactive than evaporative emissions from straight gasoline. Although the net effect of these changes will vary with gasoline composition, atmospheric conditions, and vehicle emission control equipment, recent government studies indicate that future use of ethanol blends, assuming modern vehicles, low volatility gasoline, and no volatility corrections made for blending, will have negligible impact on urban ozone levels.[4]

The net effect of using ethanol blends on the full range of emissions is not as clear. For one thing, the leaning effect, aside from reducing CO, will increase engine-out emissions of NO_x.

The use of neat ethanol in light-duty vehicles should have air quality effects similar to but milder than those associated with methanol use; ethanol is somewhat between methanol and gasoline in its physical characteristics, for example, ethanol's stoichiometric air/fuel ratio is about 9:1 compared to methanol's 6.4: 1 and gasoline's 14.5:1. In general, reactive hydrocarbon emissions should go down substantially, but the effect on ozone may be countered somewhat by higher emission levels of acetaldehydes, and development of more effective aldehyde controls will be a crucial factor in ethanol's overall air quality benefits. Assuming use of three-way catalysts with stoichiometric air/fuel ratios, emissions of carbon monoxide should be at levels similar to those of gasoline engines, and NO_x emissions may also be about the same.

COST COMPETITIVENESS

Few ethanol proponents have tried to argue that the consumer costs of ethanol, without government subsidies, could be competitive with gasoline. Recent work by the Department of Agriculture has shown that, assuming the range of corn and byproduct prices that has occurred during the past decade, the full cost of ethanol production from a new plant[5] ranges from $0.85 to $1.50/gallon,[6] compared to wholesale gasoline prices of about $0.55/gallon, with gasoline energy content nearly 50 percent greater than an equal volume of ethanol.

[1] C.A. Harvey, Technical Support Staff, Emission Control Technology Division, U.S. Environmental Protection Agency, draft memorandum to C.L. Gray, Director, Emission Control Technology Division, USEPA, September 1989.

[2] Ibid.

[3] National Advisory Panel on the Cost-Effectiveness of Fuel Ethanol Production *Fuel Ethanol Cost-1.?'activeness Study*, November 1987; also, M.R. Segal et *al., Analysis of Possible Effects of HR. 2052, Legislation Mandating Use ofEthanol in Gasoline*, Congressional Research Service report 87-819 SPR, Oct. 13, 1987.

[4] R. Scheffe, *Five City UAM Study Summary Report*, U.S. Environmental Protection Agency (Research Triangle Park, NC, in press).

[5] For moderate increases in ethanol production capacity, ethanol plants could be added to existing wet mills at a substantial saving in capital cost. However, any realistic large-scale use of ethanol, especially as a neat fuel, would require construction of new plants on a stand-alone basis.

[6] S.M. Kane and J.M. Refry, *Economics ofEthano/Production in the United States*, Agricultural Economic Report No. 607, United States Department of Agriculture, March 1989.

In directly comparing ethanol production costs to gasoline costs, the price of the corn feedstock is the most volatile component. The net cost of the corn in ethanol (full cost minus byproduct sales) ranged from 10 cents to over 70 cents per gallon of ethanol produced from 1980 to the present.[7] Other costs will vary depending on the technology selected, scale, and whether or not the plant is added to an existing corn milling operation or built as a new stand-alone plant.

Although there are several wet milling plants of sufficient scale to allow new, cost-competitive ethanol plants to be added, any large-scale expansion of ethanol production will require building new stand-alone plants. The Department of Agriculture study estimates that capital charges for a new plant would be $0.38 to $0.48/gallon of ethanol produced,[8] that is, the total production cost of each gallon of ethanol includes $0.38 to $0.48 allocated to plant capital payback.

Given these pessimistic comparisons of the *direct* costs of ethanol and gasoline, the economic argument for ethanol has centered around the positive economic impact its widespread use would have on the American farm economy, and the large savings that would accrue to the U.S. treasury because of reductions in farm support payments. These benefits are claimed to justify extension of the current Federal subsidy ($0.60/gallon) granted to ethanol use in gasohol, and the possible expansion of this subsidy to neat ethanol use in vehicles.

The true long-term costs to the U.S. economy of ethanol production and use are difficult to calculate. One reason is that different interest groups disagree about how to calculate these costs, or even whether to classify certain items as costs at all; another is that several of the cost components depend on the state of agricultural markets, which can change radically over time. For example, large-scale ethanol production is widely expected to increase the price of corn, the most likely ethanol feedstock, and possibly other crops and grain-fed livestock[9] as well. Agricultural interest groups consider this a positive benefit of ethanol production, since it will raise farm income; consumer interest groups consider higher food costs a net cost of ethanol production. Furthermore, the net change in food prices will depend on overall demand for agricultural products. If the agricultural economy is generally depressed, the price elasticity of corn supply will be high and the net cost to consumers of ethanol production will be low; if agriculture is booming, the opposite will be true.

OTA has twice examined the net costs of large-scale ethanol production and use, most recently in 1986.[10] The studies concluded the following:

1. *The size of the byproduct market. The* costs of ethanol production are highly dependent on the markets for the byproduct of ethanol distillation, corn stillage. The stillage is a high protein substitute for soybean meal as livestock feed; when the stillage can be sold as a protein substitute, net feedstock costs go down substantially. If markets for the stillage as a protein supplement became saturated, the stillage would have much lower value and might even represent a cost (for disposal). Under these circumstances, the net costs of ethanol production from corn would change markedly for the worse. Thus, the actual size of the byproduct market and the potential for increasing it are important issues to the ethanol debate. OTA concluded that the byproduct market could saturate when ethanol production reached a few billion gallons per year. At production levels beyond this point, net ethanol production costs would become substantially higher than even the high ($0.85 to $1.50/gallon) costs noted above. However, development of overseas markets for the byproduct could substantially increase the level of production that could be attained without saturating the market; the state of international trade and foreign requirements for high protein feeds add an important uncertainty to ethanol cost calculations.

---

[7] Ibid.

[8] Ibid.

[9] It is possible, however, that livestock prices may go down, if the increased availability of distiller's grains drives down the price of this feed.

[10] Office of Technology Assessment, "Staff Memorandum on the Effects of Replacing Lead With Aromatic Versus Alcohol Octane Enhancers in Gasoline," Jan. 6, 1986; and earlier, Office of Technology Assessment, *Energy From Biological Processes* (Washington D.C.: National Technical Information Service, July 1980). The more recent study examined the use of ethanol in blends only, whereas the earlier study examined the full range of potential ethanol uses.

2. *Effects of different ''states of the farm economy."* For the type of farm economy of the late 1970s, e.g., expanding demand, high land rents, etc., and with conservative (low) estimates of the magnitude of the byproduct market, OTA calculated that with ethanol production rates as low as 2 to 4 billion gallons per year, further production could yield a negative balance of oil and gas (that is, we would use more energy from oil and gas to produce the ethanol than the oil energy we would save when the ethanol replaced gasoline) and a cost to consumers, in terms of higher food prices, of $4 to $5 per additional gallon of ethanol produced.[11] On the other hand, for markets more typical of recent conditions, with a larger byproduct market and lower agricultural demand, an ethanol production rate of 4 billion gallons per year could yield a cost to consumers (in higher food prices) of about $0.45 to $0.75 per additional gallon produced and a net gain in oil and gas.

Ethanol is promoted as a means of raising farm income. However, this is also the goal of current farm programs. Although the costs of both ethanol subsidies and conventional farm support programs will fluctuate considerably from year to year, OTA's earlier analysis concluded that the cost of government subsidies needed to sustain a large-scale ethanol industry would most likely be higher than the cost per year of achieving the same (farm income) results with applicable parts of current farm programs. Other studies have concluded the opposite. For example, the General Accounting Office's (GAO) econometric study for the House Energy and Commerce Committee concluded that likely net revenues to the Treasury from a moderate scale ethanol program would be positive.[12] However, the GAO study did *not* attempt to calculate potential increases in ethanol prices, and states that ''efforts to stimulate a *large-scale (our* emphasis) expansion could raise ethanol feedstock production costs to a point that ethanol could not compete with other fuels. ' '[13]

The Congressional Research Source, (CRS) in a parallel analysis of ethanol blends,[14] also arrived at conclusions more optimistic than OTA's. This result occurs in part because CRS believed that byproduct markets would not saturate, or that such saturation could be prevented. The analysis implies that a government subsidy to replace half of all gasoline with gasohol would raise consumer food prices by $6.6 billion/year, decrease farm subsidies by $3 to $7 billion/year, and require additional ethanol subsidies of about $1 to $3 billion/year.[15] These results imply a ''net cost" to the consumer[16] of $0.6 to ***$6.6*** billion/year, or a subsidy of about $0.12 **to $1.30** for each gallon of gasoline replaced with ethanol. Other economic effects include an increase in farm income of about $1 billion/year, a decrease in oil imports of $1.1 to $2.4 billion/year (at 1987 oil prices), and a decrease in grain exports of about $500 million.[17]

In any event, OTA is skeptical of the ability of available econometric models—including the ones used by GAO and CRS—to properly account for the extensive crop switching that would likely occur in a large expansion of corn acreage for methanol production (e.g., a likely switch from sorghum to corn in Nebraska, and increased sorghum acreage in Texas), for changes in farm energy consumption with overall expansion of planted acreage, and other complex factors.

11Office of Technology Assessment, Energy ***From Biological Processes,*** op. cit., footnote ***4;*** and Office of Technology Assessment, Staff Memorandum, 1986, op. cit., footnote 4. About 40 percent of the increased prices—$1.60 to $2.00/gallon of ethanol-would go to farmers, based on historical relationships.

12J. England-Joseph, U.S. General Accounting Office, "Perspectives on Potential Agricultural and Budgetary Impacts from an Increased Use of Ethanol Fuels," testimony before the Committee on Ways and Means, U.S. House of Representatives, Feb. 1, 1990.

13Ibid.

14Although the CRS report examined the effects of a government *requirement* fo, ethanol use, the analysis can be applied to a direct subsidy of ethanol production.

15OTA estimated the required subsidy using the CRS calculation of additional production costs associated with producing gasohol, and assuming that the Federal subsidy would equalize gasoline and gasohol production costs.

16Adding changes in consumer prices to changes in Federal expenditures, assuming that consumers will eventually absorb the expenditure changes in their tax payments.

17Segal et al., op. cit., footnote 3.

In most cases, corn is the least expensive agricultural feedstock for ethanol production, especially when the byproduct of the production process can be sold. Wood and plant wastes are less expensive inputs to the ethanol plant, but the costs of available ethanol conversion processes for these materials are higher, so that the net total cost of ethanol made from wood and plant wastes is more expensive than ethanol made from corn. Future improvements in these conversion technologies could alter these conclusions, however; the Solar Energy Research Institute (SERI) currently is actively working towards improving wood-to-ethanol processes, and they believe that achievement of economic competitiveness at $20/barrel oil-or ethanol costs below $1.00/gallon-may be obtained by the year 2000 (The Tennessee Valley Authority, New York State Energy Research and Development Authority, and others are also pursuing this technology). A wood-to-ethanol process achieving this cost goal would need to be capable of converting a very high percentage of the feedstock to ethanol and other energy products (primarily methyl aryl ethers, or MAE, high-octane compounds that can be used as blending agents with gasoline) at low temperature and pressure--most likely involving enzymatic hydrolysis processes combining simultaneous hydrolysis and fermentation, xylose fermentation (30 to 60 percent of the sugars in wood are xylose), and lignin conversion.[18] Important barriers remain to pulling output as high as necessary and reducing costs sharply, including problems such as ethanol inhibition of the hydrolysis enzymes, prevention of enzyme degradation and denaturation at higher temperatures, sterility and contamination risks of enzyme recycling, and so forth, as well as the overall problem of optimizing the many process steps. Although we agree with SERI that this work is worth pursuing-especially because of the greenhouse benefits to be gained by commercial success—we find it difficult to share their strong optimism about the timing and eventual outcome of the work.

Another potential means of reducing ethanol costs is to substitute alternative separation technologies—e.g., membrane filtration--for distillation in the production process. Use of these technologies would also reduce energy use in the production process and reduce ethanol's net fuel cycle emissions of greenhouse gases. OTA has not evaluated these technologies, but they are not now commercially available for this use.

Table 5-l—Environmental Impacts of Agriculture

Water
- Water use (irrigated only) that can conflict with other uses or cause ground water mining.
- Leaching of salts and nutrients into surface and ground waters, (and runoff into surface waters) which can cause pollution of drinking water supplies for animals and humans, excessive algae growth in streams and ponds, damage to aquatic habitats, and odors.
- Flow of sediments into surface waters, causing increased turbidity, obstruction of streams, filling of reservoirs, destruction of aquatic habitat, increase of flood potential.
- Flow of pesticides into surface and ground waters, potential buildup in food chain causing both aquatic and terrestrial effects such as thinning of egg shells of birds.
- Thermal pollution of streams caused by land clearing on stream banks, loss of shade, and thus greater solar heating.

Air
- Dust from decreased cover on land, operation of heavy farm machinery.
- Pesticides from aerial spraying or as a component of dust.
- Changed pollen count, human health effects.
- Exhaust emissions from farm machinery.

Land
- Erosion and loss of topsoil decreased cover, plowing, increased water flow because of lower retention; degrading of productivity.
- Displacement of alternative land uses-wilderness, wildlife, esthetics, etc.
- Change in water retention capabilities of land, increased flooding potential.
- Buildup of pesticide residues in soil, potential damage to soil microbial populations.
- Increase in soil salinity (especially from irrigated agriculture), degrading of soil productivity.
- Depletion of nutrients and organic matter from soil.

Other
- Promotion of plant diseases by monoculture cropping practices.
- Occupational health and safety problems associated with operation of heavy machinery, close contact with pesticide residues, and involvement in spraying operations.

SOURCE: Office of Technology Assessment, 1980.

ENERGY AND ENVIRONMENTAL EFFECTS

Ethanol production's energy balance and environmental effects depend primarily on the expansion of corn production and the markets for ethanol production byproducts. Increased corn production will take place on land that is more environmentally sensitive and energy intensive than average cornland--or it will displace other crops onto such land. Table 5-1 lists the environmental impacts of agriculture, many of which could be particularly important if ethanol

[18] J.D. Wright, "Ethanol From Biomass by Enzymatic Hydrolysis," *Chemical Engineering Progress*, August 1988, pp. 62-74.

production is large enough to add significant amounts of marginal land into intensive crop production.

The expansion of crop production onto new lands will occur slowly as long as there is a market for the corn stillage byproduct of ethanol distillation. Since the stillage is a substitute for soybean meal, when the stillage can be sold as a protein substitute, the energy use and other negative environmental effects (erosion, pesticide and fertilizer use, etc.) of extra corn production for ethanol are somewhat balanced by the reduction in soybean cropping. For example, an average of about 0.8 acres of soybeans are replaced by the stillage associated with 1 acre of corn, so the net effects on land use maybe only 20 percent of the increased corn acreage. Similarly, the net increase in farming energy use (corn use minus soybean savings) is about 30 to 40 percent of the energy content of the resultant ethanol, compared to an increased farming energy use of 160 percent or more of the energy content of the resultant ethanol (leading to a net energy loss) if there is no displacement of soybean production.

The costs and energy savings of ethanol use are also dependent on the energy savings associated with ethanol's ability to boost the octane level of gasoline. Some refineries are able to use these properties of ethanol to reduce their energy needs slightly. Today's refiners have made the necessary investments to produce current high octane gasolines in a manner that is well integrated into their overall operation.[19] Because addition of ethanol generally was not factored into their investments, the opportunities for obtaining energy savings by adding ethanol are limited today. As a result, the marginal energy savings from each additional percent of ethanol addition drops rapidly after the first percent or two. However, this conclusion may not hold if refiners are forced to respond to requirements to change gasoline makeup to reduce emissions, adding new capital equipment and changing operating practices. Given the uncertainty associated with the probable makeup of so-called "reformulated gasolines" (see ch. 8), ethanol's possible role, and energy savings associated with that role, are difficult to predict but worthy of reexamination as knowledge about appropriate gasoline changes finally emerge from ongoing research programs.

Ethanol use has also been promoted as a means of reducing the $C0_2$ emissions associated with gasoline usage. Achieving a net reduction in CO_2 will be difficult, however, because the sum of the increase in farming energy (as noted above, 30 to 40 percent of the energy in ethanol *in the best case)* and distillery energy (assuming current technology) would require about the same amount of fossil fuels as found in the ethanol itself. Fuel cycle fossil fuel use could be reduced if renewable were used to power the distillery, substantial energy savings were achieved by commercializing membrane filtration or other alternative separation technologies to replace distillation, or larger-than-expected efficiency gains were achieved in ethanol use. On the other hand, saturation of byproduct markets would increase ethanol fuel cycle net energy use, with a net *increase in CO_2* emissions, because the energy savings associated with the byproduct's substitution for soybeans will be lost.

The CO_2 issue has become quite controversial because of the strong claims of ethanol proponents and recent analyses which support the position that ethanol use produces less net CO_2 than gasoline. Marland and Turhollow,[20] for example, calculate net $C0_2$ emissions from the ethanol fuel cycle at about 37 percent of gasoline emissions-implying a major greenhouse benefit. However, Marland and 'Ihrhol-10W'S assessment uses a series of assumptions which raise serious concerns for a large ethanol production program:

1. *The feedstock corn is grown on an average acre producing 119 bushels.* Yield projections for additional corn crops are a critical source of uncertainty for both energy use and economic projections. For one thing, the land used will not be 'average' land, it will be inferior to the average. For a large ethanol program, corn production will either move to marginal acreage or displace other production onto marginal acreage. The net result is that the farming energy that should be assigned to ethanol production is considerably larger than the ''average' energy used here. The frost two additional billion gallons of ethanol can be produced using set-aside land—land which, although cropped in past years, generally

[19] OTA Staff Memorandum, op. cit., footnote 10.

[20] G. Marland and A. Turhollow, ''CO_2 Emissions from production and Combustion of Fuel Ethanol from Corn,'' Migdon Segal, *Ethanol Fuel and Global Warming,* Congressional Research Service report 89-164 SPR, Mar. 6, 1989.

represents each farmers' least-productive, most energy-intensive land. If production moves to more marginal lands, energy use and environmental damages will increase further.

Tending to counteract these adverse land quality effects, future crops may produce greater yields through better plant breeding or genetic engineering; also, high fertilizer and pesticide prices and a growing awareness of environmental problems caused by overuse of agricultural chemicals may well lead to lower overall use and, probably more *efficient* use of these chemicals in the future. Finally, farmers may try to substitute varieties of corn with greater starch yields, to maximize ethanol yield per acre. Higher starch yields would likely trade off with lower protein byproduct yields, so the use of this strategy would depend on the state of the byproduct market.

While it is unlikely that average *incremental* yields from a greatly expanded corn crop would be as high as the national 10 year average used in this analysis, we recognize that the estimate can be, at best, an educated guess, and there are factors pushing these yields in both directions from the average.

As a final note, Marland and Turhollow's use of the 119 bushels/acre yield has been criticized as representing only "successful" acreage and ignoring planted acreage that was not harvested.[21] The 119 bushels/acre estimate appears to be essentially correct, however. Although there is a substantial difference between reported plant acreage and harvested acreage, the difference is primarily accounted for by land planted for corn sileage (that is, for the carbohydrate value of the plant material rather than the protein value of the grain). This land is counted in the estimate for planted corn acreage but left out of the estimate for harvested corn acreage.

2. *The "byproduct credit" to be subtracted from the total energy use and $C0_2$ production is proportional to the market value of the ethanol and byproduct.* This results in subtracting nearly 50 percent from the total CO_2 production, which is much too high. The energy required to produce enough soybeans to replace the distillery byproducts is about 8,000 Btu/gallon of ethanol, or one-fifth the amount subtracted.
3. *All of the distillery byproducts will be consumed in their highest use.* With the production of billions of gallons of ethanol, there is a real possibility of saturating the byproduct market. If this occurs, the byproduct credit cannot be taken.

Ethanol distribution and use should be safer than gasoline distribution and use. In a spill, ethanol in high initial concentrations will be quite toxic to marine life, but ethanol is highly soluble and will disperse rapidly, it is readily biodegradable, and it will evaporate quickly if spilled on land.[22] Also, cent contamination of drinking water supplies is less troublesome than for gasoline or methanol because ethanol is less toxic to humans in equal concentrations and has a recognizable taste (methanol does not, although fuel methanol would likely contain a taste additive for safety) .23 Ethanol has fire safety implications similar to those of methanol: compared to gasoline, it has lower volatility, higher flammability limit, lower vapor density, lower heat of combustion, and higher heat of vaporization, which means an ethanol spill is less likely than gasoline to ignite and, if it ignites, will burn more slowly and less violently than a gasoline fire.[24] And along with methanol, special protection must be taken to prevent fuel ignition inside storage tanks, and additives will be necessary to impart flame visibility.[25]

The greenhouse balance of ethanol use would likely be improved substantially, and the environmental impacts reduced, if processes for producing ethanol from wood and wood waste were perfected and costs substantially reduced. The overall greenhouse and environmental balance would depend importantly on the energy balance of the wood

[21] S.P. Ho, Amoco Oil Co., "Global Warmin g Impact of Ethanol versus Gasoline," 1989 National Conference on Clean Air Issues and America's Motor Fuel Business, Oct. 3-5, 1989, Washington D.C.

[22] U.S. Environmental protection Agency, *Analysis of the Economic and Environmental E fleets of Ethanol as a Motor Fuel,* special report (draft), Nov. *15, 1989.*

[23] Ibid.

[24] Ibid.

[25] Ibid.

production system (minimum use of agricultural chemicals, harvesting integrated into wood production for other uses), the sustainability of the system (intensive harvesting of wood wastes can deplete soils of critical minerals), and the avoidance of forest management problems that have plagued U.S. forestry in the past. Table 5-2 lists key impacts of logging and forestry that must be avoided or mitigated if wood-to-ethanol (or methanol) systems are to be environmentally sound. Systems based on producing wood as a crop, e.g., coppicing fast-growing species that will regenerate from stumps, resemble agriculture more than forestry and will need to deal with agricultural impacts.

DEMAND LIMITS

Ethanol production is theoretically limited by the rate at which grain, sugar, and cellulosic feedstocks can be supplied on a continuing basis, or up to several tens of billions of gallons per year. In principle, there is no limit to ethanol demand up to total oil demand, as long as ethanol is used as a direct substitute for gasoline or other oil products. However, market demand for ethanol *as a blending agent will* likely be quite small without government intervention.[26] Ethanol must compete with methanol, methyl tertiary butyl ether (MTBE), and other products for the oxygenate blend market. It must compete with refinery isomerization, polymerization, alkylation, and reforming as a means of boosting gasoline octane. In addition, the total oxygenate content of gasoline in the United States currently is limited by EPA regulations and by the fuel capabilities of current automobiles. In the longer term, ethanol also must compete with various other synthetic fuels and with advanced procedures for increasing octane.

ETHANOL OUTLOOK AND TIMING

Ethanol is, in several ways, an attractive automobile fuel. It is likely to provide important emissions benefits over gasoline, though the benefits of neat ethanol, or ethanol blended with small amounts of gasoline, must be considered uncertain because of a lack of experience with vehicles equipped with U.S.-type emission controls. It is basically a safer fuel than gasoline to distribute and use, it has a convenient liquid form, and its volumetric energy content is higher than the other leading alternative fuel contenders, minimizing range problems.

Table 5-2—Potential Environmental Effects of Logging and Forestry

Water
- Increased flow of sediments into surfaoe waters from logging erosion(especially from roads and skid trails.
- Clogging of streams from logging residue.
- Leaching of nutrients into surface and ground waters.
- Potential improvement of water quality and more even flow from forestation of depleted or mined lands.
- Herbicide/pesticide pollution from runoff and aerial application (from a small percentage of forested acreage).
- Warming of streams from loss of shading when vegetation adjacent to streams is removed.

Air
- Fugitive dust, primarily from roads and skid trails.
- Emissions from harvesting and transport equipment.
- Effects on atmospheric CO_2 concentrations, especially if forested land is permanently converted to cropland or other (lower biomass) use or vice-versa.
- Air pollution from prescribed burning.

Land
- Compaction of soils from roads and heavy equipment (leading to following two impacts).
- Surface erosion of forest soils from roads, skid trails, other disturbances.
- Loss of some long-term water storage capacity of forest, increased flooding potential (or increased water availability downstream) until revegetations occurs.
- Changes in fire hazard, especially from debris.
- Possible loss of forest to alternative use or to regenerative failure.
- Possible reduction in soil quality/nutrient and organic level from short rotations and/or residue removal (inadequately understood).
- Positive effects of reforestation-reduced erosion, increase in water retention, rehabilitation of strip-mined land, drastically improved esthetic quality, etc.
- Slumps and landslides from loss of root support or improper road design.
- Temporary degrading of esthetic quality.

Ecological
- Changes in wildlife from transient effect of cutting and changes in forest type.
- Temporary degradation of aquatic ecosystems.
- Change in forest type or improved forest from stand conversion.

SOURCE: Office of Technology Assessment, 1980.

The major roadblock to its introduction and use as a major transportation fuel is fuel supply. Ethanol is most cheaply produced from corn, and the energy, environmental, and economic effects of a substantial increase in ethanol use in the automotive fleet will be highly dependent on the state of the agricultural economy at the time and on the con.figuration of the production system created to provide the ethanol.

[26] At the time this report was being prepared, Clean Air Act proposals concerning the required oxygen content of gasolines being considered by the Congress would, if approved, have the effect of stimulating ethanol use.

Some studies have suggested that the U.S. treasury, at least, would benefit from increased ethanol production with the current $0.60/gallon subsidy because of more-than-balancing reductions in farm subsidies. OTA considers these results to be highly uncertain, and we believe it is more likely that the subsidy would outweigh the reduced farm supports in the long run-especially if production were to grow quite large. Also, because the demand for agricultural products can shift directions quite rapidly (particularly because of the volatility of export markets) whereas an ethanol infrastructure cannot, a subsidy of ethanol production may prove to be a cumbersome tool for agricultural policy. And a strategy to increase ethanol use must recognize the possibility that an ethanol production system, unless specifically designed to minimize the use of oil plus natural gas, may save little of these fuels when all portions of the production system are accounted for. Finally, policymakers must be aware that much of the potential benefit to the farm economy from ethanol production will arise from higher food prices, and consumers will count this benefit as a cost.

These policy concerns, coupled with ethanol's high direct costs, imply that prospects are not favorable for substantial increases in ethanol use in transportation *relying on the current ethanol production system.* Short-term improvements in the current system-commercializing membrane separation for distillation, for example, assuming costs can be reduced--could enhance ethanol's costs and energy balance somewhat, but seem unlikely to provide the boost necessary for a major production increase. For the long-term-beyond the year 2000--ethanol may have better prospects given the potential for relatively inexpensive production from wood and wastes. The enzymatic hydrolysis processes needed are being actively pursued by the Solar Energy Research Institute and others, and important advances have been achieved, but the outcome of current research must be considered uncertain.

Chapter 6
Electric Vehicles

Electric vehicles, or EVs, are an exciting concept to policymakers because they combine excellent urban pollution benefits-the vehicles emit virtually no air pollutants, and the power generation facilities that "fuel" them, while contributing to problems associated with long-range pollution transport,[1] often play only a minor role in urban air quality—with an existing energy delivery infrastructure (except for charging stations) and a capacity to use a variety of domestic energy resources. Assuming that vehicles would be recharged at night, when electricity demand from most other uses[2] is low, existing electricity capacity could support a very large fleet. Studies done a decade ago found that a fleet of several tens of millions of vehicles could easily be supported by the existing capacity without the use of peaking units.[3] This conclusion almost certainly still holds. Also, EVs offer the potential to reduce greenhouse emissions, particularly if the generating capacity used to recharge the fleet is nuclear or renewable-powered. For the next few decades, with the slowdown in nuclear capacity additions, the current baseload use of existing nuclear plants,[4] the limitations on new sites for hydroelectric power facilities, and the lack of availability of cost-competitive solar electric technology, the greenhouse potential is limited. Moderate improvements will be possible, however, if efficient new powerplants fueled with natural gas can become important sources of EV recharging energy.

VEHICLE CHARACTERISTICS

Although EVs can operate successfully today in certain restricted uses, it is safe to say that large fleets of such vehicles will remain only a tantalizing possibility unless there are either substantial improvements in battery technology, major changes in consumer preferences, or a willingness on the part of the Federal Government to intervene firmly in the transportation market. With available battery technology, EVs will have limited range, performance, and cargo- and passenger-carrying capacity, high first costs (batteries included), and high operating costs, because of low energy and power densities and limited battery lifetimes (which create the need for expensive battery replacements). Also, performance and range will be degraded during cold weather, because of the loss of battery performance as well as the need to heat the passenger compartment. Similarly, air-conditioning requirements during hot weather will degrade performance and range.

Even with today's limited-capability batteries, however, adequately performing vehicles can be designed for certain urban niche markets. For these markets, various performance characteristics can be traded off+. g., higher accelerations and top speeds can be obtained at the expense of range and/or carrying capacity, or vice versa.

Unlike combustion engines, electric motors will not continue running when the vehicle is stopped, conserving energy in stop-and-go urban traffic.[5] Consequently, electric propulsion can be effective for urban delivery vehicles that travel less than 100 miles per day under heavy traffic. Several hundred English-made Bedford electric vans, called the Griffon in this country and marketed by General Motors, have been used by U.S. utilities during the past few years.[6] These vehicles have a top speed of slightly over 50 mph and a range of 55 to 65 miles

[1] In particular, acid rain and degradation of visibility.

[2] Space heating is the primary exception.

[3] General Research Corp., *Prospects for Electric Cars*, for U.S. Department of Energy, Washington, DC, 1978, reported in U.S. Department of Energy, ***Assessment of Costs and Benefits of Flexible and Alternative Fuel Use in the U.S. Transportation Sector. Progress Report One: Context and Analytical Framework***, January 1988, DOE/PE-0080. Although inclusion of peaking power would theoretically increase the number of vehicles that could be supported, this is impractical from the standpoint of both cost—peaking power is very expensive-and maintenance-most peaking units are designed for limited operation only.

[4] Utilities use their lowest-operating-cost plants—which often are their nuclear plants—at as high a load factor as they can, so that these plants are likely to be in use even during periods of low load; utilities cycle down their higher-operating-cost plants during these periods (subject to physical limitations on cycling). With rising electricity demand and stagnant nuclear supply, little excess nuclear capacity will be available to charge EVs.

[5] Actually, strictly speaking, combustion engines can be turned off when the vehicle is stopped and restarted when necessary. Although vehicles have been designed with this feature, manufacturers have not placed them on the market because of their doubts about consumer acceptance.

[6] Electric Power Research Institute, "Fleet Vans Lead the Way for Electric Vehicles, " *EPRI Journal*, vol. 11, No. 5, July/August 1986.

carrying a 1,900 pound payload. Battery life for the $4,750 (in 1986) lead/acid battery is 4 years, so battery replacement is a significant part of total operating costs.[7]

Unless U.S. consumers can be convinced (or coerced) to purchase limited-use/limited-performance vehicles, EVs will not make a substantial impact on total travel until they can, *at a minimum*, extend their range considerably (the ability to travel further than 100 miles on a charge is sometimes cited as a minimum) and perform adequately in a range of traffic conditions, including highway traffic. And although these performance requirements are probably a necessary condition for high market penetration, EVs would still face substantial barriers, discussed later.

ADVANCED TECHNOLOGY

Developments during the 1980s in batteries and powertrains indicate that the design conditions necessary for successful EVs maybe moving within reach with further engineering development. Advances in microelectronics have made it possible to build lightweight dc-to-ac inverters, which allow the use of ac motors rather than the heavier, more expensive dc motors typical of previous EVs.[8] This technology has important benefits for both vehicle weight and cost, to the extent that an EV using this technology is likely to be similar in cost, *excluding* battery cost, to a comparable internal-combustion-engine-powered car. And advanced batteries, some apparently moving closer to commercialization, offer the potential for substantial improvements in performance and durability over lead/acid batteries. Advanced battery types include nickel/iron, nickel/cadmium, zinc/bromine, lithium/iron sulfide, sodium/sulfur, and metal-air.

Because none of the advanced batteries is actually commercially available, and all (with the possible exception of the nickel-iron battery) need considerable engineering development, there are strong uncertainties about their eventual durability and cost, and analysts disagree about their relative promise. For example, some analysts view the nickel-iron battery as an especially promising candidate for the next generation of EVs and close to commercialization, because it has convincingly demonstrated long cycle life and ruggedness and somewhat higher energy density than lead/acid technology.[10] However, these batteries produce substantial quantities of hydrogen during recharge, have high water consumption, and are relatively inefficient.[11] They may also be quite expensive, although cost estimates for all of the noncommercial battery types are speculative. Finally, the supply of nickel could become a constraint if similar batteries were adopted worldwide. Leading European battery developers apparently have given up on development of nickel-iron batteries.[12] However, Chrysler's concept TEVan, an electric minivan based on the Caravan/Voyager vans and apparently under discussion for production in the early -1990s timeframe, uses a nickel-iron battery developed by Eagle Picher Industries.[13]

Although requiring more development work than the nickel/iron battery, the high-temperature sodium/sulfur battery is viewed as extremely promising if cost and durability uncertainties can be resolved favorably. This battery offers much higher energy and power densities than its lead/acid and nickel/iron counterparts, no water requirement, no gas production when charging, very high charging efficiencies, and cheap, abundant reactant materials.[14] Important potential problems with the sodium/sulfur battery include durability, associated with corrosion problems from sodium compounds

[7]Ibid.

[8]M.A. Deluchi, Q. Wang, and D. Sperling, "Electric Vehicles: Performance, Life-cycle Costs, Emissions, and Recharging Requirements," *Transportation Research,* vol. 23A, pp. 255-278.1989.

[9]W. Hamilton, *Electric and Hybrid Vehicles,* paper prepared for the Department of Energy Flexible and Alternative Fuels Study, May *26,1988,* draft.

[10]DeLuchi et al., op. cit., footnote 8, table 3. Characteristics of EV storage batteries. The nickel-iron battery designed for Chrysler's TEVan, which Chrysler hopes to introduce by the 1990s, has a specific energy 65 percent greater than the lead-acid batteries in GMs G-Van L.G. O'Connell, Electric Power Research Institute, personal communication.

[11]DeLuchi et al., op. cit., footnote 8.

[12]E. Eugene Ecklund, Alternative Transportation Fuels Foundation, personal communication.

[13]Electric Power Research Institute, "The Chrysler Electric TEVan. High Performance for the Growing Minivan Market," brochure EU.2022.6.89. The brochure claims a payload of 1,200 pounds, range of 120 miles, top speed of 65 mph, and O to 60 acceleration of 14.0 seconds. This level of performance greatly exceeds existing commercial vehicles and would seem likely to make the vehicle quite attractive if lifecycle costs are competitive.

[14]Ibid.

formed at the battery electrodes, and requirements for heavy insulation to maintain high temperatures inside the battery.

For the longer term-beyond the year 2000-the metal-air batteries are intriguing because they combine high power density with mechanical rechargeability, that is, they can be recharged rapidly by replacing the metal anodes, adding water, and removing byproducts. These batteries are also farthest from commercial readiness, and their eventual practicality is far from assured; important problems remain concerning their cost, durability, the need for practical CO_2 scrubbers, and their complexity.

A common concern with the advanced batteries, and for that matter with commercial lead-acid batteries as well, is the environmental implication of the large disposal and recycling requirement associated with battery production and for any major market penetration of EVs.

MARKET COMPETITIVENESS

Despite the renewed optimism about EVs in some circles, their eventual acceptance as a significant portion of the vehicle market is highly uncertain. First, total EV costs may be quite high, though available cost estimates cover a wide range. As noted above, the advanced batteries necessary for EVs to make major inroads in the urban market are too far away from mass production to allow reliable cost estimates to be made. However, even conventional lead-acid batteries will add a few thousand dollars to initial vehicle cost, and all of the advanced batteries will be even more expensive. Consequently, it is virtually certain that EVs will be more expensive than competing gasoline-fueled vehicles. Taking into account the cost and performance uncertainties associated with the batteries as well as other uncertain variables such as electricity price, cost evaluations can yield lifecycle costs that range from extremely attractive to extremely unattractive. For example, in a recent analysis, the "breakeven price" of gasoline--the price for which an EV's lifecycle cost was the same as that of a similar gasoline-powered vehicle—ranged from $0.04/gallon assuming low nighttime charging rates ($0.05/kWh) and very optimistic EV performance and cost,[15] to $3.90/gallon for a higher electricity cost ($0.09/kWh) and pessimistic EV performance and cost.[16] In this analysis, the startlingly low ' 'optimistic breakeven price" results in part from assumed maintenance costs that are much lower than for the gasoline vehicle, vehicle lifetimes twice as long (which reduces the annual vehicle depreciation costs, a substantial portion of vehicle ownership costs), and a very high powertrain efficiency. Although the minimum breakeven gasoline price seems absurdly low, it can be put into better perspective by remembering that fuel costs represent less than one-sixth of total vehicle lifecycle costs today,[17] and maybe even less of a factor in the future as fuel economy increases.

In another analysis, the Department of Energy has projected roughly equal lifecycle costs for competing EVs and gasoline vehicles for a 1995 EV using nickel-iron batteries. The analysis assumes that battery life will be 10 years and specific energy is 53.1 Watt-hours/kilogram, about a 50 percent increase over the best lead-acid technology available today.[18] The vehicle would have a 90 mile range and quite slow acceleration (O to 50 mph in 16.4 seconds), with an initial cost nearly $6,000 higher than for a competing gasoline vehicle. As with all such analyses, the lifecycle cost estimates are extremely sensitive to uncertain future costs of gasoline and electricity; the near breakeven lifecycle cost case assume 1995 gasoline costs of $1.34/gallon and nighttime electricity charging rates of $0.05/kWh (1987 dollars).[19]

Second, the EV is competing against conventional automobiles that essentially represent a moving target. Although high gasoline prices are not absolutely necessary for successful market entry of large numbers of EVs—the use of lightweight ac

[15] Vehicle cost excluding battery, $400 less than comparable gasoline vehicle; lifetime twice as long; half the maintenance and repair costs; battery cost of $4,000; high powertrain efficiency 6.1 times competing gasoline vehicle powertrain efficiency.

[16] DeLuchi et al., op. cit., footnote 8. The analysis assumes a sodium/sulfur battery system; the equivalent gasoline-powered automobile is assumed to achieve 30.5 mpg.

[17] S.C. Davis et al., *Transportation Energy Data Book: Edition 10*, Oak Ridge National Laboratory report ORNL-6565, September 1989, table 2.23.

[18] W. Hamilton, *Electric and Hybrid Vehicles* (draft), report to DOE, Santa Barbara, CA, July 1989, cited in U.S. DOE, ***Assessment Of Costs and Benefits of Flexible and Alternative Fuel Use in the U.S. Transportation Sector. Technical Report Five: Vehicle and Fuel Distribution Requirements,*** draft, January 1990.

[19] Ibid.

drivetrains coupled with a high level of success in battery performance and cost could allow lifecycle cost competitiveness at moderate gasoline prices—the most likely scenario for a major attempt at an EV market breakthrough is one with high fuel prices. These prices may also stimulate the entry of ultra-efficient gasoline vehicles for the market niche to be occupied by EVs. Several vehicle prototypes have achieved fuel economies of nearly 100 mpg or higher in practical configurations of relatively moderate power; in fact, these perform much like a practical EV is likely to. These vehicles should provide stronger competition than the baseline vehicles typically assumed in cost analyses.[20]

The newly announced General Motors Impact is an example of a promising EV prototype with design features that, if incorporated in a gasoline-fueled configuration, would produce a vehicle capable of achieving ultra-high fuel efficiency. The Impact is discussed in box 6-A.

Third, the difficulty of rapidly recharging EVs represents an important, though uncertain, market barrier. Even though EVs would be likely to be important niche vehicles--eg., second or third cars used primarily for commuting, delivery, or shopping—many potential owners may wish the flexibility of being able to use the vehicles for more extensive trips. An inability to accommodate such trips might prove an insurmountable barrier to many potential EV buyers.

Except with metal-air batteries, which are unlikely to be available within the next few decades, rapid recharging must involve either an actual exchange of batteries or a high-current recharge. Each has problems. Battery exchanges require a high degree of battery uniformity and a leasing system, since, with privately owned batteries, EV owners would not be willing to exchange a relatively new battery for an older one. High-current recharges require expensive charging equipment and a special battery capability that is far from assured technically; even then, it is unlikely that charging could be accomplished in less than 20 minutes.[21] If charging stations would have to be highly utilized to be profitable, EV operators could have to wait through one or more charging cycles to gain access to a charger. This may create an important barrier to wide market acceptance of EVs.

HYBRID VEHICLES

An alternative to rapid recharging is to add a small internal combustion (IC) engine (and fuel tank) sufficiently powerful to maintain reasonable highway speeds.[22] This type of dual system could substantially extend an electric vehicle's useful range. Such hybrid vehicles are being actively pursued by the same Department of Energy program supporting EV research and development.[23] DOE-sponsored analyses project that such vehicles may be able to attain lifecycle costs similar to EVs.[24]

An offshoot of the above hybrid vehicle concept is to combine a small IC engine working at constant speed as an electric generator (the engine would not be needed for short trips) with a battery designed to achieve high power density (most EV engines aim primarily at high *energy* densities, to maximize range, although power density is important as well). It is hoped that such a combination could allow a hybrid EV to combine adequate range with enough power to compete evenly with gasoline-powered vehicles in performance--an attractive prospect. To achieve this goal, batteries with power densities of 600 to 1,000 watts/kilogram are necessary. Although battery developers have high hopes for being able to achieve such levels in a commercial battery—the sealed bipolar lead-acid battery is one contender—success is uncertain and, at best, demands substantial further development.[25]

The primary criticism of hybrid vehicles using IC engines is the pollution impact of the vehicle's fuel use. Advocates of the constant-speed IC generator concept argue that it would attain the oil displacement and air quality benefits generally sought by EV advocates by:

‘Typically, comparative analyses have electric vehicles competing against gasoline vehicles obtaining 35 mpg or so. See DeLuchi et al., op. cit., footnote 8.

21 Ibid.

22 For a streamlined vehicle with an efficient drivetrain, maintenance of 60 mph speeds requires little power.

23 U.S. Department of Energy, Offi ce of Transportation Systems, *Electric and Hybrid Vehicles Program: 12th Annual Report to Congress for the Fiscal Year* **1988**, February 1989.

24 Hamilton, op. cit., footnote 9.

25 Personal communication, Kenneth Barber, U.S. Department of Energy.

Box 6-A-GM's Impact: A Niche Vehicle

As discussed previously, carefully designing a vehicle to fill an appropriate niche may allow EVs to compete with gasoline-powered vehicles under special circumstances. The recently announced General Motors Impact, a sporty two-seater, is an early example of a vehicle carefully designed from the ground up to compete in a limited market. The vehicle attains an unusual combination (for an EV) of good performance (0 to 60 mph in 8 seconds) and excellent EV range (124 miles on the Federal Urban Driving Cycle) by limiting carrying capacity (350 pounds in a 2,200 pound curb weight vehicle) and introducing a number of design elements to achieve unusual vehicle efficiency. Notable efficiency features include:

- drag coefficient of 0.19, compared to about 0.3 for conventional low-drag vehicles;
- 65 psi tires that achieve about half the rolling resistance of typical tires;
- regenerative braking
- heat pump-based space conditioning
- extremely lightweight dc/ac inverter coupled with high-efficiency induction motors (90 to 95 percent efficient) and gearbox (94 to 98 percent efficient)[1]

Additional features that add to the vehicle's market attractiveness are a 2-hour recharge time and an on-board battery charger, eliminating the need for special charging equipment.[2]

Although the Impact is, at first look, a most attractive vehicle, it has uncertain long-term economic viability and remaining technical uncertainties. General Motors claims that its operating cost--electricity plus battery replacement cost—is about twice that of a gasoline-powered car in the Ins Angeles area, with future increases in battery life reducing the operating margin.[3] However, the current expected battery life of 25,000 miles is only an estimate that awaits confirmation with further testing. Further, manufacturing costs for the vehicle may be significantly higher than for a comparable gasoline-powered vehicle (with much greater range)--preliminary rough estimates are in the range of $15,000 to $20,000.[4] Other significant uncertainties remain, including tire life and ride acceptability, vehicle component longevity, cold weather operating characteristics,[5] and so forth.

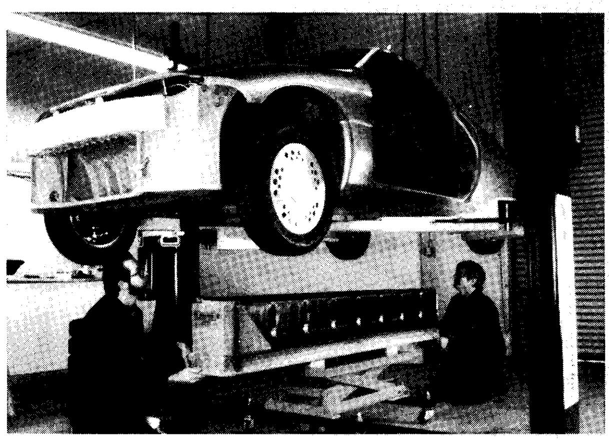


Photo crelit: General Motors Corp.

The Impact's battery pack, shown being installed, takes up the center portion of the vehicle.

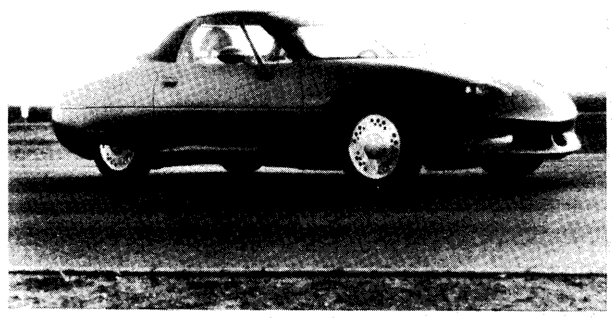


Photo credit: General Motors Corp.

General Motors' prototype electric vehicle (EV), the Impact, combines high performance (O to 60 mph in 8 seconds) with high EV range (over 100 miles).

1General Motors Corp., "Impact Technical Highlights," General Motors Technical Center, Warren, MI, Jan. 3, 1990.

2Ibid.

3General Motors Technical Center press release on the Impact vehicle, Jan. 3, 1990. According to David Sloan at the Technical Center, the gasoline vehicle was similar to a Pontiac Fiero, a vehicle with similar accommodations and utility to the Impact vehicle. However, the Fiero incorporates none of the efficiency improvements used in the Impact. In our view, it would be preferable to compare Impact to a similar size/carrying capacity vehicle incorporating similar efficiency measures, especially with respect to drag and tire resistance. This comparison would yield a less attractive *relative operating* cost estimate for the electric vehicle.

4David Sloan, General Motors Technical Center, Warren, MI, personal communication% Feb. 23, 1990.

5Cold weather presents a dual problem to the vehicle—loss of battery capability, and, at extremes, inability of the heat pump system to maintain acceptable passenger comfort.

- operating battery-only on short trips
- displacing longer trips that could otherwise be made only by petroleum-fueled vehicles, with less oil usage and pollution because part of the trip energy would be supplied by battery storage, and the constant speed engine can be both more efficient and less polluting than the larger variable-power engine it would displace.

The counterpoint to this argument is that the very attractiveness of the hybrid, concept might discourage development of, and compete in the marketplace with, advanced battery-only vehicles with longer range than today's best vehicles and emissions benefits superior to those of the hybrid. Also, a battery-only vehicle will have a longer range "battery only" capacity-and thus can replace a higher percentage of trips in a "zero vehicle emission" mode—than the hybrid because it does not carry the added weight and volume of the IC engine and fuel tank, and can substitute additional battery capacity in their place.

A third, possibly longer term alternative is to forego battery storage entirely and generate electricity from a fuel cell fueled with hydrogen or methanol. The advantage of such a system is that it combines key benefits of EVs--essentially zero vehicle emissions (including no emissions of CO_2 if hydrogen is the fuel) and high efficiency powertrain—with fast refueling capability and longer range than offered by currently available batteries of the same weight and volume as the hydrogen or methanol storage tanks plus fuel cell. It eliminates problems with NO_x and hydrocarbon emissions (the latter from engine oil burning) from hydrogen vehicles using IC engines (see next chapter on hydrogen), and of course eliminates the stronger concerns associated with methanol IC emissions. DeLuchi estimates that a high-efficiency vehicle based on hydrogen (equivalent in design and performance to a 40-mpg gasoline vehicle) with a 200 mile range would have a hydrogen storage system displacing about 40 gallons-about 8 times the volume of a gasoline tank yielding the same range—if the hydrogen was stored as a 4,500 psi compressed gas.[26] The hydrogen could also be stored as a cryogenic liquid or as a hydride, though the former would be challenging for general use because liquid hydrogen is extremely cold, and the latter would add considerable weight unless major improvements in storage capacity were made to hydride systems. A methanol-fueled vehicle should have range capability similar to that of a gasoline vehicle with similar storage volume, because of the efficiency advantages of the fuel cell/electric motor system.

Methanol would be cheaper than hydrogen and would add substantial range, though it would require the addition of a reformer to dissociate the methanol. If the issue at stake were only to reduce oil use at moderate cost, methanol would appear the superior choice. However, hydrogen offers the potential of essentially eliminating $C0_2$ emissions from the fuel cycle, so that policymakers might choose to trade off the added fuel cost for the reduction in CO_2. The fuel cell itself would emit no CO_2 if fueled with hydrogen. Also, despite hydrogen's current manufacture from fossil fuels, with consequent emissions of $C0_2$, some analysts believe that the cost of photovoltaically generated dc electricity-producing zero CO_2—will drop dramatically within a decade or two and become a cost-competitive energy source for generating hydrogen.

Aside from the options of focusing on either methanol or hydrogen, an alternative strategy would focus on both. Although considerable development work will be necessary to construct a fuel cell capable of meeting the requirements of general fleet use, which include long life, low cost, and compactness, the fuel cell work should not take nearly as long as the hydrogen work. Conceivably, if development of a commercial vehicular fuel cell came first, methanol could serve as a bridge fuel until a PV-based hydrogen fuel supply could be developed.

INFRASTRUCTURE

Although additional generating capacity may eventually be required to support a large EV system, tens of millions of EVs can be recharged daily with no additional capacity if the recharging is accomplished at night, following the evening demand peak. Consequently, the fuel delivery infrastructure required for an EV fleet consists of the charging stations. Although rapid charge stations are technically possible, they are unlikely to be widely used (see discussion above). Most recharging will likely be accomplished at millions of home stations offering overnight recharging. DOE estimates the cost for a station to be $400 to $600, assuming a

[26] M. DeLuchi, letter to Allan Lloyd, South Coast Air Quality Management District, California, Dec. 14, 1989.

240-volt, 30-amp outlet, ground-fault circuit interruptor to guard against electrical shock, and a time-of-use meter or other device to obtain reduced nighttime charging rates.[27] With 45 million EVs needed to displace 1 mmbd of gasoline, the infrastructure costs—attributed solely to charging facilities-are $21.8 billion for this level of oil displacement.[28]

EFFECTS ON EMISSIONS AND AIR QUALITY

Although EVs must surmount substantial market difficulties, and may be unlikely to save much oil (if the competing vehicles are highly fuel efficient), they *will* have an important positive impact on urban air pollution if they become a significant factor in urban travel. The vehicles have virtually no emissions[29] and the emissions from the generating facilities that would power an EV fleet are spread out over a wide area and, in most cases, have only moderate effect on any specific area such as a city. Also, although not universally true, many urban areas obtain their power from relatively distant generating facilities, and an increase in their net emissions will have little impact on the urban area's air quality.[30]

Trading local, low-level, small-source pollution for centralized pollution sources with tall stacks is not, of course, uniformly positive. As discussed below, the types of pollutants change, but the change of pollution distribution can have some negative effects as well-especially the increased contribution to long-range transport of pollution to other regions. Given the diversity of air-quality-related parameters--powerplant location in relation to population centers, powerplant fuel and control effectiveness, urban meteorologic conditions and pollution mix, regional long-range transport characteristics, and so forth-gauging the air quality benefits and costs of major shifts to electric vehicles requires location-specific examinations.

The net effect on total emissions of a shift to EVs will be mixed. Power for nighttime recharging of EVs will come from baseload and intermediate plants not needed to meet ordinary (low) nighttime demand; depending on region, these will be primarily coal-fired steam electric generators (coal fueled 57 percent of all generation in 1987, and higher percentages of baseload power[31]), natural gas-fired steam electric plants, and hydroelectric plants; some additional power will come from natural gas-fried combined cycle plants (though most of these plants are likely to be used as intermediate rather than baseload plants). Although nuclear steam electric generators provided 18 percent of baseload power in 1987,[32] they are rarely cycled down when load declines and thus may not be available to supply excess power to charge EVs.[33] Similarly, hydroelectric capacity may not be available in most cases because these plants generally are the last to cycle down.

Because utility electric generators emit few emissions of hydrocarbons and carbon monoxide, the net effect of EVs on emissions of these pollutants will be highly positive--emissions per mile of these pollutants would be reduced over 90 percent.[34] Older coal and gas-fired baseload plants produce considerable emissions of NO_x, and the net effect on NO_x emissions of a large EV fleet will be negative, especially for coal plants. More recent plants with moderate controls will have a positive net effect, so that overall, with a mix of older and newer plants, the net effect on NO_x emissions is likely to be small and, in areas with considerable nuclear and hydro capacity or with stringent NO_x controls, would be highly positive.[35] Finally, because even stringently controlled coal plants emit more SO_x than automobiles on a comparative ''per mile' basis, market penetra-

[27] DOE Technical Report Five, op. cit., footnote 18.

[28] Ibid.

[29] There *are* minor emissions from paint, adhesives, and so for@ and possibly release of some gases from the batteries, depending on their type. Also, EVs used in cold climates may have fossil-fueled heaters.

[30] However, the net increase in powerplant emissions *will* affect air quality over a wide area and will also affect acid rain and visibility.

[31] Energy Information Administration *Annual Energy Review 1987, DOE/EIA-0384(87), May,* 1988, table *83.*

[32] Ibid.

[33] At the present time, *some* excess nuclear power *is* available *t. some* utilities *at* low *cost* for off@& use. The *long-term* availability of such power is problematic.

[34] Q. Wang, M.A. DeLuchi, and D. Sperling, ''Emission Impacts of Electric Vehicles,' Transportation Research Board Paper 890682, 1989.

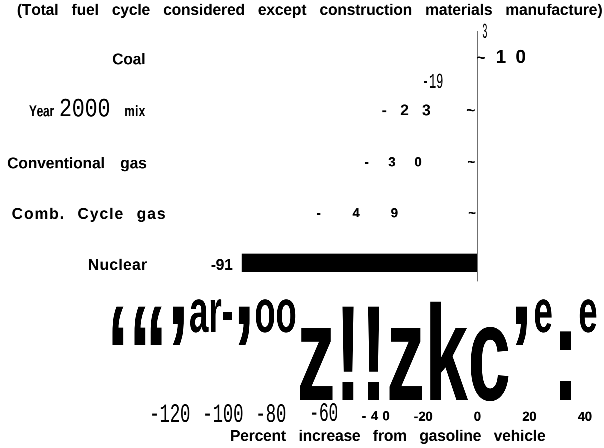
[35] Ibid.

tion of EVs will increase sulfur emissions. The actual effect will depend heavily on the timeframe (if long enough, some of the older, dirtier powerplants will retire), future controls placed on existing powerplants, and future plant retirement programs (plant life extension currently is an important part of most utilities' capacity planning programs).

The greenhouse impact of a significant shift to EVs will be extremely sensitive to the mix of power generation facilities used to power the vehicles, the efficiency of the EVs themselves, and the efficiency of the vehicles they replace. As discussed above, for the immediate future, EV power generation is likely to come from fossil fueled power plants (particularly coal-freed plants), except in the few areas where excess nuclear or hydro capacity is available. As shown in figure 6-1, if coal is the dominant fuel source for EV recharging, a switch to EVs will cause greenhouse gas emissions to increase slightly even with a high-efficiency vehicle. One source estimates that the EV/coal fuel cycle generates about 3 to 10 percent higher greenhouse emissions than a similar gasoline vehicle fuel cycle, with an EV system using the projected year 2000 mix of power generation yielding about 25 percent less greenhouse emissions than the gasoline cycle.[36] In the longer term, nonfossil capacity availability for EV recharging is likely to decrease, because no new nuclear plants have been ordered for years and no large hydroelectric facilities are in progress or planned. On the other hand, natural gas in efficient plant configurations (e.g., combined cycle plants) may dominate new plant capacity for the next few decades, and these plants offer both increased efficiency and reduced carbon emissions per unit of fuel burned. If these plants figure heavily in EV recharging, the net greenhouse effect will improve; an EV system based on these plants is estimated to yield about a 50 percent reduction in greenhouse emissions compared to gasoline vehicles.[37] The potential for powering large numbers of EVs with nonfossil electricity must wait for a revival of nuclear power or the development and construction of economically competitive solar or biomass power generators.[38]

Figure 6-l—Effect of Electricity Source on Greenhouse Impact of Electric Vehicles

(Total fuel cycle considered except construction materials manufacture)



Vehicle: EV powered by sodium sulfur batteries, ac powertrain, 150-mile range, 650-pound weight penalty v. competing gasoline car.

SOURCE: D. Sperling and M.A. DeLuchi, *Transportation Fue/s and Air Po//ution,,* **prepared for Environment Directorate, OECD, March 1990, draft.**

For the light-duty fleet, EVs seem most likely to replace vehicles with limited performance and carrying capacity, since the EVs themselves are likely to have these characteristics. Examples of ultra-high-mileage automobiles often share these characteristics. It is possible, therefore, that the fossil fuel savings and greenhouse benefits of a shift to EVs will be smaller than many analyses show, because EVs could replace gasoline or diesel vehicles with very high fuel economy rather than replacing ''average" vehicles.

ELECTRICITY OUTLOOK AND TIMING

Electric vehicles are extremely attractive in concept, because they produce no vehicular pollution, would be fueled from domestic sources, and can rely on existing power generation capacity so long as charging is done at night. Recent important improvements in EV powertrains--lightweight dc-to-ac converters coupled with small, efficient ac motors—have moved EVs considerably closer to practicality for mass application. Unfortunately, inadequate

36D. Sperling and M.A. DeLuchi, University of California at Davis, *Alternative Transportation Fuels and Air Pollution*, report to the Environment Directorate, Organization for Economic Cooperation and Development March 1990, draft. The postulated EV uses a sodium/sulfur battery.

37Ibid.

38At the present time, the solar thermal generators built by Luz in California and the wood waste-powered generators and Cogenerators Operated by the paper and wood processing industry are the primary examples of such facilities.

Photo credit: Ford Motor Co.

One potential niche market for electric vehicles is urban delivery by vans. The ETX-II Aerostar research vehicle, built by Ford and General Electric, achieves a 65 mph top speed and 100-mile range with a sodium sulfur battery.

battery technology remains a major hurdle for EVs. Without successful development of advanced batteries with high power and energy densities, EVs will have limited range and power, restrained to niche applications. Also, the environmental effects of power generation for EVs deserve careful attention.

Proponents of EV technology claim that commercialization of advanced batteries awaits only engineering development, which, they assert, could be accomplished within a reasonably well-defined time frame given adequate resources. However, more basic R&D may be needed, with considerable uncertainty about both time required and likelihood of eventual success. Certainly, the time frame suggested for alternative fuels programs in current legislative initiatives-manufacture of large numbers of vehicles starting in the mid-1990s--is too short for EVs to compete for a significant share of the programs. In the longer term, though, EVs conceivably could play an important role in urban passenger travel if there are important successes in battery development.

Chapter 7
Hydrogen as a Vehicle Fuel[1]

Using hydrogen as a vehicle fuel offers another option for reducing oil use while addressing problems of urban air pollution and, possibly, global warming as well. A hydrogen-fueled vehicle should emit virtually no hydrocarbons, particulate, carbon dioxide, or carbon monoxide;[2] the only significant air pollutant emitted would be NO_x. And because hydrogen can be produced through electrolysis of water using nonfossil electricity-nuclear, biomass, hydroelectric, or solar-a fleet powered by hydrogen conceivably could generate no net carbon dioxide and only minor quantities of other greenhouse gases.

FUEL SOURCE

Hydrogen is available from a number of sources. It can be produced from any hydrocarbons by several processes. For example, combining natural gas and steam (steam reforming) will produce hydrogen and carbon monoxide, or natural gas can be heated in the presence of a catalyst to be "cracked" into carbon and hydrogen. Coal (or biomass) can be gasified by combining it with steam under high pressure and temperature, forming carbon dioxide and hydrogen.[3] Or hydrogen can be obtained from water by applying high temperatures, with or without other chemicals, to decompose the water (thermal and thermochemical decomposition); by adding an electrolyte and applying a current to the water (conventional electrolysis); by electrolyzing steam rather than water (high-temperature steam electrolysis); or by using light with a chlorophyl-type chemical to split out the hydrogen (photolysis). At the moment, steam reforming of natural gas is the least expensive production method. The near-term production system with the largest resource base-coal gasification—will create substantial negative impacts from mining, from CO_2 emissions, and, with some gasifiers, from waste disposal problems associated with carcinogenic tars and other residues from the gasification process. The latter problem can be reduced or avoided by using higher temperature gasifiers.

VEHICLES AND FUEL STORAGE

Although hydrogen can be carried onboard a vehicle in a number of different ways, the two methods that have received the most research attention are as a liquid in cryogenic (ultra cold) storage or as a gas bound with certain metals in a hydride, and released gradually by heating the hydride.

Both systems still have substantial limitations compared to gasoline vehicles. Refueling should be similar to refueling natural gas-powered vehicles: refueling time with a hydride system should be longer than required for gasoline vehicles and may represent a market barrier; liquid hydrogen refueling may be less of a problem. Existing hydride storage systems must be very heavy and large, because they can store only a few percent hydrogen by weight[4]; hydrogen vehicles using such a storage system will have limited range between refueling and reduced storage space, performance, and efficiency compared to cryogenic systems. Ongoing research is aimed at developing a hydride storage system that can store a higher percentage of hydrogen by weight than the 3.5 percent or so that is the current practical maximum for such systems. A developer has recently made claims of a storage rate of about 7 percent using nickel-hydride in an amorphous form.[5] This high a storage rate would make a hydride-based system much more competitive. OTA is not aware of independent confirmation of the claim, however.

Cryogenic systems will not be much heavier than gasoline storage systems, so performance will not suffer. However, cryogenic storage also has impor-

[1]This section is based primarily on M.A. DeLuchi, "Hydrogen Vehicles: An Evaluation of Fuel Storage, Performance, Safety, Environmental Impacts, and Cost," *Int. J. Hydrogen Energy*, vol. 14, No. 2, Pergamon Press, 1989. Information from other references is cited in the footnotes following this one.

[2]The only source for these emissions will be the combustion of small quantities of engine oil, particularly in older vehicles.

[3]Biomass may hold an advantage here because some biomass gasifiers do not require oxygen.

[4]For most materials, the weight of hydrogen stored is only 0.5 to 2.0 percent of the total weight of the storage tank, although a magnesium system, modified to account for the high temperature needed to maintain fuel flow from a pure magnesium system, will store as much as 3.6 percent by weight.

[5]"Ovonic licenses Hydride Battery to Varta," *The Hydrogen Letter,* March 1989, vol. IV, No. 3.

tant problems. Its bulkiness will reduce vehicle space; even accounting for improved vehicular efficiency with hydrogen, such a storage system must be five or six times bulkier than a gasoline tank sized for the same range. Further, the fuel tanks' generally spherical shape is difficult to integrate into a vehicle design. Also, cryogenically stored hydrogen will begin to boil off if the vehicle is not used for a few days, as heat seeps through the insulation. This is a problem from both a safety and economic (fuel loss) standpoint, though the former is probably more important; if the vehicle is stored in an enclosed area, the leaked hydrogen could form an explosive hazard. Solutions to this problem could be either to burn off the gas or vent it.

EMISSIONS AND PERFORMANCE ATTRIBUTES

In addition to the differences in storage system volume and weight, hydrogen-fueled vehicles will differ from gasoline vehicles because of hydrogen's unique properties as a fuel. As with all other fuels, engine efficiency, performance, and emissions from a hydrogen-fueled engine are interdependent, and maximizing one attribute may increase or decrease the others. Nevertheless, the thermal efficiency of a hydrogen engine should beat least 15 percent higher than its gasoline counterpart, based on available tests.[6] Power may be higher or lower, with a major factor being the form in which the hydrogen is injected into the cylinders.[7] And as with other fuels, operating very lean will increase efficiency and reduce uncontrolled NO_x[8] at the expense of power and driveability. In general, it should be possible to keep NO_x emissions at levels at or below those of a catalyst-equipped gasoline vehicle, using only exhaust gas recirculation without exhaust treatment, while maintaining adequate power and high efficiency. And, aside from minor emissions associated with burning small quantities of engine oil, the hydrogen vehicles should emit no other air pollutants. Consequently, with appropriate selection of the remainder of the system, a hydrogen-based fleet could have a significant positive effect on urban air pollution.

SAFETY

In addition to the potential safety problem associated with boiling off of cryogenically stored hydrogen, such a hydrogen system has a few other safety concerns. In particular, hydrogen is easily ignited and, once ignited, will burn rapidly yet invisibly and odorlessly—which could cause a detection problem. Also, in an enclosed space, it is more likely to explode than an equal concentration of methane or gasoline vapors if contacted by a flame.[9]

Despite these potential problems, hydrogen is not considered a particularly dangerous fuel. Any problems associated with its lack of odor or visible flame should be solvable with additives. In some situations, its properties should *add* to safety, for example, it will disperse or evaporate extremely quickly in the event of a leak, in comparison to gasoline, which evaporates more slowly and is likely to remain a hazard until physically removed. Also, it is nontoxic and noncarcinogenic. And in hydride form, major leaks will not occur, and thus a hydride fuel system should be quite safe.

DEVELOPMENT REQUIREMENTS

The components necessary to create a hydrogen-fueled fleet-hydrogen storage and delivery systems, large-scale hydrogen production systems, and hydrogen-fueled engines-are all at an early stage of research or development. Coal gasification systems may be the closest to becoming fully commercially; the Cool Water integrated coal gasification combined cycle plant based on the Texaco gasifier has performed extremely well from both an operational and an environmental viewpoint, and the next

[6]Tested efficiencies range up to 50 percent higher than gasoline, though some analysts are extremely skeptical of the applicability of the higher values to a practical commercial vehicle. Note that with a hydride system, *vehicle* efficiency will suffer because of the added weight of the fuel storage system.

[7]Because hydrogen in gaseous form has a low energy density, engine power using hydrogen in this form will be lower than its gasoline counterpart. To recapture some of this power loss, or possibly to attain an increase, the fuel can be injected either as liquid hydrogen (if cryogenic storage is used) or at very high pressures. Liquid hydrogen injection systems are technically demanding, and high pressure systems have not yet been tested.

[8]But preclude the use of a reduction catalyst for additional NO_X control, because these catalysts cannot operate in a lean (oxygen rich) environment.

[9]Hydrogen has extremely wide flammability limits, 4 to 74 percent. ***Handbook of Chemistry and Physics, Forty Fourth Edition*** (Cleveland, OH: Chemical Rubber Publishing Co., 1962), compared to, for example, methane with flamiability limits of 5 to 15 percent. What this means is that virtually any concentration of hydrogen in air, except one below 4 percent, can explode.

[10]The L@ gasifier is fully commercial—and some others are arguably commercial—as producers of synthesis gas, a combination of hydrogen and carbon monoxide.

generation technology is expected to achieve substantial improvements in cost and efficiency. The Japanese and West Germans have strong vehicle development efforts, but these have produced only a small number of prototype vehicles, and major uncertainties remain about the configuration and performance of an optimum hydrogen engine. Current hydride storage systems impose a substantial range and performance penalty because of their high weight and volume, and a breakthrough in storage technology may be needed to produce a marketable vehicle. Work needs to be done on pipeline transport, because pure hydrogen will damage certain steels, and inhibiting agents to be added to the hydrogen must be found--or a separate pipeline infrastructure must be built. And if the greenhouse gas problem associated with coal as a hydrogen source is to be avoided, substantial advances in large-scale electrolysis systems, hopefully based on solar energy, must be accomplished.

COST COMPETITIVENESS

With these uncertainties, the costs of a hydrogen-based system are speculative. One interesting cost analysis that attempts to trace full lifecycle costs for the entire hydrogen system calculates a range of gasoline ''break even' prices-the price of gasoline for which a hydrogen system would be fully competitive, assuming the gasoline and hydrogen vehicles were roughly equivalent in size.[11] This analysis estimates the break-even gasoline price for a system based on coal gasification to range from about $1.50 to $5.00/gallon in 1985 dollars. The gasoline price computed for a system based on solar photovoltaic-generated electricity and electrolysis ranges from about $3.50 to $12-$ 14/gallon, with even the higher value assuming electricity costs substantially below that obtainable with current solar technology.

Recent improvements in photovoltaic (PV) technology have convinced some analysts that hydrogen can be generated at costs considerably below those estimated above.[12] Hydrogen delivered to vehicles at gasoline-equivalent costs below $2.00/gallon may be possible if substantial improvements can be made in PV module cost and efficiency, e.g., module production cost for amorphous silicon solar cells reduced from the current $1.60/peak watt to $0.20 to $0.40/peak watt, and module efficiency improved from 5 percent to 12 to 18 percent.[13]

Given the high level of uncertainty, these cost figures should be viewed cautiously. Of the alternative fuels considered here, hydrogen appears to be the furthest from commercial availability. The amount of development work remaining for all phases of the fuel cycle essentially guarantees that a commercial system will look very different from current conceptual systems—with, presumably, quite different actual costs than estimated here. Further, the analysis compares vehicles that are not identical, so that the direct cost comparisons, even if they were accurate, could be misleading from a market attractiveness standpoint. For a vehicle with cryogenic storage, performance and range could be comparable to that of a gasoline vehicle of equal *overall size*, but the hydrogen vehicle would have substantially less storage space than the gasoline vehicle. For a vehicle based on hydride storage, performance and range would be substantially inferior to the gasoline vehicle unless a substantial breakthrough were made in hydrogen storage capacity and power was increased by using a larger engine or untested high pressure gas injection.

Because hydrogen vehicles emit no CO_2, they may be viewed as especially attractive component of a strategy to reduce global warming trends. Their value as such a component depends on fuel production, however. Although the lowest cost coal-based system would be competitive with gasoline at

[11] DeLuchi, op. cit., footnote 1.

[12] J.M. Ogden and R.H. Williams, ***The Prospects for the Production and Utilization of Hydrogen Produced Via Electrolysis Using Amorphous Silicon Solar Cells,*** draft report to the Office of Technology Assessment, December 1988; and same authors, ***Solar Hydrogen: Moving Beyond Fossil Fuels,*** World Resources Institute, October 1989.

[13] Ibid. The cost reduction is obtained by gaining economies of scale by increasing output from 10 to 100 MWp/yr; increasing module efficiency to 12 to 18 percent, increasing the plant depreciation period from 5 to 10 years, reducing materials costs from $27.6 to $13.2/square meter, and reducing balance-of-system costs from $50 to $33/square meter. The authors compute PV electricity, in DC form, generated by these modules at $0.020 to $0.035/kilowatt-hr, and PV hydrogen at a gasoline-equivalent cost of $1.11 to $1.70/gallon. The authors also use utility accounting and assume purchase of PV modules at cost, predicated on the development of large remote electricity generating and hydrogen production sites by a utility-type organization that purchases PV manufacturing facilities rather than individual assemblies. Further, the authors calculate costs of both hydrogen and alternative fuels based on zero income and property taxes, to rid the comparison of PV hydrogen and alternative transportation fuels of a tax system bias against capital-intensive projects. Inclusion of these taxes would raise the gasoline break-even prices somewhat.

$1.50/gallon, a price that is easily imaginable within a few years, the coal-based system—which would produce high levels of CO_2 emissions during hydrogen production—would be extremely damaging to efforts to reduce greenhouse gas emissions unless it was designed only as a precursor to a system based on renewable or nuclear energy, or unless the CO_2 generated in the fuel production could be sequestered rather than released to the atmosphere. PV-based or nuclear-based systems would produced essentially no greenhouse gases, but they are likely be more expensive than coal-based systems, at least compared to the lower end of the coal range, even with the sharp cost reductions discussed for PVs; biomass-based systems might become cost-competitive with coal-based systems, however, if biomass gasifiers were improved.

HYDROGEN OUTLOOK AND TIMING

In Summary, the use of hydrogen as a vehicle fuel has strong appeal from a pollution control standpoint, and could aid in efforts to slow global warming if the hydrogen was produced from non-fossil sources. However, much development work needs to be done before a hydrogen-based system could be practical, and the likely cheapest system—a fossil-based system—would have strong negative implications for global warming and may have other environmental shortcomings. On the other hand, if PV-based electricity generation fulfills the hopes of solar optimists, solar-based hydrogen could eventually be cost-competitive with coal-based hydrogen and with gasoline priced at $2.00/gallon and below.

Aside from costs, hydrogen's major roadblock may be its bulkiness-hydrogen's low energy density implies either very limited range between refueling or very large, heavy fuel tanks. Unless there is a major breakthrough in hydride storage or in vehicle efficiency (which would ease the range problem), hydrogen-fueled vehicles cannot provide a close substitute to gasoline-powered vehicles. Given the need for important scientific development in several areas, hydrogen must be considered a long-term prospect as an alternative transportation fuel.

Chapter 8
Reformulated Gasoline

An examination of the potential for methanol and other alternative transportation fuels to compete with petroleum-based fuels should not assume that the existing fuel supply network is a stationary target. Current investors in this network may be expected to compete vigorously for market share with the new fuels, rather than see their existing investment in gasoline supply lose value. And to the extent that Federal and State support for alternative fuels takes the form of requirements for low-emission vehicles or other requirements tied to improving urban air quality, gasoline refiners can be expected to reformulate their product (see box 8-A) to obtain similar emissions benefits and avoid a mandated switch to the new fuels.

Until recently, with the important exception of the lead phasedown, there has been relatively little incentive, and little effort, to improve gasoline's performance in terms of reducing vehicle emissions. Governments had exerted limited pressure to improve this performance: on the Federal level, the past pressure has on the whole been limited to requirements for lead reduction and elimination and, more recently, to controls on fuel volatility to control smog-causing evaporative emissions; at the State and local levels, pressure has been limited to a few areas requiring addition of oxygenates to reduce carbon monoxide emissions[1] and to California's requirement for a ceiling on gasoline volatility (more stringent than the Federal requirements) and sulfur content (and the South Coast Air Quality Management District's reduction in olefinicity). With this limited pressure, the oil industry generally has avoided changing the composition of gasoline to reduce emissions, because such changes are expensive and unlikely to have market value. Instead, the

Box-8-A—What Is Reformulated Gasoline?

Unlike methanol or hydrogen, which are composed wholly of single chemical compounds, or even natural gas, which is composed of several compounds but is predominantly methane, gasoline is a complex mixture of flammable liquid hydrocarbons made from petroleum and natural gas. Some of these hydrocarbons are present in the oil and gas and are obtained by separating them from the oil and gas using distillation and other separation technologies. Others are created by a variety of physical and chemical transformation processes, often in the presence of catalysts, in a modern refinery. For example, aromatics are obtained from catalytic reforming; olefins from catalytic cracking or catalytic polymerization; and isoparaffins from distillation (separation) or by isomerization of normal paraffins, or in the alkylation process.[1]

In order to be a practical fuel for a modern automobile, gasoline must satisfy a number of requirements pertaining to its volatility, octane level, tendency to form engine deposits, and other characteristics. Refiners can satisfy these requirements using a variety of different combinations of chemical components, with their selection dependent on relative costs of the different components, market prices for other products, refinery capability, and quality of the crude oil feedstocks available. The production of reformulated gasoline simply accentuates the importance of a particular fuel characteristic—the fuel's effect on emissions-in the selection of gasoline components, and possibly also in the degree of purification applied to the fuel. For example, the addition of oxygenates-ethanol, methanol, methyl tertiary butyl ether, and so forth-to the gasoline blend can reduce exhaust carbon monoxide emissions and may serve to reduce the reactivity of exhaust hydrocarbon emissions, yielding a net reduction in ambient ozone concentrations. Reducing the more volatile components of the fuel will reduce overall volatility and yield lower evaporative emissions. Removing sulfur impurities will reduce emissions of sulfur oxides and hydrogen sulfide. Because the gasoline components undergo radical chemical transformations inside the engine, and then the exhaust emissions undergo still more transformations inside the catalytic converter, the precise form that a reformulated gasoline must take can only be learned through extensive testing.

[1]British Petroleum Co., *Our Industry Petroleum*, 1977.

[1]Denver, Albuquerque, Los Angeles, Las Vegas, Phoenix, Reno, and Tucson require gasoline to contain oxygenates corresponding to 2 percent oxygen G.A. Mills, "High Performance Oxyfuels," American Chemical Society, preprint, April 1990.

industry has focused its production and marketing efforts on changes to achieve better vehicle performance and drivability and lower maintenance--attributes that are valued by gasoline purchasers and thus provide market advantage.

ARCO'S "EMISSION CONTROL 1" GASOLINE

In August of 1989, Atlantic Richfield Oil Co. (ARCO), fired the opening salvo in the new competition for the future light-duty fuel market by introducing a so-called "reformulated gasoline' to replace leaded regular gasoline at its southern California stations.[2] This gasoline, named EC-1 ("Emission Control 1"), contains one-third less olefins and aromatics and 50 percent less benzene,[3] no lead, and 80 percent less sulfur than regular gasoline.[4] It has low volatility-its vapor pressure (RVP) is 1 psi lower than the South Coast standard. It contains methyl tertiary butyl ether, or MTBE, an octane-raising additive derived from methanol that raises the oxygen content of the fuel and provides emission benefits, especially in reducing carbon monoxide emissions, without the volatility increase--and increase in evaporative emissions-normally associated with adding oxygenates.

ARCO has claimed significant emissions reductions when EC-1 is used in place of regular leaded gasoline in pre-1975 model-year cars[5]:

evaporative emissions	–21 percent
carbon monoxide	-9 percent
nitrogen oxides	–5 percent
hydrocarbons (exhaust)	-4 percent
sulfur dioxides	–80 percent

ARCO redirects the olefin and aromatic streams removed from EC-1 into its unleaded grades, however, so there maybe some increase in emissions, or in the reactivity of emissions, from vehicles using these grades. Because the catalytic controls of the vehicles using these fuel grades are designed to handle such emissions, it is likely that any increase will be relatively small-but they should be accounted for in an assessment of costs and benefits.

The emission benefits of EC-l-type gasolines can, in theory, be gained immediately by a substantial part of the fleet--ARCO claims that pre-1975 vehicles made up about 15 percent of the vehicles in California's South Coast air basin in 1989, and emitted more than 30 percent of total vehicle emissions.[6]

If environment-conscious drivers give ARCO additional market share, or if California's legislators turn ARCO's voluntary emission reduction into a requirement, other refiners will follow ARCO's lead, probably within a short time. Reformulated versions of *unleaded* gas for catalyst-equipped vehicles are expected to appear as well, although not until the early 1990s.

REFORMULATION POTENTIAL

Gasoline is made from crude oil by mixing natural constituents of the crude with constituents formed from the crude during the refining process, as well as other nonpetroleum-based constituents such as alcohols or ethers made from alcohols. The four major groups of petroleum-based constituents of gasoline are:

- *olefins:* high-octane chemicals produced from crude during refining, and also occurring naturally in the crude in very low concentrations. Many of the olefins are both highly volatile (they evaporate easily) and highly reactive (in the presence of sunlight, they react with nitrogen oxides and other atmospheric constituents to form ozone);
- *aromatics:* even higher octane constituents, occurring naturally in crude in moderate to high concentrations and also created by refining. Aromatics are reactive, though not as much as olefins;
- *paraffins:* consisting of two groups, "highly branched" paraffins that are both high in octane and low in reactivity, and "straight chain' paraffins that also are low in reactivity but are very low octane. Paraffins, like aromatics, are present in crude at moderate to high concentrations, depending on crude type; and

[2] M.L. Wald, "ARCO Offers New Gasoline to Cut Up to 1570 of Old Cars' Pollution," *New York Times,* Aug. 16, 1989, section 1, page 1.

[3] Olefins and some aromatics are significant smog-producers; benzene is carcinogenic.

[4] "ARCO To Market Low-Emission Regular Gasoline,' *Oil and Gas Journal,* vol. 87, No. 34, Aug. 21, 1989, p. 31.

[5] Pre-1975 cars do not have catalytic converters.

[6] *Oil and Gas Journal,* op. cit., footnote 4.

. *naphthenes:* between paraffins and olefins in octane; present in crude in moderate to high concentrations.

The combination of Federal emission control and lead phaseout requirements, higher crude prices, and the growing demand for gasoline have caused major changes in the makeup of gasoline. These changes, in turn, had some negative effects on gasoline environmental quality. For example, refiners expanded cracking capacity and severity to increase gasoline yields and octane, thereby increasing production of light olefins, which are highly reactive and volatile. Refiners also channeled increasing supplies of butane into gasoline to increase yields, at the cost of higher vapor pressure and thus higher evaporative emissions.[7]

Federal requirements to reduce and eliminate lead content created a need for additional octane enhancement, because lead had been a key octane-raising constituent of gasoline. To replace lead, refiners increased the conversion of paraffins and napthenes into higher octane branched paraffins, olefins, and aromatics. Ironically, these changes, designed to allow the use of catalytic converters that would reduce tailpipe mass emissions, increased the reactivity of the fuels and presumably their emissions (thus increasing their impact per unit mass on ozone formation) and, by increasing gasoline volatility, lessened the effectiveness of new controls on evaporative emissions introduced at the same time. Although the *net* effect of the vehicle and fuel changes was a reduction in effective ozone-causing emissions, the fuel reactivity and volatility increases reduced the overall air quality benefit.

As a general rule, environmental reformulation of gasoline will lower volatility, lower the concentrations of aromatics and volatile olefins, and add oxygenates. A primary holdup in gasoline reformulation, however, is a significant lack of knowledge about the *precise* role that each gasoline constituent plays in vehicle emissions, and (to a lesser extent) the role of the emissions in ozone formation. The lack of understanding about vehicle emissions is more severe with cars equipped with catalytic controls, because sophisticated controls tend to further complicate the relationship between gasoline makeup and emissions, by destroying some hydrocarbons and converting others into new compounds with different reactivities. Directionally, refiners know that they need to reduce aromatic and olefin content, but they can't as yet quantify the effects of these reductions, and emissions benefits may be strongly nonlinear. Also, aromatics and olefins are produced during combustion and in the catalyst, so even elimination of these compounds in the fuel will not eliminate their presence in the exhaust. Further, refiners do not yet understand the potential emissions impact of switching the makeup of gasoline in subtler ways, for example, in replacing certain aromatics with other aromatics. And refiners will have to figure out how to deal with excess aromatics and olefins, since the option to move them to another product pool will vanish as reformulation requirements expand to cover a larger share of the gasoline pool.

The oil and automobile industries recently began a joint research program to better define the impact of changes in the major gasoline constituents on emissions levels, as well as to examine alternatives to gasoline.

The frost phase of the program, for completion by 1990, will test a variety of reformulated gasolines in 1989 vehicles and 1983-85 vehicles (the program will test methanol fuels in flexible fuel vehicles, as well).[8] The gasolines will be restricted to those producible in volumes from existing refineries. A critical aspect of the tests is that they will measure specific chemical constituents of the emissions, and then use the results in air quality models to estimate urban ozone levels that would result from use of the fuels. Collection of this type of speciated data has been extremely limited thus far.

The second phase of the program will conduct research on advanced technology gasoline and alternative fuel vehicles. The reformulated gasoline research will examine future gasolines including those requiring significant refinery changes, and will explore the potential to optimize the fuel-vehicle system by simultaneously reformulating gasoline and changing vehicle emission control parameters.[9]

[7]W.J. Piel, ARCO Chemical Co., "The Role of Ethers in Low-Emission Gasoline,' National Conference on Motor Fuels& Air Quality, Oct. 3-5, 1989, Washington, DC.

[8]American Petroleum Institute and General Motors Corp., "Auto/Oil Air Quality Improvement Research Program," news release of Oct. 17, 1989.

[9]Ibid.

Given the general direction in which they must move, however, refiners appear to have several options. One important option is the use of ethers, produced by combining various alcohols with olefins (examples: MTBE, made from methanol and isobutylene; ETBE, made from ethanol and isobutylene, and TAME, made from methanol and isoamylenes) to displace light olefins (primarily the C_4 olefins) and aromatics as octane boosters. Ethers have the triple advantage of being oxygenates, which tend to lean out engine combustion and reduce carbon monoxide emissions (especially in older vehicles, but recent test have shown they reduce CO in new vehicles as well), of being high in octane, and of having a low volatility effect. In addition, ether manufacture, by providing an alternative use for C_4 and possibly C_5 olefins, will dilute the concentration of these reactive compounds in gasoline.[10] Also, butane can be used to produce isobutylene, needed for MTBE or ETBE production, potentially providing an alternative use for this compound as well.[11]

Refiners may also be able to increase catalytic cracking severities[12] and selectively favor the formation of lighter constituents, e.g., isobutane and butylenes, and then use alkylation or other polymerization processes to combine these into highly branched paraffins. And refiners could increase the removal of benzene from gasoline using solvent extraction,[13] and hydrogenate the benzene to cyclohexane, which is less reactive but still moderate octane. A key question here, as elsewhere, is the expense of lowering benzene concentrations, or concentrations of other aromatics such as xylenes.

There is also evidence that some aromatics are less reactive for smog formation than others. With proper identification of reactivity levels, refiners will be able to convert highly reactive aromatics to less reactive aromatics. Again, the presence of the catalytic converter complicates these relationships.

Another option for some refiners is to increase their use of deposit control additives to reduce deterioration of vehicle exhaust emission control systems. There is substantial evidence that differences between exhaust emissions levels in on-the-road vehicles and levels achieved during EPA vehicle certification testing-the on-the-road levels are significantly higher-are caused in part by insufficient deposit control additives.[14] A 1986 survey by Chevron concluded that only 16 percent of California gasolines contained high concentrations of such additives.[15] Advertising campaigns by several of the major oil companies state that they have increased the level of detergents in their fuel formulations, primarily due to complaints from owners of cars with fuel-injected engines, so that the remaining margin for improvement may have shrunk considerably.[16]

We cannot overstress the uncertainty associated with projecting the emissions-reduction potential of reformulated gasoline. With the exception of EC-1 and perhaps one or two more recent market entries, reformulated gasoline is a concept, not a reality. The potential effect on newer, catalyst-equipped cars is particularly uncertain. *Although discussions of reformulated gasoline tend to presume that it would likely be able to match M85 in emissions performance, but not M100, there appears to be little basis for such assumptions.*

COSTS

The long-term costs of gasoline reformulation cannot be predicted accurately until the nature of the reformulation is better defined. However, some basic aspects of reformulation costs can be projected.

---

[10] Piel, op. cit., footnote 7.

[11] Ibid.

[12] Catalytic cracking subjects the feedstock to high temperature in the presence of a catalyst, producing lighter constituents by breaking down heavier ones.

[13] In many areas, benzene is already being extracted for sale as a chemical, but this market is limited.

[14] Sierra Research, Inc., "The Feasibility and Costs of More Stringent Mobile Source Emission Controls," contract report prepared for the Office of Technology Assessment, Jan. 20, 1988.

[15] Ibid.

[16] The January 1990 issue of Consumer *Reports* presents the results of a survey of gasoline marketers. The survey indicates that, while 6 major brands had passed a widely accepted test for deposit control for all 3 grades of their gasoline, 17 others had either not passed the test or had passed it for only 1 or 2 grades.

EC-1 will cost ARCO an additional 2 cents per gallon to manufacture.[17] These costs represent only changes in operating costs (for example, refinery energy costs are about 10 percent higher in producing EC-118), byproduct credits, and feedstock costs rather than capital costs. ARCO's existing Carson, California refinery has the necessary equipment to produce 36 million gallons/month of EC- 1, which is more than the 23 million gallons/month of leaded regular that ARCO previously sold in southern California,[19] so ARCO did not incur significant capital costs. Also, ARCO can use the aromatics removed from EC-1 in its other unleaded gasolines for catalyst-equipped vehicles, where the added emissions potential of these components will be controlled. However, with the current limited understanding of the relationship between fuel properties and vehicle emissions, it is not clear how much additional use ARCO can make of this fleet as a ''sink' for aromatics. The ability of refiners nationwide to repeat ARCO's experience will depend on the particular configurations and processing capabilities of their refineries. Refineries oriented to premium, high octane fuels with high aromatics contents may have a difficult time producing reformulated fuels without major processing reconfiguration and capital investment.[20] Many other refiners—especially those with modern, complex refineries—are likely to be able to repeat ARCO's experience at similar costs if the quantities of reformulated gasoline demanded are moderate—up to perhaps 20 percent of total production.[21]

Producing much larger quantities of EC-1 or other gasoline reformulations will have significantly higher costs. Manufacturers will need to revamp or replace refinery equipment at substantial capital cost, because existing refineries will not have the necessary capabilities.[22] Blending of byproducts such as aromatics will be market limited, and refiners will have to convert excess aromatics and other byproducts to more desirable components, at added energy and cost. Supply limitations for key materials, e.g., isobutylene (needed for MTBE and ETBE production) must be overcome, presumably at added cost. And with greater competition for crude feedstocks most suited for producing "EC-1 '-type gasolines, refiners will be forced to use less desirable feedstocks that require more processing.

ARCO estimates the added costs to manufacture large quantities of EC-1 at 5 to 15 cents per gallon.[23] These costs incorporate refinery capital charges, higher feedstock costs or additional processing requirements, and higher processing costs for byproduct conversion, in addition to the costs presently being incurred for EC-1. This cost range should serve as a first-order estimate for the costs of large-scale gasoline reformulations aimed at newer vehicles but similar in severity to the EC-1/leaded regular reformulation. Higher severity reformulations may be more expensive; for example, the cost of reducing aromatics to or below 20 to 25 percent by volume may exceed 15 cents per gallon.[24]

The California Air Resources Board (ARB) has been examining a number of gasoline quality-control measures that would require changes in gasoline composition that would likely be similar to those selected as part of a reformulation program. ARB's cost estimates are as follows (these are not necessarily additive):

- Reducing Reid Vapor Pressure from 9 psi to 8 psi: $0.01 to $0.02/gallon[25]
- Benzene content reductions from 2 to 0.8 percent: $0.025/gallon
- Reduction of aromatics: $0.08 to $0.20/gallon
- Oxygenate blending: $0.005 to $0.03/gallon

[17] Wald, op. cit., footnote 2, and confirmed by personal communication, Dwayne Smith, ARCO, Los Angeles, CA.

[18] Dwaine Smith, ARCO, Los Angeles, CA, personal communication.

[19] *Oil and* Gas *Journal*, op. cit., footnote 4.

[20] D.B. Barnes, office of Air and Radiation, U.S. Environmental Protection Agency, memo to C.L. Gray, Director, Emission Control Technology Division, USEPA, "Comments on Draft OTA Report Section on Reformulated Gasoline," Jan. 31, 1990.

[21] Daniel Townsend, ARCO Products Co., Anaheim, CA, personal communication.

[22] The Option of waiting t. make capital changes until capital turnover is required anyway is not available here because of the longevity of major refinery components and the shift in building new refinery capacity to overseas.

[23] Dwayne Smith, ARC(), personal communication.

[24] Barnes, op. cit., footnote 20.

[25] Nationwide, RVP averages about 11 psi. California already requires a summertime reduction to 9 psi.

- Addition of gasoline detergents/additives: not known[26]

An additional cost for some gasolines will be that of olefin reduction, not addressed in these estimates.

The potential availability of moderate quantities of reformulated gasoline at low cost, and the sharp escalation in costs when larger quantities are demanded, point to a possible strategy of promoting sale of such gasolines only in urban areas with significant air quality problems. This type of strategy can work well because the reformulations can be aimed at achieving emission reductions without vehicle modifications; vehicles can be used, unmodified, outside of the areas where reformulated gasoline is sold, and emissions benefits can be achieved for all or most vehicles in the fleet without waiting for vehicle turnover.

SECONDARY IMPACTS

Given the uncertainty associated with the nature of the changes that will be made to gasoline formulations and to refining processes, it is premature to attempt quantitative assessments of the impact of broad reformulation of the gasoline pool. However, the following qualitative impacts are plausible:

1. increases in processing energy required to produce gasoline, with some adverse consequences for emissions of greenhouse gases;
2. economic difficulties for some refiners, particularly the small independents;
3. changes in the import balance between crude and gasoline, with the direction (more or less product imports) and magnitude speculative;
4. changes in the relative desirability of different crude oil feedstocks, with accompanying shifts in the mix of supplier countries; and
5. changes in the ability of refiners to accept a range of feedstocks, and thus changes in the United States' flexibility in shifting its sources of supply (direction depends on the type of refinery process shifts adopted).

Impacts 3 through 5 may involve changes in energy security. Such changes, coupled with the substantial economic impacts that widespread reformulation may involve, demand careful analysis as research on reformulation proceeds and as the likely physical character of reformulation becomes clearer.

ADDITION OF OXYGENATES

Although it is not yet clear what perfected reformulated gasolines will look like, they most likely will contain significant quantities of oxygenates such as ethanol, ETBE, and MTBE. Concentrations as high as 15 percent are possible with some of the oxygenates, so that the energy security and other impacts of reformulated gasoline must account for this presence of gasoline constituents that are produced largely from non-oil components. For example, a large increase in either ethanol or ETBE use will affect energy security by simultaneously increasing the percentage of gasoline volume produced from domestic components (e.g., domestic corn), exposing this gasoline component to the vagaries of crop production uncertainties, and changing the economics of gasoline production. With the United States' relatively secure system of crop stockpiles, the risk of feedstock shortages should be small until ethanol production becomes quite large--but if all U.S. gasoline, or a large percentage of it, is reformulated with a high ethanol or ETBE content, this risk may become non-trivial. Similarly, large-scale use of MTBE or methanol as oxygenates would shift some supply risks from the oil supply system to the methanol supply system, probably with positive consequences as discussed in chapter 3.

[26] D. Simeroth, Chief, Criteria Pollutant Branch, California Air Resource Board, cited in Acurex Corp., *Economics Report, Volume IV*, Aug. 4, 1989, report to California Advisory Board on Air Quality and Fuels.