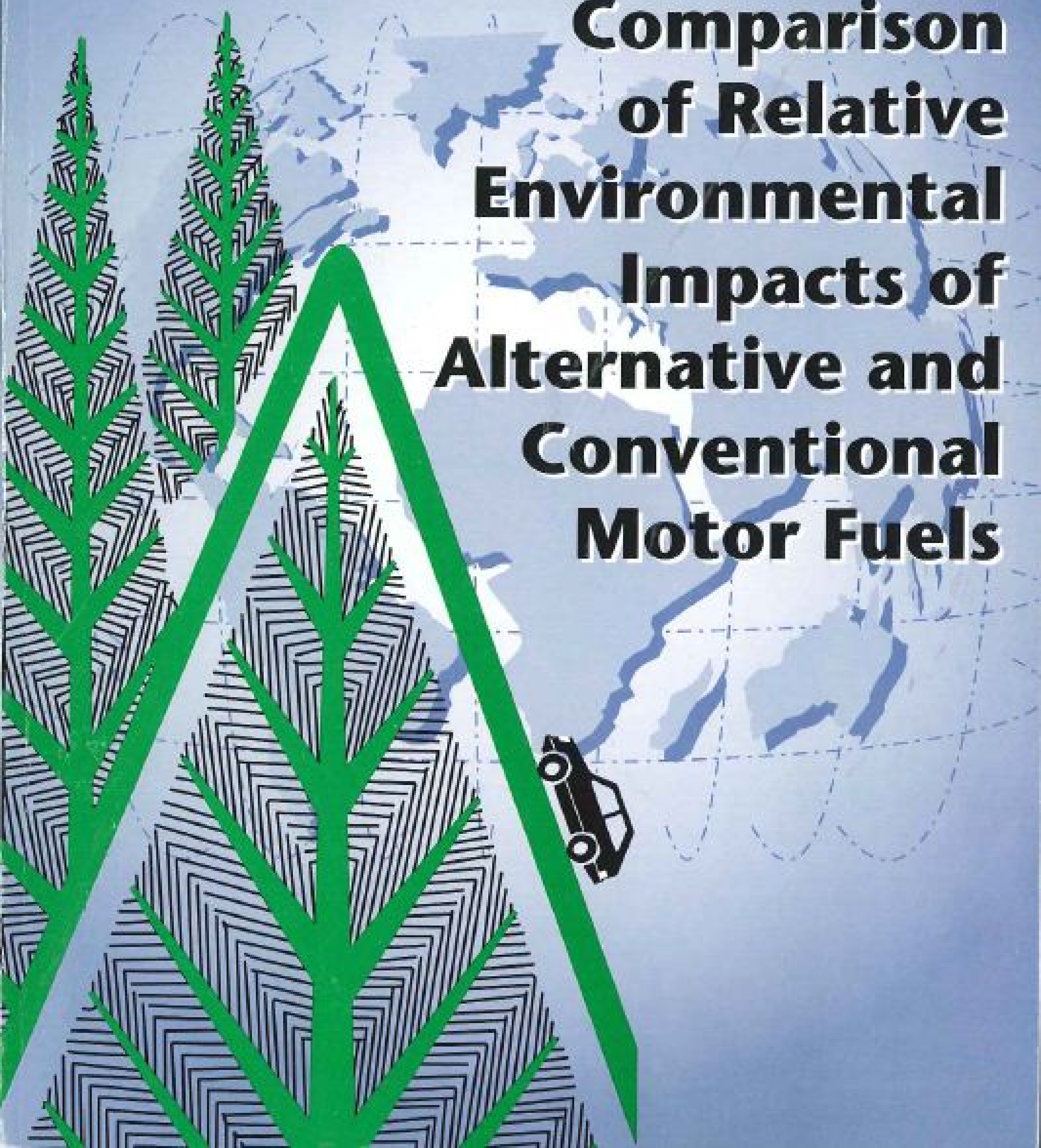
Final Report for Annex VII

International Energy Agency
IEA Alternative
Motor Fuels
Agreement

Comparison of Relative Environmental Impacts of Alternative and Conventional Motor Fuels



FOREWORD

Alternative transportation fuels are receiving considerable attention from governments around the world because of the perception that the fuels can contribute to solutions to many environmental problems and to energy security. Yet, the reported results of beneficial effects of alternative fuels are mixed and incomplete and have led to confusion over the realities of the situation. Therefore, the International Energy Agency's (IEA's) Executive Committee for Alternative Motor Fuels commissioned this study for the purposes of gathering and assimilating the results of many studies into a more concise reference that deals with the issues. This report represents the final report of Annex VII which was supported by agencies in Belgium, Canada, Finland, Italy, Japan, the Netherlands, Sweden, and the United States through their participation in IEA's Implementing Agreement on Alternative Motor Fuels. Supporting Agencies of the participating countries are listed below, and the authors gratefully acknowledge their support as well as their advice and assistance on the content of this report.

Belgium	Flemish Institute for Technological Research (VITO)
Canada	Natural Resources, Canada
Finland	The Technical Research Centre of Finland (VIT)
Italy	EURON
Japan	Ministry of Transport Japan Automobile Research Institute New Energy and Industrial Technology Development Organization
The Netherlands	Netherlands Agency for Energy and the Environment (NOVEM)
Sweden	Swedish National Board for Industrial and Technical Development (NUTEK)
United States	Department of Energy

Ralph McGill
Oak Ridge National Laboratory
Oak Ridge, Tennessee USA 37831-8087

CONTENTS

CONTENTS

CONTENTS

FIGURES

FIGURES

TABLES

TABLES

ACRONYMS AND ABBREVIATIONS

AQIRP	Auto/Oil Air Quality Improvement Research Program
BTU	British thermal unit
BTX	benzene, tolulene, and xylene
CARB	California Air Resources Board
CEC	California Energy Commission
CEE	coal burning in Eastern Europe
CFC	chlorofluorocarbon
CGCM	coupled general circulation model
CH_4	methane
CNG	compressed natural gas
CO	carbon monoxide
CO_2	carbon dioxide
CRP	current reduction plans
DHA	dehydroaromatization
DNA	deoxyribonucleic acid
DOE	Department of Energy (United States)
E10	a fuel mixture of 10% ethanol, 90% gasoline
E95	a fuel mixture of 95% ethanol, 5% gasoline
EEE	energy efficiency in Eastern Europe
EJ	exajoule
EMEP	European Monitoring and Evaluation Programme
EPA	Environmental Protection Agency (United States)
FID	flame ionization detector
FFV	flexibly fueled vehicle
g	gram
gal	U.S. gallon
GCM	general circulation model
GMC	General Motors Corporation
GWP	global warming potential
h	hour
HC	hydrocarbons
IEA	International Energy Agency
inc. reac.	incremental reactivities
IPCC	Intergovernmental Panel on Climate Change
kg	kilogram
kJ	kilojoule
km	kilometer
kWh	kilowatt-hour
LPG	liquefied petroleum gas

m^2	square meter
m^3	cubic meter
M85	a fuel mixture of 85% methanol, 15% gasoline
M100	100% methanol fuel
M.A.N.	Maschinenfabrik Augsburg-Nurnberg
MIR	maximum incremental reactivity
MJ	megajoule
MOR	maximum ozone reactivity
MTFR	maximum technically feasible reductions
mtoe	million tonnes oil equivalent
µg	microgram
NAAQS	National Ambient Air Quality Standard
NAPS	National Air Pollution Surveillance
NAS	National Academy of Sciences (United States)
NMHC	nonmethane hydrocarbons
NMOC	nonmethane organic compounds
NMOG	nonmethane organic gases
NMVOC	nonmethane volatile organic compounds
NO_2	nitrogen dioxide
NO_x	oxides of nitrogen
N_2O	nitrous oxide
NREL	National Renewable Energy Laboratory
O_3	ozone
OECD	Organization for Economic Co-operation and Development
OMHCE	organic material hydrocarbon equivalent
PAH	polycyclic aromatic hydrocarbons
ppb	parts per billion
ppb-h	parts per billion–hours (an integrated quantity)
ppmC	parts per million of carbon
ppmw	parts per million by weight
ppt	parts per thousand
RAF	reactivity adjustment factor
rel. reac	relative reactivities
RFG	reformulated gasoline
RITG	radiatively important trace gases
RNA	ribonucleic acid
ROG	reactive organic gas
SHED	sealed housing for evaporative determination
SO_2	sulfur dioxide

ACRONYMS AND ABBREVIATIONS

SO_x	oxides of sulfur
UNECE	United Nations Economic Commission for Europe
VFV	variably fueled vehicle
VOC	volatile organic compound
W	watt
wt%	percentage by weight

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support of the Executive Committee, Alternative Motor Fuels, who sponsored this work and who helped to guide the study and the report to this final product. We also wish to express appreciation to those outside the Executive Committee who contributed greatly to this process by reviewing and commenting on the draft versions of this document. Special thanks go to Karin Kvist of Bilindustriföreningen (the Association of Swedish Automobile Manufacturers and Wholesalers) who, representing an ad hoc committee of Swedish reviewers, provided valuable input on the content of the report and who gave of her time to consult with the authors in Oak Ridge. We also owe Wendy Clark of Automotive Testing Laboratories, Inc. (USA) a debt of gratitude for giving greatly of her time and effort with the authors in a final review of the report.

1. INTRODUCTION AND SUMMARY OF FINDINGS

1.1 BACKGROUND

Interest in alternative motor fuels, which has existed at least to some extent for virtually all of the history of the automobile, was rekindled within the last two decades first as a result of the oil crises of the 1970s and 1980s and later out of consideration for their potential to alleviate environmental problems. For the last several years, a movement has been under way worldwide to consider laws and legislation that would require the introduction of alternative fuels into the transportation sector—a movement having its roots in the perception that alternative fuels can provide benefits to local health and regional and global environmental problems and provide energy security by relieving the demand for petroleum.

In many cases, research evidence and in-use data have suggested that alternative fuels can have beneficial effects on environmental problems. However, such evidence is not universally true for all alternative fuels applied to all environmental problems, and not all evidence suggests that alternative fuels can help. This situation has given rise to considerable discussion and debate over the real impact of alternative fuels for use in transportation.

Although the evidence has not appeared to be conclusive yet, governments at all levels, from local to regional to national, are implementing plans to require that alternative fuels be used in transportation. The U.S. Alternative Motor Fuels Act of 1988 and the Clean Air Act Amendments of 1990 are good examples. These two acts alone are expected to put at least 20,000 alternatively fueled cars and trucks into operation in the United States by the year 2000. Furthermore, the recent U.S. Clean Air Act Amendments require "clean fuels" (alternative and reformulated fuels) to be used in very significant numbers of light- and heavy-duty vehicles in the United States by the year 2000.

The ongoing discussion of alternative fuels has, in turn, spawned a great increase in research aimed at understanding the relative merits of the different fuels and at resolving as many of the unknown factors in the discussion as possible. A notable example is the "Auto-Oil Study" in the United States which was aimed at resolving questions about the environmental benefits of several fuels, including alternative fuels, as well as reformulated gasoline and conventional gasoline. Other efforts, though generally smaller, are attempting to clarify pieces of the environmental puzzle according to the needs of the respective sponsoring agencies.

In spite of all of the research activity, it appeared to the authors that there was no plan by any organization to synthesize and integrate the results of the many studies worldwide in order to form a consensus summary of the evidence and to identify the gaps in research where more work was needed. There was a need for an objective, unbiased view of the evidence and an effort to gather and assimilate the results of the many studies into a summary document so that agencies and companies could formulate policy with regard to alternative fuels. Identification of the gaps in data and state of knowledge can help guide researchers and sponsoring agencies toward projects aimed at obtaining the results that are still needed.

Therefore, the general objectives of this study were to seek answers to the following questions: (1) What do we know now about alternative and conventional fuels that helps governments select fuels? (2) What needs to be known about alternative fuels compared with conventional fuels to enable governments to make intelligent decisions about their use to benefit the environment? (3) What are the gaps between what needs to be known and what is known about fuels and emissions, including emissions from combustion and evaporation of fuels; reactions of the emissions with the environment; and local, regional, and global effects of the various emissions?

This study was commissioned as Annex VII of the Implementing Agreement by the International Energy Agency's (IEA's) Executive Committee on Alternative Motor Fuels. Countries sponsoring the Annex were Belgium, Canada, Finland, Italy, Japan, Sweden, The Netherlands, and the United States.

Other Factors Governing Content of This Report

The reader should be mindful of several factors when reading this document in order to maintain the proper perspective. The state of knowledge of alternative fuels is a very dynamic situation, with considerable research still under way and new results of research being announced frequently. In such a situation, this report can be only a snapshot in time, representing the state of knowledge at the time of its publication. New results could conceivably change some of the conclusions that are in this report. We have made every effort to integrate the most meaningful results of alternative fuel research thus far. However, the results of many ongoing studies could not be included in the content of this report.

A number of different environmental problems are discussed in the report, ranging from global problems such as global warming to local problems like decaying urban air quality. For any of these problems, there are a variety of measures that governments can take to try to mitigate the problems, and alternative transportation fuels represent only one of the options. This report deals with the effects that alternative motor fuels would have on the problems. However, the reader should not lose sight of the many other options. For example, transportation's role in urban air pollution is typically quite significant, and many governments are looking to alternative fuels as potential solutions. However, there are other ways to curtail transportation's contribution to urban air pollution. For an extreme example, a government could choose to deprive people of the right to drive personal vehicles. Most governments would probably consider this latter option to be objectionable. However, it does point out that there are several options to any given problem, and alternative fuels represent just one option to mitigate the environmental problems described herein.

This study has not considered to any great degree the economics and potential market penetration of the various alternative fuel possibilities. For our purposes, the different alternative fuels are equally likely or equally attractive from an economic standpoint. Our charter was to treat the question of what would be the environmental impacts of alternative fuel options, if they are chosen by governments. Some of the studies cited herein have, of necessity, assumed certain market penetrations in order to project the impacts that alternative fuels could have.

We should note that the IEA's projection of worldwide energy consumption to the year 2010 (OECD 1994) shows rapid expected growth in natural gas consumption worldwide, from 1727 million tonnes of oil equivalent (mtoe) in 1991 to 2718 mtoe in 2010. However, IEA attributes much of this growth to power generation and space heating and not to the demands of transportation. With natural gas being one of the alternative motor fuels currently most often proposed, this shows either the fuel use forecasters have not yet considered the impact of future fuels for transportation, or they have considered them and do not forecast a great market penetration in transportation.

We must also recognize that the impacts of alternative fuels on environmental problems will be a function of how widely a particular alternative fuel is used in transportation. It should be obvious that if an alternative motor fuel can have a beneficial impact on a given problem, then in order for it to be effective, it must displace a great portion of the conventional fuel in use. The scale of the environmental problem then dictates the scale of the displacement that alternative fuels must reach. For example, if it is determined that a particular alternative motor fuel would reduce greenhouse gases, then for that fuel to actually reduce greenhouse gases to any measurable degree, it must be used in great quantities throughout the world. The authors believe that, in this particular example, that is not really a possibility for the foreseeable future. On the other hand, a particular alternative fuel might be seen to be beneficial to a local problem (e.g., degraded air quality in congested downtown areas). In this case, a beneficial effect might be rendered with alternatively fueled vehicles in numbers that are manageable and achievable by societies and governments.

Finally, factors other than those considered in this study may dominate the decision process, (e.g. politics, economics, natural resources). The authors hope, however, that those responsible for preparing the environmental arguments will find this study to be of value to them—primarily in terms of identifying what the issues might be and what approach should be used in arriving at an appropriate decision.

1.2 OBJECTIVES OF THE ANNEX

The objectives of the Annex (and this report) were

1. to review, synthesize, and evaluate studies of the local and regional environmental impacts—including global greenhouse and warming effects—of different motor fuels, considering the entire chain from production of the fuel to its end use in highway transportation;

2. to summarize results and identify gaps in the data and understanding in order to guide further research; and

3. to create a common basis for decision makers in government and industry with a view to facilitating the introduction of new and improved motor fuels.

This Annex should help the IEA to provide a technological response to global, regional, and local environmental issues. The guidance available in this final report should allow both industry and government to make knowledgeable decisions on motor fuels and their application in order to avoid adverse health and environmental impacts.

The alternative fuels that were considered in this report are those that have received the most attention in the recent literature. The reformulated fuels, gasoline and diesel, were grouped with the conventional fuels against which the comparisons with alternative fuels were made. Electricity was considered to be an alternative fuel. Natural gas was assumed to be in the form of compressed natural gas (CNG). (Vehicle emissions from liquefied natural gas and CNG were assumed to be the same.) The following fuels were considered in this report:

1. alternative motor fuels: methanol, ethanol, natural gas, propane, and electricity; and

2. conventional motor fuels: gasoline, reformulated gasoline, diesel fuel, and reformulated diesel fuel.

1.3 ORGANIZATION OF THE REPORT

This report surveys material from many different technologies and environmental phenomena, ranging from human medical data to engine, fuels, and emissions technologies. It is unlikely that any reader will be conversant in all of the technologies represented in the report. Out of consideration for the diversity of potential readers, the report is organized so as to facilitate their different needs, ranging from those who want to quickly read just the summary and most important points to those readers who want to learn more detail about the individual phenomena and the manner in which fuel selection can influence them.

The summary that follows represents a shortened version of the findings from the entire report. From it, a reader should be able to glean the most important findings, conclusions, and recommendations. We have written the summary in a way to provide policymakers with a quick overview of potential problems and the potential impacts of alternative fuels in the solutions of those problems. We have included a table to summarize the findings on alternative fuels with regard to the wide variety of potential health and environmental problems. The reader should be able to consult the table and obtain quick guidance on selections of fuels that might be applied to given problems. We strongly encourage the reader to consult the more detailed sections dealing with the particular problem of interest.

Chapter 2 identifies the environmental problems to be addressed in the report, starting with the global problems and working down the spectrum to regional then local health effects problems. It is more of a reference chapter in that it describes details of the environmental problems and explains why we should be concerned with them in this study, but it does not deal in any great detail with the effects of fuels on those problems. That discussion is left for the next chapter. Readers already familiar with the background and discussions of Chapter 2 could choose to move directly to Chapter 3.

Chapter 3 is the focal point of the report in that it compares the reported effects of alternative and conventional motor fuels on the environmental problems identified in Chapter 2. Its organization follows in the same pattern as that of Chapter 2, starting with the global problems and working down through the same list of problems to the regional and local health effects problems. This is the chapter that will interest the most readers in that it is the one wherein the potential impacts of the different fuels are discussed.

Chapter 4 is a discussion of several other miscellaneous factors relating to fuel selection with which decision makers will be concerned. These factors range from worker safety to the capital costs associated with a different fuel infrastructure. Even though we are not addressing the economics of the fuel contenders, we felt it important to briefly discuss the implications with regard to the capital requirements of some of the scenarios. We included these factors in a separate chapter because they were important enough to be included in the report, but they did not seem to fit precisely into the structure of any other chapter.

Reviewing the literature leads one to conclude that there are many unanswered questions in this subject area, and there are many new studies that could answer these questions. Chapter 5 represents our best effort at identifying the gaps in data and the state of knowledge. While these gaps remain, in our opinion, decisions about motor fuels selection will be less analytical and more subjective.

1.4 SUMMARY OF FINDINGS—IMPACTS OF ALTERNATIVE FUELS

This summary is a great oversimplification of the report and is provided only to give the reader a quick overview and sense of the findings. Readers are strongly encouraged to consult the body of the report for detailed information on any given environmental problem and the effects on the problem that might be associated with any given alternative fuel.

Governments around the world are faced with numerous environmental problems in which alternative transportation fuels might be considered as part of a solution package. It is important to recognize at the outset that the extent to which mobile sources contribute to environmental problems depends on the following: the extent of other sources of pollution, the geographic region of interest, the total fuel consumption in the region, the types of fuel consumed, and the technologies of the vehicles consuming the fuel. Environmental problems and transportation conditions are not the same in all places, and that which is important to one government might not be important to another. Therefore, it is very difficult to generalize the results of this study to suit the needs of all interested parties. For instance, one government might consider the prevention of acidification to be a higher priority than the prevention of ozone, and thus that government might place a greater emphasis on emissions from heavy-duty vehicles than those from light-duty vehicles (since acid precursors are emitted in greater quantities from heavy-duty vehicles).

Policymakers should satisfy themselves that they know exactly what their environmental problems are, that they know what is causing the problems, and that they know that proposed actions will alleviate them. This report is intended to help in the latter phase of this decision-making process—determining that proposed actions will have the intended beneficial effect on the environment.

We have tried to assimilate most of the potential environmental impacts of the alternative transportation fuels considered in this study and to integrate them into a single table to provide the reader with a quick summary of the results. Table 1.1 summarizes the findings regarding the life-cycle impacts (tracing the impacts from resource recovery through production and distribution to end use) of the different fuels considered. The table applies to light-duty vehicles only. There is discussion of the heavy-duty vehicle comparison later in this section. Most of the impacts included in the table relate to air-borne emissions; however, we've also included health effects concerns such as carcinogens. Unleaded gasoline was taken to be the reference against which all the other fuels were compared, and the table only indicates the direction of the effects and provides no indication of the magnitude of the effects. In many cases, the effects could not be gleaned very consistently from the data, and we have indicated those cases with question marks. In other cases, the potential effects will depend on external factors, such as the kinds of batteries used in electric vehicles in the case of impacts of lead. In the case of effects on ozone, for some of the cases we have indicated that the effect will depend on the local ratio of volatile organic compounds to

Table 1.1. Relative life-cycle emissions impact from conventionally and alternatively fueled light-duty vehicles based on 1994 technology

	Unl gas	Lead gas[a]	RFG[b]	Diesel[c]	RFD	Methanol[d]	Ethanol[d]	CNG[e]	LPG[e]	Fossil electricity	Nonfossil electricity	Notes
CO	R	+	–*	–	–	–	–	–*	–*	–	–	*Due to advantages in open loop operations
CO_2	R	≅	≅	–	+?	*	*	–	–	+	–	*Depends on how made
NO_x	R	+	–	+	+	≅	≅	≅	≅	+	–	
SO_x	R (NI)	≅	–	+	+	–	–	–	–	+	–	
O_3	R	+	–	*	*	*	*	–	–	*	–	*Depends on local VOC/NO_x ratio
NMOG	R	+	–	–	–	–	–	–	–	–	–	
Methane	R	+	–	–	–	+	≅	+	–	–*	–	*Depends on fuel/ electricity production and distribution
Pb	R (NI)	+	≅	≅	≅	≅	≅	≅	≅	*	*	*Depends on batteries
Particulates	R (NI)	+	≅	+	+	≅	≅	≅	≅	+	–	
Aldehydes	R (NI)	+	+?	≅?	≅?	+	+	≅	≅	–	–	
Carcinogens	R	+	–	+	+	–	–	–	–	+	–	

Abbreviations: Unl gas = unleaded gasoline, Lead gas = leaded gasoline, RFG = reformulated gasoline, RFD = reformulated diesel, CNG = compressed natural gas, LPG = liquefied petroleum gas, NO_x = nitrogen oxides, VOC = volatile organic compound, R = reference fuel, ≅ = essentially the SAME emissions, + = potentially MORE emissions, – = potentially LOWER emissions, ? = not enough data to determine a trend, and NI = not an issue of concern for this fuel.

[a] Leaded gasoline prevents the use of automotive catalysts.

[b] Reformulated gasoline is assumed to have oxygenates, reduced sulfur, and a different hydrocarbon mix.

[c] Differences are primarily due to lean operation, particulate emissions, high sulfur content, and higher efficiency.

[d] Differences are primarily due to a lower flame temperature, oxygen content, and exhaust gas composition. Alcohol fuels can be neat or blended.

[e] Differences are primarily due to the relative inertness of the exhaust VOCs and the gaseous state of the fuel.

nitrogen oxides. Again, we urge the reader not to rely too heavily on this table, but to use it only to obtain a sense of the more detailed body of the report.

Several of the environmental concerns in the table are not issues with unleaded gasoline—in particular, sulfur oxides, lead, particulates, and aldehydes. In the same manner then, where a particular alternative fuel is shown to be either approximately equal to or less than unleaded gasoline in one of these concerns, then it means that the concern is also not an issue with the alternative fuel. For example, there is no lead in compressed natural gas. Therefore, the impact on environmental lead from using compressed natural gas is the same as using unleaded gasoline (i.e., not an issue).

Most of the fuels are beneficial for some environmental problems and detrimental for others. Policymakers must be apprised of the various considerations so that they can avoid decisions that could have effects other than intended. For example, electric vehicles used in downtown areas would have very beneficial effects in the localized air quality problems associated with the "canyons" of many downtown areas. However, policymakers should be aware that if the electricity for these vehicles is made from coal, then emissions of sulfur compounds can be higher as a result of the energy demands upon the electrical generation system by the electric vehicles. Admittedly, these emissions typically will be at some location remote from the downtown canyon; but if the overall emissions in the region are important to policymakers, then they should be aware of the effects.

The gaseous fuels, CNG and liquefied petroleum gas (LPG), and nonfossil electricity do appear in the table to be beneficial to many of the environmental concerns and thus should be attractive to many policymakers in a package of solutions to environmental problems. However, we again emphasize that decisions ought to be those that have integrated all of the potential considerations. For example, natural gas vehicles emit methane as unburned fuel, and methane in exhaust gases is not currently regulated by most governments. However, methane is a very serious "greenhouse gas" (gas emitted into the atmosphere that contributes to the global warming effect)—much more so than carbon dioxide for a given amount of gas. Therefore, it is conceivable that governments will consider regulating methane emissions because of concern over greenhouse gases rather than concern over photochemical smog (ozone formation), carbon monoxide (CO), or particulates. The effects that such regulations would have on the attractiveness of natural gas as a transportation fuel is unknown at this time. As another example, although nonfossil electricity would be beneficial in most of the environmental problems included in the table, the decision to use nonfossil electricity as a transportation fuel cannot always be an easy decision. Nonfossil electricity is that which is generated by hydroelectric plants, solar energy, wind power, or nuclear energy. The decision to use nonfossil electricity to power transportation will likely depend on the source of energy for making the nonfossil electricity. Nuclear energy is not universally accepted, and in the United States, for example, there is great public opposition to the construction of any more nuclear power plants. This opposition is at present great enough to discourage politicians and business people from suggesting that nuclear-derived electricity should be used to power our transportation systems, even though there could be improvements in environmental problems.

We have chosen not to include a similar table for heavy-duty vehicles because the comparisons are not as clearly defined for heavy-duty vehicles, and a similar table could be more misleading than helpful. For light-duty vehicles the preponderance of vehicles in the world are powered by spark-ignited, gasoline engines; and those engines, when made to run on alternative fuels, are still very similar to the original engines. Therefore, comparisons of fuels' effects in these engines are generally on a one-to-one basis, with the engine type and characteristics being constant in the comparison. For heavy-duty vehicles, the great majority of the engines are compression-ignited, diesel-fueled engines. When these engines are made to run on the alternative fuels, many changes must be made, typically including reducing the compression ratio and using an ignition assist like spark ignition. As a result, the alternative-fuel heavy-duty engine is very different from the conventional diesel-fuel heavy-duty engine. This makes it more difficult to draw generalizations about the impacts of using the alternative fuels in heavy-duty vehicles. In addition, there simply is not as much literature on the use of alternative fuels in heavy-duty (diesel) vehicles. Therefore, we have chosen not to present a table similar to the one for light-duty vehicles; instead we encourage the reader to consult the body of the report, especially Chapter 3.

To put the discussion of alternative fuels' effects into perspective, we should note that for light-duty vehicles the single most effective strategy involving vehicle technology for reducing exhaust emissions has been the introduction of three-way catalysts and unleaded gasoline. This strategy is very effective for new vehicles. As these cleaner vehicles penetrate the vehicle population, the overall fleet becomes cleaner. There are, however, two concerns that policymakers face: (1) the rate at which the vehicle population is replaced with these newer vehicles and (2) the fact that even though the vehicle population may be cleaner in terms of grams of pollutants emitted per kilometer traveled, the total number of kilometers traveled may be increasing so rapidly that the overall emissions may not be reduced enough.

In the event that applying more stringent controls to new vehicles will not bring about the desired improvements, cleaning up the older vehicles in the fleet may be considered. While there has been a great deal of experience with modifying existing vehicles for alternative fuels, there has not been much activity directed toward retrofitting existing vehicles with three-way catalysts. This is because the fuel metering strategy required for the three-way catalyst to operate needs electronic feedback controls. Retrofitting those is considered to be too impractical. On the other hand, to retrofit a vehicle to operate on an alternative fuel (particularly the gaseous fuels) has not required such sophistication, and the use of natural gas or propane in vehicles without catalysts has been shown to be quite effective in reducing CO and unburned hydrocarbon emissions if the kits are installed properly. More recently, kits that "piggy-back" on the existing gasoline control system have appeared for use on electronically controlled engines and result in natural gas or propane vehicles operating with three-way catalysts.

The advantages of alternative fuels for new vehicles are not as well established because, for example, reports are appearing of preproduction gasoline-fueled vehicles that are capable of meeting the most stringent light-duty vehicle regulations, the California ultra-low emission vehicle standards. The emissions from such vehicles are so low that the use of alternative fuels would be difficult to justify from emissions considerations alone. The new catalyst technologies (electrically heated catalysts, hydrocarbon traps, flame heated catalysts) have the potential for removing much of the cold start emission advantage associated with gaseous fuels in new light-duty vehicles.

In the case of heavy-duty vehicles, alternative fuels appear to offer significant advantages that may not exist in the case of light-duty vehicles. First, the emissions from conventionally fueled heavy-duty vehicles have not yet been reduced as much as those from conventionally fueled light-duty vehicles. The available technologies for dealing with emissions of particulates and oxides of nitrogen from heavy-duty diesel engines still leave these engines with substantially higher emissions than those associated with the use of alternative fuels. Therefore, the reductions achievable with alternative fuels and heavy-duty vehicles are relatively greater than those achievable on light-duty vehicles. Second, since heavy-duty vehicles typically cost considerably more than light-duty vehicles, the cost associated with alternative fuels represents a smaller fraction of the total vehicle cost for heavy duty vehicles.

We should not expect that a single recipe for the implementation of alternative fuels will be satisfactory for all. Transportation environments dominated by relatively new light-duty vehicles produced under fairly stringent emissions regulations apparently will benefit the least from the use of alternative fuels from an air quality perspective. Regions where the transportation system is dominated by heavy-duty diesel vehicles will find that alternative fuels can offer more environmental benefits.

1.5 SUMMARY OF FINDINGS—GAPS IN THE STATE OF KNOWLEDGE

During this study, several technical areas which are at limited or early stages of development, but which could provide sound technical bases on which to build policy, were identified. The lack of the information and data from these areas prevents a more accurate comparison of alternative fuels' benefits to the environment. Thus, these areas are good candidates for further work to help clarify the situation. These gaps are discussed in detail in Chapter 5, and some of the major findings are summarized below.

1.5.1 Policy Issues

Although there is a great deal of popular support for decreasing greenhouse gas emissions, reducing chlorofluorocarbon use, and decreasing acid rain, there is still scientific debate on some of these issues; and this affects the basis for making policy decisions. To a certain extent, this lack of consensus is due to limitations in government-supported research, but it is also due to technical limitations. For example, current computational resources cannot support detailed models of the physical, chemical, and biological systems whose interaction governs global change.

1.5.2 Mathematical Theory and Computational Resources

Much of the available information on the impact of alternative fuels on the environment, and in fact, the information on the state of the environment itself, relies upon predictions from theoretical models. These models are based on mathematical representations of the natural processes that occur in the real world, and they are limited by our knowledge of the world around us, our ability to adequately translate that knowledge into a series of representative mathematical equations, and the computational resources available to solve the resulting set of equations.

1.5.2.1 Global environmental modeling

Current computational models do not provide effective prediction of multidimensional series, such as weather, pollutant dispersion, or the chemical interactions involved in global warming. Satellite data, coupled with predictive computer models, may provide an effective method for evaluating pollutant dispersion, the effects of global warming, and the effects of biofuel production. If an effective method for handling the massive amounts of satellite data from previous years is developed, it could provide a method for tracking historic trends.

1.5.2.2 Air quality modeling

Detailed computer simulations of air quality are available for many regions. Because the data and calculational needs of typical models are within the scope of conventional computational resources, they are increasingly used by regional governments to set and monitor emissions standards and to evaluate the potential impacts of new technologies. This study identified several areas where research to support governmental decisions is needed.

Current air quality prediction models lack validation, although they are used to support decisions with substantial economic consequence. The limited data that are available are generally required to construct the model, and the uncertainties in input make it difficult to determine deficiencies in the model itself. More detailed knowledge of atmospheric chemistry, meteorology, emissions inventories, and fuel specific ozone reactivities is required to improve models and their predictive capabilities.

1.5.3 Biochemical Basis of Toxicant Effects

Human health effects are a major factor in evaluating the value of various emissions management strategies. The data on which health effects estimates are based come from a variety of sources, including epidemiological studies, occupational safety studies, and acute exposure studies. The studies typically use either small, well-controlled populations exposed to high toxicant levels or large, uncontrolled populations typically exposed to low toxicant levels. By their design, these studies are unlikely to indicate a direct physiological response to a toxicant or pollutant. Absence of a physiological response makes it difficult to set limits, develop tests that mirror human risk, and set standards that minimize both risk and cost.

1.5.4 Effects of Alternative Fuels Production Scenarios

Because levels of production of some alternative fuels are presently relatively low, knowledge of probable production technology is limited. Different production technologies and feedstocks have substantially different outcomes. For example, electricity to recharge batteries can be made using methane, coal, biomass, nuclear fuels, hydropower, or wind power. Coal-fired electrical generation releases twice as much carbon dioxide as does methane-fired. Coal- and biomass-fired plants produce more particulates and ash than do the other technologies. Substantial investment in capital and technical resources will be required to start large scale production of some alternative fuels.

1.5.5 Emissions of Alternative Fuels in Large-Scale Use

Tests of alternative fuels in vehicles do not provide an adequate basis for predicting performance in widespread use and there are several reasons for this. Many alternative fuels have been evaluated on a limited basis, using well-maintained, modern, conventional engines, and these limited test data have been used to estimate the effects of alternative fuels use in specific high-pollution areas using computer models. With such a limited data set, predictions of alternative fuels emissions in large-scale use are difficult to determine. While we do have considerable worldwide experience with CNG and LPG, that experience has not necessarily been with vehicles calibrated to stringent emissions standards. Thus, the true emissions potential of these fuels might not necessarily have been realized and cannot be extrapolated from the data.

2. IDENTIFICATION OF PROBLEMS TO BE ADDRESSED

This chapter contains background information about the potential problems on which alternative motor fuels may have an impact. Readers already familiar with the problems to be addressed may wish to refer directly to Chapter 3 for a more specific discussion of conventional and alternative fuels and their environmental impacts.

2.1 GLOBAL AND TRANSBOUNDARY EFFECTS

2.1.1 Introduction

The term "global and transboundary effects" as it is applied to the use of conventional and alternative motor fuels refers to environmental impacts that extend beyond the local and regional geographic areas immediately affected by fuel production and use. The region affected may be across the world, across a continent, or simply across national boundaries. These phenomena are the result of atmospheric dispersion of substances released during the production, transportation, distribution, and/or combustion of the fuel and usually involve time scales that are much longer than those associated with the other atmospheric effects discussed.

The global and transboundary effects of interest in this study are global warming, stratospheric ozone (O_3) depletion, and acid deposition. A brief background discussion of each follows. Readers requiring more in-depth information are referred to the sources cited.

2.1.2 Global Warming

2.1.2.1 Introduction

The term "greenhouse effect" is used to describe the process by which the Earth's atmosphere traps radiant energy from the Earth and warms the planet. About one-half of the solar radiation intercepted by the Earth passes through the atmosphere and warms the planet surface. Thermal energy radiated by the Earth's surface (which has a longer wavelength than the incoming solar radiation) is partially absorbed by gases in the atmosphere. The net result is an increase in the surface temperature of the Earth. Without the warming effect of the atmosphere, the average surface temperature of the Earth would be −18°C and not 15°C as it is now (IPCC 1990).

The addition of greenhouse gases to the atmosphere has raised concerns about man's contribution to the warming of the Earth's surface (global warming) and the resulting alteration of existing habitats for plants, animals, and man. The as yet unknown consequences could include extremely unpleasant surprises. For example, the melting of the high-latitude tundra, resulting in a sudden release of methane (CH_4), could enhance greenhouse warming, and ocean currents, which, in part, determine weather patterns, could change significantly as a result of greater fresh water runoff in high latitudes.

The significant greenhouse gases in the atmosphere are water vapor, carbon dioxide (CO_2), CH_4, nitrous oxide (N_2O), and chlorofluorocarbons (CFCs). Major increases in greenhouse gases during the last 200 years are the result of increases in CO_2 and CH_4, and the increase in CO_2 is nearly three times as significant as the increase in CH_4 (IPCC 1990). Man-made sources of CO_2 are dominated by the burning of fossil fuels and changes in land use, such as deforestation, that involve biomass decay and burning. CH_4 comes from a variety of mostly natural sources, but human activities such as the collection and processing of natural gas, along with coal mining, also contribute to atmospheric concentrations of CH_4. Table 2.1 shows the changes in atmospheric concentration of some key greenhouse gases over time.

The direct global warming potential (GWP) of a gas is a measure of the warming effect due to the presence of the gas in the atmosphere over its lifetime, relative to CO_2. The indirect GWP is due to reaction products in the atmosphere, particularly from short-lived components such as carbon monoxide (CO), nonmethane organic compounds, and nitrogen oxides ($NO_{x)}$. Indirect GWPs are, because of incomplete

Table 2.1. Atmospheric concentrations of some key greenhouse gases

Greenhouse gas	Preindustrial atmospheric concentration (1750–1800)	Current atmospheric concentration (1990)[a]	Current rate of annual atmospheric accumulation
CO_2	280 ppmv	353 ppmv	1.8 ppmv (0.5%)
CH_4	0.8 ppmv	1.72 ppmv	0.015 ppmv (0.9%)
CFC-11	0	280 pptv	9.5 pptv (4%)
CFC-12	0	484 pptv	17 pptv (4%)
N_2O	288 ppbv	310 ppbv	0.8 ppbv (0.25%)

Abbreviations: ppmv = parts per million by volume; ppbv = parts per billion by volume; pptv = parts per trillion by volume.

Note: Ozone has not been included in the table because of lack of precise data.

[a] The current (1990) concentrations have been estimated based upon an extrapolation of measurements reported for earlier years, assuming that the recent trends remained approximately constant.

Source: Adapted from IPCC 1990.

understanding of the chemical processes, extremely difficult to quantify, but may be more significant than the direct GWPs. Table 2.2 shows the direct GWPs of some key species.

Table 2.2 also indicates that the effects of atmospheric loadings of gases can last for a long time after reductions have been implemented. For CO_2, with a residence time of around 120 years, it will take centuries before any decrease in atmospheric concentrations can be seen. However, in another example, reductions of sulfur emissions will show results in a few years because of their short residence time in the atmosphere.

Table 2.2. Estimates of the global warming potential (GWP) of several gases

Gas[a]	Lifetime (years)	Direct effect for time horizons of			Sign of "indirect effect"
		20 years	100 years	500 years	
CO_2	120	1	1	1	none[b]
CH_4	10.5	35	11	4	positive
N_2O	132	260	270	170	uncertain
CFC-11	55	4500	3400	1400	negative
CFC-12	116	7100	7100	4100	negative
HFC-134a	15.6	3100	1200	400	unknown
CO	months	-	-	-	positive
NMHC	days to months	-	-	-	positive
NO_x	days	-	-	-	uncertain

[a] CFC = chlorofluorocarbon, HFC = hydrofluorocarbon, NMHC = nonmethane hydrocarbons, NO_x = nitrogen oxides.

[b] CO_2 is not involved in chemical reactions affecting the concentrations of the radiatively active species. However, it could affect the relevant chemical reactions through its influences on the atmospheric thermal structure.

Note: The lifetimes of the various species are not as precisely known as the table indicates. CO, NMHC, and NO_x are all short-lived gases having a negligible direct GWP component. The indirect GWPs are uncertain but could conceivably be comparable in magnitude to the direct GWPs. Only the signs of the indirect effects are estimated here, based on current understanding. The estimates of the indirect effects for the chlorine-and bromine-containing compounds are based on the weight of evidence related to the observed lower stratospheric O_3 depletion. As CO_2 levels increase, GWPs will increase also.

Source: Adapted from IPCC 1992.

In an attempt to determine overall trends, measurements of the greenhouse gases CH_4 and CO_2 are being made at sites around the world (e.g., Mauna Loa, Hawaii; Tasmania, Australia; and Antarctica) that are relatively free from man-made and natural pollutants. Historical data on CH_4 and CO_2 concentrations are obtained from ice core samples from various locations in Antarctica and Greenland (Boden, Kanciruk, and Farrell 1990).

Records of man-made emissions of global CO_2 are shown in Fig. 2.1. Such data are available in more detailed form for individual countries. Figure 2.2 shows that there are large differences between countries based on per capita emissions. Table 2.3 shows the distribution of carbon emissions for three Organization for Economic Co-operation and Development (OECD) regions. The transportation sector accounts for about 25% of the total man-made emissions of nearly 3 gigatonnes of carbon per year from energy use in these regions.

Contrary opinions on causes and effects of climate change express doubts that man-made releases of CO_2 are the cause of the surface temperature changes of the Earth. Instead, these changes have been attributed to variations in the solar influx, geological processes, changes in ocean water circulation, and the content of water in the atmosphere, resulting in natural temperature changes controlling the CO_2

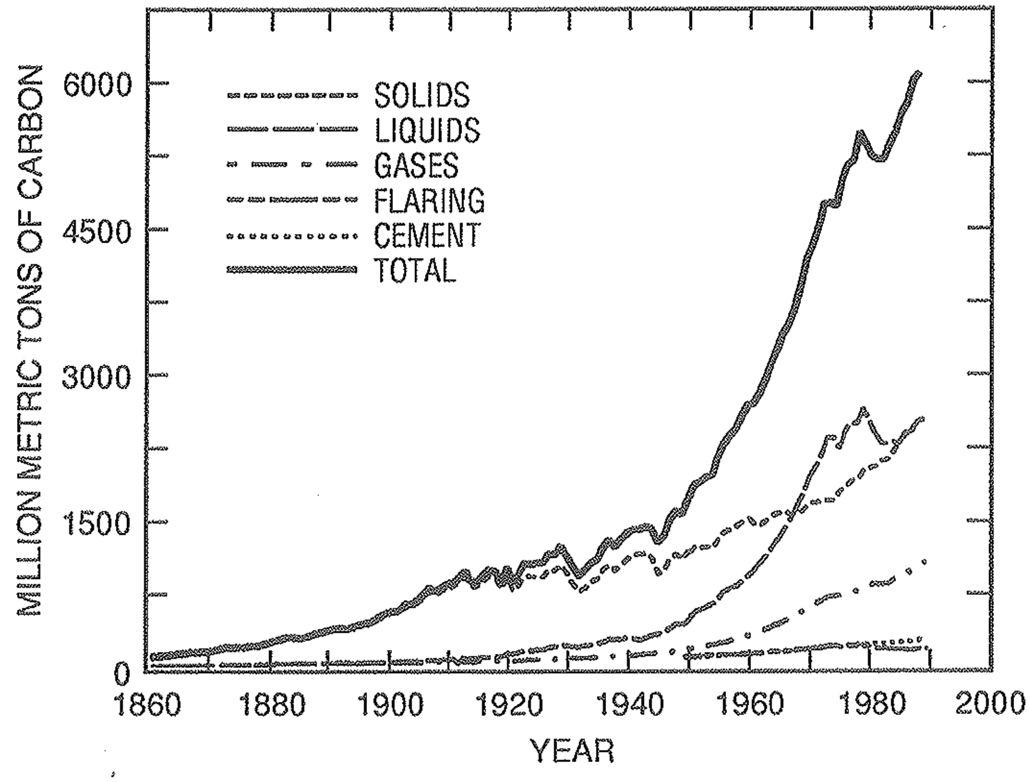


Fig. 2.1. Global CO_2 emissions from fossil fuel burning, cement production, and gas flaring from 1860 to 1989. (*Source:* CDIAC 1992)

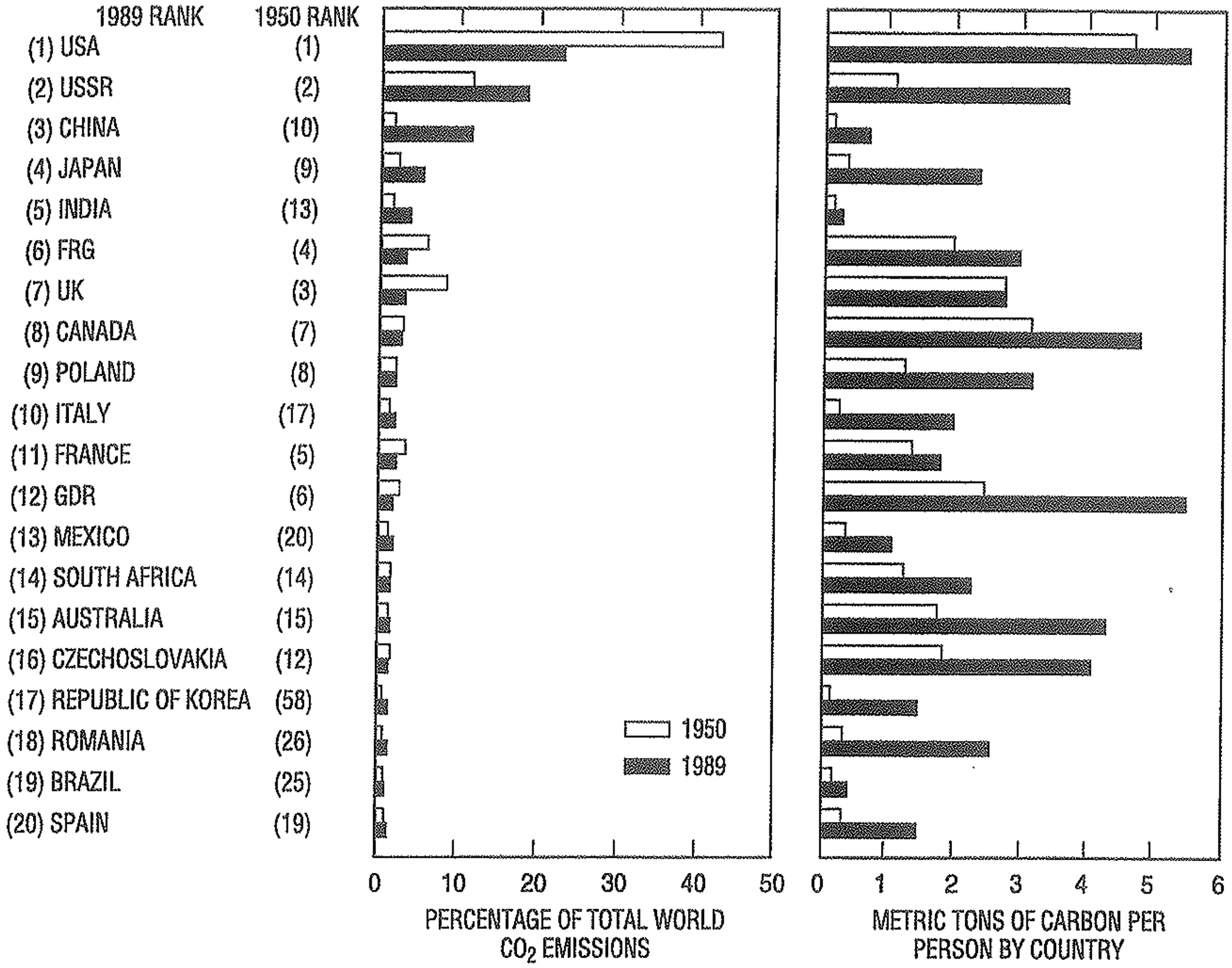


Fig. 2.2. National emissions of CO_2 for the 20 highest emitting countries in 1989, along with their rank in 1950 and their 1989 per capita emissions. (*Source:* CDIAC 1992)

concentration in the atmosphere. In Fig. 2.3, Segalstad and Jaworowski (1991) illustrate the contributions of natural forcing to global warming versus the contributions of man. As shown in the figure, the total forcing of 146 ± 5 W/m^2 due to greenhouse gases in a cloud-free atmosphere can be altered by the influence of clouds. The forcing due to cloud absorption and reflection of radiation can range from +30 W/m^2 to –50 W/m^2, whereas man's contribution to forcing due to CO_2 emissions is only 2 W/m^2. Note, however, that the role of clouds in global warming is not yet fully understood and man's contributions to global warming are more easily controlled than natural ones.

From another viewpoint, reports from the National Academy of Sciences (NAS) in the U.S. conclude that neither the available climate record nor the limited capabilities of the climate models permit a reliable forecast of the implications of continued accumulations of greenhouse gases in the atmosphere. The NAS could not

Table 2.3. Distribution of emissions in Organization for Economic Co-operation and Development (OECD) and non-OECD regions

	Carbon (million tons)[a]				
	1971	1975	1980	1985	1988
		OECD			
Canada	94	109	124	115	124
USA	1209	1240	1369	1339	1433
Japan	217	252	261	253	272
France	126	126	139	109	103
Germany[b]	208	198	219	200	198
Italy	92	97	106	101	108
UK	187	170	167	159	163
North America	1302	1349	1493	1453	1557
OECD Pacific	270	312	330	325	350
OECD Europe	855	860	934	870	886
		Non-OECD			
Africa	141	162	202	256	273
America	195	233	289	305	334
Asia	266	308	386	458	538
Eastern Europe	322	360	424	444	452
Middle East	60	70	102	144	169
USSR	691	800	907	960	1025
People's Republic of China	276	356	460	584	670
OECD	2427	2522	2756	2648	279
World	4750	4811	5528	5802	62563

[a] Data refer to man-made emissions from energy use only.

[b] Includes western Germany only.

Source: Adapted from OECD 1991.

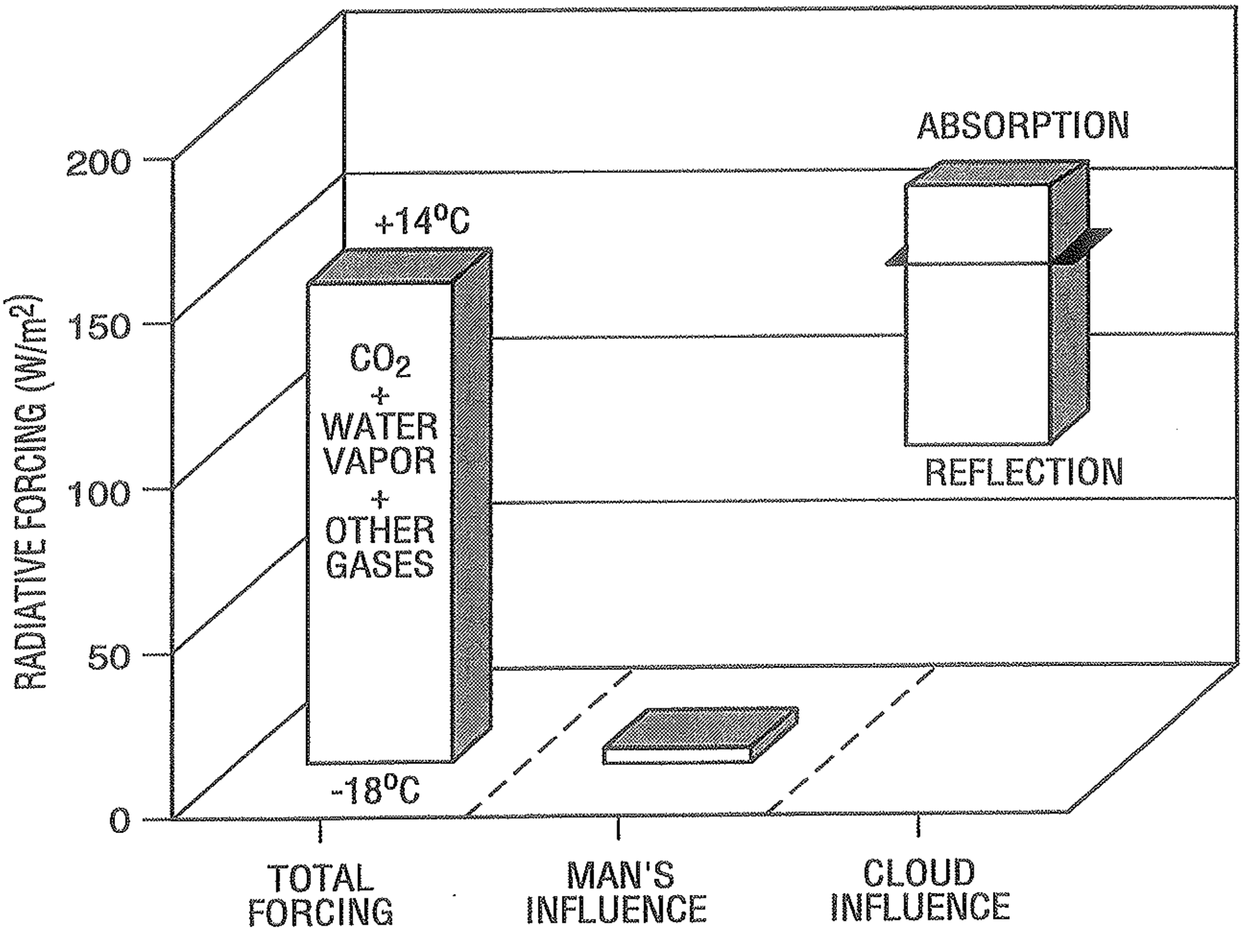


Fig. 2.3. Man's influence on the radiative forcing responsible for global warming. (*Source:* Adapted from Segalstad and Jaworowski 1991)

state that global warming will occur, though human activities of modern society suggest a good likelihood it will happen. In the most recent summary of findings on climate effects, mitigation, and adaption, the NAS (1991) explains that based on current science, it is a legitimate logical extrapolation to conclude that there is either a slight or a significant climate change problem. The NAS also believes that unless a greater human effort is made to slow down greenhouse gas emissions, there is a reasonable chance that concentrations of such gases in the atmosphere will be equivalent to double the preindustrial level by the year 2050. Benarde (1992) presents a balanced summary of all the complex interactions involved in the greenhouse effect and discusses the ongoing debate regarding the role that man's activities may play in global warming. It is important to note the following:

1. The "average temperature" of the atmosphere results from a complicated atmospheric energy balance involving incoming solar radiation; the extent to which the atmosphere reflects, absorbs, emits, and transmits radiation; the

existence of nonsensible energy sinks (primarily associated with the freezing, thawing, evaporation and condensation of water); and the exchange of sensible energy between the atmosphere and the Earth's surface, particularly the oceans.

2. Since the three gases that predominate in the atmosphere (oxygen, nitrogen, and argon) do not absorb significant electromagnetic radiation in the infrared portion of the spectrum (thermal radiation), the radiation absorption properties of the atmosphere depend on the levels of gases that do absorb radiant energy in the infrared band. These gases have been referred to as "radiatively important trace gases" (RITG). Of these, CO_2 is the most commonly mentioned.

3. There is scientific evidence that correlates the CO_2 concentration in the atmosphere with the global temperature (Benarde 1992).

4. Although CO_2 is the dominant RITG and, "Mitigation of these releases must therefore be the backbone of any climate-stabilization policy" (Krause, Bach, and Koomey 1992), other gases (CH_4, N_2O, O_3, water vapor, and CFCs) have effects that may be orders of magnitude greater on a molecule-by-molecule basis, and some of these gases are associated with the production, transportation, and use of fuels.

5. In addition to the RITGs listed above, there are other gases called "chemically-photochemically active trace gases" such as CO, NO_x, and sulfur dioxide (SO_2) which exert indirect climatic effects through their effects on the atmospheric concentrations of hydroxyl radicals, CH_4, and O_3 (Krause, Bach, and Koomey 1992).

6. Volcanic eruptions have had tremendous short term effects on climate, but these effects are consistent with global cooling rather than global warming. For example, the extinction of dinosaurs has been attributed to global cooling caused by large amounts of particulates added to the atmosphere from a volcanic eruption or a meteorite impact upon the Earth.

7. Although great strides have been made in climate modeling, there are still important effects that are not universally understood. Three of these are the role of clouds, the interaction of the atmosphere with the oceans, and the role that the oceans play in sequestering carbon.

2.1.2.2 Modeling and predictions

Predictions of climate changes (surface air temperature changes) due to natural and man-made releases of greenhouse gases are being performed by means of mathematical models. The more sophisticated, three-dimensional general circulation models (GCMs) jointly solve equations for some interactions of atmosphere–land–sea–ice for atmospheric chemistry; for wind motions; for circulations in oceans; for evaporation of water and condensation to form clouds, rain or snowfall; and surface properties (albedo, soil, hydrology). When the atmospheric components are linked with oceanic components of equal complexity, the models are named coupled GCMs (CGCMs). The ocean models used so far have been less comprehensive than the atmospheric models.

The resolution of models is still rather coarse (grid squares with sides up to 500 km), and the models include only radiative forcing induced by greenhouse gases. They have been used mainly to simulate results of parameter settings at equilibrium conditions (e.g., doubling the CO_2 levels). Climate changes (temperature, rainfall pattern) over time may influence the responses of various ecosystems and change natural emissions of greenhouse gases, soil hydrology, and surface radiative properties, creating feedback mechanisms. These are presently difficult to estimate, even directionally, and they have not been included satisfactorily in the climate models, increasing the uncertainty of the results of model calculations. Presently more transient model studies with CGCMs have been performed and are being assessed, such as modeling increasing levels of CO_2 over time. For models with improved regional resolution, computers with increased capacity will be required.

Computer models predict that the changes in the levels of greenhouse gases that have already occurred should eventually cause a global annual mean surface temperature increase of between 0.8 and 2.6°C. The thermal inertia of the ocean prevents the climate from responding immediately to greenhouse forcing and has reduced the expected warming during the past century to somewhere between 0.5 and 1.3°C. The lower predicted value is thus just barely consistent with the observed warming of about 0.5°C (Jones and Wigley 1990).

An interesting result of an independent model run (Schlesinger and Jiang 1991) is that if the recommended reduction of releases of greenhouse gases is postponed 10 years, the penalty in increased temperature rise by 2100 will be only 0.05°C. These researchers argue that strong and costly measures for reduction of greenhouse gases could be delayed and the time used to improve the climate models to obtain more certain results as a basis for the measures. A delay, however, means that stronger measures must be taken when mitigation is started.

2.1.2.3 The Intergovernmental Panel on Climate Change study

Because of concerns about the possible effects of accelerated global warming, an Intergovernmental Panel on Climate Change (IPCC) under the auspices of the United Nations Environment Program and the World Meteorological Organization was formed in 1988 to assess the scientific knowledge on climate change. The work also has OECD/International Energy Agency support. The report considered several worldwide emissions scenarios to determine the severity of global warming, but it did not specifically address the impact transportation has upon global warming. It did look at overall trends in globally averaged emissions and provided valuable insight into the state of the atmosphere.

The first assessment report was issued in August 1990 (IPCC 1990), and a supplement was issued in February 1992 (IPCC 1992), finalizing the short-term work. About 175 scientists from 25 countries participated in preparing the reports, which were critically reviewed by 200 other scientists. A majority of the participants did agree on the findings, although there was not complete consensus on the conclusions in the reports.

The IPCC work is still in progress. From the reports published to date, the major conclusions of IPCC are as follows.

1. Emissions from human activities are increasing the concentrations of greenhouse gases (CO_2, CH_4, CFCs, N_2O).
2. Doubling the CO_2 concentration in the atmosphere is likely to increase the global mean surface temperature by 1.5 to 4.5°C.
3. Many uncertainties exist because of incomplete understanding of the mechanisms influencing timing, magnitude, and regional patterns of climate change.
4. Global mean surface temperature has increased by 0.3 to 0.6°C over the last 100 years, which is broadly consistent with predictions by models, but also of the same magnitude as the natural variability.
5. Detection of an enhanced greenhouse effect on surface temperature from observations is not likely for a decade or more.

Some additional findings from the more recent IPCC work that are related to the impact of transportation on the environment are as follows.

1. The decrease in radiative forcing due to the depletion of stratospheric O_3 over the last decade is believed to have been offset by the contribution of CFCs.
2. Aerosols produced from sulphur emissions have a cooling effect that may offset some of the greenhouse warming in the Northern Hemisphere.
3. The rates of increase in the atmospheric concentrations of CH_4 and some halogen compounds have slowed in the last decade.

Global surface temperature changes

IPCC's estimate of the present rate of temperature increase is about 0.3°C per decade (0.2 to 0.5°C), which would mean a 2° increase above the preindustrial level by 2030. The Stockholm Environment Institute has proposed that the rate of 0.1°C per decade is the maximum nature can accommodate, and a total increase of 1°C should represent a low risk limit and 2°C a high risk limit. A global increase above 2 to 3°C would mean a temperature level the Earth has not experienced during the last 120,000 years (Swedish EPA 1992).

Future predictions

The basis for long-term modeling work must include assumptions on emissions of greenhouse gases in the future, so IPCC constructed a number of alternative scenarios, IS92a-f, (IPCC 1992) with two time horizons (2025, 2100), assuming different developments for the world population, economic growth, energy intensity, carbon intensity, supplies and costs for conventional and new energy sources, tropical deforestation, and legislation, as summarized in Table 2.4.

In all scenarios, the carbon emissions increase in the medium time frame (2025). Thereafter, they continue to increase unless (IS92d and c) the population stabilizes at a low level, availability of fossil fuels is restricted, costs for renewables are brought down, and emission controls are legislated worldwide (and CFCs are phased out). The commitment of many OECD countries to stabilize or even reduce present CO_2 emissions has only a small effect (IS92b) in the long-term compared with the business-as-usual scenario.

The resulting outcome of modeling the temperature change for the IPCC scenarios described is illustrated in Fig. 2.4. Only in the d and c scenarios does the temperature change stay within the proposed, tolerable risk levels (1 to 2°C in 2100). Figure 2.5 illustrates the global average temperature changes for the IPCC business-as-usual scenario. The results may be somewhat more favorable if the model is improved by incorporating feedback from the biosphere (CO_2-fertilization) and by forcing reduction by sulfate aerosol and stratospheric O_3 depletion. Inclusion of the effects mentioned may bring down the predicted temperature change in a long-term perspective (the year 2100) to approximately 1.3°C (Wigley and Raper 1992).

The IPCC predictions of future climate change are based on results from runs with theoretical models, and there are many deviations from real world observations. The models, which are not validated, include only radiative forcing induced by greenhouse gases and do not include feedbacks of biological changes on land or in the sea. In addition, the role of important feedback mechanisms such as water vapor, aerosols, and cloud formation is still uncertain. The confidence in regional climate change patterns therefore remains low. At present it is not possible to determine the validity of these models and the chances of being able to do so in the next decade are small. Improvements in the models have, however, led to reduced greenhouse warming predictions compared with the first results (Schlesinger and Jiang 1991; Wigley and Raper 1992). Although researchers in modeling seem convinced that the models at least give directionally correct results, contrary opinions have been expressed.

Table 2.4. Summary of assumptions in the Intergovernmental Panel on Climate Control's six 1992 alternative scenarios (IS92)

Scenario	Population 2100 (billions)	Economic growth	Energy supplies[a]	Other	Chlorofluorocarbons (CFCs)
IS92a	11.3	1990-2025 2.9% 1990-2100 2.3%	12,000 EJ conventional oil. 13,000 EJ natural gas. Solar costs fall to \$0.075/kWh; 191 EJ of biofuels available at \$70/barrel.	Legally enacted and internationally agreed controls on SO_x, NO_x and NMVOC emissions.	Partial compliance with Montreal Protocol. Technological transfer results in gradual phase out of CFCs also in nonsignatory countries by 2075.
IS92b	11.3	1990-2025 2.9% 1990-2100 2.3%	Same as IS92a.	Same as IS92a plus commitments by many OECD countries to stabilize or reduce CO_2 emissions.	Global compliance with scheduled phase out of Montreal Protocol.
IS92c	6.4	1990-2025 2.0% 1990-2100 1.2%	8000 EJ conventional oil. 7300 EJ natural gas. Nuclear costs decline by 0.4% annually.	Same as IS92a.	Same as IS92a.
IS92d	6.4	1990-2025 2.7% 1990-2100 2.0%	Oil and gas same as IS92c. Solar costs fall to \$0.065/kWh; 272 EJ of biofuels available at \$50/barrel.	Emission controls extended worldwide for CO, NO_x, NMVOC, and SO_x. Halt deforestation. Capture and use of emissions from coal mining and gas production and use.	CFC production phase out by 1997 for industrialized countries. Phase out of HCFCs.
IS92e	11.3	1990-2025 3.5% 1990-2100 3.0%	18,400 EJ conventional oil. Gas same as IS92a. Phase out nuclear by 2075.	Emission controls (30% pollution surcharge on fossil energy).	Same as IS92d.
IS92f	17.6	Same as IS92a	Oil and gas same as IS92e. Solar costs fall to \$0.083/kWh. Nuclear costs increase to \$0.09/kWh.	Same as IS92a.	Same as IS92a.

Abbreviations: EJ = exajoule, SO_x = sulfur oxides, NO_x = nitrogen oxides, NMVOC = nonmethane volatile organic compounds, OECD = Organization for Economic Cooperation and Development, CO_2 = carbon dioxide, kWh = kilowatt-hour, CO = carbon monoxide, and HCFC = hydrochlorofluorocarbon.

[a] All scenarios assume coal resources up to 197,000 EJ. Up to 15% of this resource is assumed to be available at \$1.30/gigajoule at the mine.

Source: Adapted from IPCC 1992.

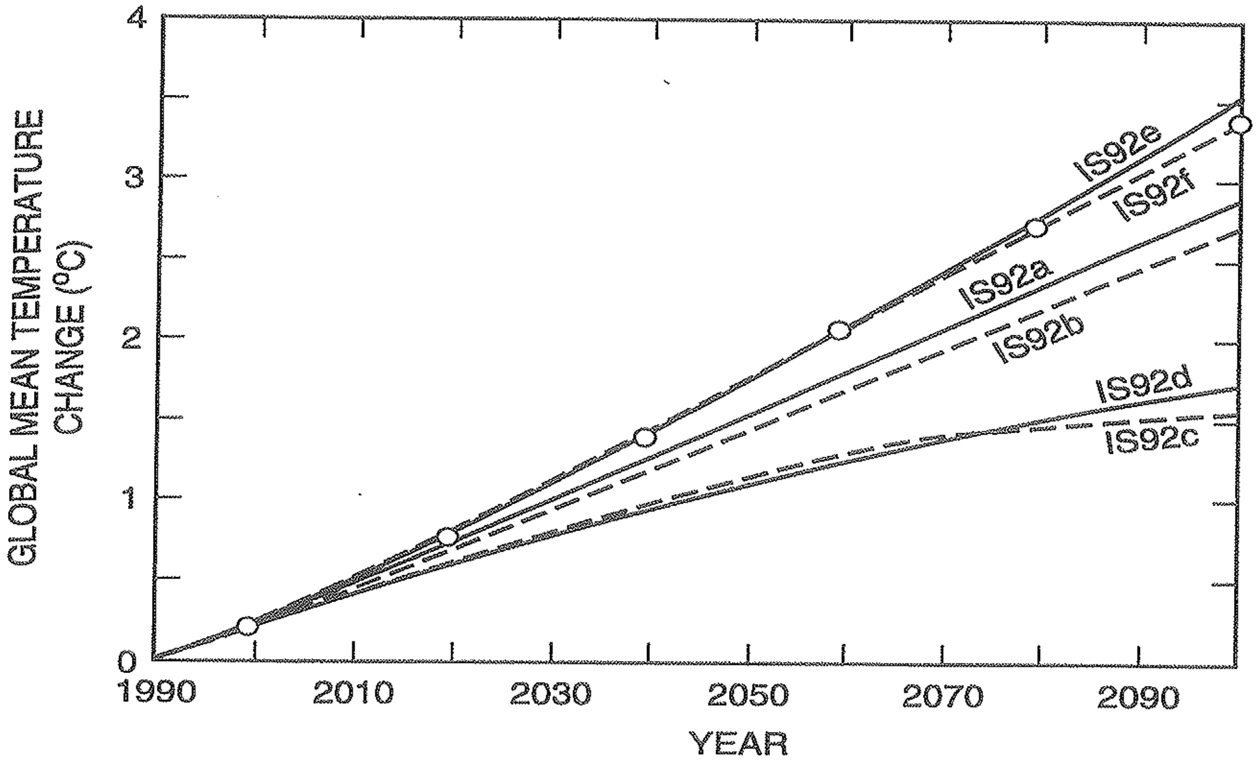


Fig. 2.4. Predicted temperature change for all Intergovernmental Panel on Climate Change scenarios. (*Source:* IPCC 1992)

Other studies

Among other reports on greenhouse warming, a 1991 scientific study from the NAS should be mentioned (NAS 1991). It broadly agrees with the IPCC assessment. There are, however, several studies expressing opposing conclusions such as reports from the Marshall Institute in the United States.

The Marshall Institute concluded that current forecasts of man-made greenhouse effects do not appear sufficiently accurate to be used as a basis for sound national policy. The institute predicted warming by the mid-21st century in the range of 0.4 to 1.8°C based on temperature changes over the past 100 years, with certain modifications. This is a range far lower than IPCC's best estimate of 2.5°C warming from a doubling of CO_2. The institute also comments that IPCC's estimate is based almost entirely on computer simulations whose predictions for the greenhouse effect currently disagree with observations in nearly every important respect.

2.1.2.4 Transportation and global warming

Determining the role that transportation fuels play in global warming is more complicated than simply examining the tailpipe emissions from conventional and

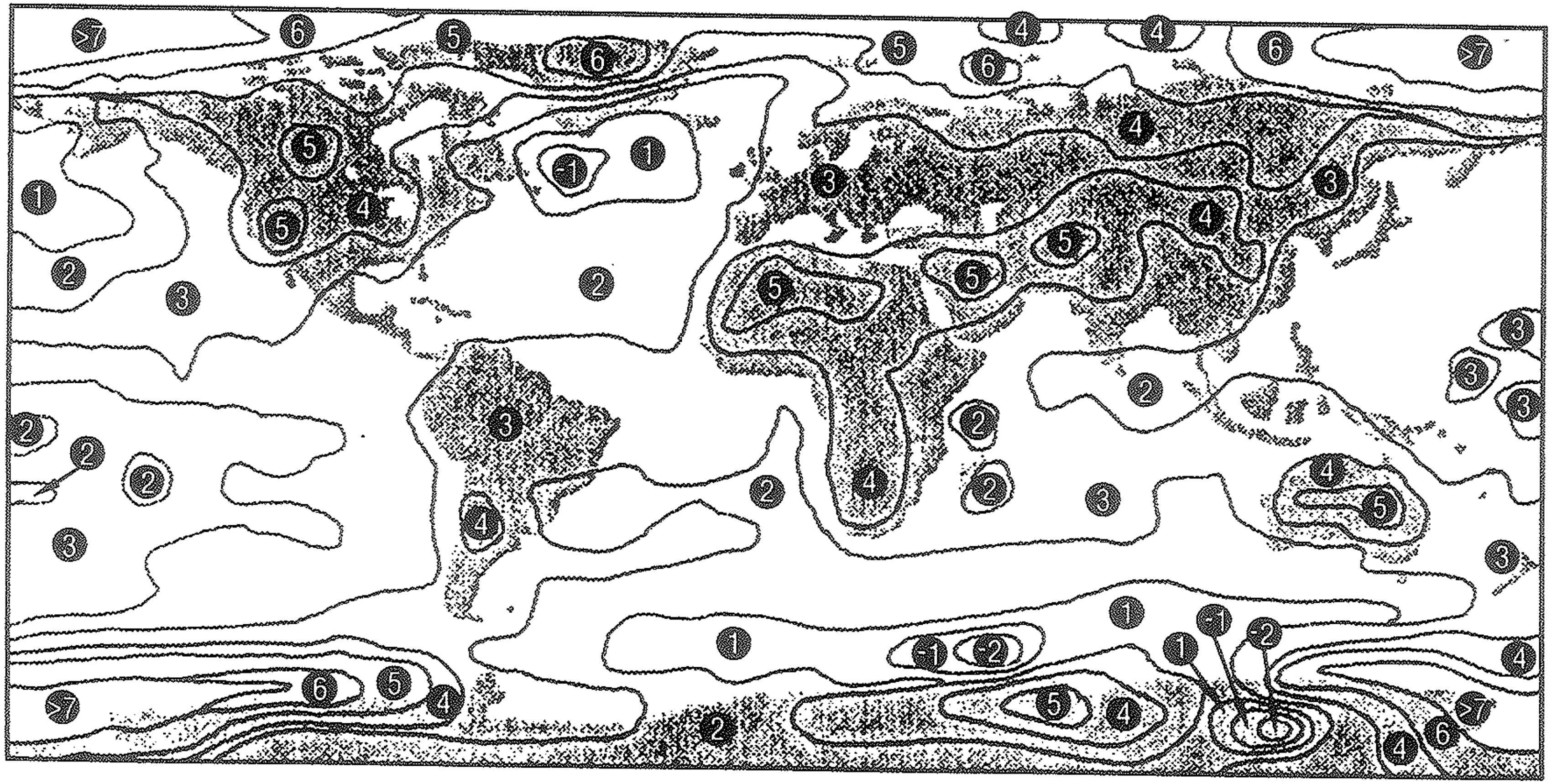


Fig. 2.5. **Predicted increase in average temperatures (in °C) by 2085 from the Intergovernmental Panel on Climate Change business-as-usual scenario.** (*Source:* Adapted from Cubasch et al. 1991)

alternative fueled vehicles—the production and transportation of the alternative fuel must also be considered (OECD 1993). It is an even more formidable task to evaluate the merits of each fuel when one considers alternative feedstocks for "manufactured" fuels. For example, methanol made from coal using traditional partial oxidation and catalytic syntheses processes produces a substantially higher CO_2 burden on the environment than does methanol made from natural gas. The situation becomes even more complicated when one considers fuels made from biomass, because then one must consider different scenarios for the fuel used in the planting, fertilizing, cultivation, harvesting, and transportation of the crop; the source of energy used in the production facility; and the effects of fertilization on emissions of the various oxides of nitrogen due to nitrification and denitrification. It is for this reason that one can read what appear to be conflicting claims related to the global warming potential of various alternative fuels—the differences in the analyses are often found in the feedstock and production scenarios used and the effects considered.

To quote DeLuchi (1991) from his discussion of various ethanol production scenarios in which he found global warming effects ranging from a 60% decrease to a 50% increase over the gasoline base case, "The general message of these corn-to-ethanol scenarios is that one can pick values for a set of assumptions that will support virtually any conclusion about the impact of the corn-to-ethanol cycle on global warming."

In addition, while the present study deals with the effects of fuels, it is significant to note that for air-conditioned vehicles the release (due to leakage or improper servicing) of CFCs has been shown to be as important to global warming as the fuel used, and the elimination of CFCs from automobile air-conditioning systems (which is being done to slow the depletion of stratospheric O_3) coupled with responsible servicing procedures will, for those vehicles affected, have a great impact on their contributions to global warming. Amann (1990) performed some calculations to support his conclusion that when service is conducted on an automobile equipped with a CFC-12 air-conditioning system without recovering the refrigerant, "the greenhouse effect of the air conditioner is greater than that of the CO_2 emitted from the tailpipe during the lifetime of the vehicle."

However, the IPCC (1992) has suggested that the warming effect of CFCs in the troposphere may be offset by the cooling effect of the CFC depletion of O_3 in the lower stratosphere.

2.1.2.5 Other production contributions to greenhouse gases

Atmospheric gas inventory changes from the production of methanol, ethanol, and electricity depend on the methods by which these materials are produced. Methanol can, for example, be produced from natural gas, from synthesis gas, and from coal. Ethanol can similarly be produced from a variety of petroleum, biomass, coal, and waste sources using many different processes. Electricity is also produced using a variety of sources and processes including coal boilers, gas turbines, and hydroelectric generation. In the future, as in the present, a mixture of methods will be used to produce these fuels. The following generalizations provide a basis for minimizing greenhouse gas accumulation during processing.

1. Coal has a lower content of hydrogen, relative to carbon, than do other sources of alternative fuels. For a given amount of energy, coal will produce a higher amount of CO_2 than fuels higher in hydrogen. Electrical energy and liquid fuels produced from coal result in a higher production (and short-term atmospheric accumulation) of CO_2 (Edmonds et al. 1989; Santini et al. 1989; Steinberg 1983; Steinberg, Cheng, and Horn 1984).

2. Because of the probable contribution of coal use to greenhouse gas accumulation, a variety of methods for sequestering carbon or CO_2 from coal while producing liquid and gaseous fuels have been developed (Morris et al. 1992; Steinberg 1983; Steinberg et al. 1984; Steinberg, Lee, and Morris 1991). Most of these technologies have not been tested at an industrial scale.

3. Substitution of CH_4, or natural gas, for coal in electrical generation could substantially decrease short-term atmospheric accumulation of CO_2.

4. Flaring, venting, and other energy-inefficient uses of CH_4 contribute to greenhouse gas accumulation (from both CH_4 and from CO_2) while providing minimal benefit.

5. Production of ethanol and methanol from biomass and waste sources forms a part of United States and European strategies for reducing greenhouse gas accumulation. This is based on the premise that CO_2 made from biomass carbon will be balanced by biomass production (Tyson, Riley, and Humphreys 1993). However, this assumption neglects short-term CO_2 and CH_4 accumulation due to inefficiencies in storage, transportation, and processing. Most calculations also appear to neglect the carbon sequestered in weed and scrub biomass displaced by improved farming techniques.

6. It is difficult to control the short term accumulation of CH_4 in the atmosphere because it is produced by a wide variety of geological, biological, and industrial sources.

7. As noted by the OECD, renewables (wind, ocean thermal, hydrogen) and nuclear energy sources can power central station electrical generation (1988). This can be used to recharge batteries.

Further study to better evaluate the role of production processes in minimizin t0he accumulation of greenhouse gases is needed. Government encouragement of th selection of appropriate fuels production and process technologies could also play factor in decreasing accumulations of greenhouse gases.

2.1.3 Stratospheric O_3 Depletion

The stratosphere (that part of the atmosphere ranging from 15 to 50 km altitude) contains O_3 at its outer region, which is created when ultraviolet light causes diatomic oxygen to split and then react with other oxygen molecules to form the triatomic molecule O_3. The O_3 acts not only as a strong infrared absorber (thus it has global warming implications) but also as a major absorber of incoming ultraviolet radiation. Since ultraviolet radiation falls in the photoabsorption spectrum of both DNA and RNA (Benarde 1992), exposure of humans to ultraviolet radiation can lead to skin cancer and cataracts (among other things). Ultraviolet radiation can also have severe effects on simpler life forms: its destruction of plankton in the oceans, for example, has implications not only for the food chain, but also for global warming because the plankton represents a significant CO_2 sink (Benarde 1992).

The greatest threat to the O_3 layer has been identified as chlorine in the stratosphere. The presence of chlorine there has been traced to the release of CFCs in the troposphere and their subsequent transport to the stratosphere where, when exposed to ultraviolet radiation, they release free chlorine. Other stratospheric ozone-destroying chemicals associated with motor vehicles are N_2O and NO_x. CH_4 also interacts with other chemicals in the stratosphere to influence the formation and destruction of O_3 (Krause 1992).

2.1.4 Acid Deposition

2.1.4.1 Introduction

The term "acid rain" is often used to describe the wet deposition of excess amounts of acids or acid precursors found in the atmosphere on the Earth's surface. However, this report discusses the impact of both dry and wet deposition of acidic compounds on the environment, and therefore the more general term "acid deposition" is used. The phenomena associated with the formation of acid deposition and the effects of excess acid deposition on the ecosystem have been the subject of intense study for decades. The effects are reversible, provided acid deposition ceases or is dramatically reduced (NAPAP 1987; Barth 1987). The most significant contributors to acid deposition are ammonia, sulfur oxides (SO_x), and NO_x. These compounds have been found to have adverse effects on soil, water, plants, animals, and building materials.

2.1.4.2 Origins

Man-made emissions of SO_x are estimated to be about equal to those of natural origin (OECD 1991). Sources of man-made SO_x emissions include the combustion of fuels, particularly heavy oils and coals, and some industries like sulfide ore smelters. The transportation sector is responsible for only a small part (a few percent) of these emissions due to the relatively low content of sulfur in the bulk of road vehicle fuels. The main contribution of the transportation sector to the problem of acid deposition is the emissions of NO_x. Emissions of NO_x are mostly man-made; natural sources only contribute around 10 to 15% of the total NO_x emissions. In the United States and Europe, the transportation sector is responsible for approximately 44% of the man-made NO_x emissions (NAPAP 1987; Derwent, Grennfelt, and Hov 1991).

2.1.4.3 Environmental impact

Water and soil

Soil acidification is an environmental threat because it reduces the availability of many nutrients for plant growth; it increases the solubility of metals (aluminum, cadmium, copper, lead), which can contaminate the ground water; and it can acidify surface and ground water. Man contributes to soil acidification by overfertilizing, removing vegetation by "clear cutting," and producing acids in the atmosphere that are deposited on the soil.

Surface waters and groundwater stores situated close to surface soils are subject to the effects of soil acidification. Acidified water can lead to corrosion in pipe supply systems and to adverse health effects due to the increased contents of harmful metals in drinking water. Acid water may also contain increased amounts of cadmium, aluminum, lead, and copper through leaching from the bedrock and from corrosion of galvanized pipes, copper pipes, and soldering material. For example, the cadmium content has been shown to be about three times higher at a pH of 5 than at a pH of 6 and increased aluminum concentrations have been reported at a pH below 5.5. Copper also causes discolorations of water at concentrations >1 mg/liter (Swedish EPA 1990a).

Forests

Since the late 1960s, significant changes in forest growth have been observed in both Europe and North America (although earlier observations had been made in the vicinities of heavily emitting industries). Although rather high concentrations are needed to cause immediate visible damage, (e.g. nitrogen dioxide (NO_2) concentrations $> 1000\ \mu g/m^3$), negative effects start at much lower concentrations for long-term exposures, (e.g. $30\ \mu g/m^3$ of NO_2 and $20\ \mu g/m^3$ of SO_2). There are also synergistic effects between sulfur, NO_x, and O_3 that enhance the damage (UNECE 1993).

Other flora, fauna, and man

Both acidification and overfertilization will decrease biological diversity on land and in water. Obvious effects of acid and nitrogen deposition have been noted for mosses and lichens growing on trees and other solid surfaces and for increased growth of green algae. Flower species characteristic of previously nitrogen-deficient fields may disappear completely. Changes in soil conditions (pH, increased nitrogen availability, decreased availability of nutrient salts and trace compounds) will also change the conditions for parasitic and disease attacks on plants, favoring different plants than before. The effects of increased nitrogen content in waters combined with the presence of nutrient salts may lead to increased algae production and uncontrollable growth—choking streams, lakes, and coastal waters. Aquatic life that is intolerant to changing pH levels will simply disappear and new, more tolerant species will take over lakes and streams.

The effects of air contamination by sulfur and NO_x on the land-living fauna are less dramatic than for the water-living fauna and occur more slowly. They are therefore more difficult to find, prove, and quantify. There are, however, many indications that fauna changes occur through indirect effects of acidified soils and waters and also possibly through increased nitrogen load. Potential health risks to man and animals can occur directly as a result of the inhalation of acid compounds affecting the respiratory system and of the ingestion of drinking water and food containing toxic metals (e.g., cadmium, mercury, aluminum, copper, lead).

Materials

Corrosion of steel, galvanized steel, reinforced concrete structures, and old steel and cast iron water pipes is of great concern. Atmospheric corrosion of steel and other metals such as zinc and nickel has been found to accelerate strongly in the presence of SO_2. Recent investigations have also shown a synergistic effect with NO_2 and O_3 which increases corrosion rates several times. Carbonate-containing stone material, limestone bonded sandstones, masonry, plaster, textiles, and paper are sensitive to acid breakdown with synergism also observed between sulfur and NO_x. Paints, particularly on glass, can also be sensitive to acid breakdown (Swedish EPA 1990b).

2.1.4.4 Critical and target loads

Deposition of acid and nitrogen compounds must be put in the context of what various ecosystems can tolerate. To this end, the concept of "critical load" has been established. The critical load is defined as "a quantitative estimate of an exposure to one or more pollutants, below which significant, harmful effects on specified sensitive elements of the environment do not occur according to our present knowledge" (Nordic Council of Ministers 1986).

The critical load is thus the exposure or dose per unit area per unit time. (The term "critical level" is used to describe exposure due to gaseous pollutants.) Critical loads are used to set goals for future deposition rates of acidifying compounds based on the measured response of selected biological receptors. Scientific evaluations of long-term effects are the basis for figures on critical loads (Nordic Council of Ministers 1986).

Critical load values for acidification and nitrogen deposition depend on several interrelated environmental factors and can vary widely from one region to the next. For example, in the Northern Hemisphere, the most sensitive areas have critical loads of less than 3.2 kg of sulfur per hectare per year, while the least sensitive areas may have critical loads in excess of 32 kg of sulfur per hectare per year. For nitrogen deposition in the Nordic countries, the maximum critical load was calculated to be 35 kg of nitrogen per hectare per year and the minimum critical load was 1.3 kg of nitrogen per hectare per year. Deposition rates are in the range of 3–25 kg per hectare per year (Kessler and Brodin 1992; Hettelingh 1991).

The concept "target load" is used to define a (short-term) goal for measures needed to improve the current situation. The target load may be set higher than the critical load if the environmental impact can be accepted for a short period of time, but it may also be set lower to include a safety margin because of uncertainties in the impact or critical load value. Determination of a target load includes a technical, economical, and political evaluation of what is achievable during a certain time frame. It may also include human values and preferences.

2.1.4.5 Assessing acid and nitrogen deposition

Maps of critical loads and of areas receiving more than their critical loads are used as a basis for negotiations between countries on the reduction of depositions and emissions. For assessment of the effects of abatement programs, modeling is used to link emissions to critical or target loads. A number of models are available, which all use

1. energy demand forecasts for country, fuel, use sector, fuel sulfur, and combustion equipment to estimate emissions;
2. dispersion models [e.g., the European Monitoring and Evaluation Programme (EMEP) grid cell model] to obtain depositions;
3. models linking depositions to critical or target loads; and
4. estimates of emission control costs.

Many parts of Europe, particularly in the north and the northwest, have a high sensitivity to acid deposition; and large areas currently receive high acid loads that continue to contribute to the damage of forests and surface waters. A comparison of levels of acid deposition and critical loads shows that the highest excesses for many ecosystems occur in central and northwestern Europe. Present loads of acidic deposition are higher than the lowest critical loads in roughly 75% of Europe. Parts of central northwestern Europe receive more than 20 times the critical loads of the most sensitive ecosystems (usually lakes), thus threatening the long-term sustainability of these ecosystems. In Finland, Norway, and Sweden, the critical loads are presently exceeded in almost 82% of the soil (Kessler and Brodin 1992).

For the Nordic countries, the question of whether critical loads can be reached at all was assessed by investigating scenarios involving the current reduction plans and the maximum feasible reductions plus increased energy efficiency in eastern Europe. As Fig. 2.6 indicates, the percentage of lakes exceeding the critical loads may be reduced from 33% to less than 8%, and the percentage of forest soils exceeding the critical loads may be reduced from 74% to less than 11%. Although the acidification problems could not be solved entirely, significant improvements seem possible, and only the most sensitive areas may require restoration by liming or other measures. However, it has been found that mapping on the European scale does not provide sufficient resolution for national assessment and determination of target loads. Similar modeling for Sweden indicates that even with 70% reduction of acidifying deposition to the year 2010, large areas will be left with 10 to 50% of the lakes (more that 50% in some areas) above the critical loads (Kessler and Brodin 1992).

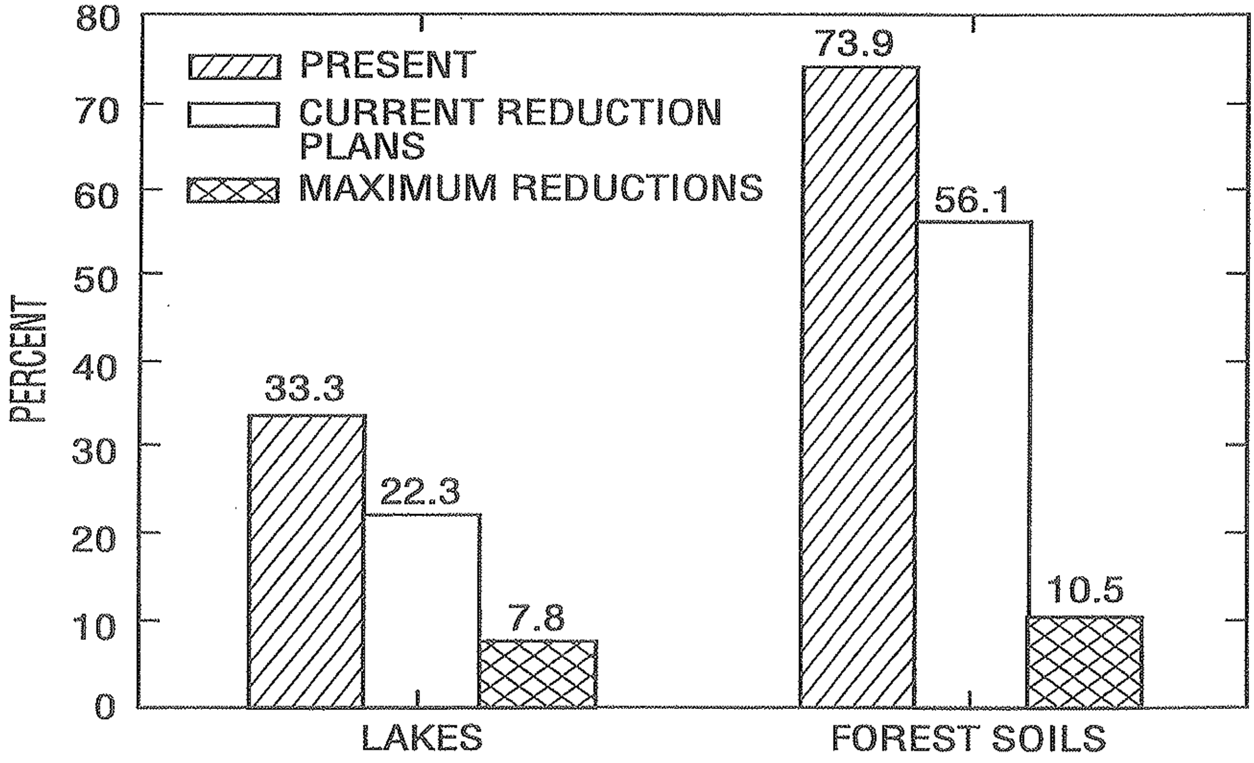


Fig. 2.6. Percentage of lakes and forest soils in Nordic countries exceeding critical load values. (*Source:* Adapted from Kessler and Brodin 1992)

In Tables 2.5 and 2.6 data on past, present, and projected emissions of SO_2 and NO_x are given for the year 2000. The projected emissions are based on calculations using the EMEP model. Three different scenarios are used. One assumes that current reduction plans (CRP) are followed, while the remaining two assume that all available emission control technologies are applied resulting in "maximum technically feasible reductions" (MTFR). One MTFR case assumes that emissions from coal burning in Eastern Europe cannot be eliminated (CEE) and the other assumes that substantial improvements of the energy efficiency in Eastern Europe are obtained (EEE) (Lövblad et al. 1992).

As Table 2.5 indicates, the SO_2 emissions from Europe in the year 2000 will be 30% lower than the 1980 emissions based on the CRP. The MTFR scenarios indicate, however, that the European reductions of the SO_2 emissions could be cut by 81% (CEE) and 86% (EEE) respectively. Model calculations assuming even reductions in all grids of a country indicate that although the domestic Nordic emissions would decrease by almost 70%, sulfur deposition in the Nordic countries would decrease only by 40 to 60%, due to their downwind position (Lövblad et al. 1992).

Nitrogen oxide emissions will tend to increase up to the year 2000 due to strong increases in emissions from those countries that have not signed the nitrogen protocol, although twelve Western countries have declared their ambition to reduce emissions by 30%. The future EEE scenario, however, shows a potential NO_x reduction of 60% as technically feasible (Lövblad et al. 1992).

2.2 REGIONAL AND LOCAL AIR QUALITY EFFECTS

2.2.1 Introduction

Regional air quality, in the context of this report, refers to the quality of air masses encompassing large metropolitan areas or those enclosed by distinct geographical features such as river valleys or coastal basins. Local air quality refers to the air quality in cities or urban areas. The oftentimes visible pollution in such areas is caused by particulates and complex chemical interactions between volatile organic compounds (VOCs), various oxides of nitrogen, carbon oxides (CO, CO_2, . . .), and other substances. These interactions lead to the production of tropospheric O_3 and to the enhancement of the greenhouse effect, both of which can be detrimental to life on earth. The greenhouse effect is not a regional air quality problem and is discussed in terms of global warming in other sections of this report. Tropospheric O_3 production and the emission of particulates are the air quality problems considered here.

The troposphere is the first 10 km layer of the Earth's atmosphere and tropospheric O_3 is the O_3 produced in this layer. On the global scale, the depletion of stratospheric O_3 is of concern because stratospheric O_3 protects the Earth's surface and its inhabitants from ultraviolet light. On a regional scale, excessive amounts of

Table 2.5. Scenarios for future emissions of sulfur dioxide in Europe (modeled as kt SO_2)

Country	1980	CRP 2000	MTFR	
			CEE	EEE
Albania	101	167	41	38
Austria	370	78	62	62
Belgium	818	430	65	65
Bulgaria	1034	520	236	11
CSFR	3100	2170	708	114
Denmark	448	176	21	21
Finland	584	116	42	42
France	3338	1334	213	213
Germany-W	3194	860	369	369
Germany-E	4264	1500	1158	431
Greece	400	919	88	88
Hungary	1632	1094	580	128
Ireland	222	240	50	50
Italy	3800	2255	231	231
Luxembourg	24	10	1	1
Netherlands	466	106	43	43
Norway	141	68	33	33
Poland	4100	2900	749	425
Portugal	266	304	26	26
Romania	1800	3261	313	232
Spain	3250	2889	2694	2694
Sweden	514	102	94	94
Switzerland	126	60	43	43
Turkey	860	3253	1341	1341
UK	4848	2446	496	496
USSR	12800	8220	2452	2452
Yugoslavia	1300	2393	321	124
Europe (subtotal)	**53800**	**37871**	**10037**	**7434**

Abbreviations: SO_2 = sulfur dioxide, MTFR = maximum technically feasible reductions, CRP = current reduction plans, CEE = coal burning in eastern Europe, EEE = energy efficiency in eastern Europe.

Source: Adapted from Lövblad et al. 1992.

Table 2.6. Scenarios for future emissions of nitrogen oxides in Europe (modeled as kt NO_2)

			MTFR	
Country	1980	CRP 2000	CEE	EEE
Albania	28	47	16	12
Austria	233	155	113	113
Belgium	442	250	184	184
Bulgaria	150	150	199	60
CSFR	1204	1000	215	131
Denmark	241	177	79	79
Finland	264	226	96	96
France	1823	1800	731	731
Germany-W	2980	1980	973	973
Germany-E	655	440	186	177
Greece	700	740	140	140
Hungary	273	279	140	76
Ireland	73	129	44	44
Italy	1480	1480	720	720
Luxembourg	23	12	17	17
Netherlands	548	268	226	226
Norway	181	155	86	86
Poland	1500	1345	478	382
Portugal	166	193	97	97
Romania	646	939	340	153
Spain	950	1624	573	573
Sweden	398	341	147	147
Switzerland	196	127	63	63
Turkey	375	1204	546	546
UK	2418	1822	871	871
USSR	3167	4400	1726	1726
Yugoslavia	350	669	187	155
Europe (subtotal)	**21,464**	**21,952**	**9193**	**8578**

Abbreviations: NO_2 = nitrogen dioxide, MTFR = maximum technically feasible reductions, CRP = current reduction plans, CEE = coal burning in eastern Europe, EEE = energy efficiency in eastern Europe.

Source: Adapted from Lövblad et al. 1992.

tropospheric O_3 are of concern because exposure to O_3 is harmful to humans and plant life. Increases in tropospheric O_3 do partially counter the depletion of stratospheric O_3 in the atmosphere as a whole, but the adverse regional effects include the impairment of plant growth and of the human respiratory system (NRC 1991).

Tropospheric O_3 is the result of a series of photochemical reactions involving VOCs and NO_x. The reactions are not linear (i.e., an increase in O_3 is not necessarily proportional to increases in VOCs). There are also many competing chemical and biological processes that will compensate for increased levels of pollutants like VOCs and NO_x. However, the series of reactions resulting in O_3 production is self-sustaining and will continually generate O_3 as long as VOCs and NO_x are present.

The single largest man-made source of VOCs and NO_x in the troposphere is the transportation sector. Almost all NO_x emissions are man-made, while VOC emissions are split between man-made and natural sources. In the United States and Europe, approximately 44% of the man-made NO_x emissions are due to transportation (NAPAP 1987; Derwent, Grennfelt, and Hov 1991). Transportation contributes to 38% of the man-made VOC emissions in the United States and to 34% of the total VOC emissions in Europe. In Europe as a whole, natural emissions of VOCs are not felt to be a major contributor to regional O_3 formation because natural emissions of VOCs are estimated to contribute only 27% of the total VOC emissions. However, for a few countries like Albania, Spain, and Sweden, natural emissions of VOCs are much greater than man-made emissions and will affect regional O_3 formation (Derwent, Grennfelt, and Hov 1991). In addition, VOCs emitted from plants and animals are often more reactive in the atmosphere than the VOCs due to the activities of man. The assessment of air quality, measurement of pollutants, and tools used to model their introduction into the atmosphere and subsequent chemical reactions are discussed in the following sections.

2.2.2 Monitoring Air Quality

Monitoring the state of the atmosphere is a difficult task because of the complexity of its behavior. Concentrations of tropospheric O_3 and its precursors vary over diurnal and seasonal cycles and also with location. For example, yearly peak O_3 concentrations are seen in the afternoons of the months April to September in the Northern Hemisphere, but the exact cycle depends upon land use, terrain, and local meteorology.

Tropospheric O_3 and O_3 precursor measurements are generally made in those areas where high pollutant concentrations are expected, such as near major roadways, near fossil-fueled power plants, and in urban centers. In addition, measurements are generally taken only at one elevation and over some set sampling interval. Several instruments may be required to measure all the different chemical species of interest, and often the amount of a particular species present must be inferred from the presence of other species. Combined, these factors result in a limited set of data and make it difficult to determine the trends in regional and global O_3 concentrations over time.

Advances are being made in measurement techniques and instrumentation (NRC 1991), but time is required to expand and update monitoring networks.

From existing data on the adverse effects of excess tropospheric O_3, limits on concentration levels of O_3 have been devised in several countries. In the United States, peak 1-h average levels of O_3 are not to exceed 120 parts per billion (ppb) more than three times in three consecutive years in order to meet the National Ambient Air Quality Standard (NAAQS). In 1985, 77 areas in the United States did not meet the NAAQS standard. By 1987, the number had dropped to 63, but by 1989 the number had increased to 96 (NRC 1991). In the European Community, the critical 1-h level of O_3 adopted in 1988 by the United Nations Economic Commission for Europe (UNECE) is 75 ppb. In 1985, 19 out of 20 stations in northwestern Europe exceeded the UNECE 1-h critical level. In 1986, 22 of 30 stations exceeded the 1-h critical level, and in 1987, 23 out of 30 exceeded the 1-h critical level (Derwent, Grennfelt, and Hov 1991). At a workshop in Finland in 1993, a new integrated critical level of 300 ppb-h over 40 ppb was proposed (Anttila 1993) and similar proposals are being considered by the U.S. Environmental Protection Agency (EPA).

2.2.3 Emissions Inventories

Knowledge of the type, origin, and amount of emissions present in a region is required in order to determine the most effective methods to improve air quality and in order to predict air quality based on changes in the emission inventory. Developing an emission inventory, including particulates, is complicated by the large number and variety of sources. Large stationary sources such as utilities or industrial smelters are fairly simple to quantify, but small stationary point sources like dry cleaning businesses or painting facilities are too numerous to monitor individually and have variable outputs of pollutants. Mobile sources like cars and trucks are even more difficult to quantify because their emissions depend on their operating condition and temperature. In general, emission inventories for an area are estimated based on the actual number of large sources, an estimated number of small sources, and an estimation of mobile source emissions based on the number of miles travelled in the area of interest multiplied by an emissions factor. An alternative approach is the use of some local measurements of pollutants to estimate an emission density for a particular region.

For large sources, the emission rates are either measured individually or based on an average of measurements from a similar size and type of facility. For small industrial sources, emissions are based upon data such as the amounts of solvents purchased in an area or an approximation of the density of a particular type of facility combined with an associated emission factor.

Emission factors for mobile sources have been developed by EPA and the California Air Resources Board and also are currently under development for the European Community by the Commission of the European Communities. Emission factors estimate the mass of emissions per unit of distance travelled and are used to estimate mobile source emissions inventories. The factors are developed based on the use of emission estimation models and laboratory testing of a few representative vehicles. The factors attempt to take into account variables like vehicle aging, cold start emissions, evaporative emissions, and driving habits. However, several comparisons in the United States between predicted and measured emissions have suggested that current mobile source emission estimation models are consistently underestimating the CO/NO_x and VOC/NO_x ratios (NRC 1991). The comparisons also suggest that VOC and CO emissions are currently being underestimated by models. These comparisons from 1991 made use of the existing mobile source emissions model related to EPA, at that time called MOBILE4. The model has subsequently been improved to the new version, MOBILE5, and is under revision again, all in an effort to better estimate the actual emissions inventories. In conjunction with these revisions, and in order to get a more representative sample of mobile source emissions, roadside testing and remote sensing have been implemented in many areas. These studies have shown that the vast majority of mobile emissions are due to a small minority of high emitting vehicles. As few as 10% of the vehicles are responsible for 50% or more of the VOC and CO emissions (NRC 1991).

An additional complication to the creation of emissions inventories is caused by the different oxygen and carbon contents of various alternative fuels. Since the instrumentation typically used to measure the VOCs emitted from vehicle exhaust pipes is the flame ionization detector (FID) and since this instrument "counts carbon," the concentrations indicated by FID are often referred to as ppmC (parts per million of carbon). The carbon, of course, is bound up in the various molecules emitted, and in order to express the emissions on a mass basis, some assumptions must be made regarding the molecular weight of the "average" hydrocarbon molecule. To avoid problems associated with this, the results are reported on a carbon basis.

Natural emissions from plants and animals are often neglected in the development of emission inventories, but they may have a significant contribution to VOC production in some areas (see Sect. 2.2.1). Emissions of VOCs from plant life are difficult to measure, vary a great deal with the seasons, and are generally more reactive than the man-made species. Thus, they may have a larger ozone-forming potential than man-made pollutants.

Considering the problems with quantifying natural and mobile source emissions, it is not surprising to note that in comparisons of predictions and measurements of emissions, overall VOC emissions in the United States are underpredicted by a significant amount using current emission estimation models and factors (NRC 1991). Such deficiencies in emission inventories will adversely affect attempts to improve or predict air quality.

2.2.4 Predicting Air Quality

2.2.4.1 Modeling

In order to effectively manage regional and local air quality and determine the measures necessary to improve air quality, computer models that predict the production of tropospheric O_3 have been developed. The models estimate future atmospheric O_3 concentrations based on a given emissions inventory, a given initial atmospheric composition, and given meteorological conditions. Air quality models are based upon the solution of mathematical equations describing the atmospheric transport and photochemical reactions of pollutants in the atmosphere.

One of the simplest models in use is called a trajectory box model. A single parcel of air, treated as a box, is transported downwind along a single trajectory in the region of interest. Concentrations of pollutants, including emissions, are assumed to be uniform within the box and O_3 formation is determined by a set of chemical equations. Site-specific meteorology and emissions are used to tailor the model to a particular location. Note that this type of model gives O_3 concentrations along a single trajectory and is not considered suitable to model multiple-day episodes of O_3 formation. However, the model is relatively simple to use and does not require detailed input data. Various implementations of the model exist around the world. When enough detailed input data are available, a three-dimensional photochemical grid model is used. Urban grid-cell models have cells that are usually a few kilometers on a side, while regional grid-cell models have cells that are usually tens of kilometers on a side. Grid-cell models may or may not have multiple vertical layers. Input data on emissions and initial concentrations of pollutant and precursor species are required for each grid cell, along with a fairly detailed description of local wind and temperature fields. The models also require boundary conditions that control the flux of pollutants across the boundaries of the region of interest. All of the models of this type are sensitive to variations in boundary conditions and in cell size.

The required input data for a grid-cell model are gathered from a particular region in what is called the "base year." The base year data are used to initialize the model and compare its predictions with the actual pollutant concentrations measured throughout the base year. Once the model is judged to be reasonably accurate, predictions of future concentrations of pollutants are calculated by combining the base year initial conditions with variable emissions. The application of the more complex photochemical grid models is a compromise between the resolution of available input data, the desired resolution of the output, and the computational time required to run the model.

Currently, variations on the grid-cell models are being developed to incorporate the strengths of the different modeling approaches. There are models that use nested grids featuring small cell sizes around urban areas and larger cells in rural regions or even more hybrid models that use nested grids and allow the scales of behavior to be different in different regions. The application of these models increases the accuracy of predictions, but only to the same level of accuracy as their input.

Based on the data collected from a region, along with the information acquired through modeling, a plot of ozone isopleths is created. An isopleth is a line showing where some datum of interest is a constant value. An ozone isopleth represents the maximum O_3 concentration resulting from various initial VOC and NO_x concentrations. Figure 2.7 shows a typical plot of ozone isopleths from a trajectory box model such as the empirical kinetic modeling approach. There is a ridge line that extends from the lower left hand corner of the plot to the upper right hand corner. To the left of the ridge line are typical concentrations for a highly polluted urban area. To the right of the ridge line are the typical concentrations in regions downwind of urban areas. In general, regions in which the VOC/NO_x ratio is <10 are considered "VOC limited," and regions with VOC/NO_x ratios >20 are considered to be "NO_x limited." In a VOC-limited region, decreases in VOC emissions will lower O_3 concentrations, while in a NO_x limited region, decreases in NO_x emissions are required to lower O_3 concentrations. Since all ozone isopleths tend to exhibit the same basic shape, the location of the peak O_3 concentrations found in an area on the isopleth plot should lead to the identification of the control measures needed to reduce tropospheric O_3

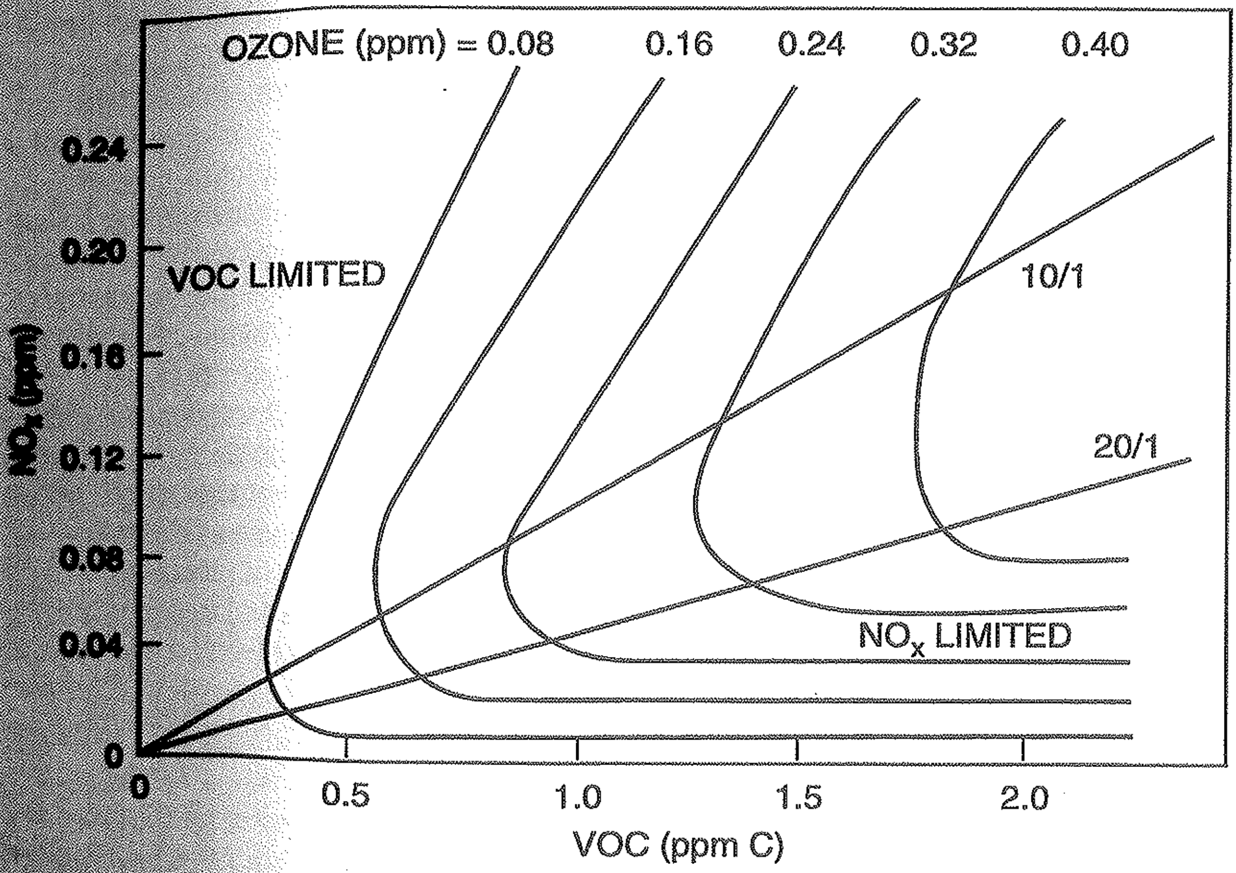


Fig. 2.7. A typical empirical kinetic modeling approach ozone isopleth plot.

(i.e., reductions in VOC or NO_x concentrations or both). However, the reliability of the data presented in the plots is uncertain. In addition, most ozone isopleth plots will not be as continuous or complete as Fig. 2.7. Plots created from data from more sophisticated models will have fewer data points due to the more extensive resources required to get each piece of data.

Most ozone control strategies have traditionally concentrated on reductions in VOC emissions, and VOC controls are appropriate in many areas. Reductions in VOC emissions will help in a VOC limited region and not change O_3 production in a NO_x-limited region. However, NO_x controls must be applied carefully. If used in a VOC-limited region, reductions in NO_x emissions alone will increase the maximum O_3 production. Reductions in both types of emissions simultaneously must be considered carefully with respect to the resulting dynamic changes in the VOC/NO_x ratio in the region.

2.2.4.2 Reactivity

The measurement of reactivity (or ozone-forming potential) is also used to determine if a fuel will reduce concentrations of O_3 or its precursors in the atmosphere. Each chemical species in the fuel and in its emissions has a certain reactivity given a specific atmospheric composition. For simplification, similar chemical species are often lumped together and given a single reactivity value, but not all VOCs or NO_x compounds have the same reactivity value. The combined reactivity of all of the chemical species emitted by an alternative fuel relative to that of a conventional fuel is used to compare the ozone forming potential of the fuels.

Reactivity is determined through the analysis of data from the air quality prediction models or through experimental measurements of exhaust and evaporative emissions. The air quality prediction models use equations describing the chemical interactions of compounds in the atmosphere to calculate the production of ozone and other pollutants. The final concentration of O_3 as compared to the initial O_3 concentration, along with the amount of pollutant (fuel) added to the atmosphere is used to determine reactivity. The chemistry models used in the air quality models are not complete and contain many approximations. Most direct measurements of reactivity are performed in a controlled laboratory environment, such as a smog chamber, where experimental limitations can change the outcome of reactivity measurements. The effects of continuous emissions of pollutants and multiday episodes of O_3 production are also not represented in the measurements. Calculations of reactivity using models can account for multiday episodes and continuous emission but are limited by the lack of model validation and incomplete chemistry models. Additional information on reactivity can be found in Sect. 3.3.1.

2.3 HEALTH EFFECTS

A large fraction of the world populace is affected by airborne emissions from the production, distribution, and use of transportation fuels. Both the exposure levels and the types of people exposed are different for all three processes. Exposures to these fuels and their emissions range in intensity from the relatively low-level, constant exposure of the residents in regions where the fuels are burned to the more concentrated, short-term exposures of workers involved in fuel production.

2.3.1 Production Workers

Workers involved in the production of fuels are, by the nature of their duties, exposed to higher levels of fuel toxicants than the general population. In most countries, production worker health is studied and on-the-job exposures to toxic materials are managed. As a result, worker health statistics associated with the production of conventional fuels and for alternative fuels produced using conventional technologies are available. Typically, these include

1. trauma from production and transportation accidents,
2. long-term or chronic exposure to significant levels of production facility or refinery organics, and
3. short-term or acute exposure to substantial levels of refinery organics.

Worker exposures to conventional, reformulated, and alternative fuels have been considered in this study. Exposure characterizations were drawn from data compiled by Fritzsche (1989), Rowe (1990), Calabrese and Kenyon (1991), and EPA (1993).

In the United States, major policy differences exist between the regulation of existing (relatively unregulated) fuels and the regulation of alternative fuels. Alternative fuels are subject to stringent health and safety regulations, but conventional fuels are exempted from these same regulations because they have been in use for many years. In particular, methanol and ethanol have been evaluated as high-volume industrial chemicals. The resulting differences in worker safety data make it difficult to compare the potential health impact of conventional and alternative fuels.

2.3.2 Residents of Fuel Producing Regions

In general, the exposure of residents of fuel-producing regions to airborne toxicants is lower than that of production workers. However, producing regions typically have higher-than-normal exposures to the constituents of the neat fuels being produced. In some cases, such as the dispersion of particulate plumes from in-factory combustion, local residents could experience higher exposures than plant workers. Toxicant exposure routes, in addition to the inhalation and skin absorption effects associated with production workers, can include ingestion of contaminated water, plants, and/or animals.

2.3.3 Residents of Airsheds

Airshed residents are generally affected by long-term, low-level exposure to postcombustion pollutants and are unlikely to receive the high exposure to feedstock and process chemicals typical of refinery workers or producing region populations. Although epidemiological studies of pollutant effects can be conducted, the combination of low-level simultaneous exposures to many pollutants and a large, diverse population make identification and evaluation of risks from individual pollutants difficult. At the same time, with a large exposed population, the number of people seriously affected by even low levels of an individual pollutant can be significant. For example, Hackney and Linn (1989) discuss the statistical design of experiments needed to understand and profile possible exacerbation of certain chronic heart diseases by O_3, a major concern addressed by current regulations. The experimental design requires the use of controls, epidemiological data on all of the test subjects, and repeated tests of lung function in response to added O_3. The experimental plans would require at least a year to complete because O_3 levels vary seasonally.

Pollutant effects are usually identified through epidemiological studies. Verification of the correlation between exposure and health effect is typically through the use of low-population, high-exposure-level animal and human studies. Regulation then limits emissions from producers to values estimated to cause little population effect. These values are difficult to establish, because a number of factors—including diet, race, age, and overall health—influence response to oxidants (Last 1989). In airshed areas, standards for controlling pollutant emissions have become increasingly stringent. Current United States air quality standards have been increasingly based on the responses of "more sensitive" sections of the population (Lippmann 1989).

Of major concern is the difference between this methodology and current research in molecular toxicology. Current emissions regulations reflect

1. little or no understanding of the fundamental mechanisms of toxicology;
2. limited data on the levels at which no toxic effect is found;
3. limited evaluation or understanding of the physiological causes of toxicity, including inherited susceptibility;
4. little or no understanding of variations in sensitivity to pollutants and other toxicants among different ethnic, age, or gender groups; and
5. physical-chemical measures of toxicant concentrations, rather than biological effects.

The new emphasis on molecular biology, biotechnology, and genetic engineering is rapidly advancing predictive understanding in this area.

2.3.4 Health Monitoring and Identification of "At Risk" Populations

Data on which to base an evaluation of fuel use risk come from a variety of sources. For alternative fuels such as methanol, ethanol, CH_4, and propane, as well as for battery systems, data from epidemiological and occupational studies of production workers are available. These studies cover short-term exposures of workers to relatively high concentrations of pure chemicals or families of chemicals. Although some data from epidemiological studies of large worker populations are available, most of the data cover relatively small groups. Exposure of fuel handlers to conventional fuels has been document, and some epidemiological studies of small populations exposed to high doses of toxicants have also been performed.

In addition to occupational safety studies, epidemiological studies of larger populations may be available. These studies typically cover long-term exposure to relatively low levels of potential toxicants and concentrate on long-term changes in the health of the population. Even so, correlations between exposure and health effects are difficult to develop. When such a correlation is found, controlled exposure of animals, and in some cases, humans, is used to confirm and quantify the correlation. The controlled exposures in clinical studies typically use toxicant levels well above likely population exposures to magnify the effect and decrease the number of individuals surveyed.

At present, EPA is conducting studies to evaluate the effects of "criteria pollutants," such as NO_x, SO_x, and CO, on airshed populations. Although "criteria pollutants" have been regulated in the United States for nearly a quarter of a century, data on which to base an assessment of the human cost of various types of pollution are limited. Major issues include

1. definition of "at risk" or "susceptible" populations ["At risk" or "susceptible" populations are likely to include those consuming low levels of antioxidants, B vitamins, and selenium, as well as those suffering from classic protein and caloric insufficiency (Last 1989)];
2. the ability to substantiate, in terms of physiological basis, the action of a controlled material;
3. correlations between root cause and perceived effect, particularly in the of "criteria pollutants;"
4. the ability to perceive small population effects only at high levels and the need to extrapolate to low levels to set "safe" standards for larger populations;
5. public perception of safety; and
6. displacement of resources by regulation.

3. IMPACT OF CONVENTIONAL AND ALTERNATIVE FUEL USE

3.1 VEHICLE EMISSIONS

Although the effects discussed in this report are not all associated with combustion products, the emissions from vehicle operation are probably the source of the most important environmental effects associated with alternative fuel use.

3.1.1 Exhaust Emissions

Emission test results for light-duty vehicles are often reported by determining the total mass of each component of interest emitted from the vehicle during a specified driving cycle. The mass is then divided by the distance driven to arrive at an "average" value of mass per unit distance traveled (grams per mile or grams per kilometer are the commonly used units). Legislated emission values are usually expressed in terms of the maximum allowable values over a specified driving cycle. For heavy-duty applications it is the engine rather than the vehicle that is certified, and the regulations are typically written to place limits on the mass of certain components emitted per unit energy delivered by the engine when tested at a series of different power output levels. Typical units used are grams per horsepower-hour or grams per kilowatt-hour.

Although for light-duty vehicles the specified cycles may be intended to be representative of "typical" driving behavior, it is clear that they may underestimate the acceleration levels and speeds encountered in actual traffic flows. This is the subject of much investigation at the present time. Sorenson (1992a), for example, tested three light-duty vehicles according to the Danish regulations [which are based on the U.S. Environmental Protection Agency (EPA) driving cycle] and then tested the same vehicles at constant speeds of up to 135 km/h. The results showed that when the vehicles are operated under these "off-cycle" conditions, significantly higher emissions can result from vehicles that were in compliance with regulations based on the "official" driving cycle.

A variety of emissions-testing data of alternatively fueled vehicles are available. Unfortunately, much of the data were obtained from vehicles that had been converted from gasoline use and therefore represent results from what might be termed "first-generation" conversion kits. It is clear that for any of the fuels considered, fairly sophisticated engine management systems are required to meet the stringent emission standards being implemented and considered worldwide. Thus, data from first-generation conversions do not adequately reflect the emissions that should be expected from original equipment alternatively fueled vehicles that have been engineered to produce low emissions.

The data necessary for meaningful comparisons of the various fuels are now appearing in the literature. A significant portion of the alcohol-fueled vehicle data are associated with "flexible fueled" or "variable fueled" vehicles—those capable of operating on a wide range of gasoline/alcohol blends. Some of the natural gas and liquefied petroleum gas (LPG) data are likewise from "dual-fueled" vehicles. In both situations it is reasonable to assume that such vehicles cannot be optimized to operate on both of the fuels they use (for example, the compression ratio and/or the spark timing must both be optimized for a given fuel). Thus, fuel consumption and emissions from such vehicles may not represent what might be possible from vehicles dedicated to one fuel.

Several locations in the United States, Canada, Brazil, and Europe have selectively switched vehicles to alternative fuels. Most of the vehicles have been converted to operate either on several different fuels or as dedicated alternatively fueled vehicles, but a few vehicles have been designed specifically to run on a particular alternative fuel. Generally, only a small subset of a country's fleet, such as city- or county-owned vehicles, have been converted to some alternative fuel, but in Brazil almost 5 million vehicles have been operating on a mixture of 95% ethanol and 5% water fuel, and there are almost 4 million LPG vehicles operating worldwide (Pitstick 1993).

3.1.2 Evaporative Emissions

Liquid fuel vapors can be released into the atmosphere at several points during the fuel use scenario: when distributed through pipelines, when tankers that transport the fuel are being filled, when the storage tanks at vehicle refueling stations are being filled, when the vehicle fuel tanks are being filled, and when the fuel vapors escape from the vehicle. The last loss is associated with natural cooling and heating cycles (diurnal losses), loss of fuel vapors during vehicle operation (running losses), and loss of fuel vapors after the vehicle engine is shut off (hot soak losses).

For volatile fuels like gasoline, methanol, and ethanol, evaporative emissions are important considerations in both fuel transfer operations and vehicle operations. Fuels stored as compressed liquids (LPG) or gases [compressed natural gas (CNG)] do not have evaporative emissions problems (except through fuel system leaks and venting of refueling lines prior to disconnecting these from the vehicle); low-volatility fuels (diesel fuels) have negligible evaporative emissions.

Control of evaporative emissions typically involves using vapor-recovery systems and a sealed fuel tank that will vent only when the tank pressure falls outside certain limits. Special refueling nozzles can capture the vapors forced out of fuel tanks as they are filled with liquid, and charcoal canisters on board the vehicle absorb fuel-tank vapors given off during vehicle operation. (The charcoal vapors are purged by drawing air through the canister while the vehicle engine is operating; the purge air and the vapors are then fed into the engine where the vapors are burned.)

Gasoline vapors can be quite reactive; therefore, control of evaporative emissions during the gasoline fuel cycle is an important strategy for ozone (O_3) control. Since the same approaches used for gasoline can be applied to alcohol-fueled vehicles, the problem would appear to be already solved for gasoline vehicles modified to burn alcohol fuels. However, gasoline/alcohol mixtures can have vapor pressures that are higher than either of the two constituents and evaporative emissions may, in these cases, be more severe.

As more stringent standards are implemented for exhaust emissions, evaporative emissions should not be ignored. The testing for evaporative emissions involves the use of the so-called SHED (sealed housing for evaporative determination) test. In this test, the vehicle is placed in a sealed chamber, where the composition of the atmosphere in the chamber is monitored and the evaporative emissions can be quantified. The magnitude of evaporative emissions can be realized from an examination of the results from the Auto/Oil study Technical Bulletin 13 (AQIRP 1995) which are shown and discussed in Section 3.1.3.

3.1.3 The Auto/Oil Study (AQIRP)

A very comprehensive program initiated by three U.S. automotive manufacturers and fourteen petroleum companies is investigating the potential reductions in vehicle emissions and subsequent air quality improvements resulting from the use of reformulated gasoline, selected alternative fuels, and developments in automotive technology. This study is called the "Auto/Oil Air Quality Improvement Research Program," or AQIRP, and focuses on light-duty vehicles. Results of this ongoing study were still being published at the time this report was being prepared. Currently, over a dozen technical bulletins have been published.

The tremendous extent of the study reflects the complexity of the subject, and it is therefore extremely difficult to summarize the findings to date. It is safe to say, however, that the study has shown that the use of reformulated gasoline can measurably reduce the mass, toxicity, and ozone reactivity of vehicle emissions when compared to conventional unleaded gasoline.

Recently published results (AQIRP 1995) examined the exhaust and hot-soak evaporative emissions from six limited-production flexibly fueled vehicles (FFVs) and variably fueled vehicles (VFVs). Five different fuels were used:

1. unleaded gasoline having a composition based on the 1988 U.S. average (fuel A),
2. reformulated gasoline meeting the California Phase 2 1996 regulatory requirements (fuel C2),
3. M85 blended with the unleaded gasoline,
4. M85 blended with the reformulated gasoline, and
5. M10 blended with C2.

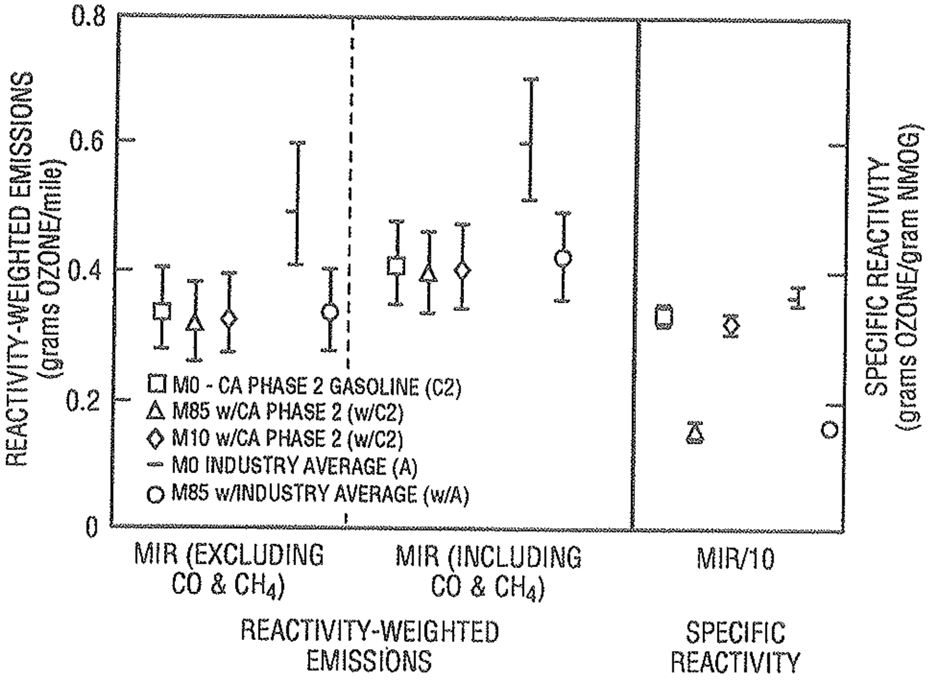


Fig. 3.2. The AQIRP fleet averaged ozone-forming reactivity. Bars represent 95% confidence intervals for comparing methanol fuel and corresponding gasoline means. NMOG = nonmethane organic gases; MIR = maximum incremental reactivity [which represents O_3 production in volatile organic compound (VOC)-limited areas]. (*Source:* AQIRP 1995)

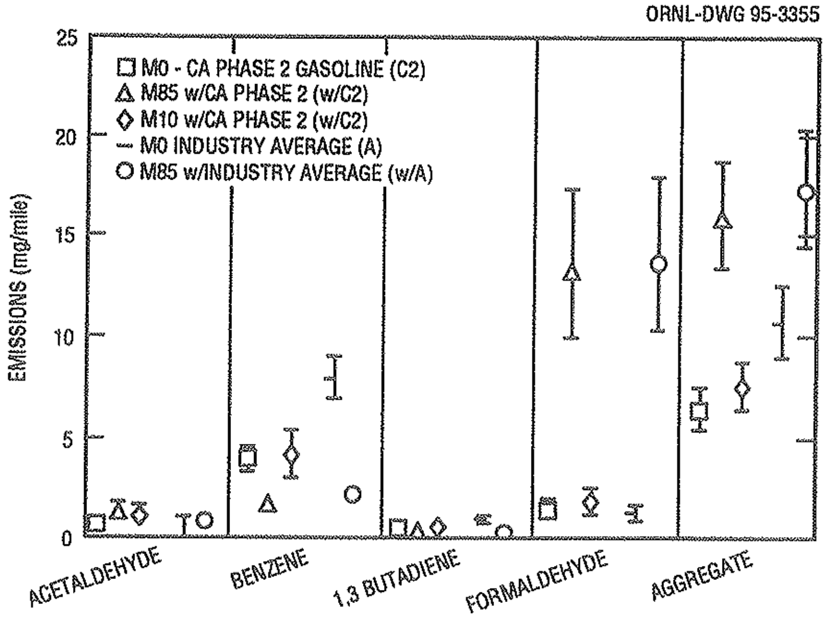


Fig. 3.3. The AQIRP fleet averaged toxic exhaust emissions. Bars represent 95% confidence intervals for comparing methanol fuel and corresponding gasoline means. (*Source:* AQIRP 1995)

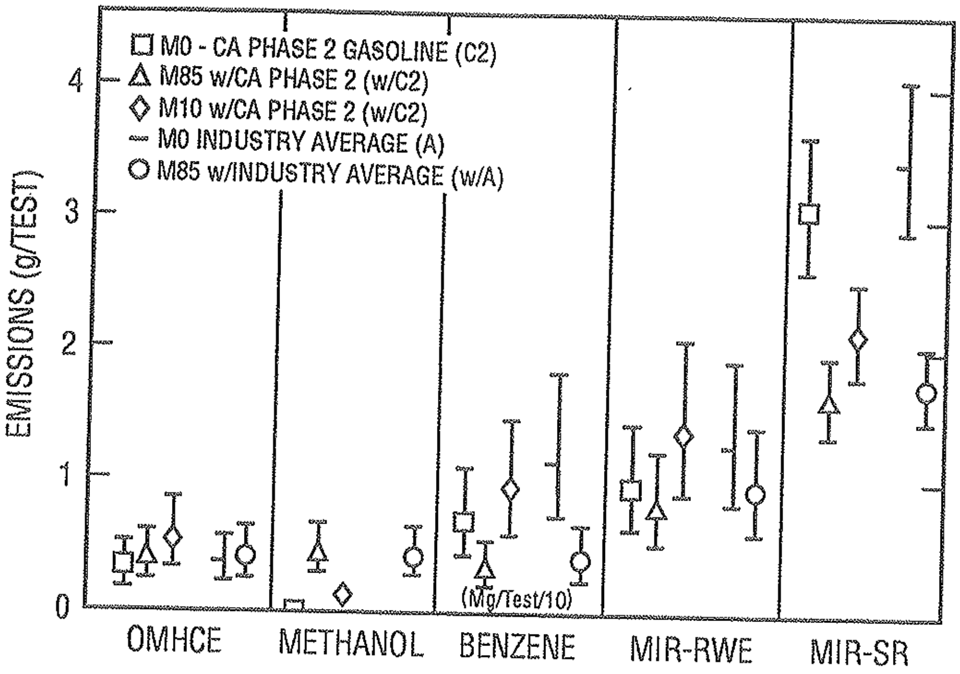


Fig. 3.4. The AQIRP fleet averaged hot-soak evaporative emissions and ozone-forming reactivity. Bars represent 95% confidence intervals for comparing methanol fuel and corresponding gasoline means. OMHCE = organic material hydrocarbon equivalent; RWE = reactivity weighted hot-soak evaporative emissions; SR = specific reactivity; MIR = maximum incremental reactivity (represents O_3 production in VOC-limited areas). (*Source:* AQIRP 1995)

3.1.4 The Nylund Study

In a study sponsored by the International Energy Agency (IEA) (Nylund et al. 1994), emission tests results were reported for several different light-duty vehicle/fuel combinations, as shown in Table 3.2. Tests were conducted at normal temperatures (20°C) and lower-than-normal temperatures (-7°C).

Several effects were investigated and are discussed in the following sections. The data include measurements of the following compounds: methane (CH_4), ethylene (C_2H_4), acetylene (C_2H_2), ethane (C_2H_6), propylene (C_3H_6), propane (C_3H_8), isobutene (C_4H_8), 1,3 butadiene (C_4H_6), butane (C_4H_{10}), isopentane (C_5H_{12}), benzene (C_6H_6), toluene (C_7H_8), xylene (C_8H_{10}), methanol (MEOH), and formaldehyde (CH_2O).

3.1.4.1 Temperature effects

Liquid fuels typically require overfueling (producing a fuel-rich mixture) to achieve acceptable cold starting and cold driveability. In the case of alcohol-based fuels, high levels of overfueling are used to accommodate the low volatilities

Table 3.1. Comparison of the mass of emissions of methanol blends and gasolines

	Percentage difference in the mass of emissions			
	M85 vs C2	M85 vs A	M10 vs C2	C2 vs A
Exhaust emissions				
OMHCE (HC)	−6	**−31**	3	**−26**
CO	9	−13	7	**−29**
NO_x	6	−11	−2	**−18**
RWE (O_3)	−5	**−32**	2	**−32**
Toxics	**146**	**57**	16	**−40**
Hot-soak emissions				
OMHCE (HC)	20	13	65	−12
RWE (O_3)	−15	−26	42	−24

Abbreviations: OMHCE = organic material hydrocarbon equivalent, RWE = reactivity weighted emissions, and HC = hydrocarbons.

Notes: The numbers in bold represent significant differences at the 90% level (or higher). Fuel A is based on the 1988 U.S. average gasoline. Fuel C2 is based on the 1996 California Phase 2 gasoline. M10 is a mix of 10% methanol and 90% C2. M85 is a mix of 85% methanol and 15% of the associated comparison fuel.

associated with the alcohol portions of the fuels. By comparison, little if any overfueling is required for gaseous fuels.

Overfueling increases engine-out emissions of carbon monoxide (CO) and hydrocarbons (HC), so one would expect to see the emissions of these increase as the starting temperature decreases. The deleterious effect of low temperatures on catalyst conversion efficiency also contributes to the problem, as the catalyst "light off" is delayed by the low initial temperature. Figures 3.5 (gasoline), 3.6 (M85), and 3.7 (E85) all show how for liquid fuels the emissions of CO and HC increase as the starting temperature decreases. Figures 3.8 (LPG) and 3.9 (CNG) show that the CO and HC emissions from the engines fueled with gaseous fuels are not only lower than those from liquid-fueled vehicles, but are much less sensitive to the starting temperature.

Table 3.2. Nylund vehicle/fuel combinations

Vehicle number	Engine technology used	Fuels used	Engine displacement (liters)	Model year	Odometer (km)	Origin
1	Carburetor	G, RFG	1.4	1990	24,000	Japan
2	MPFI, no catalyst	G, RFG	2.0	1990	84,000	Europe
3	MPFI	G, RFG	2.0	1992	39,000	Europe
4	MPFI	G, RFG	2.3	1994	21,000	Europe
5	MPFI	E0, E85, M50, M85	2.3	1993	14,000	Nordic
6	MPFI	M0, M50, M85	1.8	1992	5,500	U.S.A.
7	MPFI	M0, M50, M85	2.5	1994	8,500	U.S.A.
8	MPFI	M0, M50, M85	2.3	1993	6,000	Nordic
9	Dual MPFI	LPG	2.0	1993	8,000	Europe
10	Dual MPFI	G, LPG, CNG	2.0	1993	17,000	Europe
11	MPFI	CNG	5.2	1994	2,100	U.S.A.

Abbreviations: MPFI = multipoint (port) fuel injection; G = gasoline; RFG = reformulated gasoline (including oxygena fuels); MXX = methanol/gasoline mix containing XX% methanol by volume; EXX = ethanol/gasoline mix containing XX% ethanol by volume; LPG = Dutch liquefied petroleum gas (70% propane, 30% butane); CNG = Dutch compressed natural g (81% methane, 10% nitrogen, 4% carbon dioxide, 4% ethane).

Notes: For vehicle 11, CNG is Russian natural gas (CH_4 > 98%). Vehicles 1–9 were passenger cars with four-cylinder engines. Vehicles 10 and 11 were vans. Vehicle 10 had a four-cylinder engine, and vehicle 11 had an eight-cylinder engine. All vehicles except 1 and 2 were equipped with a catalyst.

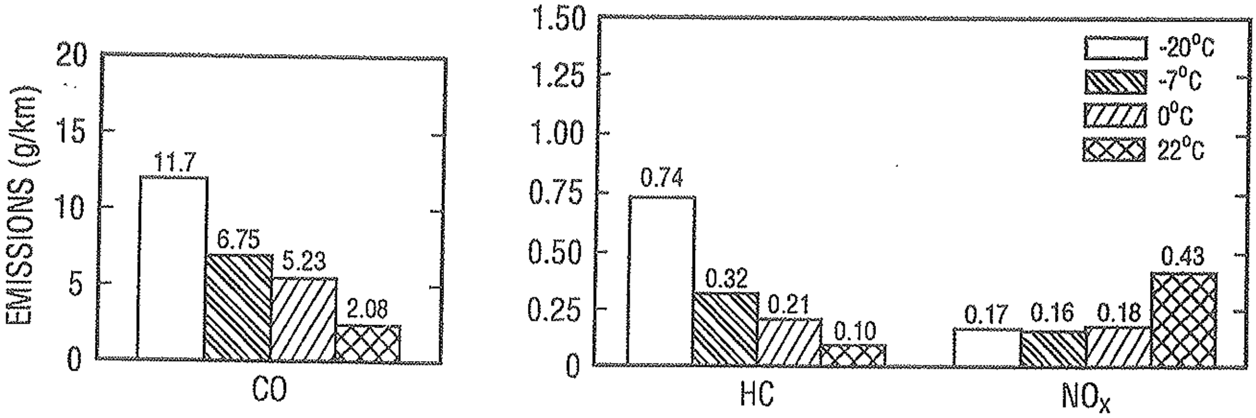


Fig. 3.5. Regulated emissions from conventional gasoline at various temperatures (˚C) using vehicle 3. (*Source:* Nylund et al. 1994)

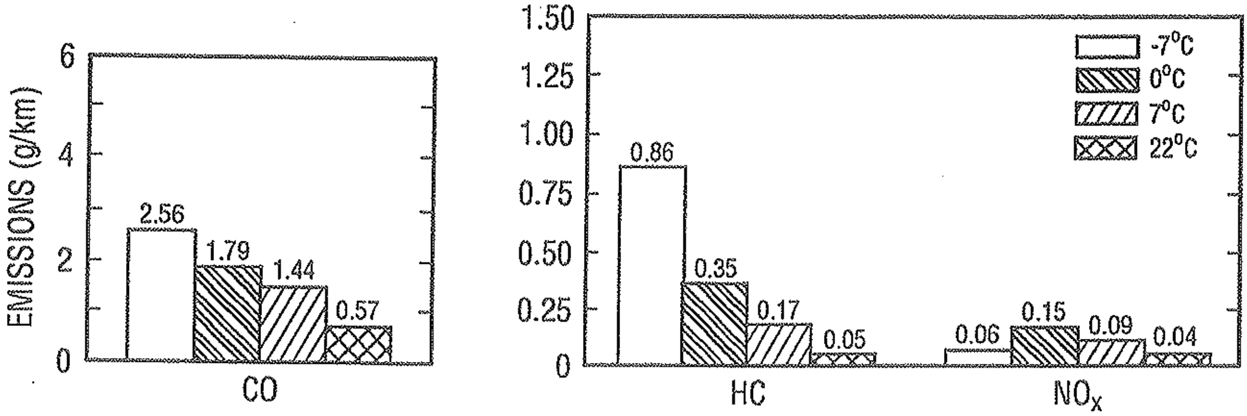


Fig. 3.6. Regulated emissions from M85 at various temperatures (˚C) using vehicle 6. (*Source:* Nylund et al. 1994)

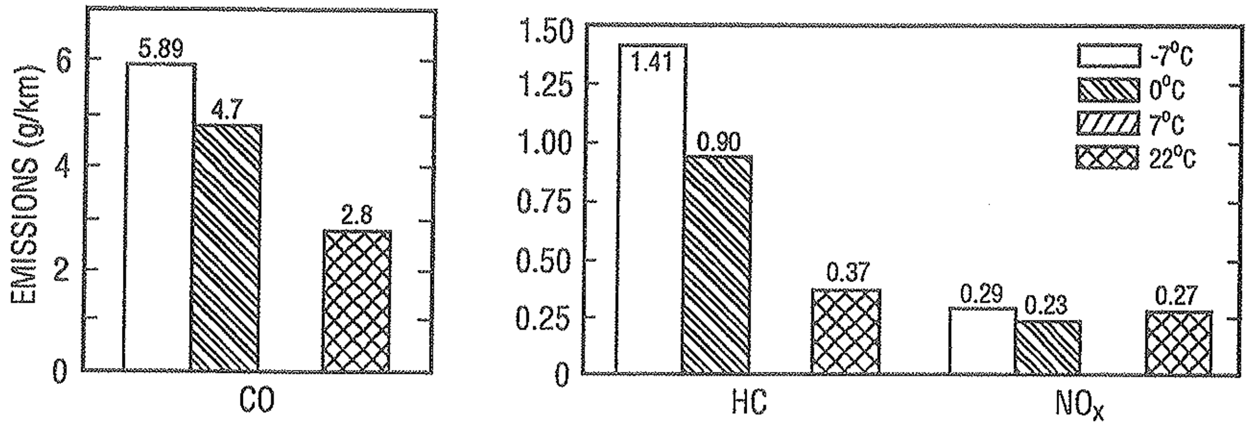


Fig. 3.7. Regulated emissions from E85 at various temperatures (°C) using vehicle 5. (*Source:* Nylund et al. 1994)

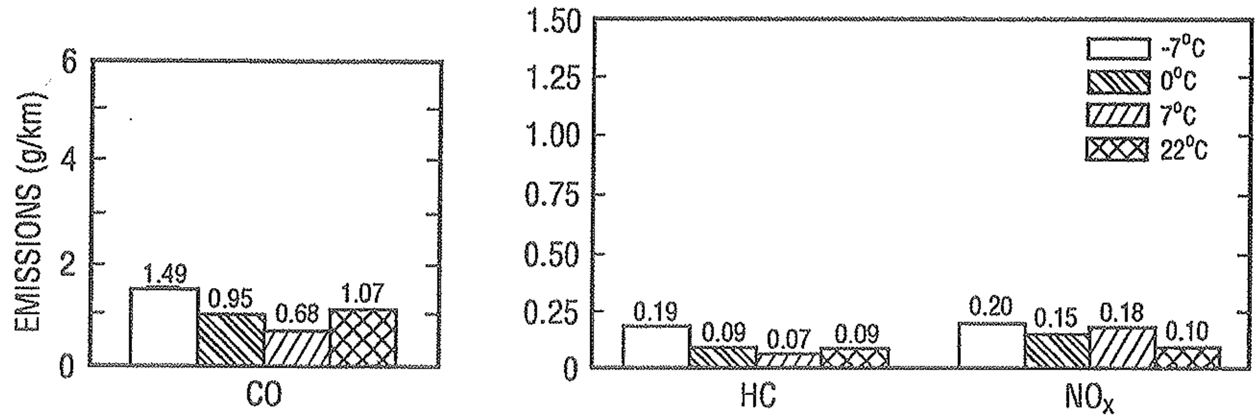


Fig. 3.8. Regulated emissions from LPG at various temperatures (°C) using vehicle 9. (*Source:* Nylund et al. 1994)

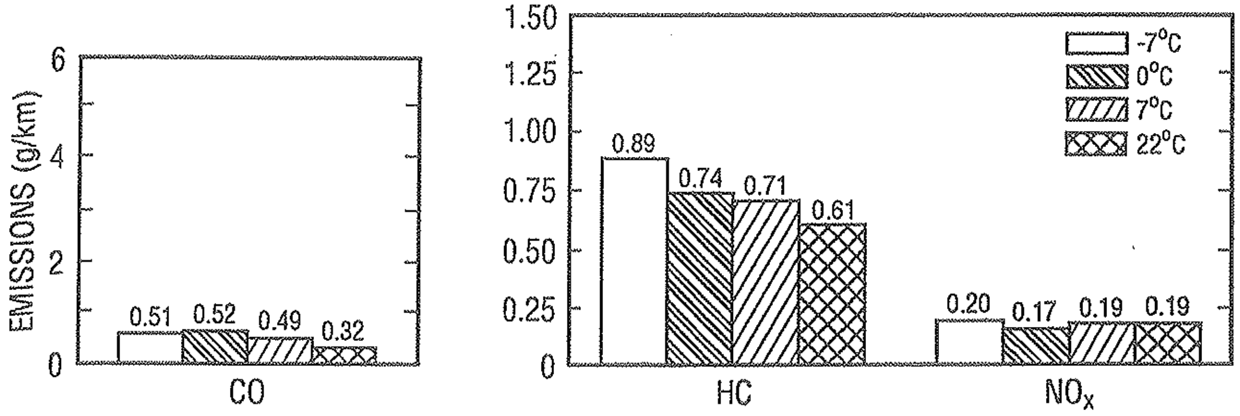


Fig. 3.9. Regulated emissions from CNG at various temperatures (°C) using vehicle 10. (*Source:* Nylund et al. 1994)

3.1.4.2 Speciated emissions and toxics

Unregulated emissions were also examined in the Nylund study (Nylund et al. 1994). Of particular interest are 1,3-butadiene (C_4H_6), benzene (C_6H_6), formaldehyde (CH_2O), and acetaldehyde (CH_3CHO) because these are classified as air toxics by the U.S. Environmental Protection Agency (EPA). Limited testing revealed significant reductions in exhaust toxics resulting from the use of reformulated gasoline.

Figure 3.10 shows the unregulated emissions from vehicle 6 using gasoline, M50, and M85. Clearly, the amounts of the various species present are affected as the methanol content of the fuel is changed. Of special note are the reductions in 1,3-butadiene and benzene as the gasoline content in the fuel decreases, and the increase in formaldehyde and methanol as the methanol content of the fuel increases.

Figure 3.11 shows the unregulated emissions from vehicle 10 using gasoline, LPG, and CNG. From these figures it is clear that the simpler chemical composition of the LPG and CNG fuels results in a correspondingly simpler chemical makeup of the exhaust organics. Although the levels of some species are increased with the use of the gaseous fuels (propane in the case of LPG, CH_4 in the case of CNG), the levels of 1,3-butadiene, benzene, and formaldehyde are significantly lower with the gaseous fuels.

3.1.5 The Volkswagen Study

Similar results were obtained from a study (Kroll et al. 1993) of five different liquid fuels:

1. Indolene,
2. reformulated gasoline,
3. M85 using Indolene,

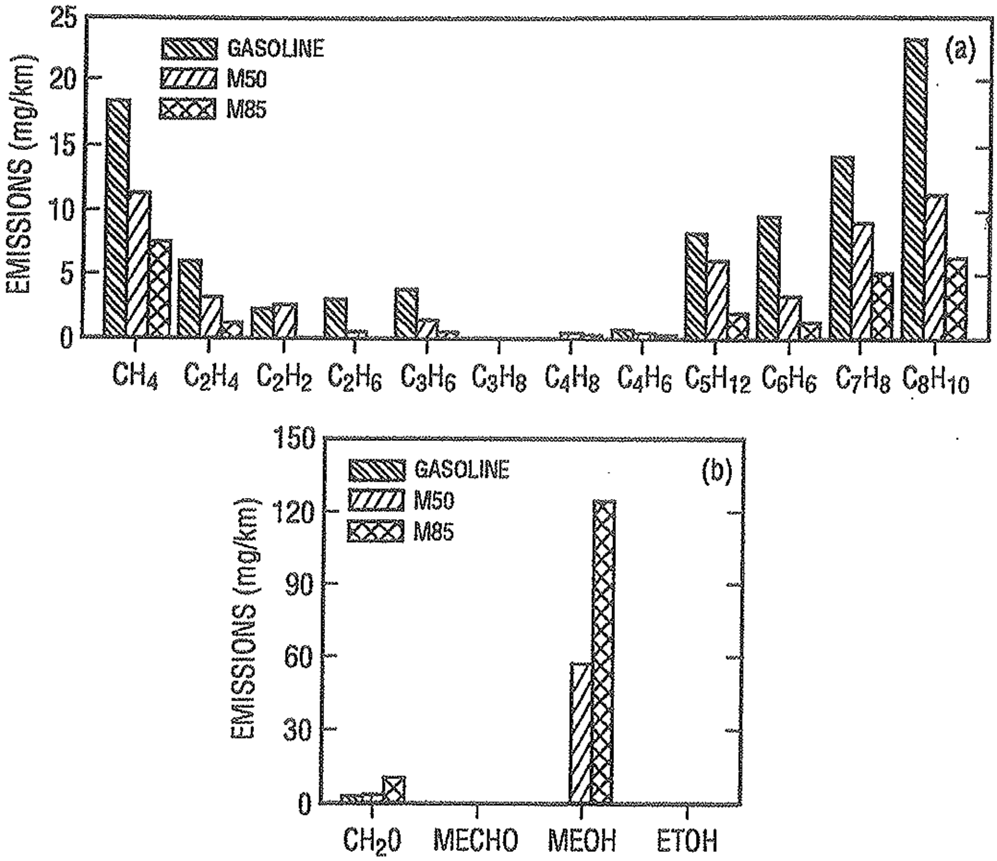


Fig. 3.10. Speciated emissions from gasoline, M50, and M85 using vehicle 6 at 22°C. (*a*) Gas chromatograph analysis; (*b*) FTIR analysis. (*Source:* Adapted from Nylund et al. 1994)

Notation:

CH_4 - methane
C_2H_4 - ethylene
C_2H_2 - acetylene
C_2H_6 - ethane
C_3H_6 - propylene
C_3H_8 - propane
C_4H_8 - isobutene
C_4H_6 - 1,3 butadiene
C_4H_{10} - butane
C_5H_{12} - isopentane
C_6H_6 - benzene
C_7H_8 - tolulene
C_8H_{10} - xylene
CH_2O - formaldehyde
MEOH - methanol
ETOH - ethanol
MECHO -acetaldehyde

4. M85 using reformulated gasoline, and
5. E85 using reformulated gasoline.

The fuels were used in the same multifuel vehicle—a Volkswagen equipped with a fuel composition sensor. The results clearly show that alcohols (methanol, ethanol) and the first levels of alcohol oxidation (formaldehyde, acetaldehyde) dominate the nonmethane organic gases (NMOG) emitted from the tailpipe when alcohol fuels are used.

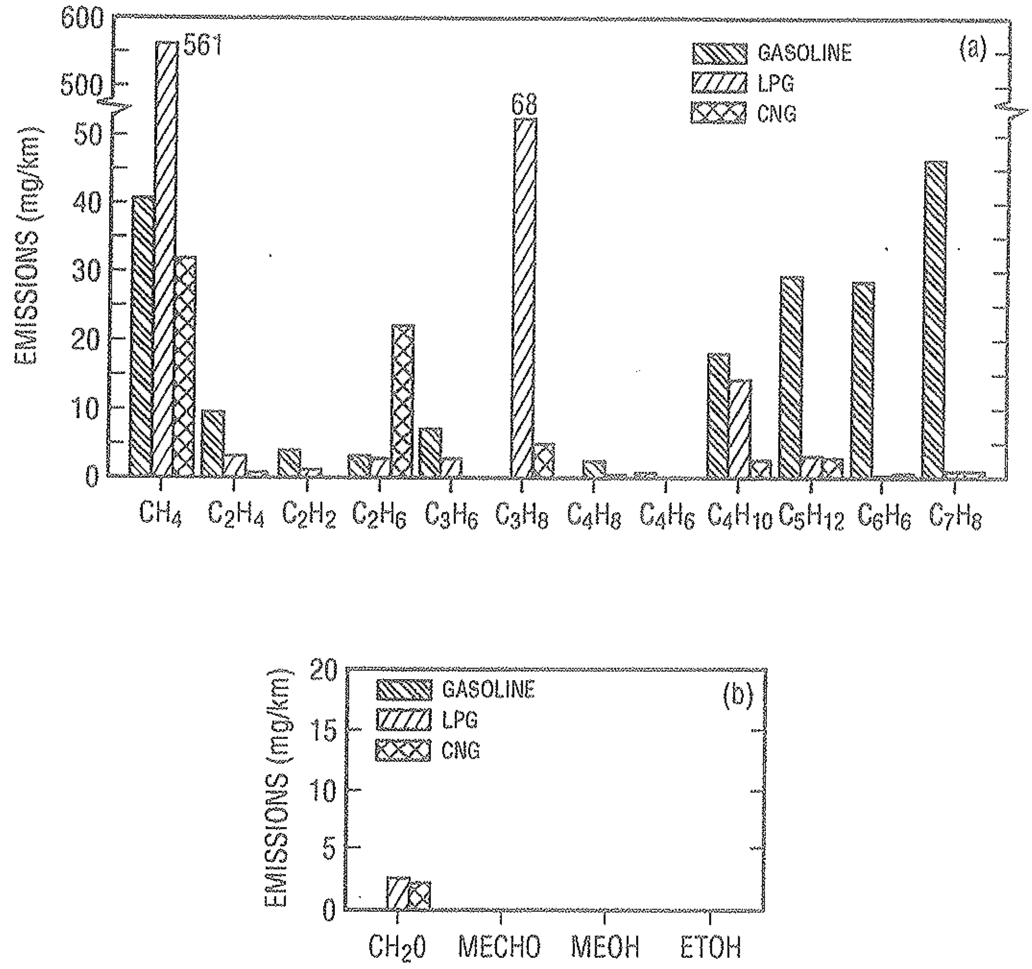


Fig. 3.11. Speciated emissions from gasoline, LPG, and CNG using vehicle 10 at 22°C. (*a*) Gas chromatograph analysis; (*b*) FTIR analysis. (*Source:* Adapted from Nylund et al. 1994)

Notation:

CH_4 - methane
C_2H_4 - ethylene
C_2H_2 - acetylene
C_2H_6 - ethane
C_3H_6 - propylene
C_3H_8 - propane
C_4H_8 - isobutene
C_4H_6 - 1,3 butadiene
C_4H_{10} - butane
C_5H_{12} - isopentane
C_6H_6 - benzene
C_7H_8 - tolulene
C_8H_{10} - xylene
CH_2O - formaldehyde
MEOH - methanol
ETOH - ethanol
MECHO -acetaldehyde

3.1.6 The TNO Study

In a comprehensive study from the Netherlands (Rijkeboer and Hendrikson 1993; Rijkeboer et al. 1994), four fuels—gasoline, LPG, CNG, and diesel—were tested in passenger cars and light-duty vans over five different driving cycles: the cold-start European driving cycle, the warm European driving cycle, the U.S. 1975 driving cycle, an actual urban driving pattern, and an actual traffic jam pattern. The gasoline, LPG, and diesel fuels were tested in four cars and one van. The CNG was tested in only one car and one van. Table 3.3 summarizes the vehicles tested.

The intent of the study was to examine the relative environmental effects of the various fuels when used in state-of-the-art vehicles. The gasoline used for the tests was not "reformulated," but the diesel fuel used had a 0.03% sulfur content and was thus representative of low-sulfur fuels for the European market. Exhaust emissions data were obtained for regulated components [e.g., CO, HC, oxides of nitrogen (NO_x), particulates] and a number of unregulated components in order to evaluate the following:

1. direct toxic and nuisance effects due to CO, nitrogen dioxide (NO_2), particulates, and formaldehyde;
2. long-term toxic effects from polycyclic aromatic hydrocarbons (PAH), benzene, tolulene, xylene, and formaldehyde;
3. summer smog potential;
4. winter smog potential;
5. acidifying potential; and
6. global warming potential.

Table 3.3. TNO vehicle/fuel combinations

Vehicle number	Vehicle type	Engine technology used	Fuels used	Number of cylinders	Number of valves per cylinder
1	Honda Civic 1.6 ESI	MPFI	G, LPG	4	4
2	Lancia Thema 2.0 I 16V	MPFI	G, LPG	4	4
3	Opel Vectra 1.6 I	SPFI, EGR	G, LPG, CNG	4	2
4	Volvo 850 GLT	MPFI	G, LPG	5	4
5	VW Transporter 2.0 I	SPFI	G, LPG, CNG	4	2
6	Mercedes 250 D Turbo	Electronic IDI, EGR, TC	Diesel	5	—
7	Nissan Sunny 2.0 D	IDI, EGR, no catalyst	Diesel	4	—
8	Peugeot 405 1.9 D	IDI, no catalyst	Diesel	4	—
9	VW Vento 1.9 TD	IDI, TC	Diesel	4	—
10	Ford Transit 2.5 DI Turbo	DI, EGR, TC, no catalyst	Diesel	4	—

Abbreviations: MPFI = multipoint fuel injection; SPFI = single-point fuel injection; EGR = exhaust gas recirculation; IDI = indirect injection; DI = direct injection; TC = turbocharged; G = gasoline; LPG = liquefied petroleum gas; CNG = compressed natural gas.

Notes: All vehicles equipped with a catalyst unless otherwise noted. None of the vehicles equipped with EGR unless otherwise noted. Vehicles 4 and 6 had automatic transmissions.

The details regarding the weighting factors and the protocol used are omitted here, but readers who are interested in quantitative comparisons with other studies should be assured that a consistent set of assumptions applies among the various studies.

A summary of the results are shown in Table 3.4. The table depicts the authors' qualitative evaluation of the four fuels based on tailpipe emissions alone. It should be noted that since the gasoline used was not reformulated, the values reported for CO, PAH, BTX (benzene, tolulene, and xylene), summer smog, and acidification may be higher than those that would result from the use of reformulated gasoline.

The study also estimates the emissions associated with evaporation, along with the production and distribution of the fuels. While consideration of these additional emissions changes the total impact of the fuels (in some cases substantially), it apparently does not change the qualitative rankings of the fuels.

The overall conclusions of the TNO study are that in terms of the effects considered, the fuels are ranked with CNG first, LPG second, gasoline third, and diesel fuel last. The study concludes that LPG is a viable alternative for diesel fuel in light-duty-vehicle applications. This is an example of how the local or regional situation can influence the recommendations of a study. While the conclusions reached in the TNO study apply to the situation in the Netherlands, the same conclusions would not be reached in other countries like the United States where the number of light-duty vehicles fueled with diesel fuel is insignificant. In areas where diesel is not widely used in light-duty vehicles, LPG would be considered in terms of a replacement for gasoline, and in the words of the authors of the TNO study, "when one compares LPG with gasoline it appears that although LPG scores consistently better than gasoline, the differences are nonetheless small in an absolute sense, due to the low absolute level of emissions."

3.1.7 The Pitstick Study

Pitstick (1993) reviewed data on the emissions from ethanol and LPG vehicles and reported general trends with respect to their environmental impact. A summary of the information in the report is presented in Table 3.5. From the point of view of regional air quality, the ozone-forming potential of each fuel is the best indicator of impact. Note that the ozone-forming potential is measured relative to conventional gasoline. Thus, gasoline is assigned an ozone-forming potential of 1, and any fuel with a potential less than 1 is expected to produce less O_3. As shown in Table 3.5, the ozone-forming potential of reformulated gasoline, diesel, and ethanol are the same, and all are less than or equivalent to that of gasoline. The ozone-forming potential of LPG is definitely less than that of gasoline and less than or equivalent to that of reformulated gasoline, diesel, or ethanol. Figure 3.12 further compares the ozone-forming potentials of gasoline, E95, and LPG fuels relative to the NMOG/NO_x ratio. Note that as this ratio increases past 18, LPG will no longer have an advantage over

Table 3.4. Evaluation of effects

	Gasoline	LPG	CNG	Diesel
Direct toxic and nuisance effects				
CO	o	o/+	++	+
NO_2	o	o	+	--
Particulates	o/+	+	o	-/--
Lower aldehydes[a]	o	o	+/++	-/--
Long-term toxic effects				
PAH	o	+	+	-
BTX	-	o	o	o
Lower aldehydes[a]	o	o	+	-
Regional and global effects				
Summer smog	-	o	+	--
Winter smog	o	o/+	o	-
Acidification	o	o/+	o/+	-
GWP	-/o	o	o/+	-/o
Summary of all effects				
Direct toxic and nuisance effects	o	o/+	+/++	-/--
Long term toxic effects	-/o	o/+	+	-
Regional and global effects	-/o	o/+	o/+	-

Abbreviations: CO = carbon monoxide; NO_2 = nitrogen dioxide; PAH = polycyclic aromatic hydrocarbons; BTX = benzene, tolulene, and xylene; GWP = global warming potential; LPG = liquefied petroleum gas; and CNG = compressed natural gas.

Key: ++ Much better than average
\+ Better than average
o Average
\- Worse than average
-- Much worse than average

[a] Formaldehyde, acrolein, and acetaldehyde.

Source: Adapted from Rijkeboer and Hendrikson 1993.

Table 3.5. Summary of emissions from ethanol and LPG vehicles

Issue	Gasoline[a]	RFG	Diesel	Ethanol	LPG
			Emission rate		
NMOG	Base	Lower	Lower	Lower	Lower
CO	Base	Lower	Lower	Equal	Lower
NO_x	Base	Equal	Higher	Equal	Higher
Evaporative	Base	Lower	Lower	Lower	Lower
Ozone-forming potential	1.00	0.8±0.2	0.8±0.2	0.8±0.2	0.65±0.2
			Toxic emissions		
Particulate	Low	Low	High	Low	Low
1,3-Butadiene	Medium	Medium	Unknown	Low	Low
Benzene	High	Medium	Low–Medium	Low	Low
Formaldehyde	Medium	Medium	Medium	Medium	Low
Acetaldehyde	Low	Low	Low	High	Low
			Global warming factors		
CO_2 emissions (g/Btu)[b]	0.094	0.094	0.096	0.083	0.081
Fuel economy (mpg)	34	34	39-48	28	31
Energy use (Btu/mile)	3350	3350	3260-2160	2920	2830
CO_2 emissions (g/mile)[b]	315	315	313-252	243	229

Abbreviations: NMOG = nonmethane organic gases, CO = carbon monoxide, NO_x = oxides of nitrogen, LPG = liquefied petroleum gas, CO_2 = carbon dioxide, Btu = British thermal unit, mpg = miles per gallon, g = gram, and RFG = reformulated gasoline.

[a] Current industry average gasoline.

[b] Values are net CO_2 emissions from production, transportation, and combustion of the fuel. Ethanol values exclude combustion emissions and assume coproduct credits.

Source: Adapted from Pitstick 1993.

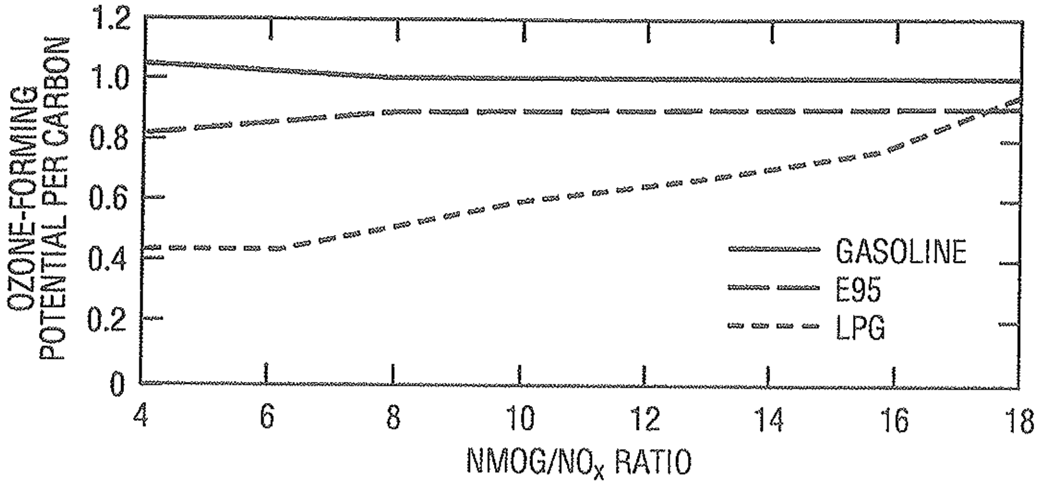


Fig. 3.12. Ozone-forming potential of gasoline, E95, and LPG vs NMOG/NO$_x$ ratio. (*Source:* Adapted from Pitstick 1993)

E95 and gasoline. Table 3.5 also contains notes on relative emission rates from gasoline, reformulated gasoline, diesel, ethanol, and LPG fuels. Tables 3.6 and 3.7 list the measured emissions rates from vehicle testing from various sources. Table 3.5 indicates that the emission rates from ethanol are expected to be equivalent to or lower than that of gasoline, but the data in Table 3.7 for E85 show some higher emission rates. The expected trends for LPG emissions reported in Table 3.5 also do not match the data given in Table 3.7, particularly for NO$_x$. Since the tables are from the same report, they illustrate the problem of too little actual data available to truly determine if the expected trends will actually occur when alternative fuels are used.

3.1.8 The Gordon Study

Gordon and Austin (1992) reviewed the results of emissions testing performed by the California Air Resources Board. The tests involved five types of vehicles: dedicated M85 (85% methanol, 15% gasoline) vehicles, flexibly fueled (M85 or gasoline) vehicles, dual-fuel CNG-gasoline vehicles, dual-fuel LPG-gasoline vehicles, and a production gasoline vehicle. None of the engines was optimized for methanol or CNG fuel use. The total distance traveled by most of the vehicles was fairly low, and all of the vehicles had rigorous maintenance. The emissions data from the tests are shown in Table 3.8. The reactivity-adjusted emissions are shown in Table 3.9. The adjusted NMOG emissions of Table 3.9 show dramatic reductions for the CNG vehicles and significant reductions for the LPG vehicle as compared to the production gasoline vehicle. However, CO emissions for the CNG and LPG vehicles as shown in Table 3.8 are much higher than for the production gasoline vehicle. The emission rates for the M85 vehicles vary over a wide range in all cases, but the data in Table 3.9

Table 3.6. Emission rates of heavy-duty engines fueled with ethanol and methanol, and EPA standards data

		Emission rate (grams/bhp-h)				
	Fuel	Total HC	OMHCE	CO	NO_x	Particulates
		Engine tests[a]				
	E95		0.73	1.71	4.15	0.04
	M100		0.1	2.05	1.7	0.03
	M85		0.23	1.6	4.05	0.03
		Standards				
91 Heavy-duty standard		1.3		15.5	5	0.25
93 Urban bus standard		1.3		15.5	5	0.1
94 Heavy-duty standard		1.3		15.5	5	0.1
94 Urban bus standard		1.3		15.5	5	0.05[b]
98 Heavy-duty standard		1.3		15.5	4	0.1
98 Urban bus standard		1.3		15.5	4	0.05[b]

Abbreviations: bhp = brake horsepower; HC = hydrocarbons; OMHCE = organic material hydrocarbon equivalent; CO = carbon monoxide; NO_x = oxides of nitrogen; E95 = fuel mixture of 95% ethanol, 5% gasoline; M100 = 100% methanol fuel; and M85 = fuel mixture of 85% methanol, 15% gasoline.

[a] A 1992 turbocharged and aftercooled Detroit Diesel Corporation urban bus engine, 6V-92TA, with a catalyst was used for emission testing.

[b] EPA can relax particulate matter standard for urban buses to 0.07 if 0.05 is not achievable.

Source: Adapted from Pitstick 1993.

suggest that NMOG emissions are generally worse than those from a production gasoline vehicle.

3.1.9 The Sorenson Study

Even though the term "zero emission vehicle" has been introduced as a euphemism for electric vehicles, it is clear that the operation of such vehicles can have undesirable air quality impacts depending on the source of the electricity. For example, in a study conducted in Denmark (Sorenson 1992b) the equivalent emissions factors for electric vehicles were determined by multiplying the electrical energy consumption of the vehicle per unit distance traveled by the emission factors (mass of emissions per unit electrical energy produced) associated with the source of the electricity used. Some accommodation for line losses and charging efficiency were made. The results

Table 3.7. Emission rates of vehicles fueled with E85, M85, LPG, and gasoline

		Emission rate (g/mile)						
Vehicle	Fuel	Total HC	NMOG	Unburned fuel[a]	HCHO	CH_3COH	CO	NO_x
92 Chevy Lumina VFV	E85		0.16		0.005	0.021	0.5	0.19
92 Chevy Lumina VFV	M85		0.18		0.018		1.5	0.21
91 Chevy Lumina VFV	E85[b]	0.32	0.26	0.19	0.005	0.021	1.7	0.26
91 Chevy Lumina VFV	M85	0.29	0.27	0.21	0.015	0.001	2.46	0.24
91 VW Jetta FFV	E85[b]	0.36	0.30	0.22	0.005	0.022	4.04	0.06
91 VW Jetta FFV	M85	0.29	0.28	0.23	0.018	0.001	2.59	0.06
89 Oldsmobile Delta 88	LPG	0.16	0.11	0.07	0.001	0.001	2.68	0.06
89 Oldsmobile Delta 88	Gasoline	0.12	0.1		0.001	0.001	2.21	0.45
89 Pontiac 6000 LE	LPG	0.14	0.1	0.07	0.004	0.001	0.72	0.29
90 Ford Taurus	LPG		0.16		0.006	0.001	1.71	0.86
90 Ford Taurus	Gasoline		0.18		0.005	0.002	1.56	0.53
Modern LPG Conversion	LPG	0.14–0.13					0.54–1.38	0.006–0.27

Abbreviation: E85 = a fuel mixture of 85% ethanol, 15% gasoline; M85 = a fuel mixture of 85% methanol, 15% gasoline; LPG = liquefied petroleum gas; g = gram; HC = hydrocarbons, NMOG = nonmethane organic gases; HCHO = formaldehydr; CH_3COH = acetaldehyde; CO = carbon monoxide; and NO_x = oxides of nitrogen.

[a] Ethanol for E85, methanol for M85, propane for LPG.

[b] Vehicle designed to run on M85.

Source: Adapted from Pitstick 1993.

Table 3.8. Emissions data from gasoline-fueled and alternatively fueled vehicles

				Emissions[a]				
Vehicle	Type/Fuel	Year	Mileage	NMOG	CO	NO_x	HCHO	M100
Toyota Camry	Prod Gas	1988	40,030	0.20	2.33	0.32	4.2	0
Ford Crown Victoria	Ded M85	1986	49,145	0.35	0.68	0.36	47.1	0.22
Ford Crown Victoria	Ded M85	1986	49,635	0.38	0.76	0.31	53.3	0.24
Toyota Corolla	Ded M85	1989	14,734	0.49	4.81	0.48	29.3	0.31
Ford Crown Victoria	FFV M85	1987	54,121	0.58	2.60	0.48	56.2	0.41
Ford Crown Victoria	FFV M85	1987	60,860	0.78	2.49	0.78	99.1	0.53
Chevrolet Corsica	FFV M85	1988	20,983	0.51	5.79	0.31	26.1	0.36
Nissan Stanza	FFV M85	1988	15,455	1.16	3.85	0.19	35.4	1.07
Plymouth Voyager	FFV M85	1990	12,853	0.24	1.71	0.36	13.5	0.20
Plym. Voyager Turbo	FFV M85	1990	12,189	0.76	8.26	0.29	195.0	0.49
Dodge Dynasty	DF CNG	1990	5,709	0.11	15.90	0.24	5.5	0
Dodge Dynasty	DF CNG	1990	5,937	0.07	3.68	0.90	9.2	0
Oldsmobile Delta 88	DF LPG	1989	22,705	0.16	5.20	0.09	5.8	0

Abbreviations: NMOG = nonmethane organic gases; CO = carbon monoxide; NO_x = oxides of nitrogen; HCHO = formaldehyde; M85 = a fuel mixture of 85% methanol, 15% gas; CNG = compressed natural gas; LPG = liquefied petroleum gas; M100 = 100% methanol; DED = dedicated; FFV = flexibly fueled vehicle; Prod = production; Gas = gasoline; and DF = dual fuel.

[a] Emissions are in grams/mile except for HCHO, which is in miligrams/mile.

Source: Adapted from Gordon and Austin 1992.

are shown in Table 3.10 for coal-fired power plants and in Table 3.11 for small natural-gas-fueled cogeneration plants.

The last line of both tables shows the emission standards for passenger cars that went into effect for Denmark in October 1990. The last two columns in Table 3.10 show the effects of selective catalytic reduction of NO_x and an assumed 95% reduction in sulfur dioxide (SO_2) from the coal-fired plant, respectively. The vehicle energy consumptions given range from advanced concept vehicles (0.1 kWh/km) to less efficient heavy vehicles (0.7 kWh/km).

Table 3.9. Reactivity adjusted NMOG emissions from gasoline and alternatively fueled vehicles

Vehicle	Type/Fuel	Year	Mileage	NMOG (g/mile)′	RAF	Adjusted NMOG (g/mile)
Toyota Camry	Prod Gas	1988	40,030	0.20	1.00	0.20
Ford Crown Victoria	Ded M85	1986	49,145	0.35	0.81	0.28
Ford Crown Victoria	Ded M85	1986	49,635	0.38	0.81	0.31
Toyota Corolla	Ded M85	1989	14,734	0.49	0.81	0.40
Ford Crown Victoria	FFV M85	1987	54,121	0.58	0.81	0.47
Ford Crown Victoria	FFV M85	1987	60,860	0.78	0.81	0.63
Chevrolet Corsica	FFV M85	1988	20,983	0.51	0.81	0.41
Nissan Stanza	FFV M85	1988	15,455	1.16	0.81	0.94
Plymouth Voyager	FFV M85	1990	12,853	0.24	0.81	0.19
Plymouth Voyager Turbo	FFV M85	1990	12,189	0.76	0.81	0.62
Dodge Dynasty	DF CNG	1990	5,709	0.11	0.52	0.06
Dodge Dynasty	DF CNG	1990	5,937	0.07	0.52	0.04
Oldsmobile Delta 88	DF LPG	1989	22,705	0.16	0.82	0.13

Abbreviations: g = gram; NMOG = nonmethane organic gases; RAF = reactivity adjustment factor; DED = dedicated; M85 = a fuel mixture of 85% methanol, 15% gasoline; FFV = flexibly fueled vehicle; Prod. = production; Gas = gasoline; DF = dual fuel; CNG = compressed natural gas; and LPG = liquified petroleum gas.

Source: Adapted from Gordon and Austin 1992.

Using a value of 0.15 kWh/km to characterize state-of-the-art electric vehicle consumption (Sorenson 1992b), even with a 95% reduction in SO_2 the electric vehicle using electricity from coal-fired plants creates much more SO_2 than its gasoline-fueled counterpart, according to Sorenson's figures. For the natural-gas-fueled cogeneration plant the situation is improved—especially when one realizes that the HC emissions are primarily CH_4. Clearly, the use of electricity from nuclear, geothermal, or hydroelectric generating stations would result in significantly lower emissions attributable to electric vehicle operation.

Table 3.10. Equivalent emissions from electric vehicles: coal-fired electric generation

Vehicle energy use (kWh/km)	Emissions (g/km)				
	NO_x	SO_2	CO_2	NO_x[a]	SO_2[b]
0.05	0.18	0.36	47	0.04	0.04
0.15	0.53	1.09	140	0.12	0.12
0.25	0.88	1.81	233	0.20	0.20
0.35	1.23	2.54	327	0.28	0.28
0.45	1.58	3.26	420	0.36	0.36
Denmark 1990 3-way cat.[c]	0.61	0.01	190	0.61	0.01

Abbreviations: g = gram, km = kilometer, kWh = kilowatt-hour, NO_x = oxides of nitrogen, SO_2 = sulfur dioxide, and CO_2 = carbon dioxide.

[a] With selective catalytic reduction applied.

[b] With 95% reduction assumed.

[c] 1990 emission standards for passenger cars in Denmark.

Source: Adapted from Sorenson 1992b.

Tables 3.10 and 3.11 (or the appropriate equivalent) can be used to determine what electric vehicle energy efficiency would be required to meet conventional vehicle emission standards.

3.1.10 Methanol Bus Study

A study by Ullman, Hare, and Baines (1986), though not recent, is included to illustrate the impact technology can have on vehicle emissions. In this study emissions data were collected on five in-service bus engines. Two of the buses were methanol-fueled, and three were diesel-fueled. The two methanol buses were part of a demonstration program in California and were tested for emissions after approximately two years of service in the San Francisco area. The M.A.N. methanol bus, built by Maschinenfabrik Augsburg-Nurnberg of Germany, was equipped with a catalyst to

Table 3.11. Equivalent emissions from electric vehicles: natural-gas-fueled cogeneration electricity

Vehicle energy use (kWh/km)	Emissions (g/km)			
	NO_x	CO_2	HC	CO
0.05	0.16	31	0.21	0.16
0.15	0.48	92	0.64	0.48
0.25	0.78	154	1.06	0.80
0.35	1.09	216	1.49	1.11
0.45	1.40	277	1.91	1.43
Denmark 1990 3-way cat.[a]	0.61	190	0.25	2.1

Abbreviations: g = gram; km = kilometer; kWh = kilowatt-hour, NO_x = oxides of nitrogen; CO_2 = carbon dioxide, HC = hydrocarbons; and CO = carbon monoxide.

[a] 1990 emission standards for passenger cars in Denmark.

Source: Adapted from Sorenson 1992b.

reduce the emission of unburned methanol and aldehydes. The M.A.N. bus had accumulated 45,500 km (28,300 miles) of service in 2 years. The GMC methanol bus, built by General Motors Corporation (GMC) of the United States, was turbocharged and aftercooled but not equipped with a catalyst. The GMC bus had accumulated 30,400 km (18,900 miles) of service in two years. The results of the emission tests are shown in Table 3.12. As can be seen, the emission results from the two buses are very different. The difference between the two illustrates the difference technology can make in emissions rates. The GMC bus is a prototype and had much higher emission levels than the more developed M.A.N. bus. For comparison purposes, three in-service buses powered by the diesel version of the engine in the GMC methanol bus were also tested. The results of these tests are shown in Table 3.13.

3.1.11 Windsor Methanol Bus Study

Exhaust emissions of two methanol buses in the Transit Windsor Methanol Bus Demonstration project have been tested periodically during the project. The methanol buses each had a Detroit Diesel methanol engine equipped with catalytic exhaust

Table 3.12. Emissions from heavy-duty engines running on methanol during steady-state operation

	M.A.N. bus			GMC bus		
Emission	Cold idle (g/h)	Hot idle (g/h)	40 kph (g/km)	Cold idle (g/h)	Hot idle (g/h)	40 kph (g/km)
HC	225	4.6	0.45	2900	660	140
Aldehydes	14	2.1	0.039	35	23	1.2
Particulates	0.58	0.81	0.02	6.8	3.8	0.19
CO	56	2.3	.21	440	290	27
NO_x	47	67	2.4	19	3.6	1.6
Unburned methanol	230	8.5	0.49	2700	380	120

Abbreviations: g = gram, h = hour, kph = kilometers per hour, km = kilometer, HC = hydrocarbons, CO = carbon monoxide, NO_x = oxides of nitrogen, M.A.N. = Maschinenfabrik Augsburg-Nurnberg, and GMC = General Motors Corporation.

Source: Adapted from Ullman, Hare, and Baines 1986.

Table 3.13. Emissions from heavy-duty engines running on diesel fuel during steady-state operation

Emission	Hot idle (g/h)	40 kph (g/km)
HC	18–40	1.0–1.2
Aldehydes	1.5–2.6	0.05–0.10
Particulates	4.0–8.0	0.40–0.50
CO	20–30	1.0–1.2
NO_x	150–200	7.3–9.3

Abbreviations: g = gram; h = hour, km = kilometer, HC = hydrocarbons; CO = carbon monoxide, NO_x = oxides of nitrogen; and kph = kilometers per hour.

Source: Adapted from Ullman, Hare, and Baines 1986.

aftertreatment. A diesel bus also in regular service in Windsor was tested for comparison purposes. The vehicles were tested using four driving cycles under two simulated loading conditions. The results of the tests conducted in Phase 3 of the study have been presented by Rideout (1994). Comparison of the emissions from the methanol and diesel buses are shown in Table 3.14 for the driving cycle that resulted in the highest emission levels—the driving cycles based on experience from the New York City bus system.

Table 3.14. Comparison of exhaust emissions from methanol and diesel buses

Emission[a]	Methanol bus 545[b]	Methanol bus 546[c]	Diesel bus 542[d]
OMHCE	10.42	30.95	2.01
HC	0.00	0.00	1.92
CO	27.32	73.78	57.23
NO_X	29.99	23.09	51.89
CO_2	6,855.51	6,631.00	6,557.00
Methanol	21.12	60.81	0.00
Formaldehyde (mg/mile)	2,753.36	9,982.17	255.74
Aldehydes (mg/mile)	2,827.44	10,010.66	386.66
Particulates	0.62	1.31	4.79
DEFE (miles/gal)	1.35	1.37	1.50

Abbreviations: OMHCE = organic material hydrocarbon equivalent, HC = hydrocarbons, CO = carbon monoxide, NO_x oxides of nitrogen, CO_2 = carbon dioxide, km = kilometer, mg = miligram, DEFE = diesel equivalent fuel efficency, and gal = U.S. gallon.

[a] Measured in grams per mile except as otherwise stated.

[b] Mileage: 86,200 km

[c] Mileage: 88,200 km

[d] Mileage: 89,900 km

Source: Adapted from Rideout 1994.

As shown in Table 3.14, the NO_x and particulate emissions of the methanol buses are much lower than the diesel bus, but the other emissions appear to be equivalent to or higher than those from the diesel bus.

3.1.12 Ethanol Bus Study

In 1990, Energy, Mines, and Resources Canada funded the operation of two ethanol-fueled buses that began regular passenger service in Regina, Saskatchewan, in 1991 (King and Prakash 1992). Data based on the first year of operation show that the buses have had good on-road performance and have required little maintenance. During the first year of service, the emissions of one bus were tested after 18,500 km of service and after 52,000 km of service. For comparison purposes, the emissions of a diesel-fueled bus placed in service at the same time as the ethanol buses were also measured. Note that the ethanol bus did not have a catalytic converter and that its engine is based on a methanol engine built by Detroit Diesel. The buses were tested in four different driving cycles. The emissions from three of the cycles were very similar, but one cycle based on actual experience in New York City produced much higher emissions than the other three. The results of the emissions tests are shown in Table 3.15.

As shown in Table 3.15, the NO_x and particulate emissions from the ethanol bus are substantially less than those from the diesel-fueled bus, and the carbon dioxide (CO_2) emissions are equivalent, but all of the other measured emissions were higher for the ethanol buses. This was the case for the other driving cycles in the report as well (King and Prakash 1992).

3.1.13 Summary of Vehicle Emissions

In summary, it is clear that the emissions levels from vehicles depend on many factors, including

1. the condition of the vehicle,
2. the sophistication of the engine emission control system,
3. the driving mode (or driving cycle) used,
4. the composition of the fuel,
5. whether the fuel is liquid or gaseous, and
6. the ambient temperature.

Examinations of emission test results to try to determine fuel effects are often thwarted or compromised by the inability to separate out the effects resulting from the other factors.

It is clear also that the technology exists to create light-duty vehicles capable of low emissions of regulated compounds using any of the fuels considered. The gaseous

Table 3.15. Comparison of emissions from an ethanol bus and a diesel bus

	Chassis transient test cycle emissions (g/km)		
Emission	Ethanol bus at 18,500 km	Ethanol bus at 52,000 km	Diesel bus
OMHCE	7.83	5.31	1.16
HC	2.09	0.01	1.10
CO	41.59	56.84	39.22
NO_x	18.78	15.39	30.97
CO_2	4114	3875	3898
Formaldehyde	0.44	0.41	0.20
CH_3COH	0.53	0.69	
Aldehydes	1.07	1.12	0.30
C_2H_5OH	17.76	16.08	
Particulates	0.78	1.30	3.36

Abbreviations: g = grams, km = kilometer, OMHCE = organic material hydrocarbon equivalent, HC = hydrocarbons, CO = carbon monoxide, NO_x = oxides of nitrogen, CO_2 = carbon dioxide, CH_3COH = acetaldehyde, and C_2H_5OH = unburned ethanol.

Source: Adapted from King and Prakash 1992.

fuels have a distinct advantage over the liquid fuels (and the gasolines have a distinct advantage over the alcohol fuels) when low-temperature starting is a factor. The introduction of preheated catalysts (electric or otherwise) and air injection to control cold-start emissions, however, may neutralize this advantage. Finally, the gaseous fuels have an inherent advantage in that fewer total toxics are emitted from the engines of these vehicles.

3.2 GLOBAL AND TRANSBOUNDARY EFFECTS

3.2.1 Introduction

In Sect. 2.1, background information on global and transboundary phenomena was presented. In this section more specific information is presented on how each alternative fuel could impact these global and transboundary effects. In order for an alternative fuel to have a significant impact on global and transboundary phenomena, there must be a significant utilization of the alternative fuel. Thus, the initial environmental impetus for the implementation of alternative fuels probably should spring from considerations of their local and regional environmental impacts rather than their global environmental impacts, because the fraction (and thus the impact) of alternatively fueled vehicles in local vehicle populations will be greater than the fraction in the global vehicle population. However, alternative fuel implementation can make incremental changes that contribute to individual geopolitical goals.

In discussing the global warming impacts of alternative fuel utilization, it is necessary to include all aspects of the fuel cycle: production, distribution, and end use. This is particularly true of fuels for which the fuel production processes themselves release significant amounts of greenhouse gases. There are also global warming effects created by the production of the vehicle, and these may depend on the type of fuel that the vehicle will use. For example, the production of composite tanks for CNG has a greater potential effect on global warming than the production of conventional tanks (DeLuchi 1991).

Note also that while improving the fuel economy of vehicles is an effective way of reducing the global effects associated with the end use of the fuel, the total reduction will not be directly proportional to the reduction in the amount of fuel consumed. This is because not all the global effects will be associated with the amount of fuel consumed by the vehicle; those effects created in the manufacturing and assembling of the vehicles, for example, will be unchanged by vehicle fuel consumption.

Before discussing the details of the information, a few points need to be emphasized. First, the diesel engine has a significantly higher efficiency than the conventional spark ignition engine since diesel engines are not throttled and use a higher compression ratio. Since the alternative fuels being considered in this study do not have the proper ignition characteristics (cetane rating) to allow direct substitution for diesel fuel, heavy-duty engines utilizing these fuels are modified to accommodate them. In some of the studies reviewed, the authors believe that this accommodation will reduce the thermal efficiency of the diesel engine when modified to operate on alternative fuels (EPA 1990c). On the other hand, spark ignition engines are often assumed to be capable of higher efficiencies when operated on alternative fuels that have octane ratings higher than those of the gasolines they replace (EPA 1990a). The assumption of higher efficiency results (at least in part) from the assumption that higher compression ratios will be used with alternative fuels in light-duty vehicles, but this is not always the case.

3.2.2 Global Warming

A summary of several independent studies of the effects of alternative fuels on global warming are presented in this section. See Sect. 3.2.2.7 for a comparison of the results of the studies discussed.

3.2.2.1 The NREL study

The National Renewable Energy Laboratory (NREL) of the U.S. Department of Energy (DOE) has developed a methodology for evaluating energy choices called "Total Fuel Cycle Analysis" (NREL 1993). One output from this analysis of alternative fuel scenarios is CO_2 emissions expressed as grams per vehicle mile traveled. The analysis does not include the emissions of CH_4 or nitrous oxide (N_2O), nor emissions associated with manufacturing or assembling the vehicles that would use the fuel.

In the NREL study, three fuels were analyzed for use in light-duty vehicles; of these, the first two are for the year 2000 timeframe and the last is for the year 2010 timeframe:

1. reformulated gasoline using methyl tertiary butyl ether,
2. E10 using ethanol made from municipal solid waste, and
3. E95 using ethanol made from biomass.

3.2.2.2 The CEC study

In a study published by the California Energy Commission (CEC) (CEC 1989), the following fuels were considered to be the most viable for use by light-duty vehicles and were analyzed for their global warming potential:

1. gasoline from crude oil,
2. diesel from crude oil,
3. CNG from natural gas,
4. methanol from natural gas, and
5. methanol from coal.

In addition to CO_2, this study also considered CH_4 and N_2O as global warming gases. As in the NREL study, the production of these gases associated with the manufacture of the vehicles was not considered.

3.2.2.3 The EPA studies

EPA has completed a series of studies in which various alternative fuels were examined for, among other things, their potential to contribute to global warming. The fuels considered were ethanol (EPA 1990a), natural gas for light-duty vehicles (EPA 1990b), natural gas for heavy-duty vehicles (EPA 1990c), and methanol (EPA 1989). The analyses used for the global warming effects are not consistent across the four studies.

In the ethanol study (EPA 1990a), an analysis of current production technology using corn as the feedstock was made. The end-use assumption was based on an optimized E100 vehicle, some credit for increased corn production displacing soybean production (and the resulting savings in fossil fuels consumed), and some assumptions regarding the efficiency of newer ethanol production plants. The study also notes that "the growing of cellulosic feedstocks (trees and herbaceous crops) could reabsorb a quantity of carbon dioxide virtually equal to the amount emitted in the production/use of ethanol produced from these sources."

The EPA study on methanol (EPA 1989) does not present any global warming figures for methanol, but does raise a concern that if regulatory agencies allow vehicle manufacturers to obtain corporate average fuel economy credits for alternatively fueled vehicles, the fuel economy of gasoline-fueled vehicles may be allowed to decrease, with a resulting increase in gasoline fuel consumption and global warming.

The EPA study dealing with the application of CNG to light-duty vehicles (EPA 1990b) considers the global warming effects from the end use (the vehicle exhaust) and also considers CH_4 and N_2O emissions, but bases the analysis on emissions data from rather unsophisticated conversions. In the case of the report dealing with the application of CNG to heavy-duty vehicles (EPA 1990c), the report deals with brake-specific CO_2 emissions (grams per brake-horsepower-hour) and does take into account emissions of CO_2 and CH_4 during production of the fuel.

3.2.2.4 The Ecotraffic study

In a comprehensive study investigating energy efficiency, discharges of greenhouse gases, discharges of acid gases, and discharges of other substances that affect health and the environment, a Swedish study (Ecotraffic 1992) investigated the entire fuel chain for ten fuels. The fuels that fell within the scope of the present study are

1. "urban diesel oil,"
2. reformulated gasoline,
3. propane,
4. natural gas,
5. methanol from natural gas,

6. methanol from biomass,
7. ethanol from biomass, and
8. electricity.

End uses considered were passenger cars, trucks, and buses—although not all the fuels were considered for all three vehicles.

3.2.2.5 The DeLuchi study

The most comprehensive U.S. study of global warming and alternative fuels that was reviewed for this report was conducted by DeLuchi (DeLuchi 1991). He considered 31 fuel-production and use scenarios—some of which are beyond the scope of the present study (hydrogen, for example). The scenarios within the scope of the present study are:

Fossil-derived fuels:

Light-duty vehicles	Heavy duty vehicles
Methanol from natural gas	Methanol from natural gas
Compressed natural gas	Compressed natural gas
Liquefied natural gas	Liquefied natural gas
LPG from oil and gas	LPG from oil and gas
Methanol from coal	Methanol from coal
Standard gasoline	Diesel
Reformulated gasoline	

Biomass-derived fuels:

Light-duty vehicles	Heavy-duty vehicles
Methanol from wood	Methanol from wood
Ethanol from corn	Ethanol from corn
Ethanol from wood	Ethanol from wood

Electric vehicles:

Light-duty vehicles	Heavy-duty vehicles
Electricity from U.S. mix	(No heavy-duty electric vehicles were considered)
Electricity from coal	
Electricity from natural gas	
Electricity from nuclear	
Electricity from solar	

DeLuchi considered CO_2, CH_4, CO, NMOG, NO_x, and N_2O as global warming gases.

3.2.2.6 The International Energy Agency study

The International Energy Agency (IEA) adopted DeLuchi's spreadsheet analysis, modified it to reflect the conditions in the Organization for Economic Co-operation and Development (OECD) regions of North America and Europe, and presented the results (OECD 1993). The study focused on light-duty vehicles and used EPA vehicle emission factors, since data for Europe were apparently not available.

The results, shown in Fig. 3.13, demonstrate the large uncertainties associated with the modeling, primarily due to the wide range of assumptions that might apply. Policymakers would be well-advised to consider the particular set of assumptions that apply to their particular situation.

The actual modeling results for North America and Europe do not differ greatly on a vehicle-distance-traveled basis (recall that EPA emissions factors were used for all vehicles). What is significant is the influence that the source of the electricity has on climate change effects of electric vehicles, as is shown in Figs. 3.14 and 3.15.

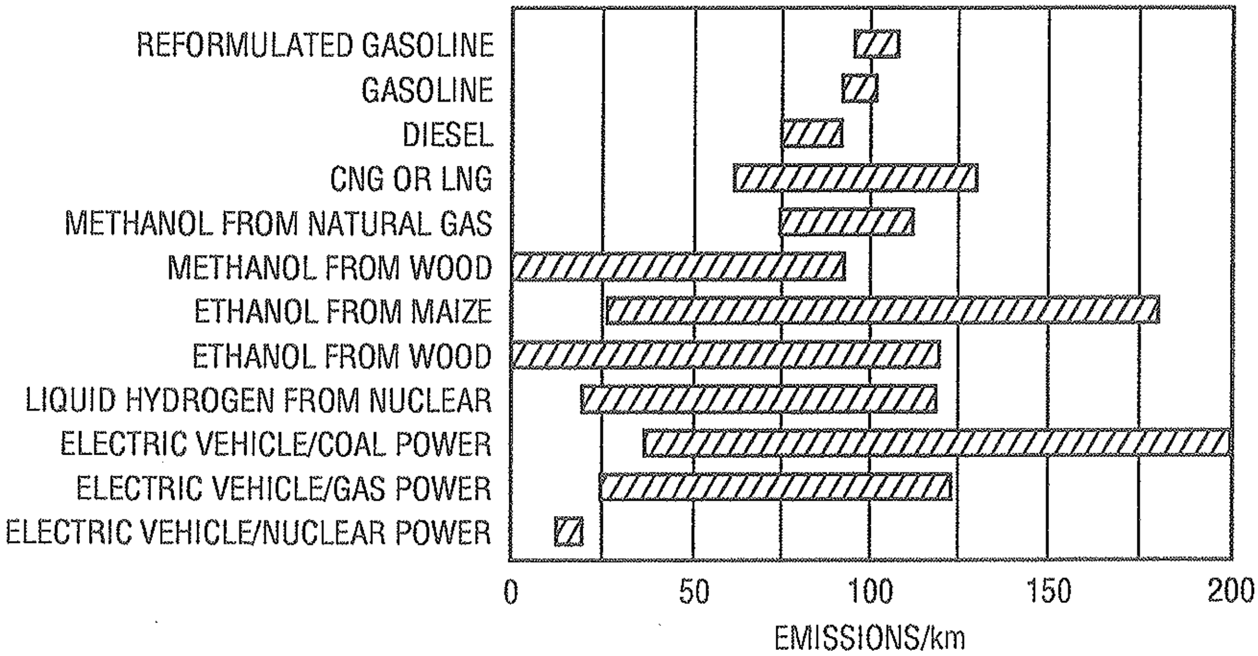


Fig. 3.13. Ranges of greenhouse gas emissions per kilometer for cars using alternative fuels. (*Source:* Adapted from OECD 1993).

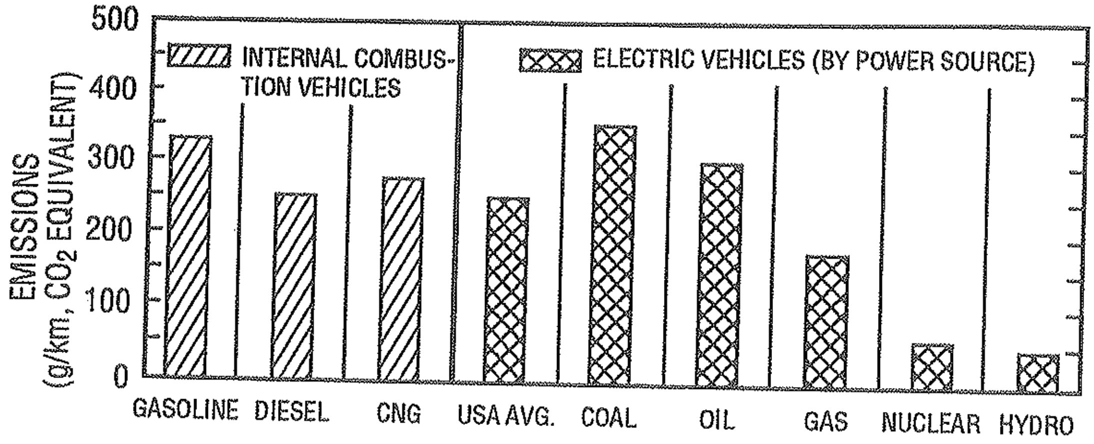


Figure 3.14. Life-cycle greenhouse gas emissions for electric vehicles in North America for the year 2000. (*Source:* Adapted from OECD 1993).

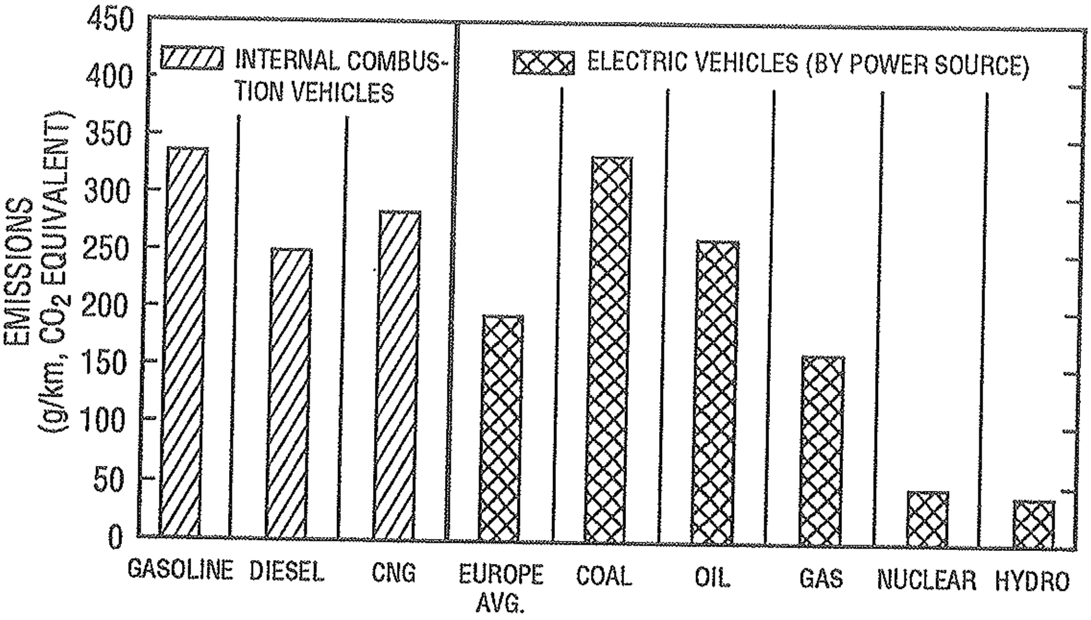


Fig. 3.15. Life-cycle greenhouse gas emissions for electric vehicles in OECD Europe for the year 2000. (*Source:* Adapted from OECD 1993).

3.2.2.7 Comparisons among the various studies

There are several differences among the studies from the different sources. These differences include

1. the global warming gases taken into account,
2. the scope of the fuel/vehicle cycle considered,

3. the effect of CH_4 and N_2O relative to that of CO_2, and
4. the vehicle fuel economy assumptions used.

With reference to the last difference cited, Table 3.16 gives the assumptions used for all of the studies except the IEA study.

The results of common scenarios from the five studies are shown in Table 3.17. The numbers represent the equivalent CO_2 released in grams per mile traveled. DeLuchi's results have been modified so that the numbers do not include the equivalent CO_2 released during production of the vehicle.

In light of the relatively consistent agreement, the results of the DeLuchi analysis will be used whenever possible to draw the conclusions about global warming gases.

Table 3.18 is taken from DeLuchi's study. The numbers in parentheses include both vehicle emissions and equivalent CO_2 emissions associated with the vehicle-manufacturing process. The table has been arranged in increasing order of CO_2 emissions levels.

The methanol from coal scenario is based on coal gasification to create a methanol synthesis gas. There has been recent publicity (deLint 1993) about a "hydrocarb" process which results in significantly lower CO_2 releases during methanol production from coal. The process has not yet been demonstrated to be commercially viable.

Note that the global warming impact of electric vehicles is highly dependent on the source of the electricity used—solar and nuclear derived electricity showing significant advantages, natural gas-derived electricity being about the same as CNG, and coal-derived electricity showing disadvantages relative to gasoline, but superior to methanol derived from coal.

3.2.3 Stratospheric Ozone Depletion

Since stratospheric O_3 depletion is primarily associated with the release of chlorine compounds, switching to alternative fuels can have little impact on this problem. Note, however, that there could be some indirect links that have not yet been fully established.

3.2.4 Acid Deposition

The causes of excess acid deposition and its effects are fairly well understood, though trends over time and the exact relationships between emission controls and subsequent decreases in acid precipitation are not known. Furthermore, specific studies of the impact of alternative fuels on acid deposition formation have not been performed. Studies to date have focused upon the emissions from utilities and other large industrial sources.

3. the effect of CH_4 and N_2O relative to that of CO_2, and
4. the vehicle fuel economy assumptions used.

With reference to the last difference cited, Table 3.16 gives the assumptions used for all of the studies except the IEA study.

The results of common scenarios from the five studies are shown in Table 3.17. The numbers represent the equivalent CO_2 released in grams per mile traveled. DeLuchi's results have been modified so that the numbers do not include the equivalent CO_2 released during production of the vehicle.

In light of the relatively consistent agreement, the results of the DeLuchi analysis will be used whenever possible to draw the conclusions about global warming gases.

Table 3.18 is taken from DeLuchi's study. The numbers in parentheses include both vehicle emissions and equivalent CO_2 emissions associated with the vehicle-manufacturing process. The table has been arranged in increasing order of CO_2 emissions levels.

The methanol from coal scenario is based on coal gasification to create a methanol synthesis gas. There has been recent publicity (deLint 1993) about a "hydrocarb" process which results in significantly lower CO_2 releases during methanol production from coal. The process has not yet been demonstrated to be commercially viable.

Note that the global warming impact of electric vehicles is highly dependent on the source of the electricity used—solar and nuclear derived electricity showing significant advantages, natural gas-derived electricity being about the same as CNG, and coal-derived electricity showing disadvantages relative to gasoline, but superior to methanol derived from coal.

3.2.3 Stratospheric Ozone Depletion

Since stratospheric O_3 depletion is primarily associated with the release of chlorine compounds, switching to alternative fuels can have little impact on this problem. Note, however, that there could be some indirect links that have not yet been fully established.

3.2.4 Acid Deposition

The causes of excess acid deposition and its effects are fairly well understood, though trends over time and the exact relationships between emission controls and subsequent decreases in acid precipitation are not known. Furthermore, specific studies of the impact of alternative fuels on acid deposition formation have not been performed. Studies to date have focused upon the emissions from utilities and other large industrial sources.

Table 3.16. **Vehicle fuel economy assumptions used for different studies**

Study	Scenario	mpg	Btu/mile
NREL	RFG (2000)	30.8	
	RFG (2010)	35.6	
	E10 (2000)	30.2	
	E95 (2010)	28.25	
CEC	Gasoline LDV	27.2	4243
	Diesel LDV	35.9	3585
	M85 LDV	16.6	4002
	CNG LDV	—	4243
EPA	Gasoline (LDV)	27.5	
	E100 (optimized)	23.9	
	E85	19.8	
Ecotraffic	Baseline LDV (gasoline)	22.4	
	Baseline truck (diesel)	8.4	
	Baseline bus (diesel)	5.2	
	Propane (LDV) efficiency	1.10 times baseline	
	Propane (bus) efficiency	0.90 times baseline	
	CNG (LDV) efficiency	1.10 times baseline	
	CNG (bus) efficiency	0.90 times baseline	
	Methanol (LDV) efficiency	1.10 times baseline	
	Methanol (bus) efficiency	Same as baseline	
	Ethanol (bus) efficiency	Same as baseline	
DeLuchi	RFG LDV (LDV baseline)	30	
	Diesel HDV (HDV baseline)	6	
	Methanol LDV efficiency	1.15 times baseline	
	CNG LDV efficiency	1.1 times baseline	
	LNG LDV efficiency	1.12 times baseline	
	Ethanol LDV efficiency	1.14 times baseline	
	LPG LDV efficiency	1.1 times baseline	
	Electricity LDV efficiency	5.7 times baseline	
	Methanol HDV efficiency	0.9 times baseline	
	CNG HDV efficiency	0.85 times baseline	
	LNG HDV efficiency	0.85 times baseline	
	Ethanol HDV efficiency	0.94 times baseline	
	LPG HDV efficiency	0.85 times baseline	

Abbreviations: mpg = miles per gallon; Btu = British thermal unit; NREL = National Renewable Energy Laboratory; RFG = reformulated gasoline; E10 = a fuel mixture of 10% ethanol, 90% gasoline; E95 = a fuel mixture of 95% ethanol, 5% gasoline; CEC = California Energy Commission; LDV = light-duty vehicle; M85 = a fuel mixture of 85% methanol, 15% gasoline; CNG = compressed natural gas; EPA = U.S. Environmental Protection Agency; E100 = 100% ethanol; E85 = a fuel mixture of 85% ethanol, 15% gasoline; and HDV = heavy-duty vehicle.

Table 3.17. Carbon dioxide releases: results for light-duty vehicles from common scenarios of the five studies (CO_2 equivalents in g/mile)

Fuel	NREL[a]	CEC	EPA	Ecotraffic	DeLuchi
Gasoline—RFG	290–324	455–507	371	563	435
Diesel	—	360–378		—	382
CNG	—	357–472		370	361
Methanol/NG	—	414–471		483	429
Methanol/coal	—	764–891		—	742
Methanol/wood	—	—	—	113	149
LPG	—	—	—	483	321
Electric/NG	—	—	—	193	334
Electric/Swedish avg.	—	—	—	16	14 (est.)

Abbreviations: CO_2 = carbon dioxide, g = gram, RFG = reformulated gasoline, CNG = compressed natural gas, NG = natural gas, LPG = liquefied petroleum gas, NREL = National Renewable Energy Laboratory, CEC = California Energy Commission, EPA = U.S. Environmental Protection Agency, est. = estimated, and avg = average.

[a] Carbon dioxide only.

The primary sources of acid deposition are the solution of sulfur oxides and NO_x in water. Transportation contributes around 44% of the manmade NO_x emissions in the United States and Europe (NAPAP 1987; Derwent, Grennfelt, and Hov 1991). Thus, the reduction of motor vehicles' contributions to acid deposition requires limits on the emissions of oxides of sulfur (SO_x) and NO_x. In Europe as a whole, emissions of sulfur dioxide from road and sea transport sectors must be reduced by at least 80%, and similar reductions are required for emissions of NO_x to meet acidification reduction goals.

The typical sulfur content of gasolines ranges from 50 to 500 ppmw, but the content can easily be reduced to less than 50 ppmw by desulfurization. A very low sulfur content is also essential to the ability of current catalysts to clean up the exhaust gas by keeping their catalytic activity high. The diesel oils used for road vehicles contain 500–5000 ppmw sulfur and may contain 100–1000 ppmw nitrogen. Lower values (10–50 ppmw) have appeared in special urban diesel oils which have been

Table 3.18. Carbon dioxide equivalent emissions from DeLuchi's study

Fuel scenario	CO_2-equivalent emissions[a] (g/mile)
Light-duty vehicles	
Electricity from solar	1 (67)
Electricity (Swedish power mix)	14 (80)
Electricity from nuclear	29 (90)
Ethanol from wood	77 (133)
Methanol from wood	149 (205)
LPG from gas and oil	321 (378)
Electricity from NG	334 (395)
CNG	361 (423)
LNG	363 (421)
Diesel	382 (424)
Methanol from NG	429 (485)
Standard gasoline	430 (486)
Reformulated gasoline	435 (491)
Electricity (U.S. power mix)	446 (507)
Ethanol from corn	532 (588)
Electricity from coal	546 (607)
Methanol from coal	742 (798)
Heavy-duty vehicles	
Ethanol from wood	565 (771)
Methanol from wood	1042 (1248)
LPG from oil and gas	2355 (2563)
Diesel	2421 (2627)
CNG	2560 (2791)
Methanol from NG	2926 (3132)
Ethanol from corn	3701 (3907)
Methanol from coal	5033 (5239)

Abbreviations: CO_2 = carbon dioxide, g = gram, LPG = liquefied petroleum gas, NG = natural gas, CNG = compressed natural gas, and LNG = liquified natural gas.

[a] Numbers in parentheses include emissions associated with the production of the vehicle.

produced to meet demands for low contents of PAH or total aromatics to reduce cancer risks. Such low levels are also needed to enable the use of oxidation catalysts for diesel engine exhausts. The process used is partial dehydroaromatization (DHA), which also reduces the nitrogen content considerably. The conventional road vehicle fuels can thus achieve the sulfur reduction required.

Nitrogen oxide emissions from engines are formed during combustion. The engine-out NO_x emissions from a light-duty Otto engine can be in the range of 1 to 2 g/km when the vehicle is driven according to the usual test cycles. Most such vehicles today are equipped with catalytic aftertreatment to reduce NO_x emissions to below 0.25 g/km. The technique has the potential to reduce NO_x to about 0.1 g/km. Heavy-duty diesel engines emit considerably more NO_x, up to 10–12 g/km for heavy buses and trucks operated on diesel oil. Catalytic NO_x reduction is not possible with current catalyst technology due to the excess of air in the diesel cycle. Cutting the emissions in half seems possible by technical development, while a value below 2 g/km is desirable to meet the emission reduction goal.

The alternative motor fuels most often considered for widespread use (natural gas, alcohols) are practically free of sulfur. Alternative fuels in the form of alcohols also have the potential to lower NO_x emissions due to their high heat of evaporation and associated lower flame temperature. Emissions lower than half of those with diesel oils have been proven for certified methanol-fueled engines. Similar low values have been achieved for extreme lean burn, natural gas operated engines. As these engines are converted to the Otto cycle, they can be operated so that catalytic NO_x reduction can be used with the potential for even lower emissions, but at the expense of fuel consumption. The search for NO_x catalysts that can be effective with lean-burn engines is continuing and, when successful, would open the door to increased efficiency and lower emissions.

3.2.5 Global Effects Conclusions

3.2.5.1 Global warming

Based on the information obtained, it is concluded that the global warming impacts of alternative fuels may be categorized relative to conventional fuels (gasoline for light-duty vehicles, diesel for heavy-duty vehicles) as being "significantly better," "slightly better," "about the same," "slightly worse," or "significantly worse." The results are shown in Table 3.19.

The introduction of reformulated gasoline should not have a significant *net* change in CO_2 emissions, even though the end use may result in lower CO_2 tailpipe emissions (due to the presence of oxygenates in the fuel). The reason for this is the release of CO_2 due to the higher energy consumption during the refining of the reformulated gasoline (DeLuchi 1991).

It should be reemphasized that substantial uncertainties can exist in climate change estimates. Policymakers should make certain that policy implementation is based upon the best available information.

Table 3.19. Impact on global warming of various alternative fuels relative to conventional fuels

Rating	Light-duty vehicles	Heavy-duty vehicles
Significantly better	Electricity from solar[a,b] Electricity from nuclear[b] Ethanol from wood[a] Methanol from wood[a]	Ethanol from wood[a] Methanol from wood[a]
Slightly better	LPG Electricity from natural gas Compressed natural gas Liquefied natural gas Diesel	None
About the same	Methanol from natural gas Reformulated gasoline Electricity (U.S. mix)[b]	LPG Compressed natural gas
Slightly worse	Ethanol from corn[c] Electricity from coal[b]	Methanol from natural gas
Significantly worse	Methanol from coal	Ethanol from corn[c] Methanol from coal

Abbreviation: LPG = liquefied petroleum gas.

[a] The *energy* production technology for this option has not yet been demonstrated to be commercially feasible.

[b] The *vehicle* technology for this option has not yet been demonstrated to be commercially feasible.

[c] The scenario for ethanol production from corn is taken from DeLuchi (1991). Other scenarios may yield a more favorable rating for ethanol from corn.

3.2.5.2 Stratospheric ozone depletion

Based on the information used in this study, it is concluded that concerns about stratospheric O_3 depletion should not be a factor in decisions regarding the utilization of alternative fuels. Efforts should continue to eliminate the introduction of CFCs into the atmosphere.

3.2.5.3 Acid deposition

In order to fulfill critical and target loads and similar guidelines, emissions from vehicles must be reduced so that air quality limits or guidelines for sulfur and NO_2 are not exceeded. Any fuel that results in decreases in sulfur and nitrogen compounds released to the atmosphere will aid the process. The current technology for limiting both of SO_x and NO_x emissions from conventially fueled vehicles driven by combustion engines is well-developed with SO_x reduction tied to the sulfur content of the fuel and NO_x reduction tied to vehicle emission standards in effect. In the case of electric vehicles, the SO_x and NO_x produced depends on the source of the electricity used, whereas for biomass fuels, the effects of fertilizers used in growing the biomass must also be taken into account.

3.3 REGIONAL AND LOCAL AIR QUALITY EFFECTS

The impacts of conventional and alternative fuels on tropospheric O_3 production are compared in two ways: comparisons of vehicle emissions and comparisons using air quality model predictions. When comparing engine or tailpipe emissions of conventional and alternative fuels, the total mass of the emissions (including particulates) and the relative reactivity of the emitted compounds are compared. When comparing model predictions of air quality, different emission inventories are developed based on the types of fuels used and their consumption patterns. The emission inventories developed for alternative fuels often depend upon the emission and reactivity measurements that are a product of the emission comparisons. Reactivity measurements and air quality modeling are discussed in the following sections. For information on vehicle emissions see Sect. 3.1.

3.3.1 Reactivity Measurements

Reactivity, in terms of fuels, is a measure of the amount of O_3 that can potentially be produced by the fuel and its use. Due to the nonlinearity of O_3 production in the atmosphere, a reduction in the mass of certain emissions may not necessarily lead to the same reduction in O_3 formation. For example, a 50% reduction in the mass of O_3 precursors emitted does not necessarily mean a 50% reduction in O_3 production. Thus, the reactivity of fuel emissions is used as a more reliable measure of impact upon O_3 production.

The reactivity of a particular fuel depends upon the reactivity of the chemical species in the fuel and its combustion products. In addition, reactivity is a function of atmospheric composition—i.e., the amount of volatile organic compounds (VOCs) and NO_x present in the local atmosphere, often expressed as the VOC/NO_x ratio. To further complicate the issue, reactivities are measured in several different ways. A commonly used measure of reactivity is referred to as the incremental reactivity. This is the amount of additional O_3 produced per amount of additional compound added to an environment; it is often used to compare fuels. Table 3.20 shows the incremental reactivities of several compounds as a function of the reactive organic gas (ROG)/NO_x ratio. (ROGs consist of only those VOCs that are highly reactive—i.e., not CO, CH_4, or CFCs.) Table 3.21 shows two different measures of reactivity: the maximum incremental reactivity (MIR) and the maximum O_3 reactivity (MOR). MIR is determined by adjusting the NO_x concentration for a given VOC concentration to find the highest incremental reactivity and is more appropriate when reactions are VOC-limited. MOR is determined by varying the NO_x concentration for a given VOC concentration to find the peak O_3 concentration and is more appropriate when reactions are NO_x-limited. Other reactivities may be given in terms of VOC production, rate constants, miles traveled, mass of emissions, or some combination of experimental

Table 3.20. Incremental reactivities (mole O_3/mole C) of selected compounds as a function of the ROG/NO_x ratio (low-dilution case)

	Incremental reactivity/carbon (by ROG/NO_x)				
Compound	4	8	10	20	40
Formaldehyde	2.42	1.20	0.77	0.24	0.051
Ethane	0.024	0.041	0.031	0.015	0.007
n-Butane	0.1	0.16	0.031	0.052	0.019
Ethene	0.85	0.90	0.64	0.3	0.14
Propene	1.28	1.03	0.61	0.25	0.14
Acetaldehyde	1.34	0.83	0.55	0.24	0.098
Methanol	0.12	0.17	0.12	0.055	0.029
Ethanol	0.18	0.22	0.14	0.038	0.006
Carbon monoxide	0.011	0.022	0.018	0.01	0.005

Abbreviations: ROG = reactive organic gas, NO_x = oxides of nitrogen.
Source: Adapted from Carter and Atkinson 1989.

Table 3.21. Maximum incremental and O_3 reactivities for emissions from fuels

	Reactivity (g of O_3/g of NMOG)	
Species	MIR	MOR
Gasoline NMHC[a]	3.44	1.3
Methanol	0.56	0.28
Ethanol	1.34	0.72
Formaldehyde	7.2	2.08
Acetaldehyde	5.5	2.17
Methane	0.015	0.01
Ethane	0.25	0.18
Propane	0.48	0.31
Butane	1.02	0.66
Pentane	1.04	0.68

Abbreviations: NMHC = nonmethane hydrocarbons, O_3 = ozone, NMOG = nonmethane organic gases, g = gram, MIR = maximum incremental reactivity, and MOR = maximum ozone reactivity.

[a] Gasoline contains components with MIRs ranging from less than 1 to about 10 and MORs up to about 3. The numbers cited are from exhausts, not from evaporation.

Source: Adapted from Pitstick 1993 and Carter 1994.

results. See Carter (1994) for a comprehensive discussion of some of the measures of reactivity. When reactivities are used for comparisons, care must be taken to ensure that the reactivities were calculated in the same fashion.

Incremental reactivity is commonly determined using photochemical models, and little work has been performed to compare the results of models to actual experiments. The incremental reactivity is determined by making a series of computations with the photochemical models while varying the emissions inventory by first using a base case and then using various amounts of pollutants. To provide a database for some initial comparisons, Carter et al. (1993) undertook an extensive series of smog chamber experiments and determined the reactivities of 37 compounds, including methanol, ethanol, and formaldehyde, for a single initial atmospheric condition. Carter et al. also note the limitations of their experimental data and its application to actual environmental conditions.

The reactivity of alternative fuels, relative to conventional fuels, is calculated using smog chamber experiments, emissions testing, and photochemical modeling. Often, similar chemical species are lumped together in order to simplify the calculations. The reactivity of each group of species is then used to estimate emission inventories for use in more extensive photochemical modeling or to compare the measured vehicle emissions of alternative fuels to those from conventional fuels. Table 3.22 shows the relative reactivities of various fuels based on measurements by the California Air Resources Board (CARB).

CARB also makes use of reactivity adjustment factors (RAFs) to compare the reactivity of the exhaust from alternative fuels to the exhaust from a particular baseline fuel on a mass basis. For example, an alternative fuel with an RAF of 2 would have twice the ozone-forming potential of the baseline fuel—e.g., 0.5 g of emissions from the alternative fuel would have the same ozone-forming potential as 1 g of emissions from the baseline fuel. RAFs are calculated from the incremental reactivities of speciated vehicle exhaust as defined by CARB.

Table 3.22. Relative reactivities of emissions from alternative fuels and conventional gasoline

Fuel	Reactivity/gram (exhaust + evaporative NMVOC)
Gasoline (indolene)	1
E95	0.84
E85	0.81
M85	0.73
Methanol	0.54
LPG	0.83
CNG	0.44

Abbreviations: NMVOC = nonmethane volatile organic compounds; E95 = a fuel mixture of 95% ethanol, 5% gasoline; E85 = a fuel mixture of 85% ethanol, 15% gasoline; M85 = a fuel mixture of 85% methanol, 15% gasoline; LPG = liquefied petroleum gas; CNG = compressed natural gas.

Source: Adapted from NRC 1991.

Chang and Rudy (1990) compared the ozone-forming potentials of alternative and conventional fuels using three methods: relative reactivity, incremental reactivity, and direct photochemical modeling. They used two sets of emissions, one based on the emission factors given by CARB and the other based on EPA emission factors. Relative reactivities were based on previous work by Chang et al. (1989), and incremental reactivities were calculated on the basis of work by Carter and Atkinson (1989). Modeling was performed for one-day simulations using a simple single-cell trajectory model that tracks a single parcel of air along a single straight-line path. Mobile sources were assumed to make up 30% of the total emission inventory. All of the reactivities were determined for two environmental conditions, a low-dilution case and a high-dilution case, both in an atmosphere with a non-methane organic compounds (NMOCs) to NO_x ratio of 8. The difference between the low- and high-dilution cases is the volume of air available to mix with the emissions. All of the results are given on a per carbon basis. The results are shown in Table 3.23.

As shown in the table, the three methods have similar results for the cases where the nonmethane hydrocarbon (NMHC) composition of the substituted fuel is similar to the base NMHC composition. For LPG and CNG with a more reactive NMHC composition than the base NMHC composition, larger differences appear between direct modeling and the two reactivity calculations. Chang and Rudy (1990) note that the two reactivity calculations assume that the NMHC compositions are similar and that vehicle emissions are highly variable from one vehicle to the next. Therefore, they note that direct modeling is the preferred approach, if more reliable and comprehensive emissions data are developed.

3.3.2 Air Quality Modeling

Most modeling has been done to determine O_3 isopleths, reactivity, and projected pollution at the current rate of emissions in urban areas for a single 24-h period. Few studies have been done to determine the effects of alternative fuels over multiday O_3 formation episodes or for long-term future tropospheric O_3 concentrations. Of the few studies available, nearly all concentrate on comparisons of methanol to conventional fuels. Since the available studies concentrate on O_3 reduction in urban areas, they do not necessarily reflect the changes that will occur over the regions downwind of the urban area. In addition, the studies are highly dependent upon estimated emissions inventories, atmospheric composition, and the chemistry mechanisms used. A few of the available studies are discussed below.

A study by Chang et al. (1989) of the Ford Motor Company used a trajectory box model with a modified chemistry mechanism to study the impact of methanol vehicles on O_3 production in 20 U.S. cities. They also used the results to derive relative reactivities of methanol and formaldehyde. The base year for modeling was 1985; predictions were also made for the year 2000. The impact of different methanol substitution scenarios was considered for both years of interest, along with a case that

Table 3.23. Relative ozone-forming potential per carbon of vehicle emissions for three different reactivity calculation methods

	Low-dilution case			High-dilution case		
	Rel. reac.	Inc. reac.	Direct	Rel. reac.	Inc. reac.	Direct
	EPA emission factors					
Current gasoline	1.00	1.01		1.00	1.01	
Interim M85	0.93	0.91		0.91	0.90	
Optimized M85	0.91	0.89		0.90	0.88	
Optimized M100	0.81	0.77		0.79	0.77	
	CARB emission factors					
Gasoline	1.02	1.05	0.93	1.03	1.04	0.92
M85	1.00	1.00	0.96	0.98	0.98	0.92
M85 (15 mg/mile HCHO)	0.96	0.95	0.92	0.94	0.94	0.89
M100	0.87	0.84	0.90	0.84	0.82	0.85
M100 (15 mg/mile HCHO)	0.79	0.74	0.83	0.77	0.75	0.79
E95	0.93	0.88	0.97	1.01	1.03	1.06
LPG	0.57	0.58	0.87	0.62	0.61	0.86
CNG	0.43	0.42	0.57	0.47	0.44	0.54

Abbreviations: Rel. reac. = relative reactivities; Inc. reac. = incremental reactivities; EPA = U.S. Environmental Protection Agency; M85 = a fuel mixture of 85% methanol, 15% gasoline; HCHO = formaldehyde; M100 = 100% methanol fuel; CARB = California Air Resource Board; E95 = a fuel mixture of 95% ethanol, 5% gasoline; LPG = liquefied petroleum gas; CNG = compressed natural gas.

Source: Adapted from Chang and Rudy 1990.

removed all light-duty vehicle emissions. For the M85 case, all the VOC emissions from light-duty vehicles were replaced with the VOC emissions from M85 vehicles. For the M100 case, all of the VOC emissions from light-duty vehicles were replaced with the VOC emissions from M100 vehicles. Table 3.24 shows the results for 1985, and Table 3.25 shows the projections for 2000. For the year 2000, the emissions inventory was projected by assuming that either the NO_x emissions were the same as in 1985, or that the median $NMOC/NO_x$ ratio stayed the same as in 1985. The studies

Table 3.24. Peak 1-h ozone concentrations (ppm) and percentage reductions from the base case—1985

City	Ratio[a]	Base[b]	M85 case[c]	M100 case[c]	No LDV[c,d]
Akron, OH	12.8	0.137	0.135 (1.0)	0.135 (1.5)	0.125 (8.8)
Atl, GA	10.4	0.161	0.157 (2.2)	0.152 (5.7)	0.135 (15.8)
Bos, MA	7.6	0.151	0.143 (5.6)	0.134 (11.5)	0.096 (36.8)
Char, NC	10.4	0.136	0.132 (3.0)	0.128 (5.9)	0.115 (15.1)
Cin, OH	9.1	0.146	0.143 (2.0)	0.141 (3.8)	0.128 (12.4)
Clev, OH	7.5	0.147	0.142 (3.6)	0.136 (7.4)	0.105 (28.4)
Dallas, TX	11.8	0.154	0.151 (2.5)	0.147 (5.0)	0.133 (13.6)
ElP, TX	11.9	0.155	0.150 (2.7)	0.146 (5.4)	0.125 (19.3)
FtW, TX	11.8	0.158	0.153 (2.7)	0.151 (3.9)	0.137 (13.1)
Hou, TX	12.9	0.219	0.215 (1.7)	0.212 (3.3)	0.198 (9.8)
Ind, IN	10.9	0.141	0.138 (1.9)	0.136 (3.5)	0.123 (12.6)
Kan, MO	8.5	0.140	0.136 (3.1)	0.132 (5.4)	0.116 (17.0)
Mem, TN	13.9	0.178	0.176 (1.1)	0.174 (2.3)	0.160 (10.1)
Miami, FL	13.3	0.193	0.187 (3.2)	0.182 (6.1)	0.152 (21.3)
Phil, PA	8.0	0.159	0.150 (5.7)	0.137 (14.0)	0.101 (36.8)
Port, ME	11.6	0.138	0.137 (0.6)	0.137 (1.2)	0.127 (8.3)
Rich, VA	11.2	0.133	0.131 (1.8)	0.130 (2.4)	0.119 (10.5)
StL, MO	9.6	0.163	0.160 (2.4)	0.157 (4.3)	0.140 (14.3)
Wsh, DC	8.7	0.149	0.143 (3.6)	0.139 (6.7)	0.117 (21.3)
Wlk, PA	14.3	0.131	0.130 (1.1)	0.128 (2.6)	0.117 (10.8)
Average		0.155	0.151 (2.6)	0.147 (5.1)	0.129 (16.8)

Abbreviations: h = hour; ppm = parts per million; M85 = a fuel mixture of 85% methanol, 15% gasoline; M100 = 100% methanol fuel; LDV = light-duty vehicle; NMOC = nonmethane organic compounds; and NO_x = oxides of nitrogen.

[a] The ratio is the median value of the NMOC/NO_x ratio from 1984 or 1985 data.

[b] Computed base values of peak O_3 are within ±10% of actual measurements except for Memphis, TN, and Miami, FL.

[c] Ozone concentration followed by percentage reduction in parentheses.

[d] No LDV emissions.

Source: Adapted from Chang et al. 1989.

Table 3.25. Peak 1-h ozone concentrations (ppm) and percentage reductions from the base (ratio) case—2000

City	Base[a] (NO$_x$)	Base[b] (ratio)	M85 case[c]	M100 case[c]	No LDV[c,d]
Akron, OH	0.133	0.132	0.132 (0.5)	0.131 (1.0)	0.127 (4.0)
Atl, GA	0.143	0.140	0.138 (1.0)	0.136 (2.5)	0.130 (6.7)
Boston, MA	0.118	0.129	0.126 (2.7)	0.123 (4.5)	0.114 (11.7)
Char, NC	0.117	0.113	0.111 (1.7)	0.110 (2.8)	0.106 (6.6)
Cin, OH	0.136	0.134	0.133 (1.1)	0.132 (1.4)	0.127 (5.3)
Clev, OH	0.125	0.132	0.129 (2.6)	0.127 (3.9)	0.118 (10.7)
Dallas, TX	0.142	0.140	0.137 (2.2)	0.136 (3.3)	0.130 (7.1)
ElP, TX	0.125	0.121	0.119 (2.1)	0.117 (3.4)	0.111 (8.9)
FtW, TX	0.145	0.142	0.141 (1.2)	0.138 (3.0)	0.134 (5.9)
Hou, TX	0.212	0.211	0.209 (1.0)	0.208 (1.5)	0.203 (4.0)
Ind, IN	0.129	0.127	0.128 (–0.5)	0.125 (2.1)	0.120 (6.0)
Kan, MO	0.123	0.124	0.122 (1.6)	0.121 (3.0)	0.115 (7.8)
Mem, TN	0.166	0.162	0.161 (0.8)	0.159 (2.1)	0.154 (4.8)
Miami, FL	0.168	0.161	0.158 (1.7)	0.157 (2.7)	0.143 (11.2)
Phil, PA	0.119	0.145	0.142 (2.1)	0.138 (5.1)	0.127 (12.4)
Port, ME	0.128	0.125	0.125 (0.5)	0.124 (1.3)	0.120 (4.4)
Rich, VA	0.122	0.119	0.118 (0.3)	0.117 (1.4)	0.113 (4.9)
StL, MO	0.147	0.146	0.145 (1.0)	0.143 (2.2)	0.138 (5.5)
Wsh, DC	0.125	0.125	0.124 (1.5)	0.122 (2.9)	0.114 (9.2)
Wlk, PA	0.122	0.119	0.118 (0.7)	0.117 (1.4)	0.114 (3.9)
Average	0.137	0.138	0.136 (1.3)	0.134 (2.6)	0.128 (7.0)

Abbreviations: ppm = parts per million; NO$_x$ oxides of nitrogen; M85 = a fuel mixture of 85% methanol, 15% gasoline; M100 = 100% methanol; NMOC = nonmethane organic compounds; and LDV = light-duty vehicle.

Note: The ratio is the median value of NMOC/NO$_x$ ratios from 1984 or 1985 data.

[a] Initial NO$_x$ concentration is taken to be the same as that in 1985.

[b] The NMOC/NO$_x$ ratio is taken to be the same as that in 1985.

[c] Ozone concentration followed by percentage reduction in parentheses.

[d] No LDV vehicle emissions.

Source: Adapted from Chang et al. 1989.

by Chang and associates suggest that a reduction of peak O_3 levels is possible with the use of methanol- or CNG-fueled vehicles, but the reduction is not large. As shown in Table 3.26, several prior studies have predicted greater benefits to the use of methanol. The variations among the studies serve to illustrate that the impact of methanol or methanol blends on urban O_3 is highly dependent on existing local conditions and the

Table 3.26. Results of several methanol-substitution modeling studies

Modeled urban area	Base year	Substituted sources	Composition of substituted NMOC (%)[a]	Peak 1-h O_3 reduction (%)
Los Angeles	1987	All gasoline vehicles	100/0/0	31
			90/10/0	22
			80/20/0	13
Los Angeles	1987	All gasoline vehicles	90/10/0	18
Los Angeles	2000	All gasoline vehicles	57/17/26	14
			28.5/8.5/13[b]	20
20 cities	1982	Light-duty vehicles	100/00/0	13(1–36)[c]
			90/10/0	3.5(0–13)
Philadelphia	2000	Mobile sources	100/6/0	10
			110/6/0	7
			105/12/0	3
Los Angeles[d]	2000+	Mobile sources[e]	*f*	9

Abbreviations: NMOC = nonmethane organic compounds, O_3 = ozone, h = hour, and NO_x = oxides of nitrogen.

Note: Unless noted otherwise, 1-day trajectory modeling with no change of NO_x.

[a] Substituted NMOC expressed as % methanol/% formaldehyde/% hydrocarbons (HC) on a per carbon basis.

[b] NO_x emissions reduced by 50%.

[c] 20-city average with the range in parentheses.

[d] 3-day airshed modeling.

[e] Full penetration of advanced-technology methanol-fueled vehicles (MFV) into on-road advanced-technology conventional-fueled vehicles (CFV) and methanol conversion of off-road mobile sources.

[f] HC emissions from CFV were replaced by equivalent carbon methanol emissions from MFV. Formaldehyde emissions from MFV were assumed to be comparable to those from CFV.

Source: Adapted from Chang et al. 1989.

assumptions about the fuel's penetration of the marketplace and about vehicle emissions, including regulatory constraints.

A similar study by Russell, St. Pierre, and Milford (1990) was performed on methanol use in the Los Angeles, California, area. They used a three-dimensional grid model to predict O_3 and formaldehyde concentrations for the years 2000 and 2010. Four emission inventory scenarios were considered: the base case, corresponding to the current fleet of conventionally fueled vehicles; an M85 case, corresponding to the replacement of the entire fleet by M85 vehicles; an M100 case, corresponding to the replacement of the entire fleet by M100 (100% methanol fuel) vehicles; and a no mobile case, where all mobile source emissions were eliminated. The base case for the future years was adjusted to account for anticipated changes in regulatory limits on emissions. Their results included the calculations of peak O_3 concentrations and the population exposure to O_3 and formaldehyde. Table 3.27 shows their results. These

Table 3.27. Predicted peak ozone (O_3), ozone exposure, and formaldehyde (HCHO) exposure for the years 2000 and 2010

	Peak O_3 (ppm)	Exposure (person-ppm-hours)		
		$O_3 > 0.12$ ppm	$O_3 > 0.20$ ppm	HCHO > 0.0 ppm
		2000		
Base case	0.26	7314	2586	2779
M85	0.24 (8)	6167 (16)	1260 (51)	2551 (8)
M100	0.22 (15)	5673 (22)	364 (86)	2326 (16)
No mobile	0.21 (19)	5384 (26)	58 (98)	1578 (43)
High HCHO	0.24 (8)	6070 (17)	1108 (57)	3203 (–15)
		2010		
Base case	0.32	9840	5159	3071
M85	0.31 (3)	8700 (12)	4234 (18)	3328 (–8)
M100	0.31 (3)	7976 (19)	3823 (26)	3478 (–13)
No mobile	0.28 (13)	7804 (21)	1950 (62)	2082 (32)

Abbreviations: ppm = parts per million; O_3 = ozone; M85 = a fuel mixture of 85% methanol, 15% gasoline; and M100 = 100% methanol fuel.

Note: The values in parentheses are the percentage reductions relative to the base case. In the M85 case, 100% of the mobile source emissions are from M85-fueled vehicles starting in 1990. In the M100 case, 100% of the mobile source emissions are from M100-fueled vehicles starting in 1990. In both cases, conventionally fueled vehicles contribute to emissions until 1990, when they are completely phased out.

Source: Adapted from Russell, St. Pierre, and Milford 1990.

results show that while peak O_3 and population exposure to O_3 are reduced substantially for the year 2000, the reductions are not nearly as large for the year 2010. The additional problem of increasing formaldehyde exposure must also be considered by the year 2010. Since changing emission controls were considered for the future cases, this suggests that advancements in emissions controls may be more significant than the fuel used as time goes on.

D. Simpson (1991), of the Norwegian Meteorological Institute, modeled the production of O_3 in several European countries by looking at reductions in emissions without considering any changes in VOC composition that will arise from the use of alternative fuels. He used a newly developed column trajectory model, similar to a box model, based on data from the ongoing European Monitoring and Evaluation Program. This model is still under development, but Simpson performed some comparisons with measured O_3 concentrations which suggest that the model is generally within 30% of observed values, with a tendency to overpredict. As with similar models, the results should be indicative of trends in O_3 concentrations, but not used for exact numbers.

Simpson (1991) considered three emission-control scenarios: a 50% reduction in NO_x emissions, a 50% reduction in man-made VOC emissions, and a 50% reduction of both NO_x and man-made VOC emissions. The predicted changes in O_3 concentrations are shown in Table 3.28. Note that while the mean O_3 concentration is reduced by any of the three options, the maximum O_3 concentration can be increased by NO_x controls alone. Combined reductions of NO_x and man-made VOCs seem the most consistently effective approach in the regions modeled.

All of the results from air quality modeling serve to illustrate the impact local conditions have on O_3 production. Most O_3 control strategies have traditionally concentrated on reductions in VOC emissions, and VOC controls are appropriate in many areas. Reductions in VOC emissions will help in a VOC-limited region and not change O_3 production in a NO_x-limited region. However, NO_x controls must be applied carefully. If used in a VOC-limited region, reductions in NO_x emissions alone will increase the maximum O_3 production. Reductions in both types of emissions simultaneously must be considered carefully with respect to the resulting dynamic changes in the VOC/NO_x ratio in the region and the subsequent effects on O_3 production.

In an attempt to resolve the questions surrounding the impact of alternative fuels on regional air quality, alternative fuel modeling is currently being pursued in many arenas. For example, the National Renewable Energy Laboratory in the United States is sponsoring work on the modeling of alternative fuel impact on three metropolitan areas.

3.3.3 Regional Air Quality Conclusions

An extensive database on the impact of alternative fuels on regional air quality is not currently available. Data are limited to emissions testing of a small number of

Table 3.28. Percentage reductions in calculated monthly mean and maximum ozone due to emissions reductions

Country	Base mean O_3 (ppb)	Emission reductions 50% NO_x	Emission reductions 50% VOC	Emission reductions 50% NO_x + VOC	Base max. O_3 (ppb)	Emission reductions 50% NO_x	Emission reductions 50% VOC	Emission reductions 50% NO_x + VOC
Albania	53.3	11	5	14	141.3	17	12	26
Austria	67.4	12	11	17	133.8	8	20	24
Belgium	63.2	6	12	13	126.6	9	15	23
Bulgaria	57.5	11	6	14	106.4	12	26	27
Czechoslovakia	64.8	8	11	14	126.8	11	20	25
Denmark	55.6	7	9	12	118.7	–7	18	10
Finland	36.7	9	3	10	117.0	17	5	23
France	58.3	11	8	16	124.8	12	7	25
G.D.R.	63.9	6	12	13	126.8	11	20	25
F.R.G.	67.0	9	13	15	124.9	–2	14	15
Greece	54.1	11	5	14	115.0	17	3	20
Hungary	62.5	9	8	14	133.8	8	21	24
Ireland	40.5	4	4	7	106.6	–1	20	21
Italy	67.4	13	9	18	144.6	14	13	25
Luxembourg	69.9	11	13	17	124.8	12	27	25
Netherlands	60.0	1	13	10	126.6	9	15	23
Norway	41.6	8	5	11	114.1	16	1	24
Poland	60.3	8	9	14	113.9	–2	17	15
Portugal	48.8	10	3	12	93.9	16	6	19
Romania	58.3	10	6	14	93.1	11	16	22
Spain	51.6	13	4	15	164.3	21	6	24
Sweden	43.3	9	6	13	137.1	11	17	23
Switzerland	63.3	14	8	18	111.4	12	13	24
Turkey	47.3	8	5	11	92.8	12	12	20
U.S.S.R.	46.4	10	5	12	119.8	10	1	27
U.K.	48.5	3	9	9	125.5	0	26	22
Yugoslavia	59.8	10	7	14	133.8	8	18	24

Abbreviations: O_3 = ozone; ppb = parts per billion; NO_x = oxides of nitrogen; and VOC = volatile organic compounds.
Source: Adapted from Simpson 1991.

relatively low-use vehicles, estimations of reactivity based on a limited number of experiments or invalidated models, or a small number of modeling predictions that are site-specific. Most of the data are for methanol or CNG. The in-use degradation of alternatively fueled vehicles is unknown, but on the other hand very few optimized alternative fueled vehicles have been designed or tested. General trends of modeling data indicate that alternative fuels will reduce particulate, VOC, and NO_x emissions. However, emissions data produce conflicting results on the impact of alternative fuels on O_3 formation. Whether or not the reductions that can be obtained in the future are greater than those that may be obtained by improved catalyst technology or reformulating conventional fuels is not certain.

3.4 HEALTH EFFECTS

The epidemiology of metropolitan air pollution as a cause of illness and death was first explored when data from death registrations initiated during the reign of Queen Victoria of England became available. In spite of the discomfort occasioned by London's fog and high-sulfur coal smoke, differences in mortality between city and country were not noted (NRC 1985). The modern emphasis on air pollution control grew out of investigations into cardiovascular mortality increases attributed to short-term disasters. These included the Meuse Valley, Belgium, where 60 deaths and several thousands illnesses in 1930 were attributed to a combination of industrial air pollution and weather; Donora, Pennsylvania, where in 1948, 20 deaths and 6000 illnesses were attributed to similar causes; London, England, where in 1952, 4000 deaths were attributed to the combination of dense smog and limited air motion; and Los Angeles, California, where in 1955, the combination of high temperatures and smog more than quadrupled the normal mortality of citizens 65 and older for a 2-month period. In 1956, London suffered a second period of severe smog and limited air movement to which more than 1000 deaths were attributed.

Between the early epidemiological investigations of air pollution started in the 1960s and current studies, there have been substantial decreases in ambient air pollution in Europe and the United States. For example, in the period between the Clean Air Act of 1970 and the present, the United States eliminated the use of lead in gasoline and has reduced sulfur oxides and particulates (NRC 1985). A review of air pollution studies from the late 1970s and early 1980s shows how much U.S. metropolitan air quality has improved and how much lower the impact on human health is (Lave and Seskin 1977; NRC 1981; OECD 1983; Waldbott 1978). However, many major metropolitan areas, for substantial portions of the year, still exceed the National Ambient Air Quality Standard for CO and for O_3 (EPA 1992). Roughly 30 to 50% of the O_3 nonattainment and virtually all of the CO nonattainment in U.S. urban areas was attributed to mobile sources. In Europe, air pollution has decreased, in large part due to the 1979 Convention on Long-Range Transboundary Air Pollution. Many of the participants in the convention have implemented new policies and standards designed to reduce air pollution, but not all of the participants have achieved the reduction goals determined by the convention (UNECE 1991).

Pollutants of major concern include CO, aldehydes, lead, NO_x, O_3, particulates, sulfur oxides, and VOCs. This study also includes materials absorbed through the skin, carcinogens, and dioxin, which is produced during combustion.

3.4.1 Carbon Monoxide

Carbon monoxide causes the formation of carboxyhemoglobin, a form of blood hemoglobin which does not carry oxygen. Graham and Holtgrave (1991) reviewed the data supporting the development of CO standards. Angina and other cardiovascular diseases have been shown to be aggravated at carboxyhemoglobin concentrations above 2–4%. At these levels, a small but significant difference in the duration of exercise causing the onset of angina was noted in a small test population of nonsmoking white males. Changes in ventricular function were apparent in a separate but similar test population at carboxyhemoglobin concentrations of 5.9%. The results were qualitatively confirmed by subsequent studies, and the observations supported in an analysis by Tukey and Sivak (1991).

Carbon monoxide is a cumulative toxicant whose major effect—the formation of carboxyhemoglobin—is reversible with the normal physiological turnover of hemoglobin. Maejima and coworkers (1992, 1993) report a period of perhaps 4 weeks is required for hemoglobin replacement in rats. Blood hemoglobin concentrations may also be increased to compensate for the oxygen-carrying capacity lost by carboxyhemoglobin formation.

Diesel and reformulated diesel fuel, reformulated gasoline, fossil and nonfossil electricity, CNG, and LPG all produce less CO than does conventional leaded or unleaded gasoline. However, as shown in Figs. 3.5 to 3.7, CO emissions from gasoline and alcohol fuels increase substantially with decreasing temperature. As shown in Figs. 3.8 to 3.9, this difference is typically lower for vehicles powered with CNG and LPG.

Carbon monoxide most strongly affects populations exposed to exhaust emissions retained and concentrated in limited areas, such as parking attendants, traffic control officers, and tunnel users. However, elevated CO levels can also occur over large metropolitan areas and affect the general populace as a whole. Common sense engineering measures, such as improved ventilation, are often effective in managing exposure.

3.4.2 Aldehydes

Formaldehyde is the smallest and simplest aldehyde in emissions gases. Several types of cancer are associated with formaldehyde exposure. Although formaldehyde's genotoxicity, or ability to cause damaging changes in genetic material, has been demonstrated in a variety of test systems, teratogenicity, or the ability to cause damage during the development of organisms, has not been demonstrated. Formaldehyde is also an irritant at 0.1 to 3 ppm. Headaches as a consequence of formaldehyde inhalation have also been noted. At concentrations ranging between 0.4 and 1.2 ppm, formaldehyde has also been reported (Bach, Pedersen, and Molhave 1990) to significantly decrease performance on tests measuring short-term memory, ability to concentrate, and ability to perform addition.

These concentrations are within the ranges that might be found near engines running on methanol. As reported by Maejima and coworkers (1992, 1993), formaldehyde concentrations were sufficient to cause tissue changes in nasal cavity and lung tissue of rats breathing diluted exhaust from an M85-fueled engine. The rats were exposed for 8 h per day for 1 to 4 weeks. Formaldehyde concentrations averaged 6.9 ppm. The changes appeared to be reversible, although the time required for reversal was considerably longer than the exposure period. Kreibel, Sama, and Cocanour (1993) similarly report that changes in volumetric lung function of students exposed to 0.49 to 0.93 ppm formaldehyde for 3 h per week for 10 weeks returned to baseline after a 14-week rest. Although human subjects and rats were able to recover from the effects of short-term exposures, the effect of long-term, low-level exposures could be substantial. This is indicated by the increasing response of human test subjects to repeated constant exposure. When formaldehyde, a mild carcinogen, is combined with other carcinogens as a part of the emissions mix from a variety of vehicles, increased cancers may also occur.

Aldehydes are found in vehicle exhaust emissions and are also produced in the atmosphere from other components of vehicle exhaust, particularly the alkenes. In the case of gasoline vehicles, the secondary production of aldehydes can dominate the amount of aldehydes in the vehicle exhaust emissions. However, in the case of alcohol fuels, the primary emissions of aldehydes are great enough that the secondary production of aldehydes is not as significant (Altshuller 1993). Several studies, including those by Pitstick (1993), Nylund et al. (1994), and Chang et al. (1991) indicate that aldehyde emissions from vehicles fueled with alcohols, such as methanol and ethanol, are higher and, with reformulated gasoline or compressed natural gas, slightly higher, than those from vehicles fuels with conventional gasoline. Aldehyde emissions from diesel vehicles and vehicles fueled with LPG, together with those from electrical generation, are expected to be low or near zero.

3.4.3 Lead

Tetraethyl lead has been used to enhance the octane rating of gasoline for decades, and leaded gasoline is still used in many countries. Combustion of leaded gasoline produces particulates containing lead. Lead is also a major component of lead-acid batteries.

The data on lead are still contradictory because clear physiological mechanisms for lead mutagenicity or carcinogenicity have not been established (Calabrese and Kenyon 1991). Lead is, however, toxic to the developing fetus and has known neurological, hematological, and renal toxicity. Children aged 1–5 years are thought to be the most sensitive to lead. Additionally, blood levels of children receiving a given atmospheric concentration of lead are roughly twice as high as those of adults (NRC 1985).

Unleaded gasoline, reformulated gasoline and diesel fuel, methanol, ethanol, LPG, and CNG contain, at most, trace amounts of lead. Their combustion should produce particulates containing little or no lead. This is important because particulates carry lead onto surfaces and soils near roads.

Effects from lead used to make batteries are confined primarily to mining and production workers who handle lead or lead compounds or who breathe fumes and vapors, although the disposal of used batteries has important ecological implications.

3.4.4 Nitrogen Oxides

Nitrogen oxides, even at reasonably low concentrations, are a respiratory irritant (Waldbott 1978). As summarized in a recent National Research Council report (1985), there appears to be a correlation between long-term exposure to low levels of NO_x and susceptibility to bacterial infection. The effect increases with increasing exercise. As noted by Lippmann (1989), NO_x effects include altered lung function, increases in acute respiratory illness or infections, and direct lung tissue damage, including the development of emphysema-like lesions in the lung. These effects have been substantiated in a variety of studies. Frampton and Roberts (1989) reviewed the interactions between respiratory infection and oxidants. The effect is thought to be caused by chemical damage to cell lung membranes. This is likely to be followed by macrophage cells, which cause further tissue damage. Nitrogen oxides and O_3 also inhibit the mucociliary transport system used to protect the lungs from infection and may also cause some lung inflammation. A review of a wide range of studies by Mauderly (1989) indicates that lung damage by oxidants in childhood may have effects measurable throughout adulthood.

This effect has also been demonstrated in epidemiological studies of young children exposed to higher concentrations of NO_x in homes with gas cooking stoves, and as indicated in a study by Abbey and coworkers (1993), indoor cooking with a gas stove produces measurable effects on indoor air quality and on development of respiratory symptoms. In small children and infants, even low concentrations of NO_x cause small but significant increases in the occurrence and duration of respiratory infections (Samet et al. 1993). These data contradict those reported by Roemer, Hoek, and Brunekreef (1993), which show little response on children in the Netherlands to NO_2 in ambient air. Susceptibility to oxidants is also strongly influenced by nutritional status, as reported by Last (1989). In healthy volunteers, Aris et al. (1993) noted no differences in any of a dozen measures of lung function resulting from exposure to 0.20 ppm O_3 or 0.20 ppm O_3 and 500 µg/m^3 nitric acid. On the other hand, Utell (1989) reports that asthmatics show significant changes in lung function in the range of 0.30 ppm NO_2. The U.S. National Institutes of Health has an ongoing program to improve understanding of the physiological mechanisms underlying sensitivity to NO_x and other oxidants (Crapo 1992).

Evaluating the effects of fuel choice on production of NO_x is difficult. During combustion itself, NO_x is produced by a long and complicated series of chemical reactions. As discussed in Sect. 3.1, diesel engines produce more NO_x than do gasoline engines; and leaded gasoline engines, which do not have catalytic converters, produce more NO_x than do engines with catalytic converters. However, ethanol and methanol have the potential to lower NO_x production in these engines. In modified conventional cars (typically with catalytic converters), NO_x production varies with operating conditions. On the other hand, electric cars do not produce NO_x emissions by themselves, but the fossil power plants that are used in many areas to generate electricity do produce significant amounts of NO_x.

3.4.5 Ozone

Ozone, as a health hazard, is primarily a pulmonary irritant (Waldbott 1978). Ozone causes short-term swelling of lung tissue and increases the lungs' sensitivity to other pollutants and allergens. In populations exposed for long periods, these effects can eventually decrease the lungs' ability to transfer oxygen to the blood. Even healthy adult populations exposed to concentrations likely in polluted air show transient effects (NRC 1985). The effects typically include reduction in pulmonary function tests, which measure both the maximal volume of air in the lungs and the rate at which air is taken into the lungs. Even in normal volunteers, there is substantial variation in the effect of O_3. Both acute and chronic effects have been noted. The effect may have a genetic basis because individuals have characteristic responses which will often persist across a study of several months. Asthmatics have been noted to have particularly severe reactions to O_3 and to other oxidant species (Lippmann 1989). It appears that O_3 may increase ease of sensitization of asthmatics to inhaled allergens. Additionally, Hackney and Linn (1989) note that individual short-term responses to O_3 appear to be consistent, and persons with these responses are at higher risk of developing chronic obstructive pulmonary disease. However, the reported response of normal healthy populations to O_3 and other oxidants are minimal in many studies.

Ozone concentration in ambient air has been noted as a significant factor in the development of respiratory symptoms in nonsmoking populations (Abbey et al. 1993). However, Folinsbee et al. have noted that short-term symptoms caused by 0.12-ppm O_3 decrease after several days of exposure in normal, healthy, exercising populations. Ostro et al. (1993) reported a significant correlation between O_3 concentration in ambient air and development of respiratory tract symptoms. Ambient O_3 concentrations of more than 180 μg/m^3 were reported by Frischer et al. (1993) to cause a reversible inflammatory response of the upper airways in normal children.

Ozone is typically produced from other emissions. Scenarios for reducing O_3 do not depend on direct control of O_3, but on reduction of precursors, including NO_x and VOCs. Sources of VOCs include both man-made and, in some regions, biogenic or geological sources of volatile organics.

As discussed in Sect. 2.2, O_3 production is extremely site-specific. In some cases, reducing the production of NO_x can decrease O_3 concentrations. In these cases, diesel engines, fossil electric generation, and leaded gasoline will increase the production of O_3 because, as discussed in Sect. 3.1, these technologies often produce higher levels of NO_x than do ethanol or methanol, unleaded or reformulated gasoline, or CNG. However, in other areas, the reduction of VOC is required to decrease O_3 formation.

3.4.6 Particulates

Particulates, the most readily visible form of air pollution, have long been associated with cancer and respiratory diseases (NRC 1981). High particulate concentrations from combustion of wood, dung, coal, and crop residues have been correlated with acute respiratory infections accounting for the deaths of over 14,000 children per day (Smith 1987). Increasingly stringent air pollution controls have considerably diminished this problem in the United States and in Western Europe. Data from the U.S. National Center for Health Statistics support correlation between fine particulate concentration and restricted activity days (Ostro 1987) and provides a basis for estimates that 1 μg/m3 increase in fine particulates corresponds to a 3% increase in acute respiratory disease (Ostro 1989). Japanese measurements have shown a high epidemiological correlation between particulate concentrations and ear, nose, and throat irritation and infection. Airborne sulfates, particulate matter, and respiratory morbidity also show reasonable correlation.

A body of Japanese researchers has been studying physiological effects of light and heavy diesel particulates using a variety of different cell and whole organism systems (Research Committee for Health Effects Research Program Studies 1988). In short-term tests, particulate extracts from both heavy- and light-duty engines behaved in a similar fashion. Diesel particulate extracts in whole-animal systems was estimated to be roughly 10% that of cigarette smoke particulates. Diesel exhaust appears to be a relatively weak carcinogen from these tests.

Studies of human subjects indicate that particulates, especially particulate sulfates, have a measurable effect on respiratory function. Ostro and coworkers (1993) evaluated respiratory symptoms in Southern California subjects. Particulate sulfates (0.019–0.37 ppm), O_3 (0.067–0.43 ppm), and the use of natural gas stoves for cooking (which increases NO_x in indoor air) correlated best with respiratory symptoms. Abbey et al. (1993), in a 10-year study of a group of vegetarians (who were also typically nonsmokers and nondrinkers) found strong correlations between long-term total suspended particulate and O_3 levels and respiratory disease (asthma and emphysema). Although O_3 increased the risk of asthma in men, it did not increase the risk in women. In this study, sulfur dioxide did not have a statistically significant correlation with respiratory disease. Similarly, Xu and Wang (1993) found significant correlations between respiratory symptoms and both indoor and outdoor levels of particulates. The levels of particulates (mean indoor, 41–152 micrograms per m^3; outdoor 151–256 $\mu g/m^3$) in these studies were high because of the use of indoor coal stoves for cooking and heating in Beijing.

Roemer, Hoek, and Brunekreef found a mild correlation between elevated particulate, black smoke, and sulfur dioxide levels and wheezing or bronchodilator use by children with chronic respiratory symptoms (1993). The research was performed in small, nonindustrial towns in the Netherlands which receive air pollution by long-range transport. Observed effects were correlated with air-pollution measurements.

In research by Koenig, Covert, and Pierson (1989) acid particles were shown to be effective in causing bronchoconstriction in exercising asthmatics at concentrations as low as 75 $\mu g/m^3$. Utell (1993) described the synergistic effect of metal-containing particulates and aerosols containing acid sulfates or sulfuric acid. In normal adults, inhalation of sulfuric acid aerosols at levels as high as 1000 $\mu g/m^3$ for extended periods produce few observable residual effects.

Particulates are typically measured as weight collected by passing a known volume of air through a standard filter. Using this protocol, particulate measurements include any airborne environmental dust, fumes, biogenic aerosols, soil, or sand that are collected by the filtration system. These materials may have bioeffects similar to those of combustion-generated particulates. For example, a Japanese study (Ikeda et al. 1986) correlated bioeffects and production of fine dust by studded snow tires during the winter months. As indicated by Ostro's studies, there is better correlation between fine particulates and morbidity than between conventionally measured particulates and morbidity. Because of the high energy and economic cost of controlling diesel particulate emissions (Brubaker and Smith 1986; Rajan and Singh 1986; Research Committee for Health Effects Research Program Studies 1988), and because of the differences in the particle size of the standard test and the size absorbed by lungs, it may be appropriate to consider a new standard in this area.

Combustion of leaded gasoline, both conventional and reformulated diesel fuel, and fossil electricity produces higher amounts of particulates than does combustion of conventional unleaded gasoline. Combustion of methanol, ethanol, CNG, LPG, and nonfossil electric produces fewer particulates.

3.4.7 Sulfur Oxides

Ostro (1990) noted that, based on data from the U.S. National Center for Health Statistics, airborne sulfate concentration, measured as tithable sulfuric acid, correlates well with acute respiratory illness. Ostro found that O_3 concentration was not correlated with acute respiratory illness and also noted that, because of coincident occurrence, it was often difficult to separate the effects of O_3 and sulfates. The study, which covered health statistics from 25 U.S. metropolitan areas, used the occurrences of respiratory conditions severe enough to restrict activity as measures of acute respiratory morbidity.

Individual studies by a variety of research groups are in agreement with Ostro's epidemiological findings. Abbey and coworkers (1993) found little correlation between ambient sulfur dioxide concentrations and respiratory symptoms in their study of a group of vegetarians (who typically did not smoke tobacco or drink alcohol). For sensitive individuals, particularly asthmatics, exposures to as little as 0.4 ppm sulfur dioxide can lead to significant bronchoconstriction (Lippmann 1989). Response of asthmatics is varied. Horstman and Folinsbee (1989) in their review of the effects of sulfur oxides on exercising asthmatics indicated that exposures as low as 0.5 ppm of sulfur dioxide, particularly under conditions of high humidity, caused significant bronchoconstriction. The research of Koenig, Covert, and Pierson (1989) indicates that concentrations of sulfuric acid aerosols at concentrations less than 0.03 ppm cause similar effects in exercising asthmatics. This is significant because, in humid air, sulfur oxide and particulates can form acid sulfates, or acid particulates. These may have much higher bioactivity than does sulfur dioxide.

Essentially all of the sulfur in a fuel becomes oxidized to sulfur oxides. Coal is typically the fuel containing the most sulfur. Production of sulfur oxides during fossil electric generation should be considered in evaluating battery-driven transport systems. Although there are essentially no sulfur oxides produced from combustion of methanol (or ethanol), the use of coal to fuel methanol production will generate sulfur oxides. Sulfur compounds, with the exception of some aromatic compounds, are generally removed from LPG and CNG to minimize engine corrosion. However, substantial amounts of reduced sulfur compounds are found in some natural gas streams (sour gas) and removed during processing. The sulfur content of reformulated gasoline and reformulated diesel fuel is limited relative to conventional gasoline and diesel fuels in order to prevent reductions in catalyst efficiency and reduce particulate emissions. This results in lower production of sulfur oxides during combustion and lower particulate emissions from diesel engines and will prevent the degradation of catalyst efficiency.

3.4.8 Volatile Organic Compounds

Except for risks associated with high concentrations of specific compounds, such as methanol, the major risk associated with VOCs is their contribution to the photochemical formation of O_3. Most U.S. atmospheric VOCs are derived from man-made sources, typically solvent evaporation, mobile sources, and surface coatings (U.S. Congress 1990). Mobile sources account for 38% of the man-made VOC emissions in the United States and 34% of the total VOC emission in Europe.

Volatile organics include a wide variety of materials. Health risk is a function of the mix of compounds. From gasoline, diesel fuel, and solvents used in coatings, this mixture includes a variety of aromatics. Based on average compositions, EPA (1992) estimates the incidence of cancer linked with the compounds in gasoline to be 400 to 754 cases annually.

Levels and production of VOCs are specific to a given region. Many sites, however, have a high naturally occurring background of VOCs. For example, Australia (Simoneit and coworkers 1991), many sections of the continental United States (Tyson, Riley, and Humphreys 1993), and Europe (Derwent, Grennfelt, and Hov 1991) have naturally occurring organics, typically produced by vegetation, that dwarf man-made emissions. In other areas of the country, industrial processes are major contributors of volatile organics (Ware et al. 1993).

3.4.9 Skin Absorption

Many alternative and conventional fuels contain compounds which can be absorbed through the skin as well as by inhalation. Compounds known to be absorbed by this route include methanol and many of the small compounds comprising gasoline, including aromatics. Methanol is mildly to moderately irritating to the eyes and skin (Calabrese and Kenyon 1991). Methanol is also mutagenic, is a developmental toxicant, and interferes with normal nervous system function. Typical components of gasoline, such as benzene and ethyl benzene, are also irritating to the eyes and skin. At high concentration, benzene is toxic to a developing fetus. It can also induce chromosomal aberrations in bone marrow cells and lymphocytes, resulting in damage to the blood and immune systems. In extreme cases, this can lead to aplastic anemia. Although an irritant, ethyl benzene has not been reported to cause genetic damage.

Of the alternative fuels, CNG and LPG contain little material that could be absorbed through the skin. (Both of these materials are capable of causing frostbite, however.) With the exception of denaturants, ethanol is poorly absorbed through the skin and has little toxicity. Methanol is readily absorbed and, in large amounts, poisonous. Both reformulated gasoline and reformulated diesel fuel contain lower levels of aromatics and are likely to have lower toxicity on skin sorption. Leaded gasoline, however, is likely to have a higher skin absorption toxicity than conventional gasoline due to the lead.

3.4.10 Carcinogens (or Toxics)

As people live longer, carcinogenicity has become a major concern, and there is public perception of substantial cancer risk from conventional fuels. However, cancers resulting from the use of conventional fuels are thought to represent an extremely tiny fraction of the total number of cancer cases (EPA 1992). Fuel-derived carcinogens result from two sources: carcinogenic compounds in the fuels (e.g., benzene and butadiene) and carcinogens resulting from combustion (e.g., aldehydes and particulates). The EPA (1992) estimates that the number of cancers in the United States associated with gasoline (400–754 cases per year) or diesel (178–860 cases per year) exposures represent approximately 50% of the number of cancers associated with carcinogenic air toxics. This aggregate is less than 0.1% of the total number of cancer cases in the United States for a given year.

Lewtas (1993) compared the carcinogenicity of emissions from a variety of combustion sources, including wood and oil residential heating systems, diesel vehicles, and both catalyst and noncatalyst gasoline engines. Emissions were defined to include both filterable (particulate) and condensable materials. Relative to fuel weight, diesel exhaust carcinogenicity was an order of magnitude higher than that of noncatalyst gasoline exhaust, and two orders of magnitude higher than that of postcatalyst exhaust. Other studies have shown that catalytic conversion will substantially decrease the carcinogenicity of fuel particulates (Maejima et al. 1992).

Both conventional and reformulated gasolines and diesel fuels contain aromatic compounds known to be carcinogenic, but the reformulation of gasoline does involve the reduction of emissions of benzene and butadiene. Methanol, ethanol, LPG, and CNG contain at most tiny amounts of carcinogens as impurities. All of these fuels produce very low levels of particulates during combustion, but methanol and ethanol combustion does produce aldehydes, which are considered less carcinogenic than either benzene and butadiene. (See Sect. 3.4.2 for a more specific discussion of aldehydes.) The requirements placed upon reformulation and catalytic conversion will dictate whether or not extensive use of these fuels would result in a substantial decrease in fuel and combustion associated carcinogens.

3.4.11 Dioxin

Epidemiological researchers have tried for a number of years to understand why dioxin is relatively evenly distributed throughout the U.S. population, even though the stationary combustion sources thought to produce dioxin are widely scattered. Trucks and cars, rather than incinerators and coal-fired power plants, have been estimated to be major sources of dioxin. Dioxin, a carcinogen of significant concern, is formed during combustion of both gasoline and diesel fuel. Calculations by Jones (1993) indicate that diesel truck engines alone, even under the stringent Clean Air Act Amendment regulations for the year 2000, will contribute more than five times the dioxin of stationary incinerators. Gasoline engines also contribute to dioxin formation, although at a lower rate per kilogram of fuel burned. The EPA, as a part of efforts to decrease dioxin production, is currently evaluating dioxin emissions from transportation sources. Because this is a relatively new research area, information is still limited.

4. OTHER FACTORS TO BE CONSIDERED IN POLICY-MAKING DECISIONS

4.1 IMPACTS ASSOCIATED WITH FUEL PRODUCTION

4.1.1 Worker Safety

A substantial number of worker safety studies are available. These typically use government accident or injury statistics as a basis for evaluating risks from different technologies. Typical of current studies are those by Fritzsche (1989), Rowe (1990), and the U.S. Environmental Protection Agency (EPA 1993). All of the studies compare risks in producing energy using different technologies. In the absence of a major accident, postproduction distribution is a poorly understood area for all fuels. Although occasional studies of, for example, fuel station workers, have been performed, the small size of typical end-use distributors and retailers has limited the collection of safety statistics.

There is clear agreement that nuclear electrical production poses the lowest risk; health risks from producing coal, oil, and natural gas are estimated to be one to two orders of magnitude higher. Rowe classified the technologies into three groups, the fuels group (high pollution, high occupational accident rates), the renewables group (high occupational accident rates, often dominated by construction accidents), and the nuclear group (high occupational risks from mining). The fuels group, which included biomass-derived fuels, was also characterized by high levels of chronic occupational illnesses (black lung, brown lung, cancer, and hazardous chemical exposures).

Fritzsche evaluated the risk for severe accidents (5–2500 fatalities per accident) and found that the bulk of these were due to coal mining, petroleum production and transport, natural gas explosion, and floods. Exposures to farming chemicals were not considered in this study.

Central station electricity/battery power systems were also considered in this report. Central stations produce emissions which affect airshed residents. The production of batteries involves a combination of mining and purifying transition and heavy metals and this can expose workers to significant levels of biotoxic metals (Rajan et al. 1989).

The mining, manufacture, recycle, and disposal of the metals used in batteries pose special safety and environmental problems. Lead-acid batteries, which predominate in current automotive use, are currently substantially recycled in Europe and the United States. As indicated by central government statistics, mining and metal recovery are generally high-accident, high-chronic-toxicity occupations. In addition, lead is a heavy metal with generally well-known toxicities. In manufacturing operations, its carcinogenicity, mutagenicity, reproductive toxicity, and nervous system toxicity are, with few exceptions, adequately characterized. Toxicities are reflected in a variety of occupational exposure standards (Calabrese and Kenyon 1991; Rajan et al. 1989).

The intermingled issues of worker and community safety (since people typically live on and near farms) include population exposures to herbicides; increased release of oxides of nitrogen, ammonia, and nitrogen-containing organics to air and water; transportation safety concerns; and increased regional infrastructure expenses (Tyson, Riley, and Humphreys 1993).

4.1.2 Localized Air Emissions

As a part of studies of the risk arising from fuels production, Rowe (1990) and Fritzsche (1989) evaluated hazards to local populations arising from fuels production. These hazards were judged to be qualitatively similar for all of the industrial processes producing liquid fuels. Typically, the health of local residents is affected by air emissions, including particulates and other carcinogens, from the processing facilities and by trauma associated with large-scale local accidents. In the case of biomass processing facilities, Rowe judged that exposure to fermentation and contaminant organisms could also pose a threat to local residents.

Rowe noted that, where biomass and coal are used for the production of steam or electrical power, local residents may be affected by air emissions from the facility. Fatalities from central station and transport emissions were estimated to be on the order of one fatality per gigawatt year.

4.1.3 Erosion

Of the conventional and alternative fuels covered in this study, only ethanol from biomass and, to a smaller extent, methanol from coal could contribute significantly to erosion. Techniques for controlling erosion from farming and forestry are well known. Reclamation techniques for managing erosion from coal strip mining operations are well understood. In both areas, research continues to provide improved methods and technology.

4.1.4 Transportation

For liquid fuels, the costs and risks related to transportation have become issues of increasing concern. With current fuels, typical concerns include transportation safety and spill management. Production of ethanol and other liquid alternative fuels will require the farming or forestry of substantial amounts of land. Production of these fuels from woody or agricultural crops will require a low-yield conversion step, such as fermentation or pyrolysis. The increases in transportation, together with the probable change toward truck transport, are likely to increase public attention to transportation safety.

It is difficult to separate production, transportation, and manufacturing operations involved in the production of ethanol from biomass. Most scenarios call for the production of ethanol by fermentation of a carbohydrate feedstock, typically derived from cereal crops or trees. The fermentation is similar to the process used to produce beverages, and the amounts of biomass required to generate enough ethanol to impact fuels use are substantial. For example, the United States pulp and paper industry currently "farms" 6 to 7% of the continental United States Adding 10% ethanol to all of the motor fuels in the United States would require nearly doubling wood production (and land area). A very large volume of wood, relative to finished fuel, would be harvested and transported. Similar problems exist with cereal crops.

4.1.5 Water Pollution

Water pollution—due to transportation spills and wastewaters from the production of coal, biomass-ethanol, and coal-methanol—is an increasing concern. Large spills of crude oil due to transportation accidents, although relatively low in number, are also major environmental issues. Few evaluations of the effects of alternative fuels spills have been made; however, the expected consequences are significantly different from those of conventional fuels. Alcohols mix readily with water, and both methanol and ethanol are readily degraded by microbes indigenous to water and land. This would, relative to crude oil, decrease the damage to beaches and the immediate damage to waterfowl in the case of neat fuels. However, rapid biodegradation of either alcohol could deplete the oxygen of still waters, such as lakes. This would kill most nonbacterial aquatic organisms. On the other hand, conventional fuels like gasoline are often blended in with neat alcohols to produce transportation fuels. A spill of the blended fuel would have all the problems related to both conventional and alternative fuels. In addition, to get the same energy output from alternative fuels as conventional fuels, a larger volume of alternative fuels must be produced and transported, increasing the risk of a transportation accident.

4.1.6 Liquid and Solid Wastes

It is difficult to compare liquid and solid wastes from different fuel cycles because they differ in character. Additionally, liquid and solid waste production are controlled by the abatement technologies required by central and local governments. The amount of liquid and solid wastes produced from a particular fuel cycle will be tied to the regulations governing the process, more than the process itself. Therefore, the following sections describe the types of pollution that result from the production of different fuels.

4.1.6.1 Conventional petroleum fuels

In addition to refinery wastewaters, secondary and tertiary oil recovery methods coproduce brines. Tertiary recovery, which can involve surfactant and polymer flooding, coproduces these organics. At some sites, these materials are returned to the geologic formation; while at others, they are treated and discharged.

4.1.6.2 Alternative fuels

With the exception of small amounts of brines and industrial wastewaters, propane and natural gas produce little liquid or solid waste and are clean processes. Ethanol production from biomass, however, could become a major source of liquid and solid wastes. The amount of waste will depend on the production method chosen. If it is similar to methods currently used for the production of beverage and fuel alcohols, high-oxygen-demand liquid wastes will be produced. Solid wastes and semi-solid wastes typically result from field collection of crops (stover), from processing residue (steep liquors, enzyme hydrolysis solids, still bottoms), from biotreatment of wastes (sludges), and from combustion (ash). These materials are, with the exception of ash, at least partially composed of rapidly biodegradable materials. Tyson and his coworkers (1993) estimate that ethanol process wastewaters are slightly higher in volume than the brines coproduced with a comparable amount of petroleum. Methanol production from coal is also likely to be a major liquid and solid waste producer. Wastes include acid mine drainage, ash, and process wastewaters high in organics (including aromatics).

4.2 EMISSIONS FROM VEHICLES AND FUEL CYCLES

While some policy makers are concerned only with vehicle emissions, others may be interested in the entire fuel cycle, which includes not only vehicle emissions, but also the emissions from production of the fuel and the production of the vehicle using the fuel. The following study was included to illustrate the impact that considering the entire fuel cycle can have on the total amount of emissions associated with a particular fuel.

A report sponsored by the Gas Research Institute in the United States compared the full fuel cycle emissions of alternative fuels for light-duty vehicles (Darrow 1994). The alternative fuels considered were natural gas, liquefied petroleum gas, gasoline, reformulated gasoline, E85, M85, and electricity. The study considered emissions from the fuel cycle (production and transportation) along with tailpipe emissions from vehicles for two timeframes, the years 1990 and 2000. In addition, the generation of electricity was based on two different power mixes, one for the United States as a whole and the other for the state of California. The use of different power mixes is significant for the use of electric vehicles, because while the U.S. power mix is made up of 50 to 55% coal-fired power plants, the state of California power mix has no coal-fired plants.

The results of the study, shown in Tables 4.1–4.6, illustrate some significant points about the impact of emissions. Before making any comparisons, note that the natural gas vehicle emissions used in the study were based on emissions from a California certification test, while the other vehicle emissions were based on the higher U.S. Tier 1 standards. The numbers for natural gas shown in parentheses in Tables 4.2, 4.3, 4.5, and 4.6 are the emission rates that would occur if the natural gas vehicle used the same emission standards as the others.

As shown in the tables, the emissions of nitrous oxides and reactive organic gas (ROG) from the fuel cycle can be on the same order of magnitude as the vehicle emissions (particularly for the U.S. power mix), while carbon monoxide (CO) emissions are extremely vehicle dependent. Also note that the differences in power mix and other scenario assumptions result in significant differences in emissions, particularly for sulfur oxides and ROG. For example, the fuel cycle emissions in California are lower in most cases than those for the United States because California does not have a large number of production facilities. In essence, decreases in emissions in California due to changes in fuels may lead to increases in other areas that have more production facilities.

4.3 INFRASTRUCTURE NEEDS AND CHANGES

4.3.1 Capital Costs

World primary energy production in 1991 was 346 quadrillion British thermal units, or quads (DOE 1993). Of this total, 136 quads were crude oil and natural gas plant liquids; 92, coal; 74, natural gas; 22, hydroelectric power; and 21, nuclear power. (Natural gas plant liquids are those liquids that are recovered from natural gas processing plants and field facilities. This includes such things as ethane, propane, normal butane, and isobutane). In the 18-year period between 1973 and 1991, crude oil production rose only 10%, making it the slowest growing energy commodity. Energy production from all sources during the same period rose 41%. In the same period, worldwide nuclear power generation increased by more than 900%. It is difficult to estimate the world market for fuels because substantial amounts of fuels are produced and used in countries with centrally planned economies. However, in the United States, energy is roughly 9% of the gross domestic product.

The infrastructure supporting fuels production was built across more than a century. It includes production facilities, land, transportation, roads, and trained people. Changes to produce significant amounts of alternative fuels will require substantial

Table 4.1. Fuel cycle emissions (grams/mile) summary—U.S. case

Summary	ROG	CO	NO_x	SO_x	PM_{10}
Fuel cycle emissions—current					
Gasoline	0.254	0.080	0.226	0.044	0.013
RFG	0.252	0.083	0.239	0.044	0.013
LPG	0.120	0.099	0.366	0.008	0.006
Natural gas	0.095	0.061	0.497	0.299	0.006
Electricity	0.028	0.060	1.192	2.669	0.041
E85	0.194	0.257	0.642	0.546	0.037
M85	0.174	0.149	0.575	0.012	0.009
Fuel cycle emissions—year 2000					
Gasoline	0.199	0.062	0.144	0.032	0.011
RFG	0.190	0.066	0.153	0.032	0.011
LPG	0.097	0.086	0.216	0.006	0.005
Natural gas	0.083	0.062	0.250	0.076	0.005
Electricity	0.056	0.063	0.827	0.965	0.041
E85	0.137	0.167	0.356	0.215	0.023
M85	0.142	0.133	0.322	0.009	0.007

Abbreviations: ROG = reactive organic gas, CO = carbon monoxide, NO_x = nitrous oxides, SO_x = sulfur oxides, PM_{10} = particulate matter less than 10 micrometers in diameter, RFG = reformulated gasoline, LPG = liquefied petroleum gas, E85 = a fuel mixture of 85% ethanol and 15% gasoline, M85 = a fuel mixture of 85% methanol and 15% gasoline.

Source: Adapted from Darrow 1994.

amounts of capital. The major questions are whether the existing infrastructure can be altered to permit production and use of alternative fuels, what the costs will be, and to whom the costs will accrue.

4.3.2 Different Transportation Safety Problems

Petroleum is generally produced and refined in centralized facilities; much petroleum transport is by pipeline or by ocean tanker. Biomass-ethanol and surface-

Table 4.2. Vehicle emissions (grams/mile) summary—U.S. case

Summary	ROG	CO	NO_x
Vehicle combustion and evaporative emissions—current			
Gasoline	0.444	3.400	0.400
RFG	0.444	3.400	0.400
LPG	0.250	3.400	0.400
Natural gas	0.021 (0.250)	0.400 (3.400)	0.040 (0.400)
Electricity	0.000	0.000	0.000
E85	0.444	3.400	0.400
M85	0.444	3.400	0.400
Vehicle combustion and evaporative emissions—year 2000			
Gasoline	0.444	3.400	0.400
RFG	0.444	3.400	0.400
LPG	0.250	3.400	0.400
Natural gas	0.021 (0.250)	0.400 (3.400)	0.040 (0.400)
Electricity	0.000	0.000	0.000
E85	0.444	3.400	0.400
M85	0.444	3.400	0.400

Abbreviations: ROG = reactive organic gas, CO = carbon monoxide, NO_x = nitrous oxides, SO_x = sulfur oxides, PM_{10} = particulate matter less than 10 micrometers in diameter, RFG = reformulated gasoline, LPG = liquefied petroleum gas, E85 = a fuel mixture of 85% ethanol and 15% gasoline, M85 = a fuel mixture of 85% methanol and 15% gasoline.

NOTE: Values in parentheses are based on natural gas vehicle emissions at the U.S. Tier 1 levels.

Source: Adapted from Darrow 1994.

mined coal (for electrical and methanol production), in contrast, are produced in smaller, less centralized facilities and are typically trucked to centralized areas for processing (Tyson, Riley, and Humphreys 1993). Higher volumes of ethanol and methanol are required to meet the same energy needs fulfilled by conventional fuels. This is likely to lead to different transportation accident scenarios, especially compared with the transport of diesel fuel. Most probable is an increase in one- and two-vehicle accidents on public roads. This is in contrast to the limited-occurrence "large accident" petroleum production and transport problems discussed by Fritzsche (1989).

Table 4.3. Full fuel cycle emissions (grams/mile) summary—U.S. case

Summary	ROG	CO	NO$_x$	SO$_x$	PM$_{10}$
Fuel cycle emissions—current					
Gasoline	0.698	3.480	0.626	0.044	0.013
RFG	0.696	3.483	0.639	0.044	0.013
LPG	0.370	3.499	0.766	0.008	0.006
Natural gas	0.116 (0.345)	0.461 (3.461)	0.537 (0.897)	0.299	0.006
Electricity	0.028	0.060	1.192	2.669	0.041
E85	0.638	3.657	1.042	0.546	0.037
M85	0.618	3.549	0.975	0.012	0.009
Fuel cycle emissions—year 2000					
Gasoline	0.643	3.462	0.544	0.032	0.011
RFG	0.634	3.466	0.553	0.032	0.011
LPG	0.347	3.486	0.616	0.006	0.005
Natural gas	0.104 (0.333)	0.462 (3.462)	0.290 (0.650)	0.076	0.005
Electricity	0.056	0.063	0.827	0.965	0.041
E85	0.581	3.567	0.756	0.215	0.023
M85	0.586	3.533	0.722	0.009	0.007

Abbreviations: ROG = reactive organic gas, CO = carbon monoxide, NO$_x$ = nitrous oxides, SO$_x$ = sulfur oxides, PM$_{10}$ = particulate matter less than 10 micrometers in diameter, RFG = reformulated gasoline, LPG = liquefied petroleum gas, E85 = a fuel mixture of 85% ethanol and 15% gasoline, M85 = a fuel mixture of 85% methanol and 15% gasoline.

NOTE: Values in parentheses are based on natural gas vehicle emissions at the U.S. Tier 1 levels.

Source: Adapted from Darrow 1994.

As noted by EPA (1993), treatment of water- and land-borne spills of conventional petroleum and alternative fuels will pose fundamentally different problems. Crude oil and other petroleum products tend to remain in a body of water until slowly biodegraded.

Table 4.4. Fuel cycle emissions (grams/mile) summary—California case

Summary	ROG	CO	NO_x	SO_x	PM_{10}
Fuel cycle emissions—current					
Gasoline	0.254	0.080	0.226	0.044	0.013
RFG	0.252	0.083	0.239	0.044	0.013
LPG	0.080	0.062	0.147	0.008	0.005
Natural gas	0.096	0.020	0.053	0.004	0.002
Electricity	0.049	0.128	0.210	0.033	0.017
E85	0.088	0.065	0.155	0.009	0.005
M85	0.109	0.081	0.193	0.012	0.006
Fuel cycle emissions—year 2000					
Gasoline	0.199	0.062	0.144	0.032	0.011
RFG	0.190	0.066	0.153	0.032	0.011
LPG	0.063	0.051	0.114	0.006	0.004
Natural gas	0.079	0.011	0.013	0.001	0.001
Electricity	0.043	0.079	0.126	0.019	0.011
E85	0.065	0.046	0.104	0.007	0.004
M85	0.088	0.066	0.149	0.008	0.005

Abbreviations: ROG = reactive organic gas, CO = carbon monoxide, NO_x = nitrous oxides, SO_x = sulfur oxides, PM_{10} = particulate matter less than 10 micrometers in diameter, RFG = reformulated gasoline, LPG = liquefied petroleum gas, E85 = a fuel mixture of 85% ethanol and 15% gasoline, M85 = a fuel mixture of 85% methanol and 15% gasoline.

Source: Adapted from Darrow 1994.

4.3.3 Limits to Agricultural Production

Biomass production is limited by a variety of factors including climate, availability of water and nutrients, and type of feedstock. A number of studies have evaluated growth conditions for woody and herbaceous biomass as a feedstock for electrical energy and liquid fuels production. Wright (1994) has summarized growth rates for a variety of species. Production rates were in the range of 9 to 17 dry metric tonnes per hectare per year, but optimal growth rates are higher. The species and

Table 4.5. Vehicle emissions summary—California case (grams/mile)

Summary	ROG	CO	NO_x
Vehicle combustion and evaporative emissions—current			
Gasoline	0.444	3.400	0.400
RFG	0.444	3.400	0.400
LPG	0.250	3.400	0.400
Natural gas	0.021 (0.250)	0.400 (3.400)	0.040 (0.400)
Electricity	0.000	0.000	0.000
E85	0.444	3.400	0.400
M85	0.444	3.400	0.400
Vehicle combustion and evaporative emissions—year 2000			
Gasoline	0.269	3.400	0.200
RFG	0.269	3.400	0.200
LPG	0.075	3.400	0.200
Natural gas	0.021 (0.075)	0.400 (3.400)	0.040 (0.200)
Electricity	0.000	0.000	0.000
E85	0.269	3.400	0.200
M85	0.269	3.400	0.200

Abbreviations: ROG = reactive organic gas, CO = carbon monoxide, NO_x = nitrous oxides, SO_x = sulfur oxides, PM_{10} = particulate matter less than 10 micrometers in diameter, RFG = reformulated gasoline, LPG = liquefied petroleum gas, E85 = a fuel mixture of 85% ethanol and 15% gasoline, M85 = a fuel mixture of 85% methanol and 15% gasoline.

NOTE: Values in parentheses are based on natural gas vehicle emissions at the U.S. Tier 1 levels for the current time frame and at California LEV levels for the year 2000.

Source: Adapted from Darrow 1994.

Table 4.6. Full fuel cycle emissions summary—California case (grams/mile)

Summary	ROG	CO	NO_x	SO_x	PM_{10}
		Full fuel cycle emissions—current			
Gasoline	0.698	3.480	0.626	0.044	0.013
RFG	0.696	3.483	0.639	0.044	0.013
LPG	0.330	3.462	0.547	0.008	0.005
Natural gas	0.117 (0.346)	0.420 (3.420)	0.093 (0.453)	0.004	0.002
Electricity	0.049	0.128	0.210	0.033	0.017
E85	0.532	3.465	0.555	0.009	0.005
M85	0.553	3.481	0.593	0.012	0.006
		Full fuel cycle emissions—year 2000			
Gasoline	0.468	3.462	0.344	0.032	0.011
RFG	0.459	3.466	0.353	0.032	0.011
LPG	0.138	3.451	0.314	0.006	0.004
Natural gas	0.100 (0.144)	0.411 (3.411)	0.053 (0.213)	0.001	0.001
Electricity	0.043	0.079	0.126	0.019	0.011
E85	0.334	3.446	0.304	0.007	0.004
M85	0.357	3.466	0.349	0.008	0.005

Abbreviations: ROG = reactive organic gas, CO = carbon monoxide, NO_x = nitrous oxides, SO_x = sulfur oxides, PM_{10} = particulate matter less than 10 micrometers in diameter, RFG = reformulated gasoline, LPG = liquefied petroleum gas, E85 = a fuel mixture of 85% ethanol and 15% gasoline, M85 = a fuel mixture of 85% methanol and 15% gasoline.

NOTE: Values in parentheses are based on natural gas vehicle emissions at the U.S. Tier 1 levels for the current time frame and at California LEV levels for the year 2000.

Source: Adapted from Darrow 1994.

optimal growing conditions vary considerably in response to differing climatic and geological conditions.

Changing over to increased biomass use will require a substantial investment in infrastructure. For example, in the United States it requires 1% of the total land for every quad of woody biomass produced. Since the United States consumes approximately 70 quads annually, this would require a substantial amount of the total land area to be dedicated to the production of biomass for fuels. Additionally, biomass production competes with other uses of crop land, agricultural water, and fertilizer. This situation is more dramatic in areas where arable land, water, fertilizer, or mechanical implementation are limited.

Ethanol, and to a smaller extent, methane, production depends on the production of biomass which—like any other agricultural product—will vary in response to climate, season, pestilence, harvesting, and labor availability. Biomass products, like switchgrass, are also difficult to store for extended periods without significant losses. These factors can result in varying production or in a requirement for a substantial (and costly) capacity excess.

5. IDENTIFICATION OF GAPS IN THE STATE OF KNOWLEDGE

Two basic trends are driving the use of alternative fuels: environmental concerns and resource depletion. Currently, several different technologies which could fundamentally change the way in which fuel is evaluated are developing rapidly. These include better understanding of the mechanisms of global warming, ozone formation, and biotoxicity or carcinogenicity; development of methods and computers capable of modeling global effects of fuel choice and emissions; and evaluations of the place of alternative fuels within the current production and distribution infrastructure. The social and economic pressures generated by these activities are driving government policy decisions, often in advance of technical development. During this study, several technical areas which are at limited or early stages of development, but which could provide sound technical bases on which to build policy, were identified. These areas are discussed below in order to detail the gaps in data and the state of knowledge.

5.1 POLICY ISSUES

The worldwide effects of fuels choice decisions have been major policy concerns. Although there is a great deal of popular support for decreasing greenhouse gas emissions, reducing chlorofluorocarbon use, and decreasing acid rain, there is still much scientific debate on some of these issues and this affects the basis for making policy decisions. To a certain extent, this lack of consensus is due to limitations in government supported research. It is also due to technical limitations. For example, current computational resources are not able to support detailed models of the physical, chemical, and biological systems whose interaction governs global change.

Ozone (O_3) depletion does not appear to be affected by alternative fuel choices. It is affected by vehicle air-conditioning decisions. Acid deposition, which is affected by three factors, [nitrous oxide (NO_x) emissions, sulfur oxide emissions, and fuel-production emissions], is controlled more by the fuel used to generate electricity than by the fuels used in transportation. This issue is probably best managed by regional governments.

In many areas, the development of scenarios which would permit better evaluation of the impacts of alternative fuels is needed. As discussed in the *World Energy Outlook* (OECD 1994), nuclear and other nonfossil electric generation and natural gas are the only alternative fuels expected to find substantial use within the next two decades. Large-scale operating experience with alternative fuel vehicles has been limited. Similarly, full evaluation of fuel production alternatives, particularly those associated with biomass production, is limited by the absence of large-scale production. The impacts of these technologies will become better understood with development and deployment of large-scale, viable systems.

Fuels are among the largest commodity chemicals in international trade. Changes in the standards for fuel composition and use are expected to have worldwide economic consequences. In the case of alternative fuels, data on production technologies, end-use technologies, human health effects, and climate stabilization are limited. A substantial amount of process and end-use research will be required to support technological development currently in progress.

5.2 MATHEMATICAL THEORY AND COMPUTATIONAL RESOURCES

Much of the available information on the impact of alternative fuels on the environment, and in fact, the information on the state of the environment itself, rely on predictions from theoretical models. These models are based on mathematical representations of the natural processes that occur in the real world, and they are limited by our knowledge of the world around us, our ability to adequately translate that knowledge into a series of representative mathematical equations, and the computational resources available to solve the resulting set of equations. A more detailed discussion of the limitations on modeling global and regional phenomena follows.

5.2.1 Global Environmental Modeling

Current computational models do not provide effective prediction of multidimensional series, such as weather, pollutant dispersion, or the chemical interactions involved in global warming. Satellite data, coupled with predictive computer models, may provide an effective method for evaluating pollutant dispersion, effects of global warming, and effects of biofuel production. Typically, concentrations are measured as functions of light radiation at a selected set of wavelengths. If an effective method for handling the massive store of satellite data from previous years is developed, it could provide a method for tracking historic trends. A number of current research efforts are directed at predicting weather and at using satellite data to study the dispersion of pollutants. Both of these efforts involve the use of extremely large data sets and push the limits of computation. Computational resources are increasing dramatically, and it appears that the massively parallel computers expected in production and development by the turn of the century could provide significant improvements in handling extremely large data sets. The model of atmosphere concentrations or weather is expected to evolve from the currently used 50- or 100-mile, single-layer cell to 21st-century cell sizes of perhaps 10 miles with several layers of cells. If this level of weather data can be correlated with satellite observations of a given area, it should be possible to substantially improve our ability to model the fate of emissions.

Early studies are currently evaluating the feasibility of working with the large data sets obtained from satellite data as input to a variety of models. Registration, or the ability to correlate data from the same spot, appears to be a major problem.

Coastline data are sensitive to tides and water level fluctuations. It is also difficult to manage data set quality by, for example, removing wildly outlying points from extremely large data sets. Software capable of making effective use of the computation power inherent in massively parallel computers is also needed.

The capability to handle large data sets, such as those collected by satellites, coupled with substantial improvements in modeling and data-handling capabilities, could permit resolution of a variety of fundamental issues, including the actual extent of global warming (flooded coastline changes), better pollutant dispersion prediction, and the effects of pollutants on large-scale vegetative cover. Resolution of these issues would substantially assist governments in setting policies and priorities.

5.2.2 Air Quality Modeling

Detailed computer simulations of air quality are available for many regions. Because the data and calculational needs of typical models are within the scope of conventional computational resources, they are increasingly used by regional governments to set and monitor emissions standards and to evaluate the potential impacts of new technologies. This study identified several areas where research is needed to support governmental decisions.

Currently used air quality prediction models lack validation, although they are used to support decisions with substantial economic consequences. The limited data available are generally required to construct the model, and the uncertainties in input make it difficult to determine deficiencies in the model itself. Several areas are of particular concern. The atmospheric chemistry responsible for the formation of tropospheric O_3 is not fully understood. The relationship between O_3 and its precursors is known to be nonlinear, but many compounds that may or may not be involved in O_3 formation have not been investigated yet. As a result, models used to predict O_3 formation are limited by the deficiencies in their chemistry algorithms. Meteorology has been shown to have a large impact on the formation of tropospheric O_3, but the complexity and variability of meteorology with time and space have led to the use of several approximations in model representations. New developments in computer technology will allow more accurate representations of meteorology in the future, but current modeling techniques are limited. Emissions inventories are approximated based on limited amounts of field data and some laboratory testing. Comparisons with actual measurements have shown that volatile organic compounds (VOCs) are underestimated by a significant margin. Since VOCs and NO_x are used as controls on O_3 formation, problems with the VOC emissions inventory can affect the usefulness of control measures. Reactivity measurements which are commonly used to compare fuels are subject to experimental limitations, including the lack of multiday O_3 formation studies and unrealistic weather and emissions conditions. In addition, comparisons of reactivity often do not account for methane (CH_4), which is a greenhouse gas.

Detailed modeling, emissions testing, and reactivity measurements have not been performed for all of the alternative fuels of interest. Development of research strategies and enhanced funding for research in this area could provide a good basis for development of policies regarding alternative fuels use.

5.3 BIOCHEMICAL BASIS OF TOXICANT EFFECTS

Human health effects are a major factor in evaluating various emissions management strategies. The data on which health effects estimates are based come from a variety of sources, including epidemiological studies, occupational safety studies, and acute exposure studies. The studies typically use either small, well-controlled populations exposed to high toxicant levels or large, uncontrolled populations typically exposed to low toxicant levels. By their design, these studies are unlikely to indicate a direct physiological response to a toxicant or pollutant. Absence of a physiological response makes it difficult to set limits, develop tests which mirror human risk, and set standards which minimize both risk and cost.

Toxicant effects data are epidemiologically based and of relatively poor quality. Because of data limitations, standards are often set more conservatively than may be necessary. Better data will permit exposure standards that more closely reflect actual risk. In many cases, better data have led to substantial cost savings due to relaxed standards.

5.4 DIFFERENTIAL SENSITIVITIES TO TOXICANTS

Although a variety of studies have attempted to evaluate the effect of air pollutants on human subjects, the studies have generally evaluated acute effects of a single pollutant on middle-aged, often chronically ill white males. Occupational risk studies generally focus on high exposures to the healthy, middle-aged white males who have classically formed factory-floor populations. There are few studies which cover long-term effects on mixed populations of healthy individuals. For some compounds, industrial safety studies have shown a correlation between ethnic background and sensitivity. It is also likely that pregnant women and young children will have lower tolerances for air pollutants, as they have for lead and for radiation.

Data showing differential sensitivity are gradually emerging in occupational studies. Since many workplace toxicants are also air pollutants, the likelihood exists that different groups will have different sensitivities to air pollutants. Data can be obtained from a variety of sources, including centrally managed medical records, screenings for biochemical and genetic markers, and more conventional epidemiologically based studies.

As mentioned above, standards are conservatively set. Increased understanding of the precise mechanisms and the population at risk for damage from a particular pollutant substantially improves the ability to minimize cost while improving safety.

5.5 EFFECTS OF ALTERNATIVE FUELS PRODUCTION SCENARIOS

Because the levels of production of some alternative fuels are presently low relative to conventional fuels, the knowledge of probable production technologies is limited. Different production technologies and feedstocks have substantially different outcomes. For example, electricity to recharge batteries can be made using CH_4, coal, biomass, or nuclear fuels; hydropower; or wind power. Coal-fired electrical generation releases twice as much carbon dioxide (CO_2) as does methane-fired. Coal- and biomass-fired plants produce more particulates and ash than do the other technologies. While electrical generation is a well-understood area, production flowsheets for alternative fuels production processes are largely undeveloped or unavailable.

Engineering estimations of possible and probable process technologies, together with their mass and energy balances, are required to permit baseline evaluation. These process technology evaluations should be based on hard data from pilot-scale units and must include mass balances on emissions and wastes.

A country which makes a decision to encourage alternative fuels production and use will have to expend substantial investment capital and technical resources.

5.6 ALTERNATIVE FUELS OPTIMIZATION IN THE PETROCHEMICAL INFRASTRUCTURE

Few studies of ways to optimize alternative fuels production or to reengineer alternative fuels within the existing production and transportation infrastructure are available. As mentioned above, technologies for producing many of these materials are still in the development/pilot stage.

In manufacturing technologies, a considerable amount of current attention is devoted to the reengineering of processes to increase efficiency, decrease waste production, or change process streams. A combination of cost-priority evaluations of alternative fuels technologies and evaluation of the process reengineering required to use conventional process facilities for fuel production would help to prioritize technology development research. Such a study would also help to identify areas in which minimal changes provide benefit. For example, current safety policy requires natural gas to be vented or flared during production operations ranging from petroleum production to sewage treatment. However, recovery of the natural gas for use as a fuel or as a feedstock for methanol production would prevent the release to the atmosphere of CH_4, a serious greenhouse gas, in the case of venting or the release of CO_2 in the case of flaring.

Information on the cost-effectiveness of technologies will improve government decision making and also encourage early adoption of "stepping-stone" technologies. This information would also help government decision makers to define alternative fuels to provide the most effective use of available fuels and materials.

5.7 EMISSIONS OF ALTERNATIVE FUELS IN LARGE-SCALE USE

Most of the information available on emissions from vehicles fueled with alternative fuels has come from relatively small fleets (sometimes from individual vehicles), operated under relatively closely controlled conditions, with periodic monitoring and, if necessary, adjustments and/or repairs. For fleet applications, this may well represent the way such vehicles would be dealt with in service, but widespread use by individuals can result in widely varying maintenance and repair practices.

The air quality effects of malfunctioning vehicles are a major concern, but little has appeared in the literature regarding the effects associated with malfunctioning vehicles using alternative fuels. It is clear that given the same malfunction (for example, a misfire due to an ignition system deficiency), the effects on the environment will depend on the type of fuel being used. For example, a misfiring engine fueled with natural gas would be expected to have less effect on O_3 than one fueled with gasoline, but it would have a greater effect on global warming. More work is required to generate data in this area.

REFERENCES

Abbey, D. E., Petersen, F., Mills, P. K., and Beeson, L. W. 1993. "Long-Term Ambient Concentrations of Total Suspended Particulates, Ozone, and Sulfur Dioxide and Respiratory Symptoms in a Nonsmoking Population," *Archives of Environmental Health* **48**(1), 33–46.

Altshuller, A. P. 1993. "Production of Aldehydes as Primary Emissions and from Secondary Atmospheric Reactions of Alkenes, Alkanes During the Night and Early Morning Hours," *Atmospheric Environment* **27A**(1), 21–32.

Amann, C. A. 1990. *The Passenger Car and the Greenhouse Effect,* SAE Paper No. 902099, Society of Automotive Engineers, Warrendale, Pa.

Anttila, P., ed. 1993. *Proceedings of EMEP Workshop on the Control of Photochemical Oxidants in Europe,* April 20–22, Porvoo, Finland, Air Quality Department, Finnish Meteorological Institute, Helsinki, Finland.

AQIRP (Auto/Oil Air Quality Improvement Research Program) 1995. *Emissions from Methanol Fuels and Reformulated Gasoline in Production Flexible/Variable Fuel and Gasoline Vehicles,* Coordinating Research Council, Inc., Technical Bulletin No. 13, Atlanta.

Aris, H., Christian, D., Tager, I., Ngo, L., Finkbeiner, W. E., and Balmes, J. R. 1993. "Effects of Nitric Acid Gas Alone or in Combination with Ozone on Healthy Volunteers," *American Review of Respiratory Disease* **148**(4), 965–973.

Bach, B., Pedersen, O. F., and Molhave, L. 1990. "Human Performance During Experimental Formaldehyde Exposure," *Environment International* **16**, 105–113.

Barth, H., ed. 1987. *Reversibility of Acidification,* Elsevier Science Publishing Co., New York.

Benarde, Melvin A. 1992. *Global Warning . . . Global Warming,* John Wiley and Sons.

Bernes, C. 1991. *Acidification and Liming of Swedish Waters* (in Swedish), Swedish Environmental Protection Agency (Naturvårdsverket), Solna, Sweden.

Boden, T. A., Kanciruk, P., and Farrell, M. P. 1990. *Trends '90: A Compendium of Data on Global Change,* ORNL/CDIAC-36, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tenn.

Boden, T. A., Sepanski, R., and Stoss, F. W. 1991. *Trends '91: A Compendium of Data on Global Change,* ORNL/CDIAC-46, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tenn.

Brubaker, K. L., and Smith, A. E. 1986. *Revised Costs and Air Quality Impacts of Alternative National Ambient Air Quality Standards for Particulate Matter,* ANL/EES-TM-313, Argonne National Laboratory, Argonne, Ill.

Calabrese, E. J., and Kenyon, E. M. 1991. *Air Toxics and Risk Assessment,* Lewis Publishers, Chelsea, Mich.

Carter, W. P. L. 1994. "Development of Ozone Reactivity Scales for Volatile Organic Compounds," *Air & Waste: Journal of the Air and Waste Management Association* **44**(7) 881–899.

Carter, W. P. L., and Atkinson, R. 1989. "Computer Modeling Study of Incremental Hydrocarbon Reactivity," *Environmental Science and Technology* **23**(7) 864–880.

Carter, W. P. L., Pierce, J. A., Malkina, I. L., Luo, D., and Long, W. D. 1993. *Environmental Chamber Studies of Maximum Incremental Reactivities of Volatile Organic Compounds,* Statewide Air Pollution Research Center, University of California, Riverside, Calif.

CEC (California Energy Commission) 1989. *Comparing the Impacts of Different Transportation Fuels on the Greenhouse Effect,* P500-89-001, Sacramento, Calif.

Chang, T. Y., Hammerle, R. H., Japar, S. M., and Salmeen, I. T. 1991. "Alternative Transportation Fuels And Air Quality," *Environmental Science and Technology* **25**(7) 1190–1197.

Chang, T. Y., and Rudy, S. J. 1990. "Ozone-Forming Potential of Organic Emissions from Alternative-Fueled Vehicles," *Atmospheric Environment* **24A**(9) 2421–2430.

Chang, T. Y., Rudy, S. J., Kuntasal, G., and Gorse, R. A. Jr. 1989. "Impact of Methanol Vehicles on Ozone Air Quality," *Atmospheric Environment* **23**(8) 1629–1644.

Crapo, J., Miller, F. J., Mossman, B., Pryor, W. A., and Kiley, J. P. 1992. "Environmental Lung Diseases," *American Review of Respiratory Disease* **145**(6), 1506–1512.

Cubasch, U. et al. July 1991. *Time-Dependent Greenhouse Warming Computations with a Coupled Ocean-Atmosphere Model,* Max Planck Institute for Meteorology, Report No. 67, Hamburg, Germany.

Darrow, K. G. April 1994. *Light-Duty Vehicle Full Fuel Cycle Emissions Analysis,* report for the Gas Research Institute, GRI-93/072, Chicago, Ill.

deLint, N. and Piersol, P. 1993. *Greenhouse Gas and Other Emissions to Air Resulting from Ethanol and Methanol Use as Alternative Fuels,* a report by Ortech International for Energy, Mines, and Resources Canada, Ottawa, Ontario.

DeLuchi, M. A. 1991. *Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity,* Technical Memo No. ANL/ESD/TM-22, Argonne National Laboratory, Argonne, Ill.

Derwent, R. G., Grennfelt, G., and Hov, Ø. 1991. *Photochemical Oxidants in the Atmosphere: Status Report Prepared for the Nordic Council of Ministers,* Nord 1991:7, Nordic Council of Ministers, Copenhagen, Denmark.

DOE (U.S. Department of Energy) 1993. *Annual Energy Review,* DOE/EIA-0384(92), Energy Information Administration, U.S. Department of Energy, Office of Energy Markets and End Use, Washington, D.C.

Ecotraffic AB March 1992. *The Life of Fuels: Motor Fuels from Source to End Use,* Stockholm, Sweden.

Edmonds, J. A., Ashton, W. B., Cheng, H. C., and Steinberg, M. 1989. *A Preliminary Analysis of U.S. CO_2 Emissions Reduction Potential from Energy Conservation and the Substitution of Natural Gas for Coal in the Period to 2010,* DOE/N88-0085, U.S. Department of Energy, Washington D.C.

EPA (U.S. Environmental Protection Agency) 1993. *Alternative Fuels Research Strategy,* EPA/600/AP-92/002 (external review draft), Washington, D.C.

EPA (U.S. Environmental Protection Agency) 1992. *Alternative Fuels Research Strategy,* EPA/600/AP-92/002 (external review draft), Washington, D.C.

EPA (U.S. Environmental Protection Agency) 1990a. *Analysis of the Economic and Environmental Effects of Ethanol as an Automotive Fuel,* Special Report, Office of Mobile Sources, Washington D.C.

EPA (U.S. Environmental Protection Agency) 1990b. *Analysis of the Economic and Environmental Effects of Compressed Natural Gas as a Vehicle Fuel,* Vol. 1, *Passenger Cars and Light Trucks,* Special Report, Office of Mobile Sources, Washington, D.C.

EPA (U.S. Environmental Protection Agency) 1990c. *Analysis of the Economic and Environmental Effects of Compressed Natural Gas as a Vehicle Fuel,* Vol. 2, *Heavy-Duty Vehicles,* Special Report, Office of Mobile Sources, Washington, D.C.

EPA (U.S. Environmental Protection Agency) 1989. *Analysis of the Economic and Environmental Effects of Methanol as an Automotive Fuel,* Special Report, Office of Mobile Sources, Washington, D.C.

Folinsbee, L. J., Horstman, D. H., Kehrl, H. R., Harder, S., Abdul-Salaam, S., and Ives, P. J. 1994. "Respiratory Responses to Repeated Prolonged Exposures to 0.12 ppm Ozone," *American Journal of Respiratory and Critical Care Medicine* **149**(1), 98–105.

Frampton, M. W., and Roberts, N. J., Jr. 1989. "Respiratory Infection and Oxidants," pp. 182–191 in Utell and Frank 1989.

Frischer, T. M., Kuehr, J., Pullwitt, A., Meinert, R., Forster, J., Studnicka, M., and Koren, H. 1993. "Ambient Ozone Causes Upper Airways Inflammation in Children," *American Review of Respiratory Disease* **148**(4), 961–964.

Fritzsche, A. F. 1989. "The Health Risks of Energy Production," *Risk Analysis* **9**(4), 565–577.

Gordon, A. S., and Austin, T. C. 1992. "Alternative Fuels for Mobile Transport," *Progress in Energy Combustion Science* **18**, 493–512.

Graham, J. D., and Holtgrave, D. R. 1991. "Predicting EPA's Forthcoming CO Standards in Light of New Clinical Evidence," *Risk Analysis* **11**(2), 325–332.

Hackney, J. D., and Linn, W. S. 1989. "Evaluating Relationships Among Personal Risk Factors, Ambient Oxidant Exposure, and Chronic Respiratory Illness," pp. 174–181 in Utell and Frank 1989.

Hettelingh, J-P., ed. 1991. *Mapping Critical Loads for Europe,* CCE Technical Report No. 1, UNECE Coordinating Center For Effects (CCE), Bilthoven, The Netherlands.

Hillborn, J., and Still, M. 1990. *Canadian Perspectives on Air Pollution,* State of the Environment Report No. 90-1, Environment Canada, Dartmouth, Nova Scotia.

Horstman, D. H., and Folinsbee, L. J. 1989. "Sulfur Dioxide–Induced Bronchoconstriction in Asthmatics Exposed for Short Durations Under Controlled Conditions: A Selected Review," pp. 195–206 in Utell and Frank 1989.

Ikeda, M., Watanabe, T., Hisamichi, S., Shimizu, H., Fujisaku, S., Ichinowatari, Y., Ida, Y., Suda, M., and Kato, K. 1986. "Upper Respiratory Symptoms Presumably Due to Studded Tire Generated Dust," *Environmental International* **12**(5), 505–511.

IPCC (Intergovernmental Panel on Climate Change) 1992. *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment,* Meteorological Office Report by Working Group 1, Bracknell, United Kingdom.

IPCC (Intergovernmental Panel on Climate Change) June 1990. *Scientific Assessment of Climate Change,* Report prepared for IPCC by Working Group 1, Meteorological Office, Departments of the Environment and Energy, Bracknell, United Kingdom.

Jones, K. H. 1993. "Diesel Truck Emissions: An Unrecognized Source of PCDD/PCDF Exposure in the United States," *Risk Analysis* **13**(3), 245–252.

Jones, P. D., and Wigley, T. M. 1990. "Global Warming Trends," *Scientific American* **263**(8), 84–91.

Kessler, E., and Brodin, Y-W., eds. 1992. *Critical Loads in Nordic Countries,* special issue of *AMBIO* **21**(5).

King, L. J., and Prakash, C. B. 1992. *Field Trials of Ethanol in Transit Buses,* SAE Paper No. 922272, Society of Automotive Engineers, Warrendale, Pa.

Koenig, J. Q., Covert, D. S., and Pierson, W. E. 1989. "Acid Aerosols and Asthma: A Review," pp. 207–213 in Utell and Frank 1989.

Krause, F., Bach, W., and Koomey, J. 1992. *Energy Policy in the Greenhouse,* John Wiley and Sons, New York.

Kreibel, D., Sama, S. R., and Cocanour, B. 1993. "Reversible Pulmonary Responses to Formaldehyde," *American Review of Respiratory Disease* **148**(6), 1509–1515.

Kroll, M., Decker, G., Hartung, A., Postulka, A., and Georgi, B. 1993. *Influence of Fuel Composition on NMOG Emissions and Ozone-Forming Potential,* SAE Paper No. 932676, Society of Automotive Engineers, Warrendale, Pa.

Last, J. A. 1989. "Nutritional Status and Oxidants," pp. 162–173 in Utell and Frank 1989.

Lave, L. B., and Seskin, E. P. 1977. *Air Pollution and Human Health,* Johns Hopkins University Press, Baltimore, Md.

Lewtas, J. 1993. "Impact of Fuel Choice on Comparative Cancer Risk of Emissions," *Energy and Fuels* 7, 4-6.

Lippmann, M. 1989. "The Influence of Responses in Susceptible Populations in Establishing Standards for Ambient Air Pollutants," pp. 6–20 in Utell and Frank 1989.

Lövblad, G., Amann, M., Andersen, B., Hovmand, M., Joffre, S., and Pedersen, U. 1992. "Deposition of Sulfur and Nitrogen in the Nordic Countries: Present and Future," *AMBIO* 21(5).

Maejima, K., Suzuki, T., Niwa, K., Numata, H., Maekawa, A., Nagase, S., and Ishinishi, N. 1992. "Toxicity to Rats of Methanol-Fueled Engine Exhaust Inhaled Continuously for 28 Days," *Journal of Toxicology and Environmental Health* 37(2), 293–312.

Maejima, K., Suzuki, T., Numata, H., Maekawa, A., Nagase, S., and Ishinishi, N. 1993. "Recovery from Changes in the Blood and Nasal Cavity and/or Lungs of Rats Caused by Exposure to Methanol-Fueled Engine Exhaust," *Journal of Toxicology and Environmental Health* 39(3), 323–340.

Mauderly, J. L. 1989. "Susceptibility of Young and Aging Lungs to Inhaled Pollutants," pp. 148–161 in Utell and Frank 1989.

Morris, S. C., Lee, J., Goldstein, G, and Steinberg, M. 1992. *Comparison of Pre- and Post-Combustion Carbon Removal,* BNL-47320, Brookhaven National Laboratory, Upton, N.Y.

NAPAP (National Acid Precipitation Assessment Program) 1987. Executive Summary to *Interim Assessment: The Causes and Effects of Acidic Deposition,* Vol. 1, Washington, D.C.

NAS (National Academy of Sciences) 1991. *Policy Implications of Greenhouse Warming*, National Academy Press, Washington, D.C.

Nordic Council of Ministers 1986. *Europe's Air—Europe's Environment,* Copenhagen, Denmark.

NRC (National Research Council) 1991. *Rethinking the Ozone Problem in Urban and Regional Air Pollution,* National Academy Press, Washington, D.C.

NRC (National Research Council) 1985. *Epidemiology and Air Pollution,* National Academy Press, Washington, D.C.

NRC (National Research Council) 1981. *Health Effects of Exposure to Diesel Exhaust,* National Academy Press, Washington D.C.

Nylund, N.-O., Ikonen, M., Kytö, M., Lappi, M., Westerholm, M., and Laurikko, J. 1994. *Performance Evaluation of Alternative Fuel/Engine Concepts,* draft final report to the International Energy Agency for Alternative Fuels Annex V, VTT Technical Research Centre of Finland, Espoo, Finland.

OECD (Organization for Economic Co-operation and Development) 1994. *World Energy Outlook,* OECD/IEA, Paris, France.

OECD (Organization for Economic Co-operation and Development) 1993. *Cars and Climate Change,* OECD/IEA, Paris, France.

OECD (Organization for Economic Co-operation and Development) 1991. *The State of the Environment,* OECD, Paris, France.

OECD (Organization for Economic Co-operation and Development) 1988. *Environmental Impacts of Renewable Energy.* OECD, Paris, France.

OECD (Organization for Economic Co-operation and Development) 1983. *Environmental Effects of Energy Systems,* OECD, Paris, France.

Ostro, B. D. 1990. "Associations Between Morbidity and Alternative Measures of Particulate Matter," *Risk Analysis* **10**(3), 421–427.

Ostro, B. D. 1989. "Estimating the Risks of Smoking, Air Pollution, and Passive Smoke on Acute Respiratory Conditions," *Risk Analysis* **9**(2), 189–196.

Ostro, B. 1987. "Air Pollution and Morbidity Revisited: A Specification Test," *Journal of Environmental Economics and Management* **14**, 87–98.

Ostro, B. D., Lipsett, M. J., Mann, J. K., Krupnick A., and Harrington, W. 1993. "Air Pollution and Respiratory Morbidity Among Adults in Southern California," *American Journal of Epidemiology* **137**(7), 691–700.

Pitstick, M. E. 1993. "Emissions from Ethanol and LPG Fueled Vehicles," Paper No. 930527, 72nd Annual Meeting of the Transportation Research Board, January 10–14, Washington, D.C.

Rajan, J. B., Saricks, C. L., Singh, M. K., and Walsh, W. J. 1989. *Environmental, Health, and Safety Concerns Associated with Nonpetroleum Fuel Use in U.S. Transportation,* ANL/ES-163, Argonne National Laboratory, Argonne, Ill.

Rajan, J., and Singh, M. K. 1986. *Cost Analysis of Particulate Emission Control Technology for Heavy-Duty Diesel Vehicles,* ANL/EES-TM-310, Argonne National Laboratory, Argonne, Ill.

Research Committee for Health Effects Research Program Studies 1988. *Diesel Exhaust and Health Risks,* Japan Automobile Research Institute, Tsukuba, Ibaraki, Japan.

Rideout, G. 1994. *Exhaust Emissions from Methanol Fueled Transit Buses,* unpublished report of the Technology Development Directorate, Environmental Technology Centre, Environment Canada, Ottawa, Ontario.

Rijkeboer, R. C., and Hendriksen, P. 1993. *Regulated and Unregulated Exhaust Gas Components from LD Vehicles on Petrol, Diesel, LPG, and CNG,* TNO Report No. 93.OR.VM.029/1/PHE/RR, TNO Road-Vehicle Research Institute, Delft, The Netherlands.

Rijkeboer, R. C., Hendriksen, P., Hollemans, B., and van der Weide, J. 1994. *Potential Impact of Four Different Car Fuels on the Dutch Environment,* SAE Paper 941914, Society of Automotive Engineers, Warrendale, Pa.

Roemer, W., Hoek, G., and Brunekreef, B. 1993. "Effect of Ambient Winter Air Pollution on Respiratory Health of Children with Chronic Respiratory Symptoms," *American Review of Respiratory Disease* **147**(1), 118–124.

Rowe, M. D. 1990. *National Energy Strategy: Recent Studies Comparing the Health Impacts of Energy Technologies,* BNL-45030, Brookhaven National Laboratory, Upton, N.Y.

Russell, A. G., St. Pierre, D., and Milford, J. B. 1990. "Ozone Control and Methanol Fuel Use," *Science* **247**, 201–205.

Samet, J. M., Lambert, W. E., Skipper, B. J., Cushing, A. H., Hunt, W. C., Young, S. A., Mclaren, L. C., Schwab, M., and Spengler, J. D. 1993. "Nitrogen Dioxide and Respiratory Illness in Infants," *American Review of Respiratory Disease* **148**(5), 1258–1265.

Santini, D. J., DeLuchi, M. A., Vyas, A., and Walsh, M. 1989. *Greenhouse Gas Emissions from Selected Alternative Transportation Fuels Market Niches,* CONF-890814-10, Argonne National Laboratory, Argonne, Ill.

Schlesinger, M. E., and Jiang, X. 1991. "Revised Projection of Future Greenhouse Warming," *Nature* **350**, 219–221 (March 21).

Segalstad, V. T., and Jaworowski, Z. 1991. "Carbon Dioxide and the Global Climate," *Kjemi* **51**(10), 13–15.

Simoneit, B. R. T., Crisp, P. T., Mazurek, M. A., and Standley, L. J. 1991. "Composition of Extractable Organic Matter of Aerosols from the Blue Mountains and Southeast Cost of Australia," *Environment International* **17**, 405–419.

Simpson, D. 1991. "Long-Period Modelling of Photochemical Oxidants in Europe," *Atmospheric Environment* **26A**(9) 1609–1634.

Smith, K. R. 1987. *Biofuels, Air Pollution, and Health: A Global Review,* Plenum Press, New York.

Sorenson, S. C. 1992a. *Equivalent Emissions Factors for Electric Cars,* RE 92-2, Laboratory for Energetics, Technical University of Denmark, Lyngby, Denmark.

Sorenson, S. C. 1992b. *Emissions from Three Passenger Cars at High Speeds,* RE 92-3, Laboratory for Energetics, Technical University of Denmark, Lyngby, Denmark.

Steinberg, M. 1983. *Analysis of Concepts for Controlling Atmospheric Carbon Dioxide,* DOE/CH/00016-1, Brookhaven National Laboratory, Upton, N.Y.

Steinberg, M., and Cheng, H. C. 1988. *Modern and Prospective Technologies for Hydrogen Production from Fossil Fuels,* BNL-41633, Brookhaven National Laboratory, Upton, N.Y.

Steinberg, M., Cheng, H. C., and Horn, F. 1984. *A Systems Study for the Removal, Recovery, and Disposal of Carbon Dioxide from Fossil Fuel Power Plants in the U.S.,* DOE/CH/00016-2, Brookhaven National Laboratory, Upton, N.Y.

Steinberg, M., Lee, J., and Morris, S. 1991. *An Assessment of CO_2 Greenhouse Gas Mitigation Technologies,* BNL-46045, Brookhaven National Laboratory, Upton, N.Y.

Swedish EPA (Environmental Protection Agency) (Naturvårdsverket) 1992. *Greenhouse Gases: Emissions and Actions in International Perspective* (in Swedish), Report No. 4011 (1992/02), Solna, Sweden.

Swedish EPA (Environmental Protection Agency) (Naturvårdsverket) 1990a. *Effects of Sulfur and Nitrogen Deposition on Forest Land, Surface and Ground Water* (in Swedish), Report No. 3762, Solna, Sweden.

Swedish EPA (Environmental Protection Agency) (Naturvårdsverket) 1990b. *AIR '90: Action Programme Against Air Pollution and Acidification* (in Swedish), Solna, Sweden.

Tukey, J. W., and Sivak, A. 1991. "Comments on Predicting EPA's Forthcoming CO Standards in Light of New Clinical Evidence," *Risk Analysis* **11**, 575–576.

Tyson, K. S., Riley, C. J., and Humphreys, K. K. 1993. *Fuel Cycle Evaluations of Biomass: Ethanol and Reformulated Gasoline,* NREL/TP-463-4950, National Renewable Energy Laboratory, Goldon, Colo.

Ullman, T. L., Hare, C. T., and Baines, T. M. 1986. *Emissions from Two Methanol-Powered Buses,* SAE Paper No. 860305, Society of Automotive Engineers, Warrendale, Pa.

UNECE (U.N. Economic Commission for Europe) 1993. *Critical Levels for Ozone,* United Nations, Bern, Switzerland.

UNECE (U.N. Economic Commission for Europe) 1991. *Strategies and Policies for Air Pollution Abatement,* ECE/EB.AIR/27, United Nations, New York.

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

Utell, M. J. 1993. "Particulate Air Pollution and Health," *American Review of Respiratory Disease* **147**(6), 1334–1335.

Utell, M. J. 1989. "Asthma and Nitrogen Dioxide: A Review of the Evidence," pp. 218–223 in Utell and Frank 1989.

Utell, M. J., and Frank, R., eds. 1989. *Susceptibility to Inhaled Pollutants,* STP 1024, American Society for Testing and Materials, Philadelphia.

Waldbott, G. L. 1978. *Health Effects of Environmental Pollutants,* C. V. Mosby Co., St. Louis, Mo.

Ware, J. H., Spengler, J. D., Neas, L. M., Samet, J. M., Wagner, G. R., Coultas, D., Ozkaynak, H., Schwab, M. 1993. *American Journal of Epidemiology* **137**(12), 1287-1301.

Wigley, T. M. L., and Raper, S. C. B. 1992. "Implications for Climate and Sea Level of Revised IPCC Emissions Scenarios," *Nature* **357**, 293–300 (May 28).

Wright, L. L. 1994. "Production Technology Status of Woody and Herbaceous Crops," *Biomass and Bioenergy* **6**(3), 191–209.

Xu, X., and Wang, L. 1993. "Association of Indoor and Outdoor Particulate Level with Chronic Respiratory Illness," *American Review of Respiratory Disease* **148**(6), 1516–1522.

APPENDIX A

BACKGROUND INFORMATION ON FUELS

In this appendix, the reader will find some background information about the various fuels discussed in the text. Table A.1 gives physical and chemical properties of the various fuels.

Table A.1. Some physical and chemical properties of conventional and alternative fuels

Fuel	SG	HFG (kJ/kg)	A/F (mass)	RON	MON	LHV (MJ/kg)
Diesel	.84-.88	270	14.5	n/a	n/a	42.5
Gasoline	.72-.78	305	14.6	92-98	80-90	44.0
Methanol	0.792	1103	6.47	106	92	20.0
Ethanol	0.785	840	9.00	107	89	26.9
Propane	0.51	426	15.7	112	97	46.4
Butane	0.579	386	15.5	94	90	45.8
Methane	(gas)	n/a	17.2	120	120	50.0
Ethane	(gas)	n/a	16.1	115	99	47.6

Abbreviations: SG = specific gravity, HFG = latent heat of vaporization, A/F = stoichiometric air-fuel ratio, RON = research octane number, MON = motor octane number, and LHV = lower calorific value.

A.1 CONVENTIONAL FUELS

In this study conventional fuels are defined as gasoline, diesel fuel, reformulated gasoline, and reformulated diesel fuel. The discussion that follows is, by necessity, a summary, and readers are referred to the references for sources of more detailed information.

A.1.1 Gasoline

Gasoline is used to fuel most of the light-duty vehicles in the world and a smaller portion of the heavy-duty vehicles. It is a highly developed fuel, blended to meet octane and distillation specifications with various chemicals added to enhance its performance. Additives used include oils to provide lubricity, detergents to maintain fuel system cleanliness, agents to limit and scavenge deposits, antioxidants to maintain "shelf-life,"and other substances such as dyes and, possibly, oxygenates. The use of some additives (such as lead antiknock compounds) is being phased out for reasons related to public health and the effectiveness and durability of emission control components. The composition of gasoline affects the emissions from motor vehicles, and this relationship is the subject of ongoing research. In the United States and elsewhere, regulations specify allowable limits for certain components and the distillation characteristics of gasoline.

While gasoline has been synthesized from other sources (coal, for example), essentially all the gasoline used today comes from petroleum processed through refineries. Very often both the crude oil and the finished product are shipped long distances to the end user, and as a result, the environmental effects of gasoline use are associated not only with the combustion of the fuel but also with the production, transportation, and transfer of the product.

It is no accident that gasoline is the fuel of choice for light-duty vehicles. It is available to the consumer at a low price (in many countries, taxes represent the largest portion of the total cost to the consumer); as a liquid it is relatively easy to store and transport; and it has a high calorific value on both a gravimetric and volumetric basis. Its disadvantages are that its feedstock (petroleum) is a finite resource and that the environmental consequences associated with the production, transportation, and use of gasoline are considered by many to be unacceptable.

A.1.2 Diesel Fuel

Many of the comments made about gasoline also apply to diesel fuel because it is also a product refined from crude oil. The combustion process in a diesel engine is significantly different from that in a spark ignition engine, and the two types of engines have different (often contradictory) fuel requirements. The advantages and disadvantages of diesel fuel are similar to those of gasoline; however, diesel fuel comes in for additional criticisms because of its propensity to create particulates and its higher sulfur content that contributes more to the acid deposition problem.

A.1.3 Reformulated Gasoline

Reformulated gasoline is gasoline that is blended to reduce the impact of its use on air quality and health. Typically, reformulated gasolines have different aromatic and olefin content, lower sulfur content, the addition of oxygenates, and different distillation characteristics as compared with "conventional" gasolines. The reformulation process is designed to decrease the ozone-forming potential of the engine exhaust; decrease the masses of hydrocarbons, carbon monoxide (CO), and oxides of nitrogen produced; and decrease the emissions of toxic air pollutants.

A.1.4 Reformulated Diesel Fuel

Reformulated diesel fuel is intended to reduce the environmental effects of diesel-fueled vehicles by changing the formulation of the fuel used. The reformulations most often involve reducing the polycyclic aromatic hydrocarbons in the fuel so that the exhaust levels of these will also be reduced and reducing the sulfur content of the fuel, which serves to reduce particulate emissions and the emissions of sulfur oxides. While vegetable oils have been proposed as substitutes for diesel fuel, they are not considered reformulated diesel fuel and are generally blended with diesel fuel for use in engines.

A.2 ALTERNATIVE FUELS

A.2.1 Methanol

Methanol is a colorless liquid at normal temperatures and pressures and, as a pure substance, has a vapor pressure that is a function of temperature. At very low temperatures, the vapor pressure is so low that under equilibrium conditions a combustible air-fuel ratio is not achieved in a mixture of air and saturated methanol vapor. As the temperature rises, however, a combustible mixture can exist, and there is some concern about fuel tank fires because of this.

Although methanol can be made from a variety of feedstocks, almost all the methanol made today comes from natural gas. The natural gas is used to prepare a synthesis gas, and this gas is then exposed to a synthesis catalyst to form the methanol.

Methanol has a high octane rating, which is desirable for spark ignition engine fuels, but its low cetane rating means that its use in compression ignition (diesel) engines requires some sort of ignition enhancement in the form of glow plugs, spark plugs, ignition improvers, or a pilot charge of diesel fuel to start the ignition process.

Methanol also has a stoichiometric air-fuel ratio that is significantly different from that of gasoline. As a result, fuel metering systems must be recalibrated to introduce more fuel per unit mass of air drawn into the engine. The low stoichiometric air-fuel ratio (on a mass basis) coupled with a very high latent heat of vaporization lead to a significant cooling effect as the methanol evaporates in the intake system. This cooling effect results in an increase in the engine's volumetric efficiency and usually an increase in engine torque when methanol is used.

Methanol is corrosive to some materials used in automotive fuel systems, and care must be exercised to make sure that only methanol-compatible materials are exposed to the fuel.

Methanol is poisonous, and there have been well-publicized incidents of illness and death attributed to accidental ingestion of methanol. The combustion of methanol results in the creation of formaldehyde as an intermediate product, and because this product both is carcinogenic and has a relatively high ozone-formation reactivity, methanol-fueled vehicles must be designed to limit the emissions of formaldehyde.

Methanol-fueled engines typically produce exhaust streams that are less reactive (from an ozone-formation point of view) than those from gasoline-fueled engines (assuming that the formaldehyde emissions are kept low enough). The use of neat (100%) methanol in vehicles, however, is difficult in cold climates because of the cold starting difficulties and also because of concerns about the luminosity of methanol flames.

The low calorific value of methanol on both gravimetric and volumetric bases relative to gasoline and diesel fuel means that either a greater volume of methanol must be carried on a vehicle or more frequent refueling must occur than in the case of gasoline or diesel fueled vehicles.

A.2.2 Ethanol

All the comments made above for methanol apply to ethanol with the following exceptions:

1. Ethanol is produced primarily by the fermentation of various grains rather than the production of synthesis gas from natural gas.

2. Ethanol is less corrosive than methanol, but material compatibility must still be ensured when it is used in vehicles.

3. Although ethanol does not create formaldehyde, ethanol combustion results in the formation of acetaldehyde, which is also an undesirable component from air quality and health perspectives.

Because ethanol is an intoxicant and its distribution as a beverage is normally tightly controlled and taxed, its use as a fuel typically involves the addition of a denaturant (usually at least 5% gasoline) to make it unpalatable and to exempt it from beverage taxes.

Ethanol is presently the only biomass-based fuel used on a massive scale for transportation. The fermentation process used to make it, however, makes the fuel more expensive than methanol on an energy basis, and research continues on new processes that are intended to lower the costs of this fuel.

A.2.3 Liquefied Petroleum Gas

Liquefied petroleum gas (LPG) is primarily composed of propane and butane and must be pressurized to exist as a liquid at normal temperatures. It is obtained as a by-product of natural gas or gasoline production.

As a fuel for spark ignition engines, it is normally vaporized outside the engine and then metered into the engine as a gas. Because LPG occupies volume in the intake system of the engine, the air flow to the engine is decreased and the power output of the engine is diminished somewhat. This effect may be offset by taking advantage of the high octane rating of LPG by raising the engine's compression ratio.

As in the case of methanol, ethanol, and natural gas, LPG's high octane rating is particularly well-suited for spark ignition engines. Its low cetane rating, however, means that (as in the case of the other fuels mentioned) diesel engine applications require that steps be taken to ensure reliable ignition of the fuel.

The reactivity of the exhaust products from engines fueled with LPG is low, and the health hazards associated with exposure to the exhaust hydrocarbons and to the fuel itself are low. The primary disadvantages of the fuel are the requirement for pressurized storage (although this reduces evaporative emissions) and the limited supply of LPG, which would limit its widespread use as a transportation fuel.

In at least one country (the United States) there has been organized opposition to the implementation of LPG as a motor fuel. The opposition is based on a fear that a greater demand for LPG would result in increased prices for those who presently rely on the fuel for domestic heating and as a chemical feedstock.

Although the calorific value of LPG is close to that of gasoline, the fact that it must be stored in a pressurized tank gives the vehicle designer less flexibility in terms of the shape and location of the fuel tank (relative to gasoline or diesel fuel tanks).

A.2.4 Natural Gas

Natural gas is primarily methane, although its composition can vary both with time, and geographic location. It is a widely used fuel, but in transportation applications at the present time it must be either compressed to very high pressures or liquefied at cryogenic temperatures to increase its density for efficient (space-wise) storage. There are research programs under way to identify a means by which the gas can be stored using new approaches (such as adsorption), but these have not yet been shown to be commercially viable.

As in the case of the other fuels listed above, natural gas typically has a high octane rating and can be used in high-compression-ratio engines when the octane quality of the gas can be ensured. As in the case of the other fuels, its use in diesel engines requires that steps be taken to ensure reliable ignition.

Also, as in the case of LPG, the power output of the engine is diminished somewhat because of the displacement of air by the gaseous fuel. The high octane rating, however, opens the door to higher compression ratios to offset this power loss.

The exhaust from engines fueled with natural gas normally has a lower reactivity than the other fuels listed above because the primary hydrocarbon emitted is methane, a relatively inert hydrocarbon. For this reason, some emission regulations for vehicles are written with specifications for nonmethane hydrocarbons rather than total hydrocarbons. Note, however, that methane is a greenhouse gas.

Health effects associated with exposure to methane are primarily due to the combustion hazard of the gas, although asphyxiation could occur under extremely high concentrations.

The use of high-pressure cylinders on transportation vehicles has been of concern, and the recent failure of two cylinders in the United States has resulted in new activity in the area of cylinder safety. It must be pointed out, however, that compressed natural gas (CNG) cylinders have an impressive safety record.

The relatively low density of CNG (even at high pressures) dictates that CNG tanks have much greater volume than a gasoline or diesel fuel tank carrying the same calorific energy. The fact that the tanks are invariably cylindrical also limits the packaging of the fuel tanks, and CNG vehicles normally have reduced range compared to their conventionally-fueled counterparts.

A.2.5 Electricity

Electric vehicles have been in existence essentially since the beginning of the automobile, and at one time, they were more plentiful than gasoline-fueled automobiles. The advantages and disadvantages of electric vehicles are fairly well known. These vehicles are quiet, they have no significant emissions, they present the potential for load-leveling electricity-generating facilities, and they could reduce the demand for petroleum resources. On the other hand, batteries for electric vehicles are expensive, the vehicles have a limited range, and except for lead-acid batteries, a means of battery recycling has yet to be developed.

APPENDIX B

SUMMARY OF KEY CHARACTERISTICS OF TRACE GASES IN THE ATMOSPHERE

Table B.1. Overview of key characteristics of trace gases: CO_2, CH_4, and N_2O

Characteristics	Trace gases		
	CO_2	CH_4	N_2O
1. Current concentration in the atmosphere	1. 346 ppm (1986)	1. 1.7 ppm (1985)	1. 0.31 ppm (1985)
2. Atmospheric residence time	2. ca. 100 years (for atmosphere, biosphere and upper ocean)	2. 7–10 years	2. ca. 170 years
3. Current concentration trend	3. ca. + 0.4 %/year	3. 1.1 ± 0.1%/yr (1951–1983)	3. 0.2–0.3 %/year
4. Radiatively and chemically interactive	4. One of the most important infrared absorbers in ranges 550–800, 850–1100, 2100–2400 cm^{-1}	4. Infrared absorber (950–1650 cm^{-1}). Chemically reactive in both troposphere and stratosphere.	4. A strong infrared absorber (520–660, 1200–1350, 2120–2270 cm^{-1}). Inert in troposphere. Destroyed in stratosphere through photolyses.
5. Direct climate effect	5. The global mean equilibrium surface temperature increase due to the direct radiative effect of a CO_2 doubling (2 × CO_2) is ΔT_e = 1.3 K; including climatic feedbacks it is ΔT_e = 1.5–4.5 K.	5. For 2 × CH_4 = ΔT_e = 0.2–0.4 K.	5. For 2 × N_2O ΔT_e = 0.3–0.4 K

Table B.1. (continued)

Characteristics	Trace gases		
	CO_2	CH_4	N_2O
6. A relative measure of the contribution of a gas to radiative forcing from 1980–2050	6. A surface temperature change of 2°K for CO_2 gives a value of 10.	6. If $CO_2 = 10$, $CH_4 = 2 \pm 1$	6. If $CO_2 = 10$, $N_2O = 1.4 \pm 1$
7. Direct chemical effect	7. None	7. Increasing CH_4 • reduces OH in troposphere, • produces O_3 in troposphere, • produces O_3 in lower stratosphere, • decreases O_3 in upper stratosphere through HO_x production, • increases H_2O in stratosphere, and • decreases effectiveness of CI and NO_x on O_3 in the stratosphere	7. Through reaction of N_2O with O, main source of NO_x in stratosphere. Decreases O_3 in the stratosphere. Interacts with $C1O_x$ and HO_x.
8. Chemical-climate interactions	8. Changes in the atmosphere's temperature profile affect reaction rates of gases. Temperature changes in stratosphere change O_3 distribution, which feeds back on surface climate.	8. Reduction of OH in troposphere slows removal of CH_4 and other trace gases. Effects on O_3 and H_2O have climatic implications. Warmer climate changes biochemical sources of CH_4. Changes in temperature distribution affect atmospheric loss rate of CH_4.	8. O_3 destruction in the stratosphere has climatic implications. Warming of troposphere affects biogenic source rates.

Table B.1. (continued)

Characteristics	Trace gases		
	CO_2	CH_4	N_2O
9. Uncertainties	9. Line half-widths and temperature dependencies and overlap with H_2O need refinement.	9. Line half-widths and temperature dependence on CH_4 need to be better evaluated. Reactivity of CH_4 oxidation byproducts and their effects on O_3 in the troposphere need to be evaluated. The reaction of CH_4 with Cl in the stratosphere is a major uncertainty that could affect chemical impacts of CFCs on O_3.	9. Need further study of • the spectral line intensities, • mechanisms and production rates from biogenic and combustion sources in the troposphere, and • the photo-dissociation rate of N_2O in the stratosphere.
10. Other	10. Further flux measurements needed to refine understanding of biogenic sources and for making better projections for the future. Studies of biomass growth due to CO_2 stimulation must take into account counteracting effects of acid rain and O_3, etc., (e.g., forest dieback).	10. More information is needed on the emission fluxes from various sources and the causes of the current CH_4 trends.	10. Better measurements of sources and sinks required. Biogenic source response to temperature change is largely unknown.
11. Climate effect of one molecule relative to CO_2	1	25–32	150–250

Abbreviations: CO_2 = carbon dioxide, CH_4 = methane, N_2O = nitrous oxide, Cl = chlorine, O_3 = ozone, CFC = chlorofluorocarbon, ClO_x = oxides of chlorine, OH = hydroxyl radical, HO_x = oxides of hydrogen, and NO_x = oxides of nitrogen.

Source: Adapted from Krause 1992.

Table B.2. Overview of key characteristics of trace gases: CFC-11 and CFC-12, O_3, and OH

Characteristics	Trace gases		
	CFC-11 CFC-12[*]	O_3	OH
1. Current concentration in the atmosphere	1. 0.20 ppb (1985) 0.32 ppb (1985[*])	1. Troposphere: 0.02–0.1 ppm; 2–3 times higher in urban areas Stratosphere: 0.1–10 ppm based on ground-based and satellite data for 1978–1985.	1. In troposphere: ca. 0.015 ppt. In lower stratosphere: ca. 0.02 ppt. In upper stratosphere: ca. 0.3 ppb.
2. Atmospheric residence time	2. ca. 65 years; ca. 110 years[*]	2. O_x (ozone + oxygen atoms) is • ca. 1 hr in upper stratosphere. • months in lower stratosphere. • hours to days in troposphere.	2. Seconds to minutes.
3. Current concentration trend	3. ca. 5% year	3. Uncertain. But satellite and ground-based data indicate that O_3 is decreasing in the upper stratosphere and increasing in the troposphere.	3. Largely unknown. Growth in CH_4 and CO suggests decrease in troposphere by ca. 25% since 1900.
4. Radiatively and chemically interactive	4. Strong infrared absorbers (800–1200 cm^{-1}) (850–1250 cm^{-1});[*] inert in the troposphere. Dissociation in stratosphere leads to highly reactive chlorine species.	4. A major absorber of both solar and infrared radiation (600–800, 950–1200 cm^{-1}). O_3 production and destruction strongly affected by chemical processes.	4. Radiatively: no; chemically: yes.

Table B.2. (continued)

Characteristics	Trace gases		
	CFC-11 CFC-12*	O_3	OH
5. Direct climate effect	5. For change from 0 to 2 ppb $\Delta T_s \approx$ 0.3 K*	5. Increase in troposphere O_3 and decrease in surface in stratosphere O_3 increase surface temperature. A 50% increase in troposphere. O_3 leads to a warming increase of ca. 0.3 K.	5. None.
6. A relative measure of the contribution of a gas to radiative forcing from 1980–2050	6. If $CO_2 = 10$, CFC-11 ≈ 2 ± 1 CFC-12 ≈ 4 ± 1*	6. If $CO_2 = 10$, $O_3 \approx$ 2 ± 1	6. None.
7. Direct chemical effect	7. Dissociation leads to chlorine species which also react with HO_x and NO_x and together may lead to significant O_3 destruction in stratosphere.	7. Troposphere O_3 may change • directly, due to CO, NO_x, CH_4, HC, or • indirectly, due to stratosphere O_3. Stratosphere O_3 may change due to CFCs, N_2O, NO_x, H_2O, CH_4, CO_2 and circulation.	7. In troposphere: • controls lifetime and abundance of CH_4 and CO, • chief oxidant of CO, H_2O, CH_3CCl_3, NO_x and all HC, and • initiates photochemical smog. In stratosphere: • is a catalyst in O_3 destruction and • affects other catalysts through reactions with Cl and NO_x.

Table B.2. (continued)

Characteristics	Trace gases		
	CFC-11 CFC-12*	O_3	OH
8. Chemical-climate interactions	8. O_3 destruction in stratosphere has climatic implications in troposphere.	8. O_3 affects temperature distribution, which influences O_3 destroying mechanisms.	8. Has a strong indirect effect on climate due to its effect on radiatively important gases (CH_4, O_3, H_2O, CH_3CCl_3). It determines the ultimate effects of other trace species on O_3.
9. Uncertainties	9. The band strengths for infrared absorption. The effects of odd-chlorine chemistry on O_3.	9. Chemical reactions determining O_3 concentration. Measurement techniques for more reliable trends.	9. Radiative techniques to measure OH need further evaluation.
10. Other	10. Better emission data and concentration measurements both in troposphere and stratosphere required also for other CFCs. Have high significance due to their direct effects on climate and their effects on the ozone layer.	10. Is one of the most important species: • plays major role in climate, • in stratosphere protects us from UV-radiation, and • in troposphere it is harmful to health and forest.	10. Plays a significant role in climate and O_3 chemistry. Its global atmospheric abundance must therefore be better assessed.
11. Climate effect of one molecule relative to CO_2	14000–17500 17000–20000*	2000	NA

Abbreviation: CFC = chlorofluorocarbon, O_3 = ozone, OH hydroxyl radical, CH_4 = methane, CO = carbon monoxide, NO_x oxides of nitrogen, N_2O = nitrous oxide, H_2O = water, CO_2 = carbon dioxide, CH_3CCl_3 = methylchloroform, HC = hydrocarbons, Cl = chlorine, HO_x = oxides of hydrogen, and NA = not applicable.

Source: Adapted from Krause 1992.

Table B.3. Overview of key characteristics of trace gases: CO and NO_x

Characteristics	Trace gases	
	CO	NO_x
1. Current concentration in the atmosphere	1. NH: 20 ppm (1984) SH: 0.05 ppm (1984)	1. In troposphere remote areas: 10-30 ppt; populated areas: >1000 ppt. In stratosphere: ca. 0.02 ppm.
2. Atmospheric residence time	2. 0.4 years (global); 0.1 years (in tropics)	2. In troposphere: ca. 1–7 days; In stratosphere: much longer
3. Current concentration trend	3. 2 (1–5)%/year	3. Very uncertain due to large spatial and temporal variations.
4. Radiatively and chemically interactive	4. Is a weak absorber in the infrared. Reacts with OH, also produced in atmosphere by oxidation of CH_4 and other HC.	4. Radiatively yes, but not likely to be important. Chemically interactive through ◦ reactions with OH, HO_2 in troposphere ◦ by determining O_3 distribution in stratosphere
5. Direct climate effect	5. No direct climate effect.	5. NO_2 is an absorber of solar radiation but is unlikely to be important. Indirect effects are not well known.
6. A relative measure of the contribution of a gas to radiative forcing from 1980–2050	6. No direct climate effect.	6. NO_2 is an absorber of solar radiation but is unlikely to be important. Indirect effects are not well known.
7. Direct chemical effect	7. CO uses OH for oxidation which, in turn, affects the rate of oxidation of CH_4 and other HC. In the presence of NO_x it leads to O_3 formation in the troposphere. It reacts ultimately to form CO_2.	7. In troposphere: NO and NO_2 are very active catalysts in reactions creating O_3 and photochemical smog. In stratosphere: NO_x are important chemical species determining O_3. NO_x also strongly influence reaction pathway for CH_4 oxidation.

Table B.3. (continued)

Characteristics	Trace gases	
	CO	NO_x
8. Chemical-climate interactions	8. Affects climate through its effects on OH, O_3, CH_4 and other HC.	8. NO_x chemical interactions with other species change O_3 and affect climate.
9. Uncertainties	9. Increased CO may be linked to increased forest clearing and fossil fuel burning, increased CH_4 or decreased OH. Greater spatial and temporal variabilities make trend assessment more difficult than for CH_4 and CO_2. Need to develop airborne and satellite sampling techniques.	9. Photodissociation of NO_x species (e.g., NO_3, N_2O_3) is not well understood Global distribution not well understood. Uncertain NO_x reactions are: • reaction rates of odd-N with aerosols • reaction rates of nitric acid aerosols with chlorine species (important in explaining Antarctic O_3 hole) • reactions involving organic nitrates in the troposphere.
10. Other	10. As a toxic pollutant, CO is controlled locally. As a trace gas affecting climate indirectly, we need to assess its emissions and concentration time history.	

Abbreviations: CO = carbon monoxide, NO_x = oxides of nitrogen, NH = Northern Hemisphere, SH = Southern Hemisphere, CH_4 = methane, HC = hydrocarbons, OH = hydroxyl radical, HO_2 = hydroperoxyl radical, O_3 = ozone, NO = nitrogen oxide, NO_2 = nitrogen dioxide, CH_4 = methane, CO_2 = carbon dioxide, NO_3 = nitrate, and N_2O_3 = nitrogen trioxide.

Source: Adapted from Krause 1992.