APPENDIX E

ETHANOL AND REFORMULATED FUEL END USE

APPENDIX E

ETHANOL AND REFORMULATED FUEL END USE

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd)

LIST OF FIGURES

LIST OF FIGURES (Cont'd)

LIST OF TABLES

Page

Executive Summary

Appendix E

LIST OF TABLES (Cont'd)

LIST OF EXHIBITS

EXECUTIVE SUMMARY

SUMMARY[1] OF END-USE EMISSIONS AND ENGINE EFFICIENCY

Light-Duty Vehicle Emissions

Emissions from light-duty spark ignition engines are impacted by fuel composition and vehicle technology improvements, but the primary impact on emission levels is from government regulations. Regulations force both the fuel composition and the vehicle technology to comply to the government standards. The U.S. Environmental Protection Agency (EPA) publishes data on current emission levels and projected emission levels for all types of mobile equipment including light-duty spark ignition vehicles.[2] The projections from EPA currently contain information relating to only conventional fuels and have not yet addressed the impacts from emerging reformulated gasolines or ethanol-based fuels. The information published by EPA therefore can be used as a baseline of current technology from which projections of the impacts of new fuel technology can be made. Current emission levels will change in the future primarily in response to emissions regulations such as those included in the proposed EPA Tier I and Tier II standards, but will also be influenced by the fuels that are used and engineering technology that takes advantage of the properties of those fuels.

The emission values used as input to the ethanol full fuel cycle analysis were generated using published EPA data as a starting point. The baseline for the ethanol fuel cycle is reformulated gasoline. Emission improvements that will be realized from the use of reformulated gasoline were first identified. From this baseline, changes in emission levels expected from the use of ethanol fuels were projected. Both reformulated gasoline emission performance and ethanol fuel emission performance levels were identified through an engineering analysis of the technical literature. Reformulated gasoline emissions performance was based on results from the Auto/Oil Study[3] and from other published data. Ethanol fuel emissions performance was based on a theoretical analysis of the physical and chemical property differences between reformulated gasoline and ethanol fuels. The theoretical analysis was then supported through a comparison with empirical data presented in the literature of actual engine performance measurements.

Current gasoline emisssions and projected reformulated gasoline emissions from light-duty vehicles are presented in Table 1. The emissions for conventional gasoline in the year 1990

[1]Bailey, B.K. (1991), National Renewable Energy Laboratory, Golden, CO.

[2]United States Environmental Protection Agency (1991). "Supplement A to Compilation of Air Pollutant Emission Factors, Volume II--Mobile Sources," AP-42, Office of Mobile Sources, Ann Arbor, Michigan, January.

[3]Auto/Oil Air Quality Improvement Research Program (1991). "Technical Bulletins No. 1-6", A Research Consortium of Three U.S. Automobile Manufactures and Fourteen Petroleum Companies, Reports released through the Coordinating Research Council, Atlanta, GA.

Table 1 Current Gasoline & Projected Reformulated Gasoline Emissions from Light Duty Vehicles (grams per mile)			
Year	1990(1)	2000(2)	2010(2)
Fuel	Conventional Gasoline	Reformulated Gasoline	Reformulated Gasoline
Exhaust VOC	0.27	0.19	0.09
CO	2.8	2.2	1.7
NO_x	0.6	0.4	0.20
CO_2	317	280	243
SO_2	0.07	0.05	0.04
Evaporative VOC	0.27	0.19	0.09
Toxic VOC (mg/mi)			
benzene	1.7	0.74	0.37
butadiene	0.13	0.09	0.05
formaldehyde	0.27	0.19	0.09
acetaldehyde	0.19	0.13	0.06

(1) Emission values based on average 1990 U.S. gasoline with 8.0 psi RVP
(2) Emission values based on reformulated gasoline with 6.7 psi RVP

are from published EPA data[4]. The emission levels for reformulated gasoline are based on a scenario of proposed Tier I Standards being met in the year 2000 and proposed Tier II Standards being met in the year 2010. Evaporative emission standards have not been proposed by EPA for either the Tier I or Tier II standards. In this analysis evaporative emissions are projected to equal the exhaust volatile organic compound (VOC) levels as observed in the base year. Carbon dioxide and sulfur dioxide emissions are based on fuel carbon and sulfur content respectively and on projected fuel economy for each fuel. Toxic VOC emission levels in the base year were based on data published by the Auto/Oil Study[5]. Projections of Toxic VOC emissions are based on relative reductions in total VOC emissions.

---

[4]Same as reference 1.

[5]Same as Reference 2.

Current conventional gasoline and projected ethanol fuel emissions from light-duty vehicles are presented in Table 2. Ethanol fuel for the year 2000 is a blend of reformulated hydrocarbon base gasoline and 10 volume percent ethanol (E10). Ethanol fuel for the year 2010 is a blend of reformulated gasoline and 95 volume percent ethanol (E95). The projections of emissions in 2000 and in 2010 assume implementation of Tier I and Tier II Standards respectively. Carbon dioxide and sulfur dioxide emissions are based on fuel carbon and sulfur content respectively and on projected fuel economy for each fuel. Toxic VOC emission levels in the base year and in the year 2000 were based on data published by the Auto/Oil Study[6]. Projections of Toxic VOC emissions are based on relative reductions in total VOC emissions and changes in fuel ethanol content.

Light-Duty Vehicle Fuel Economy

Achievable new car fuel economy for several fuel and vehicle combinations are presented in Table 3. The fuel economy projections are based on predictions published in the National Energy Strategy[7] for a compact size vehicle. Fuel economy projections for reformulated gasoline are based on changes in fuel energy content resulting from the hydrocarbon distribution in a reformulated gasoline. E10 fuel economy is based on a net 1-2% increase in the miles per Btu resulting from the effects of charge air cooling and increased volume of combustion products in this fuel formulation. E95 fuel economy in a dedicated vehicle is based on a 7% efficiency gain from the increase in exhaust product volume, charge air cooling, and compression ratio. E85 fuel in a flexible fuel does not take advantage of the increase in compression ratio available in a dedicated vehicle and therefore has less energy efficiency than the dedicated vehicle.

Comparable new car energy efficiencies in terms of miles per million Btu are presented in Table 4.

Heavy-Duty Engine Emissions

Current and projected high speed heavy-duty diesel engine emissions are presented in Table 5. These data are used in the transportation portion of the full fuel cycle analysis, but are not considered in the end-use portion because it is restricted to only light-duty vehicle use. The 1990 base year emissions are taken directly from the EPA AP-42 publication[8]. Projected emission levels are also made by EPA and the projections in Table 5 are based on this information, future heavy-duty diesel engine standards, and on research goals now set by the

---

[6]Same as Reference 2.

[7]Energy Information Administration (1990). Energy Consumption and Conservation Potential: Supporting Analysis for the National Energy Strategy, SR/NES/90-92, Washington, D.C., December.

[8]Same as Reference 1

Table 2 **Current Gasoline and Projected Ethanol Fuel (E10 & E95)** **Emissions from Light Duty Vehicles** (grams per mile)			
Year	1990[1]	2000[2]	2010[3]
Fuel	Conventional Gasoline	E10 (10vol% Ethanol)	E95 (95vol% Ethanol)
Exhaust VOC	0.27	0.19	0.09
CO	2.81	2.1	1.7
NO_x	0.6	0.4	0.2
CO_2	317	278	209
SO_2	0.07	0.005	0.0035
Evaporative VOC	0.27	0.19	0.07
Toxic VOC (mg/mi)			
benzene	1.7	0.86	0.17
butadiene	0.13	0.11	0.02
formaldehyde	0.27	0.48	0.18
acetaldehyde	0.19	0.42	0.51

(1) Emission values based on average 1990 U.S. gasoline with 8.0 psi RVP
(2) Emission values based on 10 vol% blend (E10) with 6.7 psi RVP
(3) Emission values based on 95 vol% blend (E95) with 3.5 psi RVP

Table 3
Achievable New-Car Mileage Efficiencies [1]
(miles per gallon)

Fuel/Vehicle	1990	1995	2000	2005	2010
Conventional Gasoline	28.2	30.1	32.1	34.4	37.1
Reformulated Gasoline		28.9	30.8	33.0	35.6
E10,Reformulated Gasoline		28.3	30.2	32.3	
E85, Flexible Fuel Vehicle		22.5	24.0	25.7	
E95, Dedicated Vehicle				26.2	28.3

(1) J.E. Sinor Consultants, Inc., 1991.

Table 4 **Achievable New-Car Energy Efficiencies** [1] (miles per million Btu)					
Fuel/Vehicle	1990	1995	2000	2005	2010
Conventional Gasoline	245	262	279	299	323
Reformulated Gasoline		262	279	299	323
E10,Reformulated Gasoline		266	282	303	
E85, Flexible Fuel Vehicle		276	294	315	
E95, Dedicated Vehicle				337	364

(1) J.E. Sinor Consultants, Inc., 1991.

engine industry[9]. The EPA reports that evaporative VOC emissions from a diesel powered vehicle are negligible and not measured. Exhaust VOC emissions are known to contain toxic polynuclear aromatic compounds, but the level in the exhaust has not been quantified.

Current and projected high speed heavy-duty ethanol engine emissions are presented in Table 6. These data are used in an ethanol-based transportation scenario as part of the full fuel cycle analysis. The base year emissions have been derived from actual measurements made on a newly developed heavy-duty ethanol engine[10]. Projected heavy-duty ethanol emissions are based on typical improvements expected relative to new emission standards and on anticipated research to optimize the performance of this engine. The final projected emission levels are for operation with an exhaust catalyst where significant reductions are expected as indicated in the table.

Current and projected medium speed heavy-duty engine emissions are presented in Table 7. These data are used where inland water barge and railroad transportation is called for in the upstream portions of the full fuel cycle analysis. These values are based on current research that is being conducted in medium speed diesel engines which is now emphasizing emissions performance since California is now considering off-highway emission standards[11].

Current and projected diesel farm tractor emissions are presented in Table 8. These data are used in the upstream portions of the full fuel cycle analysis where farm tractors are used such

[9]Southwest Research Institute (1991). Clean Heavy Duty Engine Research Consortium, A cooperative industry program to develop low emission engines, San Antonio, Texas.

[10]Carroll, J. N., Ullman, T. L., and Windsor, R. E., (1990). "Emission Comparison of DDC 6V-92TA on Alcohol Fuels", SAE Technical Paper Series No. 902234, Presented at the Truck and Bus Meeting and Exposition, Detroit, Michigan, October 29-November 1.

[11]Winner, J. (1991). "Locomotive Emission Study for the California Air Resources Board", Booz, Allen & Hamilton, Inc.

Table 5
Current And Projected
High Speed Heavy Duty Diesel Engine Emissions (1)
(g/bhp-hr)

	1991	2000	2010
Exhaust VOC	1.1	1.0	0.5
CO	4.8	3.0	2.0
NO_x	4.8	3.8	2.0
Particulates	0.5	0.08	0.08
Evaporative VOC	nil	nil	nil
Exhaust VOC Breakdown (2)	---	---	---

(1) Projections based on emissions data in EPA Report AP-42, future Heavy-Duty Diesel Engine Standards, and research goals now set by the engine industry.

(2) Poly Nuclear Aromatic (PNA) compounds are components of diesel exhaust emission, but have not been sufficiently characterized to report on a quantitative basis.

Table 6
Current and Projected
High Speed Heavy Duty Ethanol E95 Engine Emissions [1]
(g/bhp-hr)

	1991	2000	2010	2010 w/catalyst
Exhaust VOC	3.5	1.5	1.0	0.3
CO	7.0	5.0	4.0	1.2
NO_x	3.5	2.5	2.0	1.5
Particulates	0.3	0.08	0.05	0.04
Evaporative VOC [2]	2.0	1.5	1.0	1.0
Aldehydes [3]	0.25	0.15	0.10	0.05

(1) Ethanol emission estimates are based on engine test results conducted on a Detroit Diesel 2-stroke engine converted for ethanol use using the latest technology (SAE 902234) and on projected improvements in technology and future emission standards.

(2) Evaporative VOC expected to consist primarily of ethanol and denaturant (gasoline).

(3) Exhaust VOC expected to consist primarily of acetaldehyde.

Table 7
Current and Projected
Medium Speed Heavy Duty Diesel Engine Emissions [1]
(g/bhp-hr)

	1991	2000	2010
Exhaust VOC	0.5	0.4	0.3
CO	2.0	1.5	1.0
NO_x	10.0	7.0	5.0
Particulates	0.25	0.15	0.10
Evaporative VOC [2]	nil	nil	nil
Exhaust VOC Breakdown [3]	---	---	---

(1) Emission estimates based on current engine data from Southwest Research Institute on projected emission reduction trends.

(2) EPA has reported diesel fueled engines to have insignificant evaporative emission.

(3) Poly Nuclear Aromatic (PNA) compounds are components of diesel exhaust emission, but have not been sufficiently characterized to report on a quantitative basis.

Table 8 Current and Projected Diesel Farm Tractor Emissions (g/bhp-hr)			
	1991 [(1)]	2000	2010 [(2)]
Exhaust VOC	1.70	1.4	1.1
CO	3.34	4.0	4.8
NO_x	9.39	7.1	4.8
Particulates	1.28	0.9	0.5
Evaporative VOC [(3)]	nil	nil	nil
Exhaust VOC Breakdown [(4)]	---	---	---

(1) EPA AP-42 Data

(2) Year 2010 projection based on farm tractor emissions reaching levels of high speed on-road engines of 1991.

(3) EPA has reported diesel fueled engines to have insignificant evaporative emission.

(4) Poly Nuclear Aromatic (PNA) compounds are components of diesel exhaust emission, but have not been sufficiently characterized to report on a quantitative basis.

as in the cultivation and harvesting of energy crops. The base year data are taken from published EPA figures[12]. Final projections are based on on-highway technology being applied to farm tractor engines where the emission levels for farm tractors in 2010 are similar to the on-highway high speed diesel engine levels of 1991. Comparable projections for an ethanol fueled farm tractor are presented in Table 9. These data are used in a scenario of high ethanol fuel penetration and local use of biomass-derived ethanol in cultivation and harvesting. Data for ethanol fueled tractors are not available so the values in Table 9 have been derived from an engineering comparison of current diesel tractor performance relative to high speed diesel and ethanol heavy-duty engine emission performance.

Heavy-Duty Vehicle Fuel Economy

Current and projected heavy-duty diesel truck and ethanol truck fuel economy are presented in Table 10. The base year diesel truck fuel economy is taken from data provided by the Motor Vehicle Manufacture's Association (MVMA) for class 7 & 8 tractor trailers[13]. Projected improvements are calculated from projected fuel economy improvements published in supporting technical documentation for the National Energy Strategy[14]. Comparable fuel economy values for ethanol (E95), are based on relative energy efficiency of the compression ignition cycle using E95. The relative energy efficiency in 1990 is similar for E95 and diesel fuel. In 2000, E95 has an overall energy efficiency gain of 5 to 6% over diesel due to an expected 2% internal engine efficiency advantage, and a 4% penalty for diesel engines due to the use of particulate exhaust traps. In the year 2010 improvements in diesel trap technology results in a net 4% energy efficiency advantage for E95.

---

[12]Same as Reference 1

[13]Motor Vehicle Manufacture's Association of the United States, Inc. (1990). MVMA Motor Vehicle Facts and Figures '90, Detroit, Michigan.

[14]United States Department of Energy (1991). "National Energy Strategy Technical Annex 2, Integrated Analysis Supporting The National Energy Strategy: Methodology, Assumptions, and Results", DOE/S0086P, Washington, DC.

Table 9
Projected Ethanol (E95) Farm Tractor Emissions [1]
(g/bhp-hr)

Emission\Year	1990	2000	2010
Exhaust VOC	5.4	3.5	2.0
CO	4.9	4.0	3.0
NO_x	6.8	5.0	4.0
Particulates	0.8	0.6	0.4
Evaporative VOC	3.0	2.0	1.0
Aldehydes	0.4	0.3	0.2

(1) Projections are engineering estimates based on relative high speed ethanol engine emission levels

Table 10
Current & Projected Heavy Duty Diesel Truck and Heavy Duty Ethanol Truck Fuel Economy
(miles per gallon)

Fuel\Year	1990	2000	2010
Diesel[1]	5.3	5.7	6.1
Ethanol[2] (E95)	3.1	3.5	3.7

(1) E.A. Mueller, 1991
(2) J.E. Sinor Consultants, Inc, 1991

APPENDIX E

ETHANOL AND REFORMULATED FUEL END USE

E.1 Physical and Chemical Properties of Ethanol Compared to Conventional Fuels

E.1.1 Basic Data on Fuel Properties

A list of fuel properties compiled from various sources is given in Table E-1. Ethanol, being a pure compound, has a fixed boiling point, specific gravity, heat of vaporization, heat of combustion, etc. in contrast to gasoline, which is a mixture of many compounds. Thus a comparison of ethanol to gasoline depends upon the particular gasoline sample used.

Measurements of intrinsic chemical and physical properties, such as those listed in the preceding paragraphs, should yield the same results regardless of the experimental approach used. Many ways of measuring the performance of fuels in engines, however, depend upon the details of the experimental procedure and are not precisely reproducible. Engine data in particular are subject to large variations from engine test to engine test. Caution must be used in drawing conclusions based on limited engine test data.

E.1.2 Fuel Properties Which Affect Engine Performance

Intrinsic properties and derived properties of ethanol which vary from gasoline and diesel fuel in such a way as to affect potential engine power and/or vehicle efficiency include:

- Energy density
- Heat of vaporization
- Flame temperature
- Ratio of product gases to reactants
- Specific energy
- Octane number
- Flammability limits and flame speed

Each of these is discussed briefly in the following.

E.1.2.1 Energy Density

Differences in energy mass density, BTU per pound, and energy volumetric density, BTU per gallon, do not in themselves have major effects on engine performance. However, they do directly affect the volume and weight of fuel tank plus fuel which must be carried on a vehicle. This in turn will affect the vehicle's average miles per gallon.

The magnitude of the change in fuel consumption can be estimated with the aid of Figure E-1, derived from Argonne National Laboratory (Mintz 1991). Shown in the figure are current and projected miles per gallon for U.S. automobiles as a function of curb weight.

To illustrate the calculations, a 10-gallon tank of gasoline has an energy content of about 1,170,000 BTU and the gasoline weighs 61.8 pounds. To hold the same energy content, an ethanol tank would have to hold 15.4 gallons of ethanol weighing 101.6 pounds. The weight of the tank itself would be about 0.6 pounds per gallon, resulting in an added 3.2 pounds for the ethanol case. Thus, to travel the same distance, the total weight of tank plus fuel is 43 pounds higher for ethanol than for gasoline. In the case of larger cars with a 15-gallon tank, the difference would be 65 pounds.

Again referring to Figure E-1, it is possible to choose any vehicle weight and year, read the miles per gallon, then move down the curve by an amount on the order of 40 to 60 pounds, and read the new miles per gallon. Because the vehicles will not always be traveling with a full tank, it would be incorrect to use these weights for an estimate of average mileage. They instead give the maximum possible effect. Based on Figure E-1 this maximum effect ranges from about 0.22 miles per gallon for the heaviest vehicles to 0.43 miles per gallon for the lightest vehicles. In both cases, this amounts to a decrease of 1.4 percent. If it is assumed that drivers oscillate between a full tank and one-quarter tank of fuel, then the average efficiency penalty associated with neat ethanol due to low energy density is on the order of 0.9 percent.

E.1.2.2 Heat of Vaporization

Ethanol has a much higher heat of vaporization (about 390 BTU per pound) than gasoline (about 170 BTU per pound). As the liquid fuel evaporates in the air stream being charged to the engine, a high heat of vaporization cools the air, allowing more mass to be drawn into the cylinder. This increases the power produced from a given engine size.

A second benefit is that a lower charge-air temperature decreases the maximum combustion temperature and thereby decreases the thermal load on the engine, that is, the amount of heat which must be removed to keep the engine below its high-temperature operating limit.

At a stoichiometric weight ratio of 9 to 1, the charge-air cooling effect of ethanol will be about 170°F on the intake air compared to about 45°F on the intake air from gasoline. Charge-air cooling can be especially important with supercharged engines to counteract the compressive heating of the intake air (Powell 1975). Cooling can, of course, be detrimental at low temperatures, where it becomes even more difficult to vaporize the fuel during cold start. It will also act to quench combustion in diesel engines. Because the ignition delay in a diesel engine is strongly related to temperature, too low temperatures will result in excessive ignition delay and poor combustion.

E.1.2.3 Flame Temperature

A lower flame temperature reduces heat losses from an engine and increases thermal efficiency. Ethanol's stoichiometric flame temperature of 1,930°C, compared to 1,977°C for gasoline and 2,054°C for diesel fuel, would contribute to a higher efficiency for an optimized ethanol engine. The lower luminosity of ethanol flames also reduces heat loss by radiation.

E.1.2.4 Ratio of Product Gases to Reactants

Because of its higher hydrogen to carbon ratio, ethanol produces a greater volume of gases per BTU burned than does gasoline or diesel fuel. This leads to higher mean cylinder pressures and more work performed during the expansion stroke (Owen 1990). Because the largest part of the working fluid in an engine cylinder is nitrogen, regardless of the fuel used, the effect of a change in volume of combustion products is considerably diluted. However, the results tabulated in Table E-2 show that ethanol yields an appreciably higher volume of total exhaust gas (in standard cubic feet) than gasoline, while having to compress only about the same amount of air on the compression stroke. In the last column of Table E-2, the standard cubic feet of exhaust gases are adjusted by the theoretical flame temperatures listed in the paragraph above in order to obtain the ratios of actual cubic feet produced by each fuel. The results indicate ethanol would be able to produce about 7 percent more work than gasoline and 1 percent more than diesel fuel.

E.1.2.5 Specific Energy

One important parameter that provides a method of comparing the heat release of different fuels in an engine is the specific energy (SE). The theoretical SE is calculated by dividing the lower heating value of the fuel by the air-fuel ratio so that it represents the fuel energy delivered to the combustion chamber per unit mass of air inducted. The specific energy of ethanol is 3.00 compared to 2.92 for gasoline.

E.1.2.6 Octane Number

The high octane number of ethanol compared to gasoline means that higher compression ratios can be used in an optimized engine. Higher compression ratios result in higher engine efficiencies and in higher power from a given engine size. The standard tests for research octane number (RON) and motor octane number (MON) are not completely applicable to ethanol. There is a great deal of scatter in RON and MON values reported for ethanol in the literature. Nevertheless, there is general agreement that ethanol has excellent antiknock properties allowing higher compression ratios and improved engine efficiencies (Owen 1990). Conversely for diesel engines, the high octane rating is correlated to a low octane rating, which makes ethanol difficult to use in compression ignition engines.

E.1.2.7 Flammability Limits and Flame Speed

Once ignited, ethanol burns faster than gasoline, allowing more efficient torque development (Owen 1990).

Ethanol has wider flammability limits on the rich side than gasoline or diesel fuel. Wide flammability limits may be useful because rich air/fuel ratios can be used when needed to maximize power by injecting more fuel per charge. Operating at higher power levels in this way reduces efficiency. Wide flammability limits on the lean side are useful in extending the operating range of lean burn engines.

E.1.2.8 Otto Cycle Versus Diesel Cycle Engines

The Otto cycle is a theoretical thermodynamic cycle associated with spark-ignited gasoline engines. It consists of an isentropic compression phase and an isentropic work phase interspersed between two constant-volume phases. Combustion of the premixed fuel/air mixture occurs rapidly at constant volume.

In the true diesel cycle, fuel is injected slowly and burns during a constant-pressure combustion phase. In an actual engine with a given compression ratio and air/fuel ratio, the Otto engine has the higher efficiency. However, engine knock limits the Otto engine to a compression ratio of about 10, whereas a diesel engine can operate at higher compression ratios and therefore higher efficiency. Also, the diesel engine is not throttled, so there are lower compression losses at part load.

Real diesel engines operate at lean A/F ratios, and efficiency is increased because the specific heat ratio for air is higher than for the combustion products. The relationship between efficiency, E, and compression ratio, CR, for an ideal constant-volume combustion cycle is given approximately by:

$$E_t = 1 - CR^{1-g}$$

where g is the ratio of specific heats for air (Adelman 1979). Based on an allowance of 1 unit of compression ratio for every 3 to 6 units of octane number (Owen 1990), we can estimate that ethanol's approximate 12 to 14 octane number advantage over gasoline could allow an increase from 9 to 12 or 13 in compression ratio. This would result in a 6 to 10 percent increase in theoretical thermal efficiency in Otto cycle gasoline engines. (The average compression ratio for 141 different model cars listed in reference 7 is 9.2, but this includes a number of foreign models designed for leaded gasoline.) Compression ratios of even 15 or 16 may be possible, but actual efficiency increases much less than the theoretical values at such high ratios.

A calculation of theoretical diesel cycle work for ethanol and for diesel fuel (Figure E-2) shows almost exactly the same mean pressures and efficiencies for these two fuels in an ideal Diesel cycle (Hardenberg 1981).

E.1.2.9 Summary of Ethanol Efficiency Effects

The largest factors differentiating the efficiency of optimized ethanol engines from gasoline and diesel engines are:

- Loss of efficiency due to higher fuel and tank weight: approximately 1 percent loss for ethanol

- Increased volume of combustion products: 7 percent gain for ethanol against gasoline, 1 percent against diesel fuel

- Potential advantage for higher octane number: 6 to 10 percent gain for ethanol against gasoline, no difference against diesel

In total, therefore, we would predict that ethanol should have about the same efficiency as diesel in compression ignition engines, but be around 15 percent more efficient than gasoline in spark ignited engines. Other factors less important than the three above are generally slightly favorable for ethanol, so they should not change the general conclusion. The overall theoretical comparisons are succinctly presented in Figure E-3 (Pischinger 1983). At the same compression ratio in Otto engines, ethanol should be more efficient, and it also has the ability to move up the compression ratio curve past the gasoline knock limit. For diesel engines, the theoretical differences between the fuels are much smaller.

E.1.3. Fuel Properties Which Affect Emissions

Essentially anything which affects engine performance and efficiency will affect emissions because of the tradeoffs which must be made between them in tuning an engine. Therefore any of the fuel properties discussed in the preceding section may be also said to affect emissions. However, some fuel properties which may have a pronounced effect include:

- Carbon to hydrogen ratio
- Oxygen content
- Flame temperature
- Heat of vaporization
- Combustion mechanism
- Vapor pressure
- Energy mass density
- Chemical composition

Each of these is discussed briefly in the following.

E.1.3.1 Carbon/Hydrogen Ratio

Ethanol has a lower carbon/hydrogen ratio than gasoline; therefore, other things being equal, its combustion products will tend to lower concentrations of carbon monoxide. Lower concentrations of carbon monoxide going into a catalytic converter reduce the potential level of carbon monoxide coming out the tailpipe.

E.1.3.2 Oxygen Content

The oxygen atom present in ethanol still carries some oxidation potential. Thus switching to a fuel containing some ethanol may be thought of as a way to bring some oxygen into the engine within the fuel stream. Carbureted engines without closed-loop emission control systems will operate at a constant air/fuel ratio, thus resulting in an excess of oxygen. This oxygen will react with any carbon monoxide or hydrocarbons remaining in the exhaust stream.

Engines with an oxygen sensor in the exhaust and closed-loop emission control systems would be expected to detect the additional oxygen contributed by ethanol and readjust the air/fuel ratio accordingly. However, even these engines usually operate in the open-loop mode during warm-up and during some accelerations. Thus carbon monoxide emissions from all types of spark ignited engines are likely to be reduced when small amounts of ethanol are added to gasoline.

When near-neat ethanol fuels are used, the engine will have to be tuned for operation with these specific fuels and the relative level of carbon monoxide will be affected only by the carbon/hydrogen ratio as discussed previously.

It must be noted that while the addition of oxygen to gasoline in open-loop engines will shift the effective air/fuel ratio and reduce carbon monoxide and hydrocarbons, it can simultaneously increase nitrogen oxide levels due to the tradeoff that usually exists between CO and HC on the one hand and NO_x on the other. This is illustrated in Figure E-4. Depending on the exact A/F ratio at which an engine is operating, an increase in oxygen could either decrease or increase NO_x levels. A mitigating factor is that the addition of ethanol will also lower the flame temperature, which should reduce NO_x.

E.1.3.3 Flame Temperature

Because the nitrogen in NO_x comes not from the fuel but from the air, NO_x emissions are relatively unaffected by fuel composition <u>per se</u>. They are strongly affected by the maximum temperatures reached during the combustion process. Thus the lower flame temperature of ethanol relative to gasoline and diesel fuel would be expected to yield lower engine-out emissions of NO_x.

An unfavorable effect of low combustion temperature is that the exhaust temperature is also lowered, which may make catalytic converters less effective.

It also appears that low exhaust temperatures may inhibit the oxidation of aldehydes in the exhaust.

E.1.3.4 Heat of Vaporization

Ethanol's high heat of vaporization simply contributes to the low flame temperature, discussed above.

E.1.3.5 Combustion Mechanism

Because one of the first intermediate products of combustion of ethanol is acetaldehyde, increased concentrations of this material are detected in the exhaust. Acetaldehyde is photochemically reactive, contributing to smog formation.

A great advantage for ethanol combustion in diesel engines is the lack of black smoke in the combustion products. For example, on the basis of test results shown in Figure E-5, the maximum power output for the engine used in the test is limited to what is obtained at a relative (to stoichiometric) air/fuel ratio of 1.35 when a smoke limit of 3 Bosch units is required. The same engine operating on ethanol with the same smoke limit can be run with only 1.1 times the stoichiometric amount of air and with a correspondingly higher power output (Hardenberg 1981).

E.1.3.6. Vapor Pressure

In current-model cars, about half the total hydrocarbon emissions do not come from the tailpipe, but are the result of evaporative emissions. Evaporative emissions are broken down into three categories:

- Running losses
- Hot soak losses
- Diurnal losses

Running losses consist of any raw fuel vapors emitted by a vehicle during normal operation. Hot soak losses are those which occur after a vehicle is parked and the engine heat gradually dissipates. Diurnal losses are those which occur from a parked vehicle due to day/night temperature changes.

Evaporative emissions are strongly affected by the ambient temperature and by the vapor pressure (usually reported as Reid vapor pressure, RVP) of the fuel. Although the relationship between evaporative emissions, temperature and RVP becomes nonlinear at high values of temperature and RVP (API 1988), a linear dependence of emissions on RVP may be a reasonable assumption at low values of RVP (IEA 1986).

Mixtures of ethanol and gasoline exhibit highly nonideal behavior with respect to vapor pressure for low-ethanol blends. When 10 percent ethanol is added to 9 psi gasoline, the RVP increases about 1 psi even though the RVP of pure ethanol is only 2.3 psi. The percent increase in RVP when ethanol is added also increases with lower RVP gasolines. Based on partial data (API 1988), an estimated RVP curve for ethanol blends is shown in Figure E-6.

Currently, gasohol is given a 1 psi exemption from EPA requirements for RVP. It is assumed that this exemption will be removed in the future. Therefore, low-ethanol blends will have to meet the same vapor pressure requirements as normal and/or reformulated gasoline. There is some disagreement about whether alcohol/gasoline blends will have the same evaporative emissions as gasolines having the same RVP. Test data have shown that evaporative emissions from low-alcohol blends are generally the same or lower than from gasoline of a corresponding RVP (Reddy 1986). However, other studies have shown that a gasohol blend with the same RVP as gasoline can still have higher evaporative emissions. The EPA estimating procedure assumes that RVP-adjusted gasohol will have lower hot-soak and diurnal emissions than gasoline in fuel injected cars but higher emissions than gasoline in carburetor cars (EPA 1987). Because alcohol may be absorbed more strongly than gasoline on the charcoal in the fuel tank canister, the actual emissions will depend on the state of the canister, whether it has excess capacity, the degree to which the fuel system is sealed, and the effectiveness of the purging cycle.

For high-ethanol blends, the effect of blending with an 8 or 9 psi base gasoline can be estimated from Figure E-6. If no other blending adjustments are made, both E85 and E95 would have lower RVPs and would be expected to result in lower evaporative emissions than the reference gasoline. Because high-ethanol blends are subject to cold start problems precisely because of their low vapor pressure, such emission reductions might never be realized in practice. Butane could be added, for instance, to improve the cold start characteristics of E85 or E95 and bring the RVP back up somewhat. For engine designs which solve the cold start problem, emission reductions could be possible.

E.1.3.7 Energy Mass Density

Producing a given quantity of energy in an engine requires a greater mass of ethanol than of gasoline. Thus in every stroke of the engine there are more molecules of ethanol than gasoline squeezed into the crevices and cracks in the combustion chamber where they may be protected from the peak combustion temperature, to be exhausted only partially combusted.

E.1.3.8 Chemical Composition

Unregulated exhaust gas pollutants that are influenced by the use of ethanol in the fuel include benzene and polynuclear aromatics (PNAs). Benzene from the exhaust is a direct function of the benzene and other aromatics content of the gasoline and so the use of ethanol improves this situation by dilution. PNAs are very low from spark ignition engines fitted with a catalyst, but reductions have been demonstrated by the use of oxygenates in gasolines (Owen 1990).

Because ethanol contains none of the sulfur usually present in diesel fuel, there are no sulfate emissions.

E.2 Comparison of Engine Efficiencies with Ethanol and Conventional Fuels

E.2.1 Spark Ignited Engines

The available data from the literature giving relative performance of gasoline and ethanol fueled SI engines are tabulated in Exhibits E-1 and E-2. Exhibit E-1 contains all the data on ethanol blends at higher than 10 percent concentration. Exhibit E-2 contains E10 data only.

Because of the large variability between engines and test conditions, absolute values of miles per gallon or engine efficiency are of relatively little value. Only those data sources in which a reference value for gasoline is clearly given are included in the exhibits. All fuel economy data were converted to a common energy basis, miles per million BTU. The ratio of miles per million BTU from ethanol to that from gasoline was then computed. Results from the data in Exhibit E-1 are plotted in Figure E-7.

Although the data are widely scattered, there appears to be a clear upward trend with increasing ethanol content. The line shown in Figure E-7 is the theoretically expected relationship for equal compression ratios. The agreement appears reasonable but several cautions must be stated. In converting the data to a common basis, values for heat of combustion of the different fuels were assumed, based on Table E-1. This value was almost never measured experimentally. Gasoline composition and heating value can vary appreciably with time and source, throwing the calculated ethanol to gasoline ratio in error.

In other cases it is not clear what engine adjustments were made in converting to ethanol operation. If the compression ratio were changed, then the theoretically expected line in Figure E-7 would be different. In one case (AES 1983), where the compression ratio was increased from 8 to 12, the efficiency (with E95 in both cases) increased by 8 percent, whereas the expected increase would have been 12 percent.

E.2.2 Compression Ignition Engines

Efficiency data on ethanol fuels in diesel type engines are summarized in Exhibit E-3 and Figure E-8. The small number of data points makes any conclusion hazardous at best, but they do not seem to contradict the theoretically expected relationship.

E.3 Comparison of Emissions from Ethanol and Conventionally Fueled Engines

E.3.1 Spark Ignited Engines

The available data from the literature giving relative emissions from gasoline and ethanol fueled SI engines are given in Exhibits E-4 through E-9 for high-ethanol blends and Exhibits E-16 through E-21 for E10. Comparative emissions data are confounded by a host of factors which may have greater effects than the differences between fuels. These include engine fuel metering technology, exhaust control technology, age of vehicle, maintenance history, test procedures, test conditions, etc. Therefore, single-vehicle tests are of limited value. Tests without a well-defined baseline run on gasoline are of no value.

The effect of advances in emission control technology over the last 12 years is shown in Figure E-9. Changes in emissions due to different engine and control technology have been much larger than the differences due to E10 versus gasoline as a fuel. Furthermore, almost all the data on ethanol were obtained in engines not fully optimized for ethanol, and these data are being compared to engines which have been fully engineered for optimum performance on gasoline. Thus the following comparisons must be viewed with a great deal of caution.

E.3.1.1 Carbon Monoxide

The extensive data on CO emissions from E10 fueled engines are presented in Exhibit E-16 and plotted as the star in Figure E-10, representing an average drop of slightly over 20 percent. The high-ethanol fuel data from Exhibit E-4 are then represented by the circular data points in Figure E-10, indicating that essentially no further improvement occurs with higher ethanol concentrations. Many of the data points represented by the star were obtained in older autos, before the advent of fuel injection and closed-loop engine control systems. Therefore the improvement shown in future automobiles is likely to be less.

E.3.1.2 Nitrogen Oxides

The extensive data on NO_x emissions from E10 fueled engines are presented in Exhibit E-17 and plotted as the star in Figure E-11, representing an average increase of 3.3 percent. Beyond 10 percent ethanol, NO_x emissions appear to decrease, based on limited data from Exhibit E-5. The correlation in Figure E-11 suggests an approximate 20 percent decrease in NO_x when using E85 or E95.

E.3.1.3 Exhaust VOC

The available data on exhaust VOC emissions from E10 fueled engines are presented in Exhibit E-18 and plotted as the star in Figure E-12, representing a decrease of 7 percent. The high-ethanol fuel data from Exhibit E-6 are represented by the circular data points in Figure E-12.

With the exclusion of some outlying data points at VOC levels of more than twice normal, a regression line indicates a definite benefit from high-ethanol fuels. The calculated benefit works out to a little more than a 0.3 percent drop in VOC emissions for each 1 percent increase in ethanol fuel concentration. Results from a fully optimized E100 vehicle are likely to be better than the early experimental values shown but such data are not yet available.

E.3.1.4 Evaporative Emissions

The limited data available on evaporative emissions from SI engines using E10 are tabulated in Exhibit E-19 and those from higher-ethanol fuels are shown in Exhibit E-7. While the data are insufficient for quantitative predictions, two tentative conclusions appear evident:

- Evaporative emissions from E10 are higher than from baseline gasoline.

- Evaporative emissions from high-ethanol blends are lower than from gasoline.

This is the behavior which would be predicted from vapor pressure curves, because the vapor pressure of E10 is higher than that of either gasoline or E85. Because the vapor pressure of E100 is much less than gasoline or any of the ethanol/gasoline blends, evaporative emissions of E100 should be very low.

E.3.1.5 Aldehydes

One of the major environmental concerns about increased use of ethanol fuels is the increase in exhaust emissions of reactive aldehydes. Acetaldehyde, a decomposition product of ethanol, and formaldehyde, are detected in the exhaust at considerably higher levels than in the exhaust from gasoline engines.

Data available from tests on E10 (Exhibit E-20) indicate acetaldehyde levels slightly more than twice as high as from gasoline engines. Formaldehyde levels are about 30 percent higher. The very limited data available on high-ethanol blends (Exhibit E-8) are inconclusive. They suggest that formaldehyde levels might not be higher than for E10 but that acetaldehyde levels could be several times higher. Thus a key factor with respect to possible ethanol effects on urban ozone will be the durability and effectiveness of catalyst systems for aldehyde control (Black 1991).

E.3.1.6 Other Toxic Emissions

Relative concentrations of toxic aromatics such as benzene, toluene, ethylbenzene, PAH (polycyclic aromatic hydrocarbon) and BaP (benzo-a-pyrene) are tabulated in Exhibit E-21 for E10 and Exhibit E-9 for the higher blends. Emissions of benzene, toluene, xylene and ethylbenzene are clearly lower with the ethanol fuels. Extremely limited data suggest that emissions of these compounds would be reduced by more than one-half for E85. This is not as much as would be expected from the straight dilution effect.

No effect could be discerned for PAH, BaP and 1,3-butadiene.

Because E100 contains no benzene, toluene, xylene, etc. unless added as a denaturant, toxic emission from E100 should be much lower than from gasoline blends.

E.3.2 Compression Ignition Engines

Emissions data from ethanol fueled compression ignition engines are extremely sketchy. The data available are presented in Exhibits E-10 through E-15 for carbon monoxide, nitrogen oxides, VOC, aldehydes, particulates, and PAH/BaP, respectively. These engines were not optimized for ethanol. No firm conclusions may be drawn from these data, but the indications are that for ethanol fueled CI engines:

- Carbon monoxide emissions are considerably higher
- Nitrogen oxide emissions are considerably lower
- VOC emissions are considerably higher
- Aldehydes are considerably higher
- Particulate emissions are much lower
- PAH and BaP emissions are lower

E.4 Trends in Automotive Technology

E.4.1 Efficiency as Affected by Fuel Composition

Although the automobile was invented over 100 years ago, substantial technical advances continue to be made. Increased efficiency and reduced emissions are both certain to come about in the next 10 to 20 years.

Automotive fuel efficiency is affected by both engine and nonengine technologies. Some of the possible future trends, and the way in which ethanol would interact with them are discussed in the following.

E.4.1.1 Improved Quality Control

Octane requirements vary from engine to engine of identical design because of manufacturing variability. This variability may be as much as 7 octane numbers (Owen 1990), and all engines must be designed to operate at lower compression ratios to allow for the range of variability with respect to knock. Improved quality control would allow the average engine to operate at a higher compression ratio, perhaps making octane obtained from ethanol more valuable.

E.4.1.2 Variable Valve Timing and Variable Compression

For traditional load control by means of throttling, engine efficiency drops considerably at part load. The use of variable compression engines with variable valve timing can reduce charge-cycle work, develop higher torque at low speed, and decrease expansion losses (Figure E-13). Engine management systems aided by sensors will be able to ensure that optimum conditions of air/fuel ratio, ignition timing, valve timing, etc. are always met. This will let every engine optimize itself to take advantage of fuel properties. This trend could allow ethanol to achieve maximum premium value as high-performance fuel. Substantial future progress is expected in this field.

E.4.1.3 Lower Drag Coefficients

Lower vehicle drag coefficients are a chief ingredient of fuel-efficient vehicles. Achieving lower drag coefficients makes it more difficult to direct air streams into the engine compartment for cooling. This makes the lower combustion temperature of ethanol more valuable. Lowering the drag coefficient by 30 percent would increase miles per gallon by about 10 percent. Figure E-14 illustrates the history of progress in drag coefficients and suggests that future large gains are unlikely.

E.4.1.4 Lean Burn Engines

Lean burn engine designs may make vehicles more susceptible to cold weather driveability problems, which would tend to make ethanol less desirable.

E.4.1.5 Direct Injection Light-Duty Diesel

A large reduction in fuel consumption could result from the introduction of direct fuel injection for high-speed passenger car diesel engines. To date, good mixing could be obtained with the small quantities of fuel injected into passenger car engines only by "indirect" injection into precombustion and swirl chamber engines (Seiffert 1991). Direct injection has been limited to larger, slower speed engines. Ethanol is not a very good diesel engine fuel and could lose market opportunity.

E.4.1.6 Automotive Turbine Engine

Development of the gas turbine for automobile applications would eliminate much of the emphasis on fuel properties. Turbines are not affected by such parameters as octane number and cetane number. Fuel would be valued almost entirely on a BTU basis. Thus ethanol would have neither an advantage nor a disadvantage with respect to gasoline and diesel fuel.

E.4.1.7 Continuously Variable Transmission

Use of continuously variable transmission systems will allow motors to operate at higher, more constant speeds. This could increase the importance of optimum operation at high speed, where ethanol's high flame speed and high octane number would be an advantage.

E.4.2 Emissions as Affected by Fuel Composition

E.4.2.1 Reduced Evaporative Emissions

The use of fuel injectors instead of carburetors reduces evaporative emissions. In the future it is likely that improved vapor control systems will eliminate the vapor pressure disadvantage of gasohol as well as the vapor pressure advantage of near-neat ethanol fuels.

E.4.2.2 Lean Burn Engines

Development of lean burn gasoline engines, such as that recently announced by Honda (Miller 1991), will be feasible for larger automobiles only if NO_x emissions can be reduced. The lower flame temperature of ethanol could help achieve such a reduction. Lean burn engines must operate at high compression ratios to maintain competitive power levels.

E.4.2.3 Advanced Engine Regulations

Systems are being developed to control the injection and ignition of fuel individually in each cylinder while sensing knock in each cylinder. This will allow each cylinder to be individually optimized for lowest emissions, and any intrinsic property of fuel which acts to lower exhaust emissions will become more important. This should work to the advantage of ethanol.

E.4.2.4 Particulate Control in Diesel Engines

Probably the most significant emissions benefit of ethanol in diesel engines is the reduction in particulate emissions. Advances in other methods of particulate control could reduce the attractiveness of ethanol. Such potential advances include the development of particulate filter traps, reducing the duration of injection and improving electronic engine control systems.

E.4.2.5 NO_x Control Measures in Diesel Engines

The lower flame temperature of ethanol theoretically reduces NO_x emissions from diesel engines. Advances in other methods of NO_x control could reduce the value of this potential advantage. Such advances might include exhaust gas recirculation and improved electronic engine control.

E.4.2.6 Improved Exhaust Catalysts

The ultimate conversion efficiency of current catalysts is so good that today's most stringent emission requirements are easily met under ideal conditions. However, the efficiency falls with time due to thermal aging and catalyst poisoning through deposits from fuel and oil components. A catalyst pack which could maintain its new performance level indefinitely would make differences between fuels so small as to be moot.

E.5 Summary of Emission Regulations

E.5.1 Tier 1 Tailpipe Standards for LDVs and LDTs

On July 5, 1991, the United States Environmental Protection Agency issued new tailpipe emission standards for petroleum and methanol fueled light-duty vehicles (LDVs) and light-duty trucks (LDTs). These standards apply to 1994 and later model year vehicles. The Tier 1 standards include both a set of certification standards (Table E-3) and a set of in-use standards (Table E-4).

E.5.2 Tier 2 Tailpipe Standards for LDVs and LDTs

By the end of 1999, EPA is to determine the need, cost and feasibility of Tier 2 standards for 2004 and later model years. If needed and feasible, these standards will be set at:

- NMHC 0.125 grams/mile
- CO 1.7 grams/mile
- NO_x 0.2 grams/mile

E.5.3 Cold Temperature CO Tailpipe Standard

The CO standard of 3.4 grams per mile is measured at 75°F. However, almost all high CO pollution days occur at colder temperatures. Therefore EPA has added a new low-temperature standard for cars and light trucks beginning with 1994 models. In addition to the 3.4 grams per mile limit at 75°F, these vehicles must emit no more than 10.0 grams of CO per mile at 20°F.

More stringent standards will be imposed in the year 2002 if six or more cities remain in nonattainment for carbon monoxide in mid-1997.

E.5.4 Urban Buses and Heavy-Duty Trucks

On September 10, 1991 the EPA proposed new particulate matter control regulations specifically for urban buses. Table E-5 lists the new schedule. The previously promulgated exhaust standards for heavy-duty diesel engines are listed in Table E-6.

The September 10 proposal also includes a first-ever requirement to retrofit existing buses to reduce diesel emissions. Starting in 1995, urban buses in cities with populations greater than 750,000 (representing about 80 percent of bus service in operation nationwide) that have their engines replaced or rebuilt would have to meet emission standards set by EPA reflecting the best retrofit technology available.

If EPA later finds that buses in-use are not meeting the 1994 standard, it must implement a "low polluting fuels" program for new buses in large cities.

E.5.5 Non-Road Engines

EPA has been given new authority to control emissions from non-road engines that contribute to urban air pollution. By November 15, 1991 EPA must complete a study of non-road engines. By November 15, 1992 EPA may issue regulations requiring emission reductions for any category of engines which contributes significantly to urban air pollution.

Standards must be set for new railroad locomotives within 5 years.
States, including California, may not regulate emissions from construction and farm equipment engines with less than 175 horsepower. California may regulate other non-road engines and other states may require California-type engines to be sold within their boundaries.

E.5.6 Air Toxics

By May 15, 1992 EPA must complete a study of the need for and feasibility of controlling emissions of toxic pollutants emitted by motor vehicles and fuels. By May 15, 1995, based on the study, EPA must issue regulations to control emissions of benzene and formaldehyde.

At EPA's discretion other toxic pollutants may also be controlled.

E.6 Reformulated Gasoline and Diesel Fuel

E.6.1 Gasoline Requirements

The Clean Air Act Amendments of 1990 require that "reformulated" gasoline be sold in the nine worst ozone nonattainment areas starting in 1995. Other cities can elect to be included in the program. The Act defines a reformulated gasoline as one which either (whichever is more stringent):

- Matches a formula set forth in the Act, or
- Reduces emissions of volatile hydrocarbons and air toxics by 15 percent by 1995 and 25 percent by 2000, in comparison with a current baseline gasoline.

The formula gasoline specified in the Act is one which:

- Contains at least 2.0 weight percent oxygen
- Contains no more than 1.0 volume percent benzene
- Contains no more than 25 volume percent aromatics
- Does not increase NO_x emissions over baseline levels

In addition, for the 41 cities in nonattainment for carbon monoxide, the minimum oxygen content is increased to 2.7 percent during the winter months.

In mid-June the EPA released a package of proposed rules and guidelines for reformulated gasoline. A public hearing on the proposals was held in mid-July. The final regulations must be in place by November 15, 1991.

For gasoline sold during the high ozone season (summertime), the baseline gasoline is defined by the specifications in Table E-7. There are, however, no parameters for the level of oxygen, lead and deposit control additives in the baseline fuel. EPA's proposed specifications for winter baseline gasoline are shown in Table E-8.

For reformulated gasoline, the Act is silent regarding some of the parameters that have been defined for baseline gasoline: sulfur content, Reid vapor pressure, octane, distillation points, API gravity, olefins, and saturates. EPA proposes that where some compositional characteristics are not specified for reformulated gasoline, these characteristics will be the same as for baseline gasoline. Other compositional characteristics are not constrained.

Anti-dumping provisions of the proposed regulations will not allow the transfer of benzene and other high polluting compounds removed from reformulated gasoline into conventional gasoline sold in the remainder of the country.

The other 87 ozone nonattainment areas may request to be included in the reformulated gasoline program. If all eligible areas elected to participate, with no overflow into surrounding attainment areas, reformulated gasoline could account for 55 percent of all gasoline sold in the United States.

E.6.1.1 The Reg-Neg Agreement

In February EPA established a regulatory advisory committee with representatives from the affected industries, consumer groups, environmentalists, and state and local air pollution control agencies to negotiate the issues surrounding these programs. The regulatory negotiation (reg-neg) procedure was designed to forestall lengthy court challenges over the proposed rules.

In August EPA announced that the advisory committee had reached an agreement. The terms of the agreement will be accepted by EPA as comments on the proposed rules. A final rule based on the negotiations is to be issued by November 15, 1991.

In reaching the agreement, the oil industry agreed not to count the effect of reductions in evaporative emissions that it was already required to make as contributing toward the 15 percent reduction (by 1995) in volatile organic compounds (VOC). In exchange, the industry won some flexibility that allows it to average batches of gasoline in satisfying the 15 percent reduction.

E.6.1.2 Certification

Reformulated gasoline produced before March 1, 1997 will be certified by EPA as meeting the VOC and toxic reductions requirements; if it results in no increase in oxides of nitrogen; contains no more than 1.0 volume percent of benzene; contains at least 2.0 percent oxygen by weight; contains no heavy metals unless waived; and meets the RVP specification during the ozone season. For the period 1995 to 1997 the ozone season RVP specifications are:

- In Class B areas, 7.2 psi RVP
- In Class C areas, 8.1 psi RVP

In addition, the gasoline must meet the VOC and toxics reduction requirements on the basis of calculations considering its benzene, oxygenate and aromatics content. This is to be known as certification by the simple model. The model will also take into account the VOC effects of both higher and lower RVP and oxygen values.

In addition, the refiner's annual reformulated gasoline averages for sulfur, T_{90} and olefins cannot exceed the refiner's corresponding 1990 annual averages.

EPA will issue a proposed rule by November 30, 1992 containing the specifics of a more complex model and addressing the year 2000 performance standards. The complex model is anticipated to include at least the following parameters: sulfur, olefins, RVP, oxygen, aromatics, benzene and T_{90}. This rule will be finalized by March 1, 1993. Reformulated gasoline produced on or after March 1, 1997 must be certified under the complex model. EPA will establish, by November 1991, a working group comprised of all interested persons to expedite the development and promulgation of this rule.

For the period 1995 to 1997, reformulated gasoline certified under the simple model will be deemed to result in no increase in oxides of nitrogen if:

- It contains no greater than 2.1 percent oxygen by weight, or

- The only oxygenate it contains is MTBE at a concentration no greater than 2.7 percent oxygen by weight.

EPA will expeditiously process petitions for approval of oxygenates other than MTBE at concentrations up to 2.7 percent oxygen by weight, if it is demonstrated that use of the oxygenate will not adversely impact NO_x.

Reformulated gasoline may be certified by means of the complex model before May 1, 1997. However, such certification cannot result in deterioration in VOC and toxics performance from that achieved with the simple model and the refiner's 1990 annual averages for sulfur, T_{90} and olefins.

The reg-neg agreement leaves gasohol (E10) fuels in limbo for the time being. In order to be certified under the simple model, reformulated gasoline cannot contain more than 2 percent oxygen. Therefore the only way a gasohol blend can be sold after 1995 is for the marketer to present specific emissions data showing that NO_x levels have not been increased over the 1990 baseline level. Although ethanol can be used up to the 2 weight percent oxygen level, this level does not qualify for federal highway tax exemption. The only subsidy available to ethanol in this situation is the blender tax credit, which is valuable only if the blender has sufficient tax liabilities to offset.

E.6.2 Manufacturing Approach

Every refiner will be free to follow his own approach in developing a reformulated gasoline. However, there are some general guidelines which suggest that most refiners will:

- Reduce vapor pressure to control evaporative emissions--but not so far as to induce starting problems.

- Reduce sulfur and olefin contents to control nitrogen oxides and reduce reactivity.

- Reduce aromatics levels and boiling range (especially T_{90}) to reduce hydrocarbon emissions.

- Reduce benzene levels to control toxics emissions.

- Add oxygen, in the form of ethers (MTBE, ETBE, TAME, etc.) to reduce carbon monoxide emissions and to restore octane lost by the reductions mentioned above.

In order to accomplish the above in a particular refinery, there are many different processing routes which might be chosen. One set of possibilities would include:

- Operate the catalytic cracker to produce a substantial quantity of C_3-C_5 olefins.
- Increase alkylation capacity to combine these light olefins with isobutane.
- Reduce boiling range (T_{90}) by fractionation.
- Reduce benzene by extraction or isomerization.
- Reduce vapor pressure by distilling out all butanes.
- Reduce aromatics levels by cutting back on reformer severity.
- Reduce olefin and sulfur levels by light hydrotreating.
- Add oxygenates by purchasing from outside the refinery.

E.6.3 Reformulated Gasoline Example

The only published gasoline formula claiming to meet the requirements of the Clean Air Act Amendments is ARCO's EC-X. The company says its gasoline formula will reduce gasoline's smog-producing potential by at least 37 percent and toxic emissions by at least 47 percent (Riley 1990).

In designing the new formula, ARCO used data from the joint Auto/Oil Air Quality Improvement Research Project and ARCO's own Clean Fuels Task Force. Testing was conducted on a fleet of 10 late-model cars.

Compared to the average United States conventional gasoline in late-model vehicles, EC-X showed reductions of 28 percent in hydrocarbon tailpipe emissions, 36 percent in evaporative emissions, and 26 percent in NO_x emissions, according to ARCO. The fuel also achieved a 25 percent reduction in carbon monoxide emission and a 47 percent reduction in tailpipe emissions of toxic compounds.

EC-X is also characterized by very low sulfur content, low distillation temperatures, very low olefin content, high oxygen content, and reduced Reid vapor pressure and aromatics content (Table E-9).

Although every refinery's product will be somewhat different, most are likely to bear a strong resemblance to EC-X in the year 2000. Because of the cost involved in producing such a product, the industry average result will be a gasoline which meets the Clean Air Act requirements of a 25 percent reduction in emissions but no more.

Making the changes required to manufacture reformulated gasoline by the year 2000 will require large expenditures by the petroleum refining industry. The result will be an appreciable increase in gasoline cost. It appears unlikely either that the refining industry will pursue further modifications on its own, or that the public will insist on further changes when the costs become apparent. Therefore, no changes are projected between the years 2000 and 2010.

E.6.4 Diesel Fuel

The Clean Air Act Amendments require that by October 1993 diesel fuel have a maximum sulfur content of 0.05 weight percent and a minimum cetane index of 40. These specifications should still be in effect in 2000 and 2010.

E.7 Emission Projections for 2000 and 2010

E.7.1 Gasoline

E.7.1.1 New-Car Average Emissions

Projections of emissions on a year-by-year basis are made by the Environmental Protection Agency's MOBILE4 model and results are published in Report AP-42 (EPA 1991). For gasoline powered light-duty vehicles, the agency's projections for January 1 emissions of same-model-year vehicles for model years 1992 and later are:

- NMHC 1.1 grams/mile
- CO 3.0 grams/mile
- NO_x 0.6 grams/mile

These numbers include factors for the effects of tampering, misfueling, and deterioration with age; adjustments for speed, temperature, altitude, and average daily miles; as well as refueling emissions. They are based on EPA's projections of vehicle types and technology. In the year 2000, 95.7 percent of new autos will use fuel injection rather than carburetion. The EPA projections are based on existing gasolines and make no forecast of the effect of reformulated gasoline. In order to estimate the difference between reformulated gasoline and ethanol fuels, a breakdown between exhaust emissions and evaporative emissions is required.

E.7.1.2 Fleet Average Evaporative and Exhaust HC Emissions

The fleet average HC emission levels for 1990, 2000 and 2010 are listed in AP-42 as shown in Table E-10. These data are for conventional 9.0 RVP gasoline, 60 to 84°F diurnal temperature range, and 80°F hot soak conditions.

E.7.1.3 Reformulated Gasoline

Reformulated gasoline cannot take credit for future evaporative reductions due to already-mandated RVP reductions. The already-mandated RVP reductions are presumed by EPA to be a reduction to 8.7 psi in Class C (cold) areas and 7.8 psi in Class B (warm) areas. As a result of the regulatory agreement negotiated in August 1991, EPA will presume that an evaporative VOC reduction of 15 percent, satisfying 1995 requirements, is achieved when a reformulated gasoline has an RVP of 8.1 psi in Class C areas and 7.2 psi in Class B areas. ARCO's suggested formula for its EC-X gasoline includes an RVP of 6.7 psi, which should result in about another 17 percent reduction in evaporative emissions in Class C areas or 7 percent in Class B areas. The average of 12 percent additional reduction (beyond the 15 percent achieved with 7.2 and 8.1 psi gasolines) would make it possible for EC-X to meet the Clean Air Act requirements of a 25 percent reduction in evaporative emissions by the year 2000.

Because the RVP adjustment is one of the easiest changes for a refiner to make, it is assumed that most refiners would follow suit. The sum of evaporative and tailpipe emissions is required to be reduced by 25 percent, which means that tailpipe emissions must also be reduced by 25 percent. It is assumed that most refiners would stop at the 25 percent reduction point rather than going slightly further to match EC-X and that they would tradeoff any potential NO_x reduction against other performance parameters because the law does not require NO_x reductions. The net result is a comparison shown in Table E-11 for year-2000, zero-miles, new light-duty vehicles.

E.7.2 Year-2000 and 2010 Spark Ignited Engines

E.7.2.1 Exhaust Emissions, E10

With respect to emissions of CO, VOC and NO_x in low-concentration blends with gasoline, ethanol can reduce tailpipe emissions in two ways. First, the enleanment effect of the oxygen in ethanol will generally cause a decrease in carbon monoxide, possibly a decrease in hydrocarbons and likely an increase in NO_x. Many studies have shown that the enleanment effect is roughly proportional to the oxygen content, regardless of the chemical form of the oxygenate

(Taljaard 1991). The second way in which ethanol affects emissions is through a substitution or dilution effect. For example, aromatic constituents are thought to contribute disproportionately to tailpipe hydrocarbon emissions. If ethanol is used to substitute for aromatic components in gasoline, the effect on emissions could be much stronger than if ethanol is just used to dilute the original gasoline.

Because the type of oxygenate does not seem to matter greatly, a reformulated gasoline containing 2 percent oxygen in the form of MTBE would be expected to have basically the same emissions as one containing 2 percent oxygen in the form of ethanol. By the year 2000, most gasoline is expected to contain 2 percent oxygen, mostly in the form of MTBE. Therefore, the net emissions benefit of switching to gasohol is expected to be the difference between a 2 percent oxygen and a 3.7 percent oxygen blend.

In accordance with the Clean Air Act Amendments of 1990, reformulated gasoline by the year 2000 must result in 25 percent lower emissions of volatile organic carbons and air toxics than the 1990 baseline gasoline formula. Because producing such a gasoline will be expensive, improvements beyond the legal requirement are unlikely. In light of the changes expected in gasoline, what will be the effect when gasohol is made in the year 2000? In order to hazard an answer to this question, the following observations may be noted:

- The enleanment effect will still appear as in Figure E-4, although the height of the HC and CO curves may be reduced throughout their range.

- Almost all cars will have closed-loop control systems, reducing the average enleanment effect.

- It is assumed that no RVP waiver will be allowed for gasohol blends.

- A major reformulation technique for reducing VOC will be to make lower-RVP gasoline. It may be very difficult to make an even lower-RVP base gasoline to accommodate the RVP increase when 10 percent ethanol is added.

In light of the above, it is projected that gasohol marketed in the year 2000 will have the same or higher evaporative emissions as reformulated gasoline.

With respect to exhaust carbon monoxide, VOC and NO_x, it is presumed that engine emissions will still be governed by curves of the general shape shown in Figure E-4. Therefore, changing the air/fuel ratio by a given percent will still make the same percent change in CO, VOC and NO_x, although the absolute magnitudes will change.

An estimate of current exhaust effects is given in Table E-12. Because reformulated gasoline will have 2.0 percent oxygen, most likely from MTBE, the difference between reformulated gasoline and gasohol may be obtained as the difference of the two sets of values in Table E-12.

Only the last line in Table E-12 is applicable in the year 2000. Therefore, with respect to typical reformulated gasoline in 2000, gasohol should exhibit:

- A 4.6 percent decrease in CO
- A 2.0 percent decrease in VOC
- A 2.9 percent increase in NO_x

Because the Clean Air Act Amendments require that gasoline sold in 2000 emit no more NO_x than the 1990 baseline value, the sale of gasohol will require a blendstock with lowered NO_x emissions. It is not certain how this would be achieved.

Recall that with respect to VOC exhaust emissions, there are two effects to consider, enleanment and substitution. The above estimate presumes that the substitution or dilution effect of ethanol would be the same in 2000 as in 1990. Although this is not likely to be the case, it is not possible to estimate what the effect of the changes in gasoline composition would be. Reformulated gasoline will have lower concentrations of aromatics, which some believe to be a major contributor to VOC and NO_x from today's gasoline. If so, then the future substitution or dilution effect of ethanol would be less than today. However, a recent cooperative study between the California Air Resources Board and Chevron found no substantial linkage between aromatics content and VOC or NO_x emissions (Gething 1990). Until more basic research has been carried out it cannot be said that the effect of future ethanol substitution would be greater or lesser than now, although the latter seems more likely.

Sulfur dioxide emissions were calculated by assuming that all fuel sulfur is converted to SO_2. According to national surveys of gasoline composition carried out by the National Institute for Petroleum and Energy Research, the average level of sulfur is around 350 parts per million by weight. Because ethanol contains no sulfur, blends containing ethanol or other oxygenates would emit less sulfur in direct proportion to the fraction of gasoline replaced. Information developed by the Auto/Oil program (Auto/Oil, February 1991) indicates that the sulfur content of gasoline has a strong influence on exhaust emissions by interacting with the exhaust catalyst. It therefore appears likely that sulfur content will become regulated at low levels in the future, in which case the SO_2 emissions of gasoline would be greatly reduced.

E.7.2.2 Evaporative Emissions, E10

Evaporative emissions from E10 will depend upon how the ethanol is blended. If the ethanol is "splash-blended" by simply adding to a marketed gasoline, the RVP will rise and evaporative emissions will increase proportionally. On the other hand, if ethanol is added at the refinery to a specially prepared low-RVP gasoline base, then it can be marketed with the same RVP as competing gasoline.

For this exercise, two possibilities are considered for the years 2000 and 2010. The first is to splash blend ethanol with a 6.7 psi reformulated gasoline to give E10 with an RVP of approximately 8.1 psi, satisfying national regulations. The second is to refinery-blend ethanol into a special base gasoline yielding E10 (gasohol) with an RVP of 6.7 psi to match reformulated gasolines being sold. The results of these two cases are shown in Table E-13.

E.7.2.3 Evaporative and Exhaust Emissions, High-Ethanol Blends

Estimates for E85 and E95 are also shown in Table E-13. In the year 2000 it is assumed that E85 and E95 will be used only in flexible fuel vehicles. These are vehicles which have been optimized for gasoline performance, but adapted to accept alcohol fuels. They are not optimized for alcohol performance. For this reason, exhaust emissions may not be greatly improved over the results with E10. Additional enleanment effects over that obtained with E10 are unlikely with closed-loop engine control systems. Most correlations show a rapidly decreasing benefit for HC and CO reductions after about 4 percent oxygen is reached in oxygenated fuel blends (e.g., OFA 1990). Therefore VOC and CO engine emissions are assumed to be similar to those obtained with E10.

Emissions of NO_x from high-ethanol fuels used in stoichiometric combustion engines should be reduced because of the lower flame temperature of ethanol. If lean combustion ethanol engines are used, there may be no NO_x benefit. The projection in Table E-13 assumes stoichiometric engine operation.

Evaporative emissions should be lower because of the very low RVP values of E85 and E95. Because evaporative emissions are based on physical rather than chemical processes, they are more easily modeled than exhaust emissions. In addition, field data are quite sparse and variable. Therefore, predictions from a computed curve are probably more reliable than plotting field data. Unfortunately, the correlations in EPA's MOBILE4 do not extend to extremely low RVP values. Data points from AP-42 are plotted in Figure E-15, and the curves extended somewhat arbitrarily to zero RVP. RVP is measured at 100°F, so that temperatures above 100°F would result in evaporative losses even from zero-RVP fuels. Because hot-soak temperatures can exceed those for running losses, it might be expected that hot-soak losses at zero RVP would exceed running losses. At any rate, the curves in Figure E-15 were used to estimate the evaporative emissions from E85 and E95 relative to reformulated gasoline, with the results shown in Table E-13.

E.7.3 Toxic Air Emissions

Under the Clean Air Act Amendments of 1990, "toxic air pollutants" are defined as:

- Benzene
- 1,3-Butadiene
- Formaldehyde
- Acetaldehyde
- Polycyclic organic matter

Reformulated gasoline is required to achieve a 15 percent reduction in aggregate toxic air emissions from vehicles by 1995 and a 25 percent reduction by 2000. Although these are the same percentage reductions as are required for aggregate VOC emissions, the toxic pollutant reductions are required year-round rather than only during the high ozone season.

In order to measure the degree of reduction in toxic air pollutants, EPA is required by November 15, 1991 to determine a baseline level of emissions from baseline vehicles using baseline gasoline.

Without having an established toxics baseline projection, such as those in AP-42 for CO, NO_x and VOC, it was necessary to construct a psuedo-baseline emissions inventory against which the effects of ethanol fuels could be evaluated. For this purpose, data presented by the Auto/Oil Air Quality Improvement Research Program in Technical Bulletin No. 5 were used (Auto/Oil, June 1991). The emission rates, in milligrams per mile, for the current vehicle fleet, are approximately:

- Benzene = 11
- 1,3-Butadiene = 0.8
- Formaldehyde = 1.7
- Acetaldehyde = 1.2

Polycyclic organic matter was not measured.

In order to convert the above fleet-average numbers to zero-miles, new-car emission rates such as were used for the regulated pollutant projections, were multiplied by the ratio of exhaust VOC in Tables E-10 and E-11. The resulting psuedo-baseline toxic emission numbers are:

- Benzene = 1.7 mg/mile
- 1,3-Butadiene = 0.13 mg/mile
- Formaldehyde = 0.27 mg/mile
- Acetaldehyde = 0.19 mg/mile

Emissions tests with reformulated gasoline having a lower benzene content have shown reductions in benzene emissions approximately proportional to the benzene content (Schoonveld 1991). It was therefore assumed that going from today's average benzene content of 1.6 percent to a mandated limit of 1.0 percent in reformulated gasoline would produce a proportional reduction in benzene emissions regardless of automobile technology. Further reductions would then occur in proportion to reductions in total exhaust VOC.

According to results published in Technical Bulletin No. 6, the Auto/Oil program found that the addition of 10 percent ethanol had the following effect (Auto/Oil, September 1991):

- Reduced benzene by 11 percent
- Reduced butadiene by 6 percent
- Had no effect on formaldehyde
- Increased acetaldehyde by 160 percent

Except for formaldehyde, these results are in conceptual agreement with the data reported in Exhibits E-8, E-9, E-20 and E-21. All sources were used to arrive at the following judgmental estimates of the relative toxic emissions to be expected with ethanol fuels:

- Benzene: 10% and 60% reductions for E10 and E85
- 1,3-Butadiene: 8% and 60% reductions for E10 and E85
- Formaldehyde: 30% and 50% increases for E10 and E85
- Acetaldehyde: 150% and 600% increases for E10 and E85
- Polycyclic organic matter: 8% and 60% reductions for E10 and E85

Aggregate air toxic emissions from current vehicles are heavily dominated by benzene. Therefore the above projections suggest that total air toxics would remain approximately constant for all fuels in spite of the large increase in aldehydes when ethanol is used. It must be emphasized that these estimates are classed as little more than educated guesswork for high-ethanol blends.

E.7.4 Emissions Summary

A summary of emission levels by year for different fuels and pollutants is presented in Table E-14.

E.8 Efficiency Projections for 2000

E.8.1 Gasoline

Projections of light-duty vehicle efficiency in terms of miles per gallon have been made by various groups. Plotted in Figure E-16 are projections to the year 2010 made by Argonne National Laboratory (Mintz 1991). These are fleet average values representing all vehicles on the road in the year indicated. The curves to 2010 are concave upward, indicating an accelerating rate of progress over that time period. Such curves of course cannot be extrapolated for long periods of time. Engineering progress in any field in general will eventually be plotted as an S-curve, where advances came slowly at first, then accelerate as basic knowledge is multiplied, then finally level off as the technology matures and theoretical limits are approached. As an example contributing to vehicle fuel efficiency, Figure E-14 showed the progress made in reducing vehicle drag coefficients (Seiffert 1991). The shape of the curve in Figure E-14 will also apply to other components of the automobile over some time scale, and therefore overall vehicle efficiency should exhibit the same behavior. Shown in Figure E-16 as the dashed line is the fleet average mileage projection made by the Energy Information Administration for the National Energy Strategy (NES) analysis (EIA 1990). This projection to the year 2030 shows the expected long-term S-curvature for automobile fuel efficiency. It is based on achieving a maximum EPA new-car mileage rating of 41 miles per gallon in 2030.

The NES projections used to derive the curve in Figure E-16 will be used as a reference point. These projections are for EPA new-car efficiency ratings for the years 1990, 2000 and 2010 of 28.2, 32.1 and 37.1 miles per gallon, respectively. The actual values achieved will depend not only on technological progress, but on legislation, gasoline prices, and general economic conditions.

E.8.1.1 Reformulated Gasoline

The traditional units for discussing vehicle efficiency are miles per gallon. Gasoline is sold by the gallon, rather than by its energy content, which varies somewhat (Table E-1). However, with the advent of reformulated gasoline, energy studies should consider BTU content rather than volume alone. Reformulated gasoline will require more energy to manufacture, and thus each BTU delivered to an automobile tank will represent more BTUs of primary energy than before. That issue is not addressed in this report. Because the components likely to be removed from gasoline have different energy densities than the components likely to be added, reformulated gasoline will have an appreciably lower energy content per gallon than conventional gasoline. Projections of miles per gallon will have to consider this difference. The logical procedure is to make all future projections in terms of miles per million BTU instead of miles per gallon.

An estimate of the energy density of reformulated gasoline compared to conventional gasoline is given in Table E-15. The estimate ignored any nonideal volume changes on mixing, and assumed that the reformulated fuel contained 15 percent MTBE plus enough added alkylate to replace aromatics and olefins to the extent indicated in the table. The net result is a decrease of about 4 percent in the number of BTUs per gallon.

Converting the NES data points to miles per million BTU, based on Table E-15, yields a fleet average mileage projection of 21.5 miles per gallon in 2000 and 27.0 miles per gallon in 2010 using reformulated gasoline. On an energy basis, this corresponds to 194 and 244 miles per million BTU, respectively.

Because of the change in reformulated gasoline energy density, the energy ratio between gasoline and alternative fuels will change. Using calculated heating values and ignoring changes in mixing volumes, a comparison between current and year 2000 heating values for ethanol blends is shown in Table E-16.

E.8.2 Ethanol in Spark Ignited Engines

E.8.2.1 Gasohol (E10)

Gasohol is assumed to be sold in the year 2000 in exactly the same way as now--as an undifferentiated product for use by any standard gasoline-burning vehicle. Advances in engine technology will not be of a type to have a significant effect on efficiency when the fuel changes from reformulated gasoline to E10. For instance, in Figure E-13, the use of variable valve timing may be adopted but would not have different effects for different fuels. Variable compression, also illustrated in the figure, would be able to derive additional benefit from ethanol, but is less likely to be adapted by 2000.

When burned in a gasoline-optimized engine, the only large efficiency effects associated with E10 should be the increase in volume of combustion products, and the effect of charge-air cooling. The charge-air cooling effect of 12°F should produce about 2 to 3 percent more power from a given engine, but would have a much smaller effect on thermal efficiency. The increase in volume of combustion products should increase efficiency by about 1 percent. In total, the theoretical expectation would be for about a 1 to 2 percent increase in miles per million BTU when switching from gasoline to E10, which would be compatible with the data to date (Figure E-7).

E.8.2.2 High-Ethanol Fuels (E85 and E95)

In the year 2000 the major mode of utilizing high-ethanol fuels will be in flexible fuel vehicles, designed for operation on gasoline, methanol or ethanol. The vehicles therefore will not be optimized for ethanol and will operate at a compression ratio suitable for gasoline. Therefore, based on the effect of gas volume only, efficiency may be projected to be about 6 percent higher than gasoline for E85 and 7 percent higher for E95. This is the same order of magnitude as suggested by the data to date (Figure E-7).

E.8.3 Ethanol in Compression Ignition Engines (E100)

Actual fuels used in diesel engines are likely to contain denaturant and perhaps some water and will not be pure E100, but this is a minor point. Because the theoretical efficiency of ethanol in compression ignition engines is practically the same as that of diesel fuel, the goal of engine research will be to achieve somewhat better than equivalent performance. Building on the experience achieved to date with ethanol in diesel cycle engines, that goal appears easily achievable. Promising approaches include ignition aids like sparkplugs, glowplugs or fuel additives. Based on the data in Figure E-8, it is assumed that ethanol engines can be as effective as diesels today and that by the year 2000, ethanol engines will have an internal engine efficiency 2 percent higher than conventional diesel. A steady improvement in compression engine and vehicle technology is expected, according to Argonne National Laboratory (Mintz 1991).

In the meantime, in order to meet strict new particulate emission standards, engines burning conventional diesel fuel will probably have to add particulate traps. Regenerating these traps is estimated to require fuel equivalent to 4 percent of engine consumption (Lawson 1991). Thus the overall energy efficiency of ethanol-fueled diesel engines could surpass diesel fuel by 5 or 6 percent by the year 2000.

It should be noted that for long-range trucks, which carry large fuel tanks, the efficiency penalty associated with the extra weight and volume of ethanol needed to achieve equal range could be more than that calculated in this study for passenger cars.

E.9 Efficiency Projections for 2010

E.9.1 Ethanol in Spark Ignited Engines

By the year 2010, engines fully optimized for ethanol fuels could be available. They could take the form of dedicated-fuel, high-compression engines designed to run specifically on E85 or E95, or they could be variable-fuel, variable-compression engines with highly sophisticated engine control systems able to completely optimize engine performance for a variety of fuels.

The theoretical analysis suggested a 15 percent efficiency advantage for ethanol over gasoline, including the effect of greater tank and fuel weight. On a proportional basis, this would translate to a 13 percent advantage for E85 and a 14 percent advantage for E95. Insufficient data are available to confirm these percentages experimentally (Figure E-7). Because little effort has been devoted to optimizing ethanol engines to date, this is not surprising. On a constant compression ratio basis the theoretical advantage for ethanol would be 7 percent. The scatter of the data is enough to encompass this difference. Nothing in the data observed appears to negate the possibility of a 15 percent advantage in an optimized engine, so this theoretical value will be assumed to be a correct measure of future potential.

A summary of potential new-car mileage ratings as a function of the fuel burned is given in Table E-17 and Figure E-17. Because of its low mass density, ethanol fuels always achieve fewer miles per gallon. However, E10 made with conventional gasoline should achieve higher mileage than reformulated gasoline. In making E85, it makes no significant difference whether conventional or reformulated gasoline is used.

A better standard of comparison than miles per gallon is miles per million BTU. Potential new-car efficiency ratings on this basis are given in Table E-18 and Figure E-18. In this mode of comparison, all of the ethanol fuels are superior to the gasolines. The high efficiency shown for a dedicated E85 vehicle relative to gasoline is based on the assumption that the technology advances used to increase the efficiency of gasoline vehicles does not diminish ethanol's octane advantage. Certain technology directions, such as direct-injection lean burn engines, could perhaps eliminate that advantage, in which case the E85 dedicated vehicle efficiency would be no greater than the flexible fuel vehicle efficiency.

E.9.2 Ethanol in Compression Ignition Engines

Extending the trend which was projected to the year 2000, it is assumed that in the year 2010, ethanol-fueled compression ignition engines will continue to have a 2 percent greater internal efficiency than diesel-fueled engines. Also, the external energy requirements of particulate trap oxidizers will continue to result in an even lower overall efficiency for diesel relative to ethanol. Unless some new technique for particulate control is developed, this difference will be maintained, but gradually decreased due to improvements in trap technology. By 2010, the energy usage of particulate traps is assumed to drop to 2 percent leaving a 4 percent total difference between ethanol and diesel fuel. Using the base-case diesel truck projections from the

NES analysis (EIA 1990), the resulting comparison between diesel fuel and ethanol is shown in Figures E-19 and E-20, and summarized in Table E-19. These figures and the table are not strictly comparable to those presented for spark ignition engines in light-duty vehicles because the latter were new-car efficiencies for the years plotted. The diesel fuel data in Figures E-19 and E-20 and Table E-19 are on-the-road fleet averages Therefore, the ethanol/diesel comparison must be interpreted as the hypothetical result of upgrading an average on-the-road engine to state-of-the-art ethanol capability in the year indicated.

An alternative case for heavy-duty trucks was constructed as follows. The National Energy Strategy (DOE, 1991, Table C-14) overall projection for highway freight vehicles is an 8 percent increase in miles per gallon between 1990 and 2000, and a 15 percent increase by 2010. These percentage increases were applied to the average miles per gallon (5.3) for combination tractor-trailer vehicles reported for 1990 by the Motor Vehicle Manufacturers Association (MVMA 1990). The results are shown in Table E-19 and in Figures E-19 and E-20 as the Alternate Heavy-Duty Case.

E.10 Greenhouse Gas Effects

In calculating relative carbon dioxide emission factors for different fuels, the only relevant statistic is fuel usage. Within the precision of the data and calculating techniques available, it is sufficient to assume that all carbon atoms in the fuel are converted to carbon dioxide within a relatively short timeframe.

The fuel efficiency projections in Figures E-17 and E-19 were converted to grams of carbon dioxide emitted per mile of travel. For spark ignited engines, the necessary fuel conversion factors and the calculated grams of CO_2 per mile are presented in Table E-20. Comparisons between ethanol (E100) and diesel fuel for medium and heavy-duty trucks are presented in Table E-21.

One factor sometimes overlooked in greenhouse gas discussions is the effect of the energy required to manufacture materials. As pointed out by DeLuchi (1991), this can produce a distinct difference between alternative fuels if one requires the use of more or heavier equipment. With respect to ethanol, it is not known whether its use will significantly affect average engine life. Because of its higher heat of vaporization, the use of high-alcohol fuels could result in incomplete vaporization, with liquid in the cylinder washing away the protective oil film (Owens 1980). If engines would have to be replaced significantly more often, the emissions resulting from manufacturing the engines should be considered when making greenhouse gas comparisons.

It is of interest to note which factors can have the greatest influence on relative greenhouse gas emissions from different fuels. Carbon dioxide emitted from passenger cars can be calculated from an equation similar to that presented by Amann (1990):

$$\text{gm } CO_2/\text{mile} = C_E(1/E_e E_d Q_f)Q_j$$

where C_E = CO_2 emission factor for the fuel, gm/kg
E_e = Thermal efficiency of the engine
E_d = Efficiency of the drivetrain
Q_f = Heating value of the fuel
j = Tractive energy required per mile

Only the values of C_E, E_e and Q_f are functions of the fuels used. A graphic comparison of the values of these parameters for different fuels is shown in Figure E-21. It is apparent that changes in the relative values of Q_f (large values desirable) and C_E (low values desirable) are almost directly proportional and therefore cancel out. The only factor which has a large independent effect on the amount of carbon dioxide emitted per vehicle mile is the engine efficiency when burning each particular fuel.

E.11 References

Abthoff, Jorg, et al. 1982. "Adaption and Optimization of 4-Stroke-Engines for Operation with Alcohol Fuel," paper presented at the Fifth International Alcohol Fuel Technology Symposium, Auckland, New Zealand, May 13-18.

Adelman, Henry. 1979. "Alcohols in Diesel Engines--A Review," SAE Technical Paper 790956, Society of Automotive Engineers, Warrendale, Pennsylvania.

Alcohol Energy Systems, Inc. 1983. *Alcohol Fleet One Test Program,* report prepared for the California Energy Commission, August.

Alternate Fuels Committee of the Engine Manufacturers Association. 1982. "A Technical Assessment of Alcohol Fuels," SAE Technical Paper 820261, Society of Automotive Engineers, Warrendale, Pennsylvania.

Amann, Charles A. 1990. "The Passenger Car and the Greenhouse Effect," report from General Motors Research Laboratories, Warren Michigan, August 23.

American Petroleum Institute. 1988. *Alcohols and Ethers: A Technical Assessment of Their Application as Fuels and Fuel Components*, API Publication 4261, Second Edition, July.

Auto/Oil Air Quality Improvement Research Program. 1991. *Exhaust Emissions of Toxic Air Pollutants Using Reformulated Gasolines, Technical Bulletin No. 5*, June.

Auto/Oil Air Quality Improvement Research Program. 1991. *Emissions Results of Oxygenated Gasolines and Changes in RVP, Technical Bulletin No. 6*, September.

Auto/Oil Air Quality Improvement Research Program. 1991. *Effects of Fuel Sulfur Levels on Mass Exhaust Emissions, Technical Bulletin No. 2.*, February.

Baker, Richard E., et al. 1991. "Future Transportation Fuels and the Environment," *Automotive Engineering*, January, pp. 27-29.

Bindel, Heinz H.W. (1984). "Implementation Experiences With MWM Pilot-Ignition Diesel Cycle Engines Burning Alcohol as Main Fuel," paper presented at the Sixth International Symposium on Alcohol Fuels Technology, Ottawa, Ontario, Canada, May 21-25.

Black, Frank. 1991. "An Overview of the Technical Implications of Methanol and Ethanol as Highway Motor Vehicle Fuels," SAE Technical Paper 912413, Society of Automotive Engineers, Warrendale, Pennsylvania.

Brinkman, N.D., et al. 1975. "Exhaust Emissions, Fuel Economy, and Driveability of Vehicles Fueled With Alcohol-Gasoline Blends," SAE Technical Paper 750120, Society of Automotive Engineers, Warrendale, Pennsylvania.

Brinkman, Norman D. 1981. "Ethanol Fuel: A Single-Cylinder Engine Study of Efficiency and Exhaust Emissions," SAE Technical Paper 810345, Society of Automotive Engineers, Warrendale, Pennsylvania.

California Air Resources Board. 1989. *Definition of a Low-Emission Motor Vehicle in Compliance with the Mandates of Health and Safety Code Section 39037.05*, Mobile Source Division, El Monte, California, October 2.

Carroll, James N., et al. 1990. "Emission Comparison of DDC 6V-92TA on Alcohol Fuels," SAE Technical Paper 902234, Society of Automotive Engineers, Warrendale, Pennsylvania.

Coordinating Research Council, Inc. 1982. *Performance Evaluation of Alcohol-Gasoline Blends in 1980 Model Automobiles, Phase I--Ethanol-Gasoline Blends*, Atlanta, Georgia, July.

Davis, Stacy C., et al. 1991. *Transportation Energy Data Book: Edition 11*, Oak Ridge National Laboratory, January.

DeLuchi, Mark A. 1991. *Emissions of Greenhouse Gases From the Use of Transportation Fuels and Electricity*, University of California-Davis and Center for Energy and Environmental Studies, Princeton University, June 26.

Energy Information Administration. 1990. *Energy Consumption and Conservation Potential: Supporting Analysis for the National Energy Strategy*, SR/NES/90-02, Washington, D.C., December.

Furey, Robert L., et al. 1980. "Evaporative and Exhaust Emissions From Cars Fueled With Gasoline Containing Ethanol or Methyl tert-Butyl Ether," SAE Technical Paper 800261, Society of Automotive Engineers, Warrendale, Pennsylvania.

Gallopoulos, N.E. 1985. "Alcohols for Use as Motor Fuels and Motor Fuel Components," paper presented at the Co-ordinating European Council Second International Symposium on The Performance Evaluation of Automotive Fuels and Lubricants, Wolfsburg, West Germany, June 5-7.

Gething, Jeff A., et al. 1990. "The Effect of Gasoline Aromatics Content on Exhaust Emissions: A Cooperative Test Program," SAE Technical Paper 902073, Society of Automotive Engineers, Warrendale, Pennsylvania.

Gibbs, L.M., et al. 1981. "Contra Costa County's One-Year Experience With Gasohol," SAE Technical Paper 810440, Society of Automotive Engineers, Warrendale, Pennsylvania.

Gurney, M.D., et al. 1980. "Gasohol: Laboratory and Fleet Test Evaluation," SAE Technical Paper 800892, Society of Automotive Engineers, Warrendale, Pennsylvania.

Hardenberg, H.O., et al. 1981. "The Use of Ethanol as a Fuel for Compression Ignition Engines," SAE Technical Paper 811211, Society of Automotive Engineers, Warrendale, Pennsylvania.

Heath, Michelle. 1991. *Alternative Transportation Fuels: Natural Gas, Propane, Methanol & Ethanol Compared With Gasoline & Diesel*, Canadian Energy Research Institute, Study No. 37, February.

Ho, S.P., et al. 1990. "Global Warming Impact of Gasoline vs. Alternative Transportation Fuels," SAE Technical Paper 901489, Society of Automotive Engineers, Warrendale, Pennsylvania.

Interagency Commission on Alternative Motor Fuels. 1990. *First Interim Report*, September 30.

Iseminger, Dan. 1991. "E85 Vehicles and Technology," presentation at the National Conference on Reformulated Gasoline and Clean Air Act Implementation, Washington, D.C., October.

Lang, John M., et al. 1981. "Impact of Gasohol on Automobile Evaporative and Tailpipe Emissions," SAE Technical Paper 810438, Society of Automotive Engineers, Warrendale, Pennsylvania.

Larsson, Egon. 1990. "Fleet Testing of 32 Innercity Buses in Stockholm," paper presented at the Fifth Annual Conference on Oxygenated Fuels in Europe, London, United Kingdom, May 22-23.

Lawson, Alex. 1991. Paper presented at Alternative Fuels: Overview of Current and Future Technology conference, Vancouver, British Columbia, Canada, April 3-4.

Lyford-Pike, E.J., et al. 1986. "Development of a Commercial Cummins NT Series

Engine to Burn Ethanol Alcohol," paper presented at the Seventh International Symposium on Alcohol Fuels, Paris, France, October.

Miller, Karen Lowry, et al. 1991. "55 Miles Per Gallon: How Honda Did It," *Business Week*, September 23, pp. 82-83.

Mintz, M.M., et al. 1991. *Forecast of Transportation Energy Demand Through the Year 2010*, Energy Systems Division, Argonne National Laboratory, April.

Miron, William L., et al. 1986. "Ethanol-Blended Fuel as a CO Reduction Strategy at High Altitude," SAE Technical Paper 860530, Society of Automotive Engineers, Warrendale, Pennsylvania.

Motor Vehicle Manufacturers Association of the United States, Inc. 1990. *MVMA Motor Vehicle Facts and Figures '90*, Motor Vehicle Manufacturers Association of the United States, Inc., Detroit, Michigan.

Murayama, Tadashi, et al. 1984. "Achievement of Stable and Clean Combustion Over a Wide Operating Range in the Spark-Assisted IDI Diesel Engine With Neat Ethanol," SAE Technical Paper 840517, Society of Automotive Engineers, Warrendale, Pennsylvania.

Naman, T.M., et al. 1980. "Exhaust and Evaporative Emissions From Alcohol and Ether Fuel Blends," SAE Technical Paper 800858, Society of Automotive Engineers, Warrendale, Pennsylvania.

Niemi, S., et al. 1991. "Exhaust Emissions of an Ethanol D.I. Spark-Assisted Diesel Engine Equipped With a Catalytic Converter," SAE Technical Paper 910850, Society of Automotive Engineers, Warrendale, Pennsylvania.

Owen, Keith, et al. 1990. *Automotive Fuels Handbook*, Society of Automotive Engineers, Inc., Warrendale, Pennsylvania.

Owens, E.C., et al. 1980. "Effects of Alcohol Fuels on Engine Wear," SAE Technical Paper 800857, Society of Automotive Engineers, Warrendale, Pennsylvania.

Oxygenated Fuels Association, Inc. 1990. "Performance Characteristics of Oxygenated Fuels for Emission Reduction Programs," Washington, D.C., February.

Palmer, F.H. 1987. "The Vehicle Performance of Gasolines Containing Oxygenated Supplements," presented at the European Fuel Oxygenates Association Second Conference, Rome, Italy, October 22-23.

Pischinger, F.F. 1983. "Alcohol Fuels for Automotive Engines," paper presented at the 11th World Petroleum Congress, London, United Kingdom, September.

Pischinger, F.F. 1983. "Alcohol Fuels for Automotive Engines," paper presented at the 11th World Petroleum Congress, London, United Kingdom, September.

Powell, T. 1975. "Racing Experiences With Methanol and Ethanol-Based Motor-Fuel Blends," SAE Technical Paper 750124, Society of Automotive Engineers, Warrendale, Pennsylvania.

Prezeij, M. n.d. "Pool Octanes Via Oxygenates," *Hydrocarbon Processing.*

Reddy, S.R. 1986. "Evaporative Emissions From Gasolines and Alcohol-Containing Gasolines With Closely Matched Volatilities," SAE Technical Paper 861556, Society of Automotive Engineers, Warrendale, Pennsylvania.

Riley, Kenneth. 1990. "Refining and New Reformulated Gasolines," paper presented at the National Conference on Reformulated Gasolines and Clean Air Act Implementation, Washington, D.C., October.

Ritchey, Benjamin, et al. 1990. *Effects of Alternative Fuels on the U.S. Trucking Industry*, report prepared for the ATA Foundation, Inc., Trucking Research Institute, Alexandria, Virginia, November 9.

Robert Bosch GmbH. 1986. *Automotive Handbook,* Second Edition, Federal Republic of Germany.

Schoonveld, G.A., et al. 1991. "The Total Effects of a Reformulated Gasoline on Vehicle Emissions by Technology," SAE Technical Paper 861556, Society of Automotive Engineers, Warrendale, Pennsylvania.

Seiffert, Ulrich, et al. 1991. *Automobile Technology of the Future*, Society of Automotive Engineers, Inc., Warrendale, Pennsylvania.

Seiffert, Ulrich. 1984. "Volkswagen's Prospects for Alcohol-Fueled Engines Compared With Other Alternative Options," paper presented at the Sixth International Symposium on Alcohol Fuels Technology, Ottawa, Ontario, Canada May 21-25.

Sierra Research, Inc. 1990. *The Air Pollution Consequences of Using Ethanol-Gasoline Blends in Ozone Non-Attainment Areas*, report prepared for the American Petroleum Institute, No. SR 90-05-01, Sacramento, California, May 8.

Society of Automotive Engineers, Inc. 1991. *Automotive Industry in Expanding Countries,* Conference Proceedings, P-245, Warrendale, Pennsylvania, September.

Stump, Fred D., et al. 1990. "The Seasonal Impact of Blending Oxygenated Organics With Gasoline on Motor Vehicle Tailpipe and Evaporative Emissions--Part II," SAE Technical Paper 902129, Society of Automotive Engineers, Warrendale, Pennsylvania.

Sukandar, Suyoso, et al. 1984. "Research & Experimentation on Hydrous Ethanol/Gasoline as a Motor Vehicle Fuel in Indonesia," paper presented at the Sixth International Symposium on Alcohol Fuels Technology, Ottawa, Ontario, Canada, May 21-25.

Taljaard, H.C., et al. 1991. "The Effect of Oxygen Content in Different Oxygenate-Gasoline Blends on Performance and Emissions in a Single Cylinder, Spark-Ignition Engine," SAE Technical Paper 910379, Society of Automotive Engineers, Warrendale, Pennsylvania.

The Swedish Motor Fuel Technology Company. 1986. *Alcohols and Alcohol Blends as Motor Fuels*, Volume II B "State-of-the-Art" report, International Energy Agency, Stockholm, Sweden, October.

United States Department of Energy. 1991. *Integrated Analysis Supporting the National Energy Strategy: Methodology, Assumptions and Results, First Edition, Technical Annex 2*, DOE/SL-0086P, 1991/1992.

United States Environmental Protection Agency. 1990. *Analysis of the Economic and En vironmental Effects of Ethanol as an Automotive Fuel*, Office of Mobile Sources, April.

United States Environmental Protection Agency. 1987. *Guidance on Estimating Motor Vehicle Emission Reductions From the Use of Alternate Fuels and Fuel Blends*, Office of Mobile Sources, Ann Arbor, Michigan, July.

United States Environmental Protection Agency. 1991. *Supplement A to Compilation of Air Pollutant Emission Factors, Volume II--Mobile Sources*, AP-42, Office of Mobile Sources, Ann Arbor, Michigan, January.

United States Environmental Protection Agency. 1991. *Federal Register* (56 FR 25724), June 5.

Unzelman, George. 1991. "Refineries and Fuel Alcohol," *Alcohol Outlook*, March, pp. 15-17.

Volkswagen A.G. 1989. *Unregulated Motor Vehicle Exhaust Gas Components*, Research and Development, Wolfsburg, Federal Republic of Germany.

Warner-Selph, Mary Ann, et al. 1990. "Assessment of Unregulated Emissions From Gasoline Oxygenated Blends," SAE Technical Paper 902131, Society of Automotive Engineers, Warrendale, Pennsylvania.

Weidmann, Kurt, et al. 1984. "Fleet Test, Performance and Emissions of Diesel Engines Using Different Alcohol-Diesel Fuel Blends," SAE Technical Paper 841331, Society of Automotive Engineers, Warrendale, Pennsylvania.

Western Interstate Energy Board. 1987. *Alternative Fuel Use in Motor Vehicles: An Air Quality Perspective*, report prepared for the State of Colorado, Office of Energy Conservation, Denver, Colorado.

Winsor, Richard E. 1991. Personal communication, September.

Yaccarino, Philip A. 1988. "The Effect of Oxygenated Fuel, Altitude and Temperature on CO Emissions," SAE Technical Paper 892063, Society of Automotive Engineers, Warrendale, Pennsylvania.

E.12 References for Table E-1 and All Exhibits

1. Davis, Stacy C., et al. 1991. *Transportation Energy Data Book: Edition 11*, Oak Ridge National Laboratory, January.

2. Mintz, M.M., et al. 1991. *Forecast of Transportation Energy Demand Through the Year 2010*, Energy Systems Division, Argonne National Laboratory, April.

3. Energy Information Administration. 1990. *Energy Consumption and Conservation Potential: Supporting Analysis for the National Energy Strategy*, SR/NES/90-02, Washington, D.C., December.

4. Owen, Keith, et al. 1990. *Automotive Fuels Handbook*, Society of Automotive Engineers, Inc., Warrendale, Pennsylvania.

5. Unzelman, George. 1991. "Refineries and Fuel Alcohol," *Alcohol Outlook*, March, pp. 15-17.

6. Seiffert, Ulrich, et al. 1991. *Automobile Technology of the Future*, Society of Automotive Engineers, Inc., Warrendale, Pennsylvania.

7. Robert Bosch GmbH. 1986. *Automotive Handbook*, Second Edition, Federal Republic of Germany.

8. Volkswagen A.G. 1989. *Unregulated Motor Vehicle Exhaust Gas Components*, Research and Development, Wolfsburg, Federal Republic of Germany.

9. Heath, Michelle. 1991. *Alternative Transportation Fuels: Natural Gas, Propane, Methanol & Ethanol Compared With Gasoline & Diesel*, Canadian Energy Research Institute, Study No. 37, February.

10. Ho, S.P., et al. 1990. "Global Warming Impact of Gasoline vs. Alternative Transportation Fuels," SAE Technical Paper 901489, Society of Automotive Engineers, Warrendale, Pennsylvania.

11. Brinkman, Norman D. 1981. "Ethanol Fuel: A Single-Cylinder Engine Study of Efficiency and Exhaust Emissions," SAE Technical Paper 810345, Society of Automotive Engineers, Warrendale, Pennsylvania.

12. Alternate Fuels Committee of the Engine Manufacturers Association. 1982. "A Technical Assessment of Alcohol Fuels," SAE Technical Paper 820261, Society of Automotive Engineers, Warrendale, Pennsylvania.

13. Powell, T. 1975. "Racing Experiences With Methanol and Ethanol-Based Motor-Fuel Blends," SAE Technical Paper 750124, Society of Automotive Engineers, Warrendale, Pennsylvania.

14. Miller, Karen Lowry, et al. 1991. "55 Miles Per Gallon: How Honda Did It," *Business Week*, September 23, pp. 82-83.

15. Adelman, Henry. 1979. "Alcohols in Diesel Engines--A Review," SAE Technical Paper 790956, Society of Automotive Engineers, Warrendale, Pennsylvania.

16. Hardenberg, H.O., et al. 1981. "The Use of Ethanol as a Fuel for Compression Ignition Engines," SAE Technical Paper 811211, Society of Automotive Engineers, Warrendale, Pennsylvania.

17. Gallopoulos, N.E. 1985. "Alcohols for Use as Motor Fuels and Motor Fuel Components," paper presented at the Co-ordinating European Council Second International Symposium on The Performance Evaluation of Automotive Fuels and Lubricants, Wolfsburg, West Germany, June 5-7.

18. Carroll, James N., et al. 1990. "Emission Comparison of DDC 6V-92TA on Alcohol Fuels," SAE Technical Paper 902234, Society of Automotive Engineers, Warrendale, Pennsylvania.

19. Winsor, Richard E. 1991. Personal communication, September.

20. Coordinating Research Council, Inc. 1982. *Performance Evaluation of Alcohol-Gasoline Blends in 1980 Model Automobiles, Phase I--Ethanol-Gasoline Blends*, Atlanta, Georgia, July.

21. Niemi, S., et al. 1991. "Exhaust Emissions of an Ethanol D.I. Spark-Assisted Diesel Engine Equipped With a Catalytic Converter," SAE Technical Paper 910850, Society of Automotive Engineers, Warrendale, Pennsylvania.

22. The Swedish Motor Fuel Technology Company. 1986. *Alcohols and Alcohol Blends as Motor Fuels*, Volume II B "State-of-the Art" report, International Energy Agency, Stockholm, Sweden, October.

23. United States Environmental Protection Agency. 1990. *Analysis of the Economic and Environmental Effects of Ethanol as an Automotive Fuel*, Office of Mobile Sources, April.

24. California Air Resources Board. 1989. *Definition of a Low-Emission Motor Vehicle in Compliance with the Mandates of Health and Safety Code Section 39037.05*, Mobile Source Division, El Monte, California, October 2.

25. Abthoff, Jorg, et al. 1982. "Adaption and Optimization of 4-Stroke-Engines for Operation with Alcohol Fuel," paper presented at the Fifth International Alcohol Fuel Technology Symposium, Auckland, New Zealand, May 13-18.

26. American Petroleum Institute. 1988. *Alcohols and Ethers: A Technical Assessment of Their Application as Fuels and Fuel Components*, API Publication 4261, Second Edition, July.

27. Ritchey, Benjamin, et al. 1990. *Effects of Alternative Fuels on the U.S. Trucking Industry*, report prepared for the ATA Foundation, Inc., Trucking Research Institute, Alexandria, Virginia, November 9.

28. Reddy, S.R. 1986. "Evaporative Emissions From Gasolines and Alcohol-Containing Gasolines With Closely Matched Volatilities," SAE Technical Paper 861556, Society of Automotive Engineers, Warrendale, Pennsylvania.

29. Interagency Commission on Alternative Motor Fuels. 1990. *First Interim Report*, September 30.

30. Larsson, Egon. 1990. "Fleet Testing of 32 Innercity Buses in Stockholm," paper presented at the Fifth Annual Conference on Oxygenated Fuels in Europe, London, United Kingdom, May 22-23.

31. Palmer, F.H. 1987. "The Vehicle Performance of Gasolines Containing Oxygenated Supplements," presented at the European Fuel Oxygenates Association Second Conference, Rome, Italy, October 22-23.

32. Sukandar, Suyoso, et al. 1984. "Research & Experimentation on Hydrous Ethanol/Gasoline as a Motor Vehicle Fuel in Indonesia," paper presented at the Sixth International Symposium on Alcohol Fuels Technology, Ottawa, Ontario, Canada, May 21-25.

33. Seiffert, Ulrich. 1984. "Volkswagen's Prospects for Alcohol-Fueled Engines Compared With Other Alternative Options," paper presented at the Sixth International Symposium on Alcohol Fuels Technology, Ottawa, Ontario, Canada May 21-25.

34. Lyford-Pike, E.J., et al. 1986. "Development of a Commercial Cummins NT Series Engine to Burn Ethanol Alcohol," paper presented at the Seventh International Symposium on Alcohol Fuels, Paris, France, October.

35. Bindel, Heinz H.W. (1984). "Implementation Experiences With MWM Pilot-Ignition Diesel Cycle Engines Burning Alcohol as Main Fuel," paper presented at the Sixth International Symposium on Alcohol Fuels Technology, Ottawa, Ontario, Canada, May 21-25.

36. United States Environmental Protection Agency. 1987. *Guidance on Estimating Motor Vehicle Emission Reductions From the Use of Alternate Fuels and Fuel Blends,* Office of Mobile Sources, Ann Arbor, Michigan, July.

37. Taljaard, H.C., et al. 1991. "The Effect of Oxygen Content in Different Oxygenate-Gasoline Blends on Performance and Emissions in a Single Cylinder, Spark-Ignition Engine," SAE Technical Paper 910379, Society of Automotive Engineers, Warrendale, Pennsylvania.

38. Gething, Jeff A., et al. 1990. "The Effect of Gasoline Aromatics Content on Exhaust Emissions: A Cooperative Test Program," SAE Technical Paper 902073, Society of Automotive Engineers, Warrendale, Pennsylvania.

39. Riley, Kenneth. 1990. "Refining and New Reformulated Gasolines," paper presented at the National Conference on Reformulated Gasolines and Clean Air Act Implementation, Washington, D.C., October.

40. Furey, Robert L., et al. 1980. "Evaporative and Exhaust Emissions From Cars Fueled With Gasoline Containing Ethanol or Methyl tert-Butyl Ether," SAE Technical Paper 800261, Society of Automotive Engineers, Warrendale, Pennsylvania.

41. Brinkman, N.D., et al. 1975. "Exhaust Emissions, Fuel Economy, and Driveability of Vehicles Fueled With Alcohol-Gasoline Blends," SAE Technical Paper 750120, Society of Automotive Engineers, Warrendale, Pennsylvania.

42. Naman, T.M., et al. 1980. "Exhaust and Evaporative Emissions From Alcohol and Ether Fuel Blends," SAE Technical Paper 800858, Society of Automotive Engineers, Warrendale, Pennsylvania.

43. Lang, John M., et al. 1981. "Impact of Gasohol on Automobile Evaporative and Tailpipe Emissions," SAE Technical Paper 810438, Society of Automotive Engineers, Warrendale, Pennsylvania.

44. Miron, William L., et al. 1986. "Ethanol-Blended Fuel as a CO Reduction Strategy at High Altitude," SAE Technical Paper 860530, Society of Automotive Engineers, Warrendale, Pennsylvania.

45. United States Environmental Protection Agency. 1991. *Supplement A to Compilation of Air Pollutant Emission Factors, Volume II--Mobile Sources*, AP-42, Office of Mobile Sources, Ann Arbor, Michigan, January.

46. Weidmann, Kurt, et al. 1984. "Fleet Test, Performance and Emissions of Diesel Engines Using Different Alcohol-Diesel Fuel Blends," SAE Technical Paper 841331, Society of Automotive Engineers, Warrendale, Pennsylvania.

47. Iseminger, Dan. 1991. "E85 Vehicles and Technology," presentation at the National Conference on Reformulated Gasoline and Clean Air Act Implementation, Washington, D.C., October.

48. Oxygenated Fuels Association, Inc. 1990. "Performance Characteristics of Oxygenated Fuels for Emission Reduction Programs," Washington, D.C., February.

49. Baker, Richard E., et al. 1991. "Future Transportation Fuels and the Environment," *Automotive Engineering*, January, pp. 27-29.

50. Murayama, Tadashi, et al. 1984. "Achievement of Stable and Clean Combustion Over a Wide Operating Range in the Spark Assisted IDI Diesel Engine With Neat Ethanol," SAE Technical Paper 840517, Society of Automotive Engineers, Warrendale, Pennsylvania.

51. Western Interstate Energy Board. 1987. *Alternative Fuel Use in Motor Vehicles: An Air Quality Perspective*, report prepared for the State of Colorado, Office of Energy Conservation, Denver, Colorado.

52. Sierra Research, Inc. 1990. *The Air Pollution Consequences of Using Ethanol-Gasoline Blends in Ozone Non-Attainment Areas*, report prepared for the American Petroleum Institute, No. SR 90 05-01, Sacramento, California, May 8.

53. Gibbs, L.M., et al. 1981. "Contra Costa County's One-Year Experience With Gasohol," SAE Technical Paper 810440, Society of Automotive Engineers, Warrendale, Pennsylvania.

54. Stump, Fred D., et al. 1990. "The Seasonal Impact of Blending Oxygenated Organics With Gasoline on Motor Vehicle Tailpipe and Evaporative Emissions--Part II," SAE Technical Paper 902129, Society of Automotive Engineers, Warrendale, Pennsylvania.

55. Pischinger, F.F. 1983. "Alcohol Fuels for Automotive Engines," paper presented at the 11th World Petroleum Congress, London, United Kingdom, September.

56. Lawson, Alex. 1991. Paper presented at Alternative Fuels: Overview of Current and Future Technology conference, Vancouver, British Columbia, Canada, April 3-4.

57. Warner-Selph, Mary Ann, et al. 1990. "Assessment of Unregulated Emissions From Gasoline Oxygenated Blends," SAE Technical Paper 902131, Society of Automotive Engineers, Warrendale, Pennsylvania.

58. Yaccarino, Philip A. 1988. "The Effect of Oxygenated Fuel, Altitude and Temperature on CO Emissions," SAE Technical Paper 892063, Society of Automotive Engineers, Warrendale, Pennsylvania.

59. Black, Frank. 1991. "An Overview of the Technical Implications of Methanol and Ethanol as Highway Motor Vehicle Fuels," SAE Technical Paper 912413, Society of Automotive Engineers, Warrendale, Pennsylvania.

60. Gurney, M.D., et al. 1980. "Gasohol: Laboratory and Fleet Test Evaluation," SAE Technical Paper 800892, Society of Automotive Engineers, Warrendale, Pennsylvania.

61. Alcohol Energy Systems, Inc. 1983. *Alcohol Fleet One Test Program,* report prepared for the California Energy Commission, August.

62. Society of Automotive Engineers, Inc. 1991. *Automotive Industry in Expanding Countries,* Conference Proceedings, P-245, Warrendale, Pennsylvania, September.

63. Pischinger, F.F. 1983. "Alcohol Fuels for Automotive Engines," paper presented at the 11th World Petroleum Congress, London, United Kingdom, September.

64. Prezeij, M. n.d. "Pool Octanes Via Oxygenates," *Hydrocarbon Processing.*

65. DeLuchi, Mark A. 1991. *Emissions of Greenhouse Gases From the Use of Transportation Fuels and Electricity,* University of California-Davis and Center for Energy and Environmental Studies, Princeton University, June 26.

66. Owens, E.C., et al. 1980. "Effects of Alcohol Fuels on Engine Wear," SAE Techni cal Paper 800857, Society of Automotive Engineers, Warrendale, Pennsylvania.

67. Amann, Charles A. 1990. "The Passenger Car and the Greenhouse Effect," report from General Motors Research Laboratories, Warren Michigan, August 23.

68. Auto/Oil Air Quality Improvement Research Program. 1991. *Exhaust Emissions of Toxic Air Pollutants Using Reformulated Gasolines, Technical Bulletin No. 5,* June.

69. Auto/Oil Air Quality Improvement Research Program. 1991. *Emissions Results of Oxygenated Gasolines and Changes in RVP, Technical Bulletin No. 6,* September.

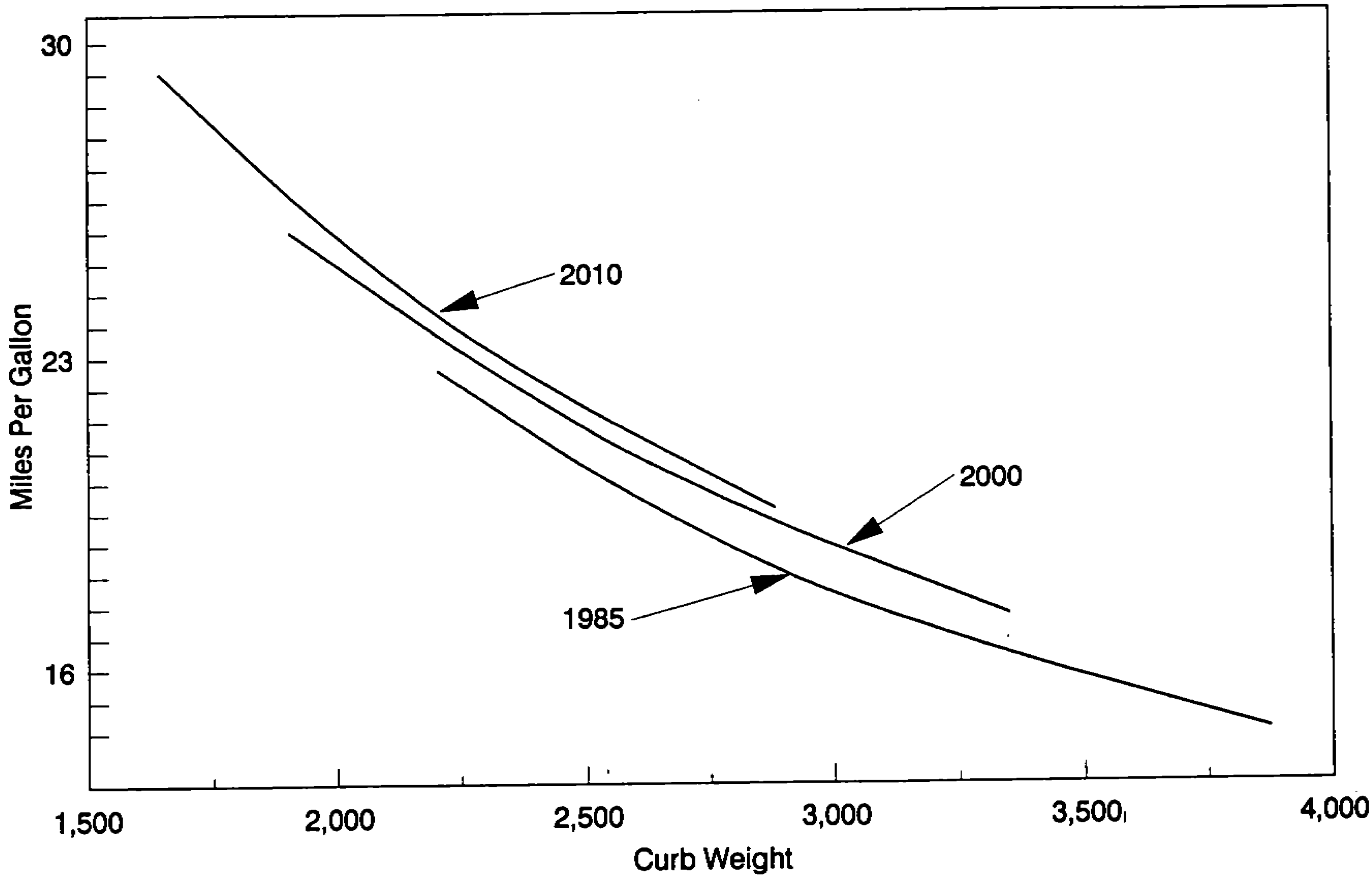
70. United States Environmental Agency. 1991. *Federal Register* (56 FR 25724), June 5.

71. Auto/Oil Air Quality Improvement Research Program. 1991. *Effects of Fuel Sulfur Levels on Mass Exhaust Emissions, Technical Bulletin No. 2.*, February.

72. Motor Vehicle Manufacturers Association of the United States, Inc. 1990. *MVMA Motor Vehicle Facts and Figures '90*, Motor Vehicle Manufacturers Association of the United States, Inc., Detroit, Michigan.

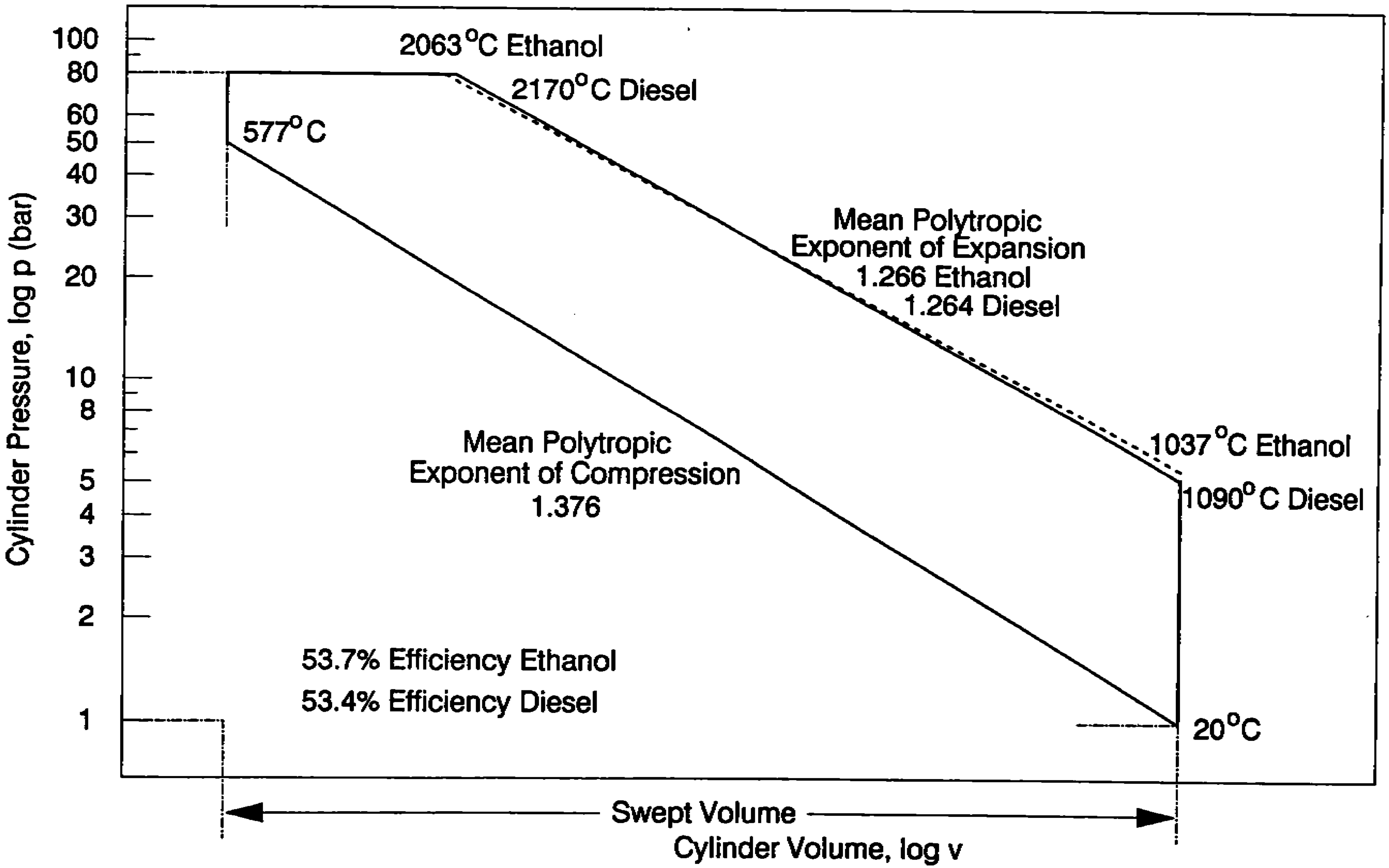
73. United States Department of Energy. 1991. *Integrated Analysis Supporting the National Energy Strategy: Methodology, Assumptions and Results, First Edition, Technical Annex 2*, DOE/SL-0086P, 1991/1992.

74. Schoonveld, G.A., et al. 1991. "The Total Effects of a Reformulated Gasoline on Vehicle Emissions by Technology," SAE Technical Paper 861556, Society of Automotive Engineers, Warrendale, Pennsylvania.



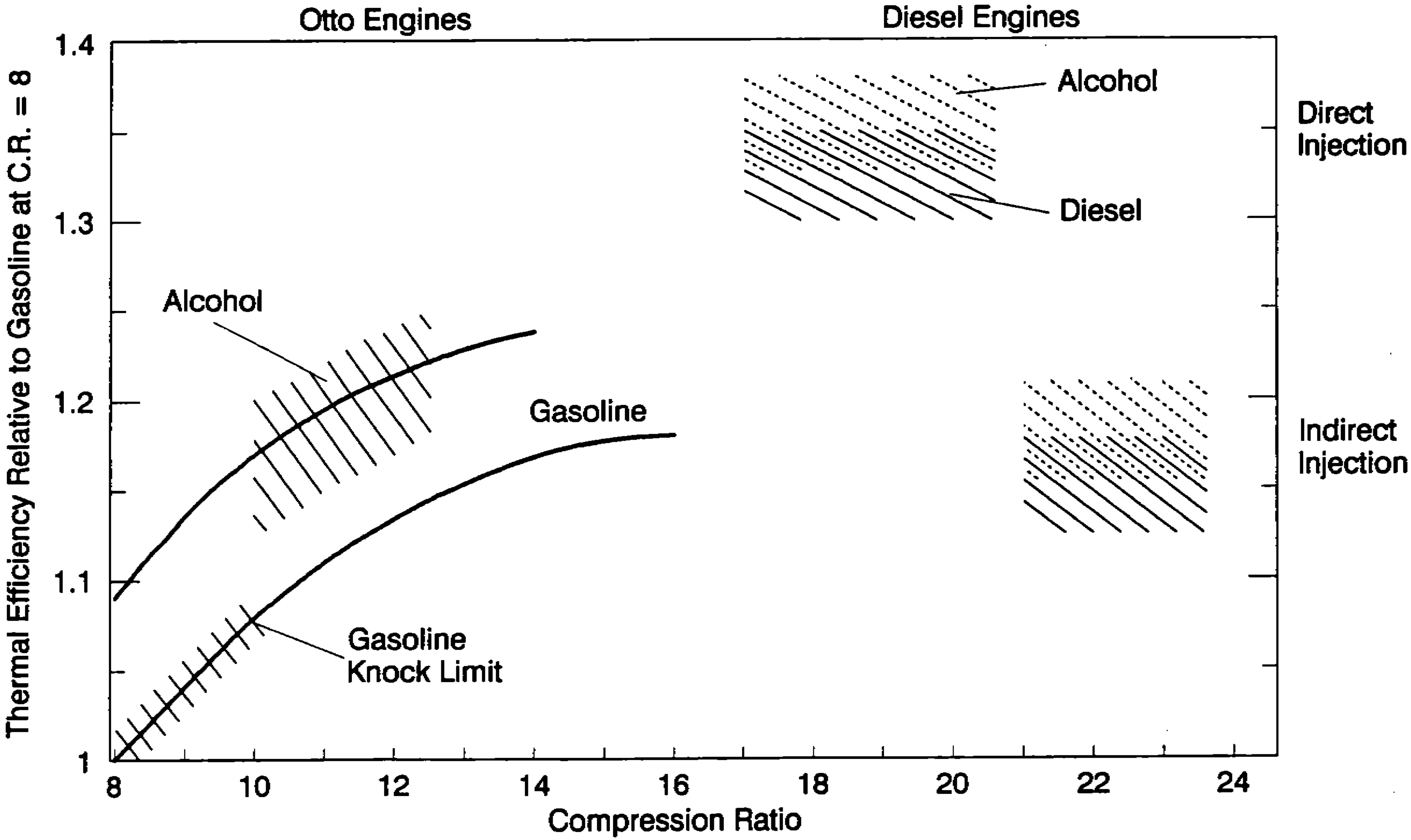
Source: Argonne National Laboratory

Figure E-1. Miles Per Gallon as a Function of Vehicle Weight



Source: Adapted from Hardenberg and Schaefer

Figure E-2. Cycle Analysis of a Compression Ignition Engine with Diesel Fuel and Ethanol



Source: Adapted from Pischinger

Figure E-3. Relative Thermal Efficiency of Otto and Diesel Engines for Alcohol and Conventional Fuels

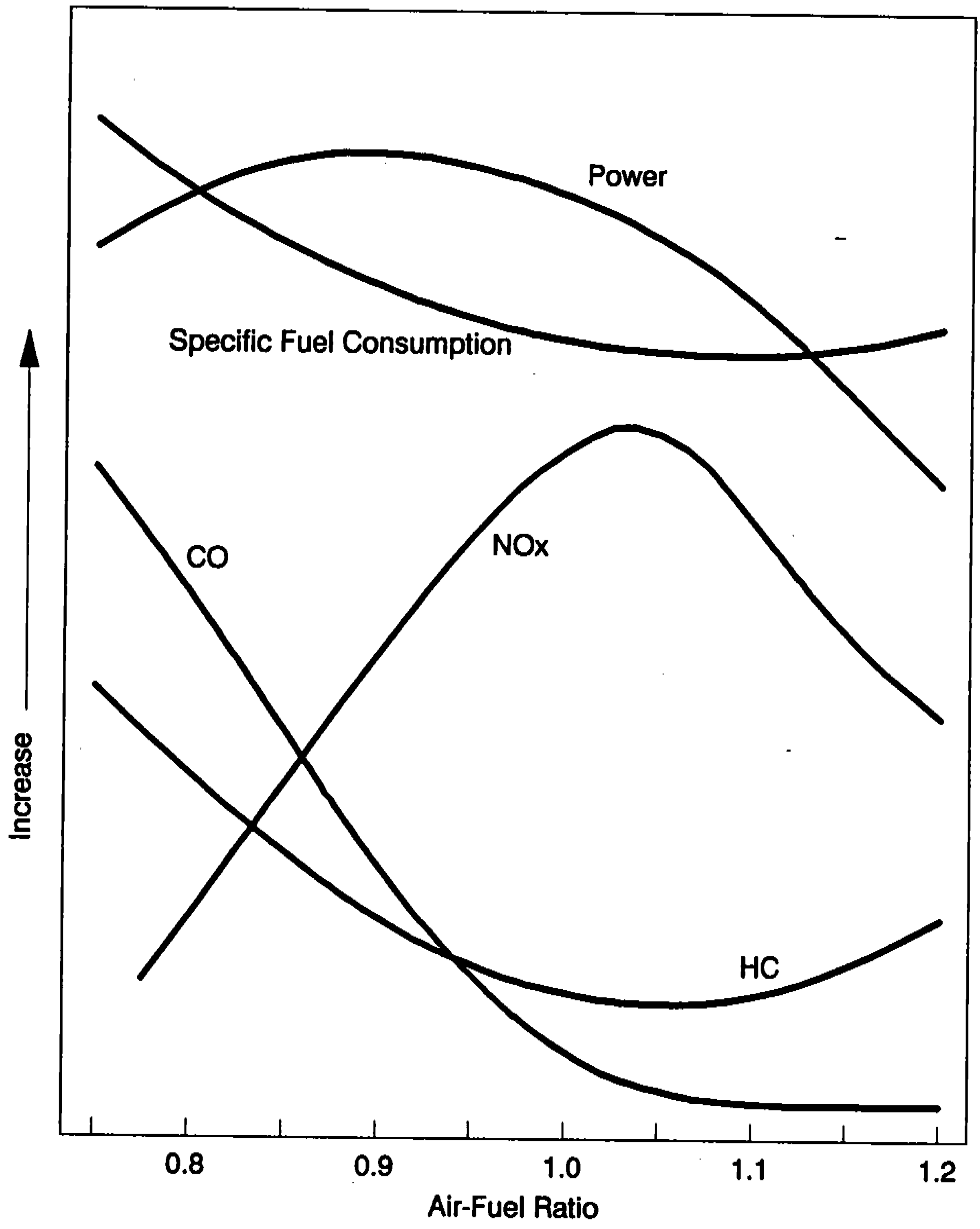
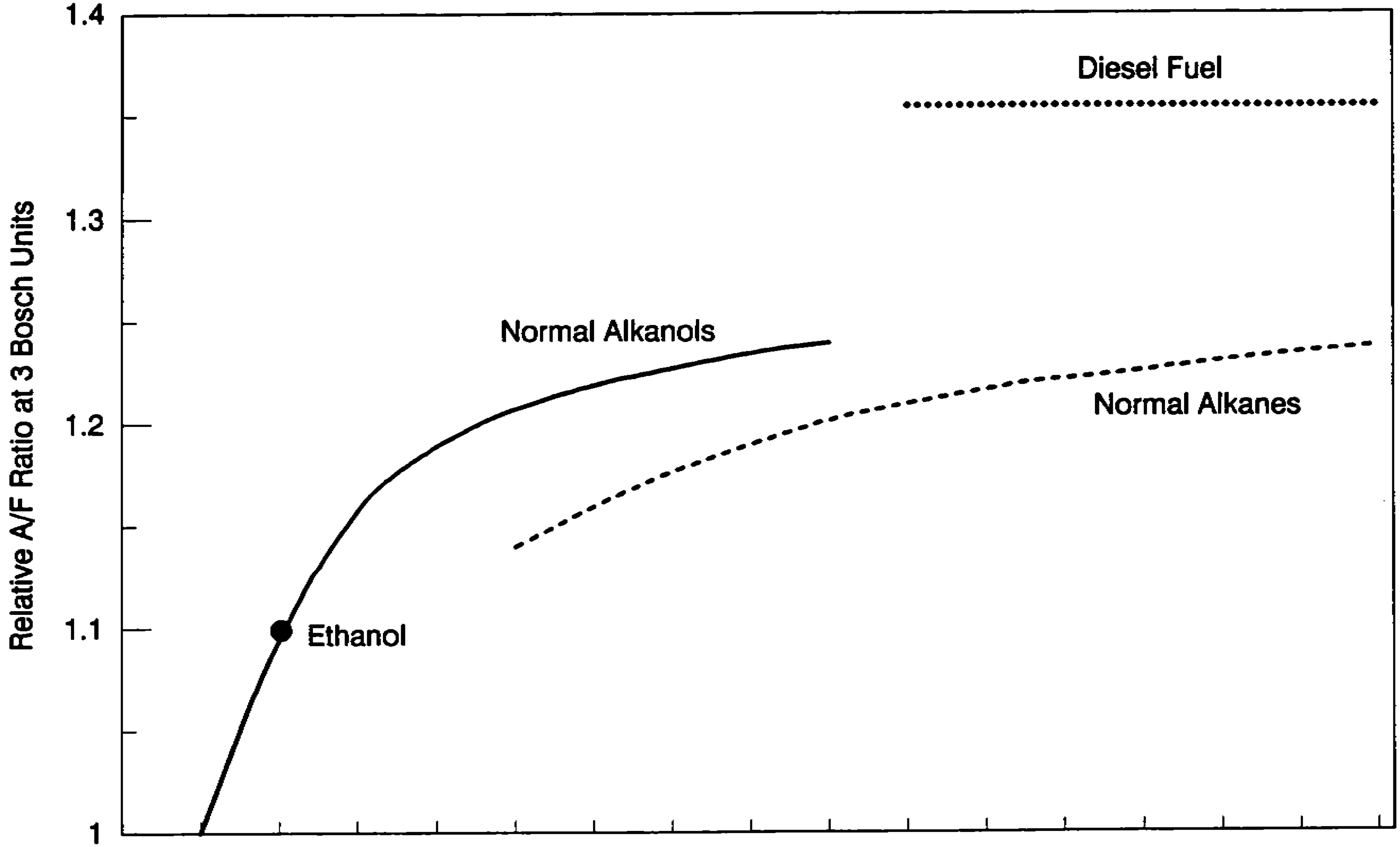
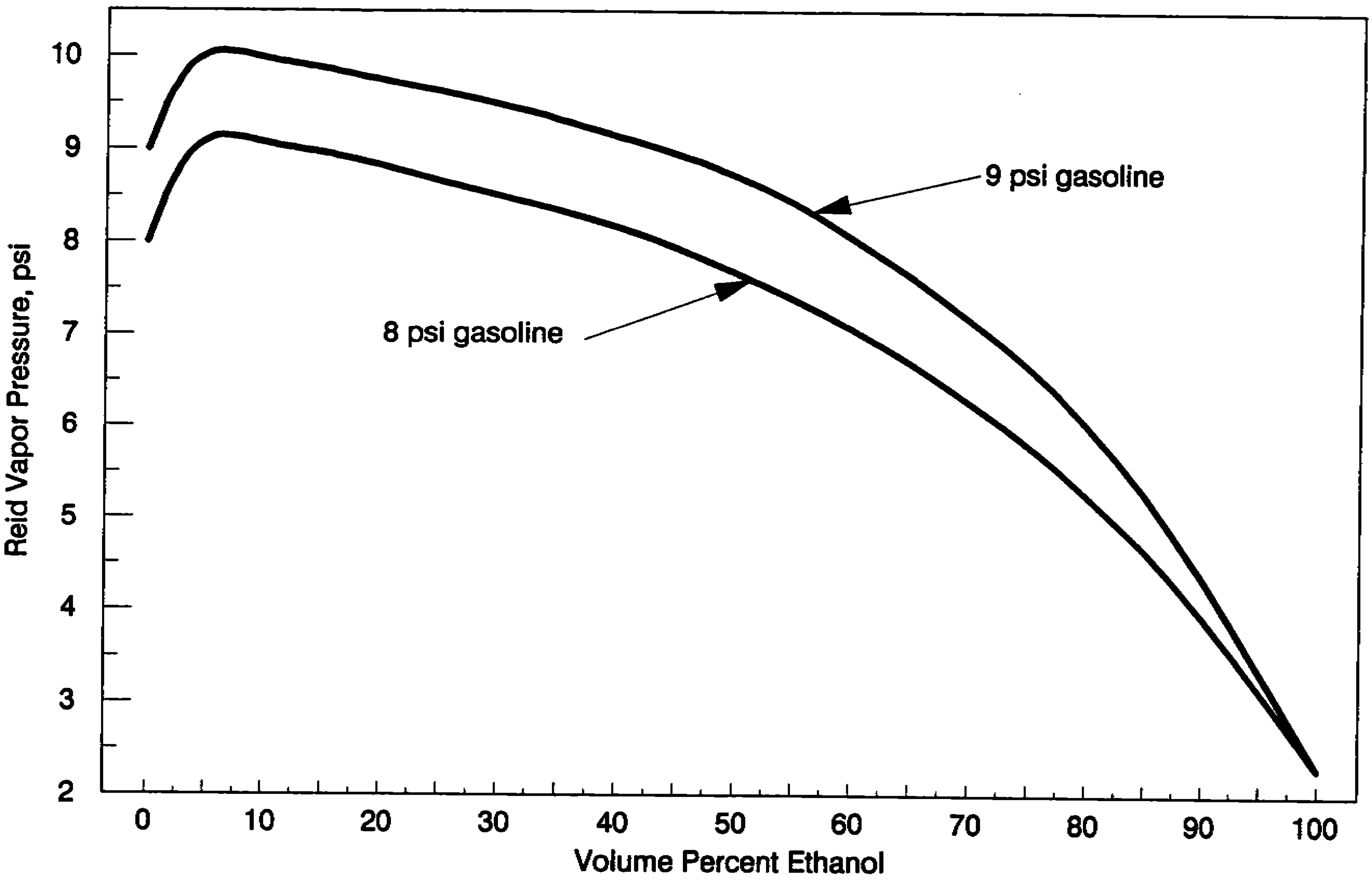


Figure E-4. Influence of Air-Fuel Ratio on Exhaust Emissions, Power, and Specific Fuel Consumption



Source: Hardenberg and Schaefer

Figure E-5. Smoke Formation Properties of Normal Alkanes and Alkanols



Source: Estimated from API (1988)

Figure E-6. Estimated RVP of Ethanol Blends

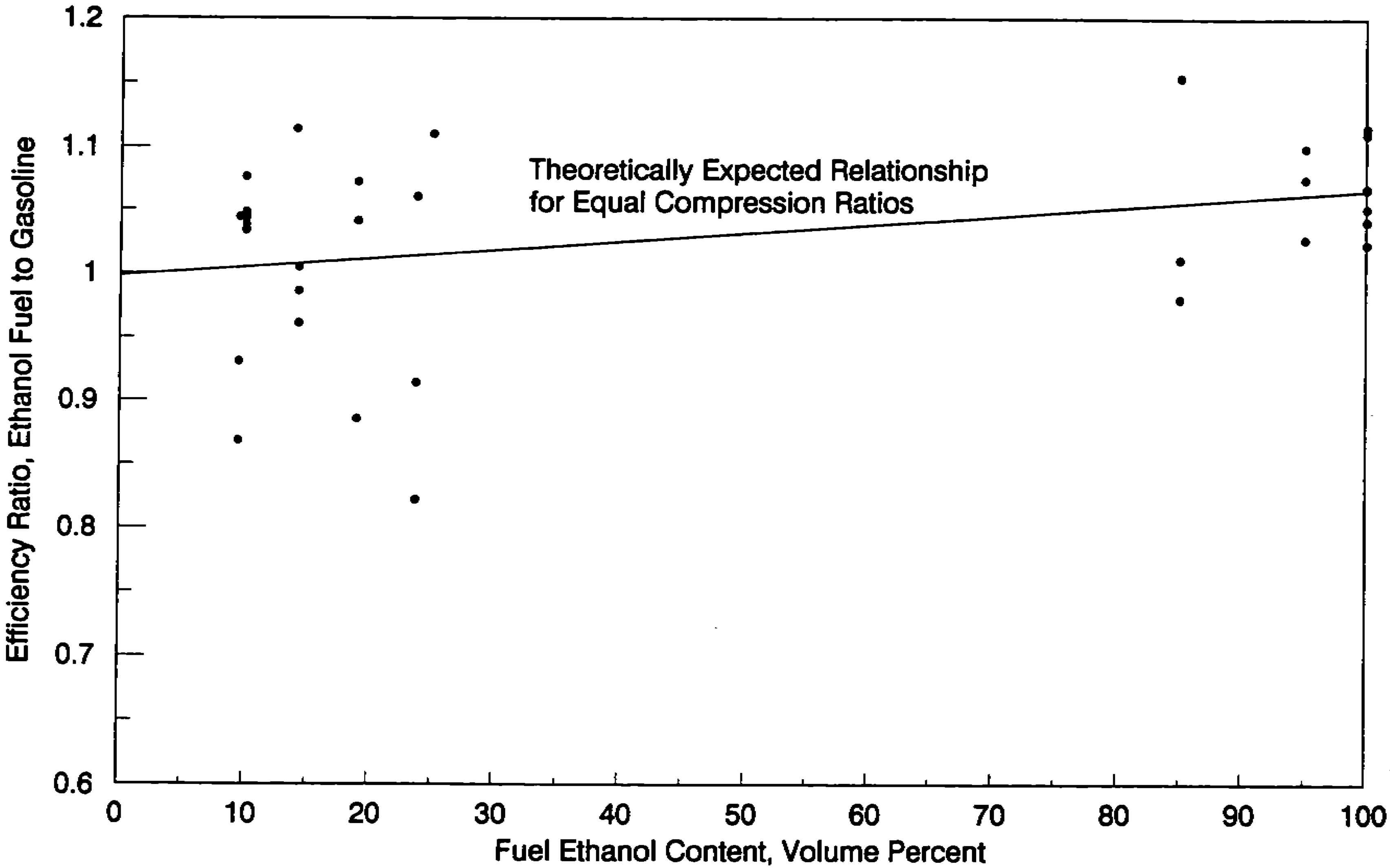


Figure E-7. Expected and Observed Efficiencies of Spark Ignited Ethanol Engines Compared to Gasoline

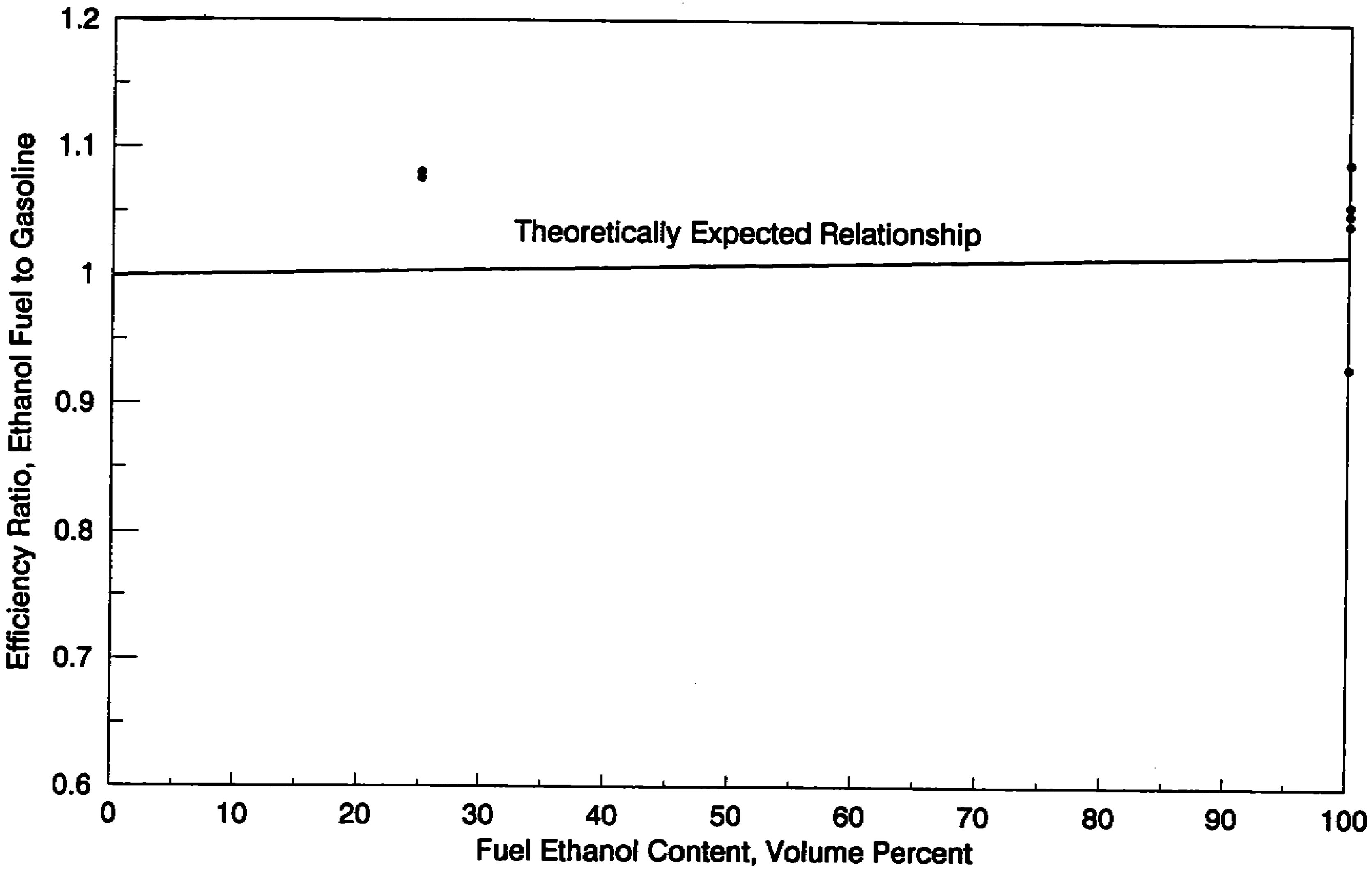
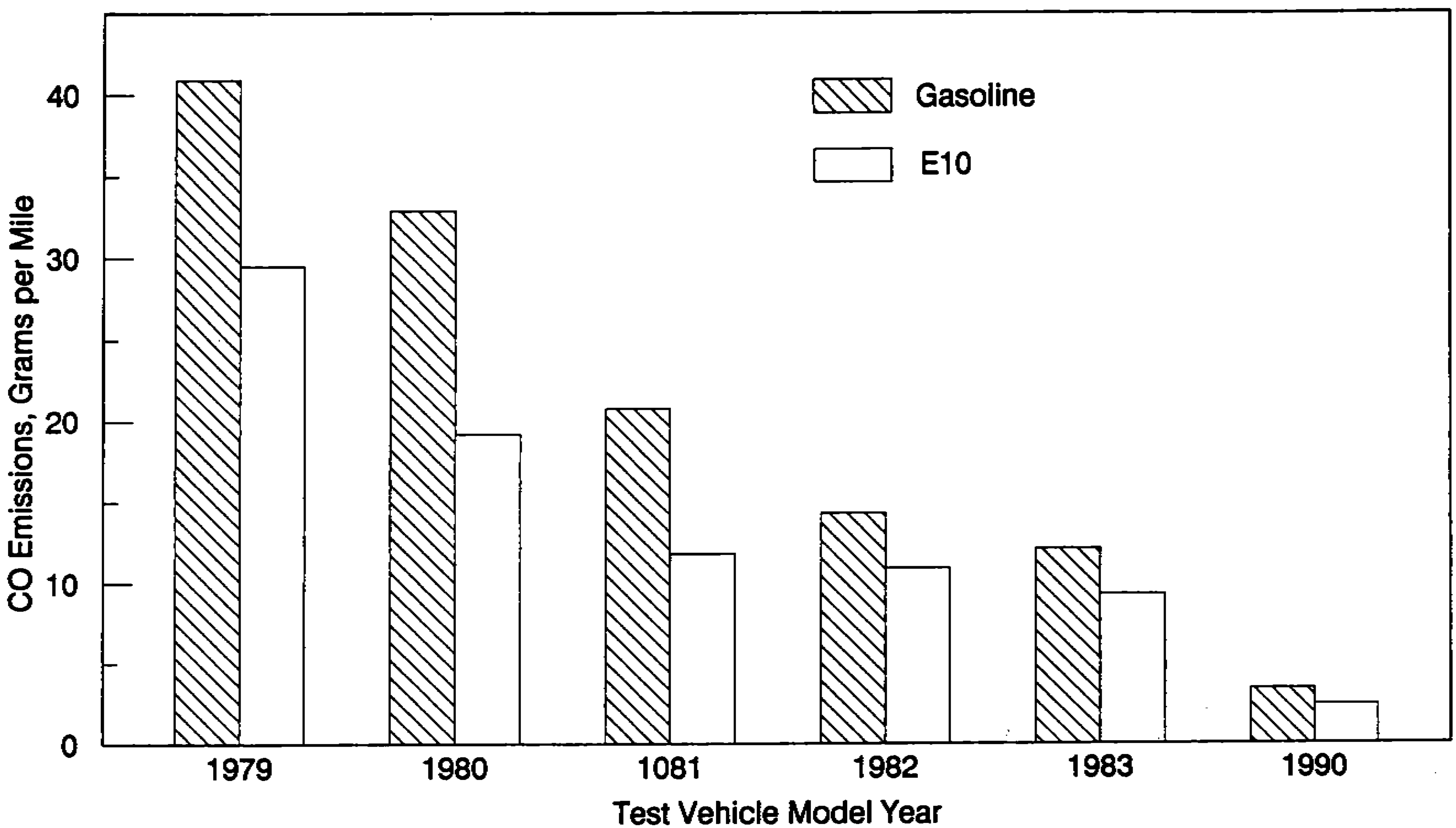


Figure E-8. Expected and Observed Efficiencies of Compression Ignition Ethanol Engines Compared to Diesel



Data Sources: Miron, Warner-Selph

Figure E-9. Effect of Technology Advances on Carbon Monoxide Emissions

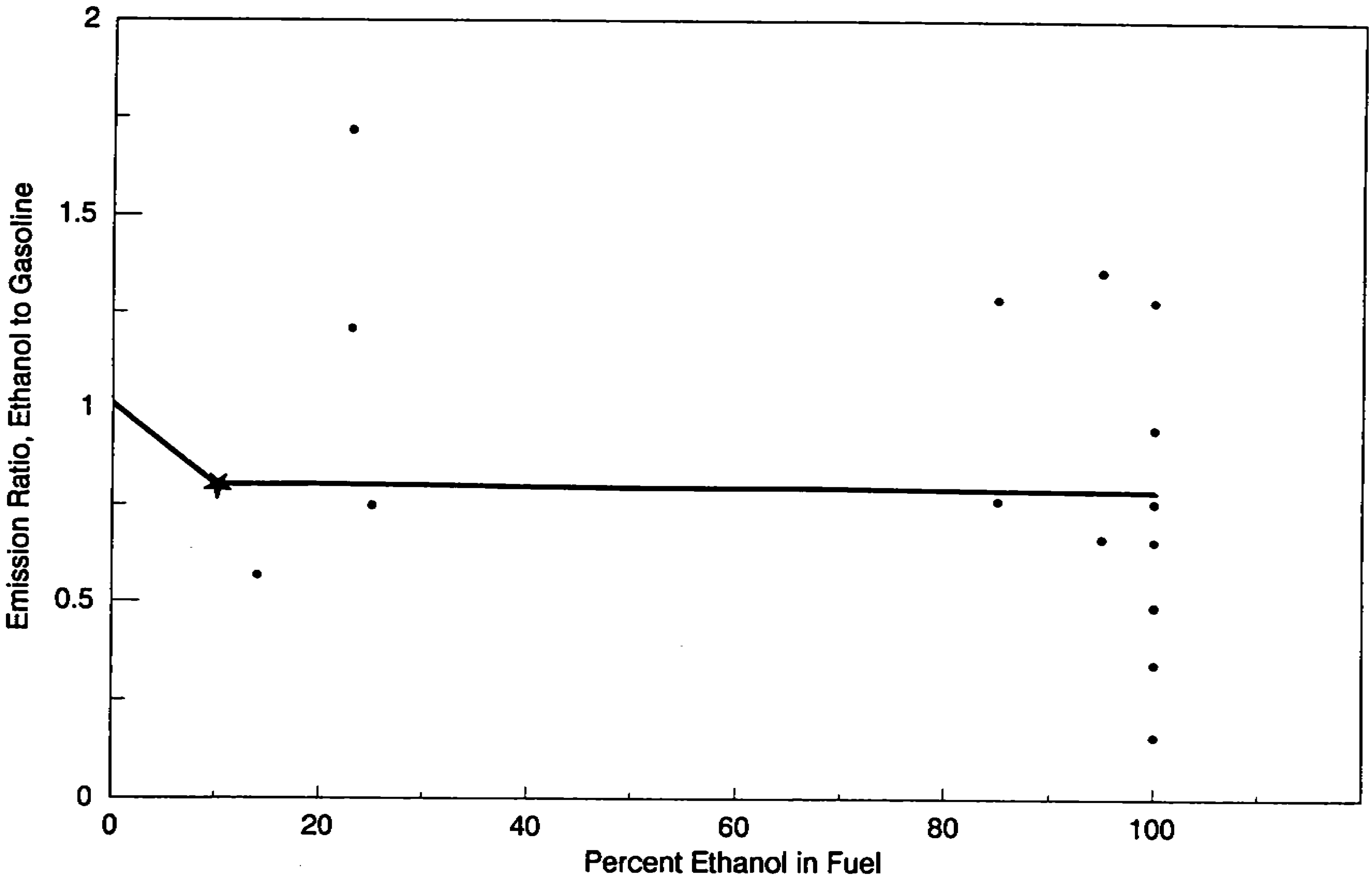


Figure E-10. Relative Carbon Monoxide Emissions from Ethanol and Gasoline Fueled Engines

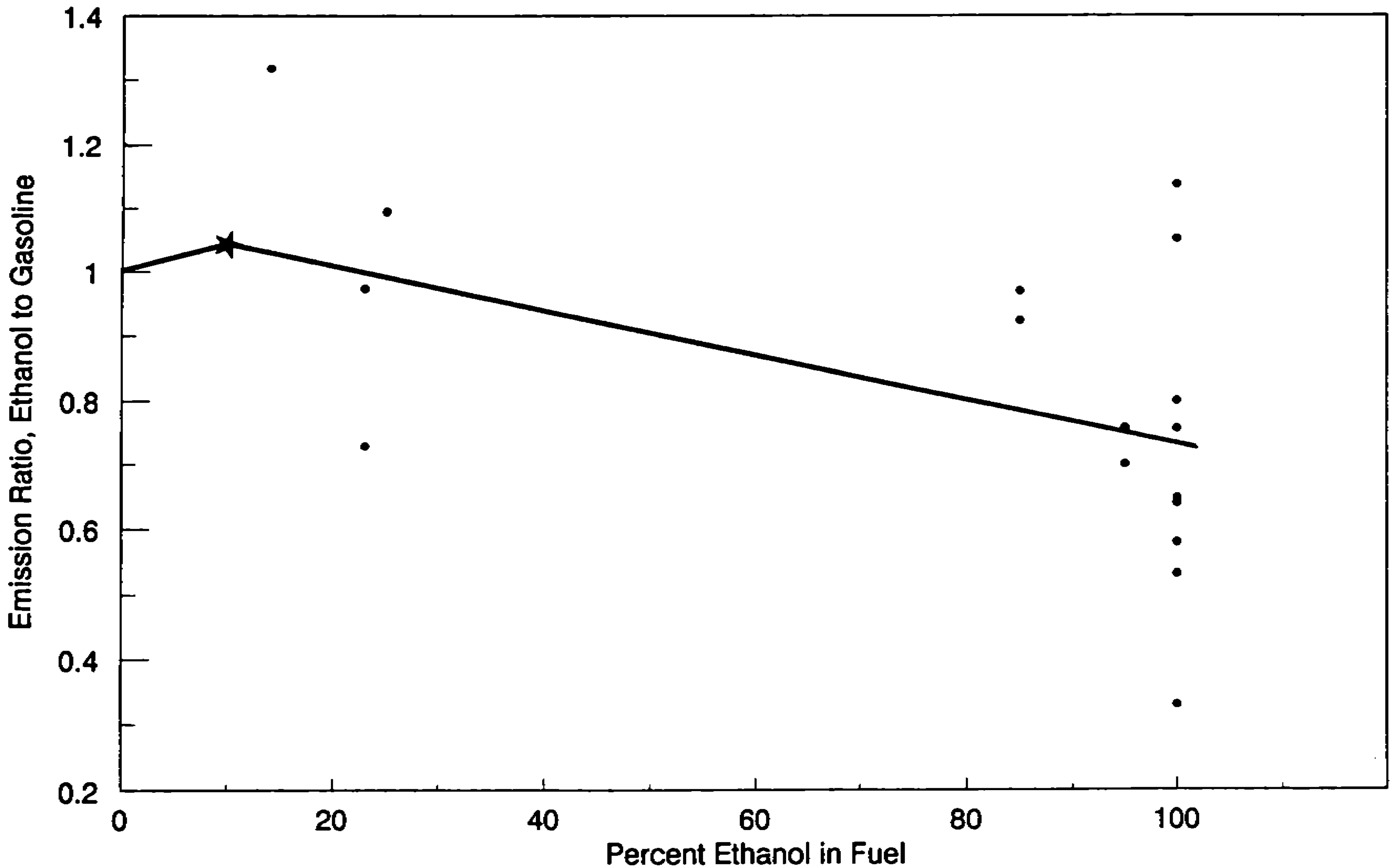


Figure E-11. Relative Nitrogen Oxide Emissions from Ethanol and Gasoline Fueled Engines

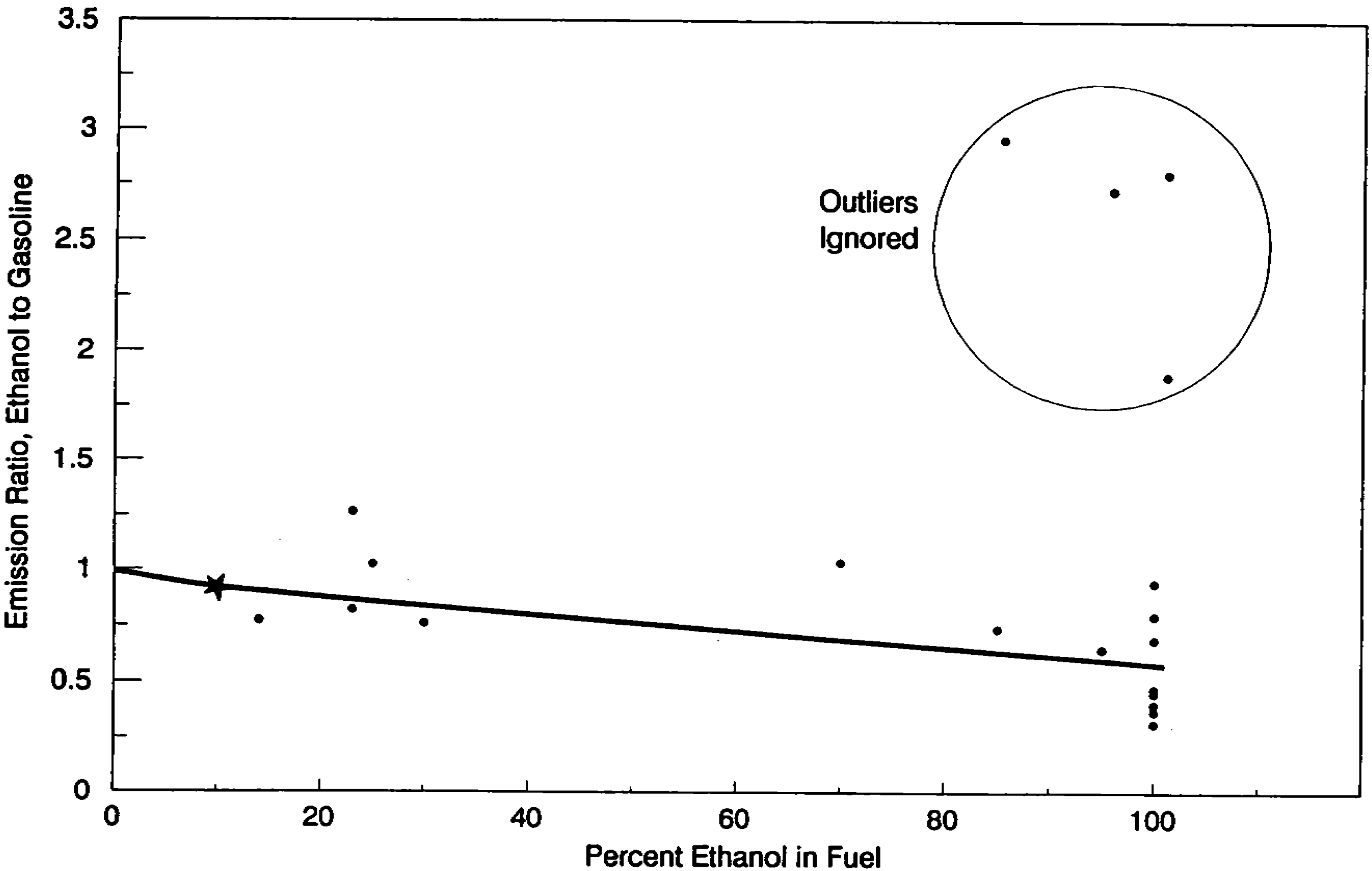


Figure E-12. Relative Exhaust VOC Emissions from Ethanol and Gasoline Engines

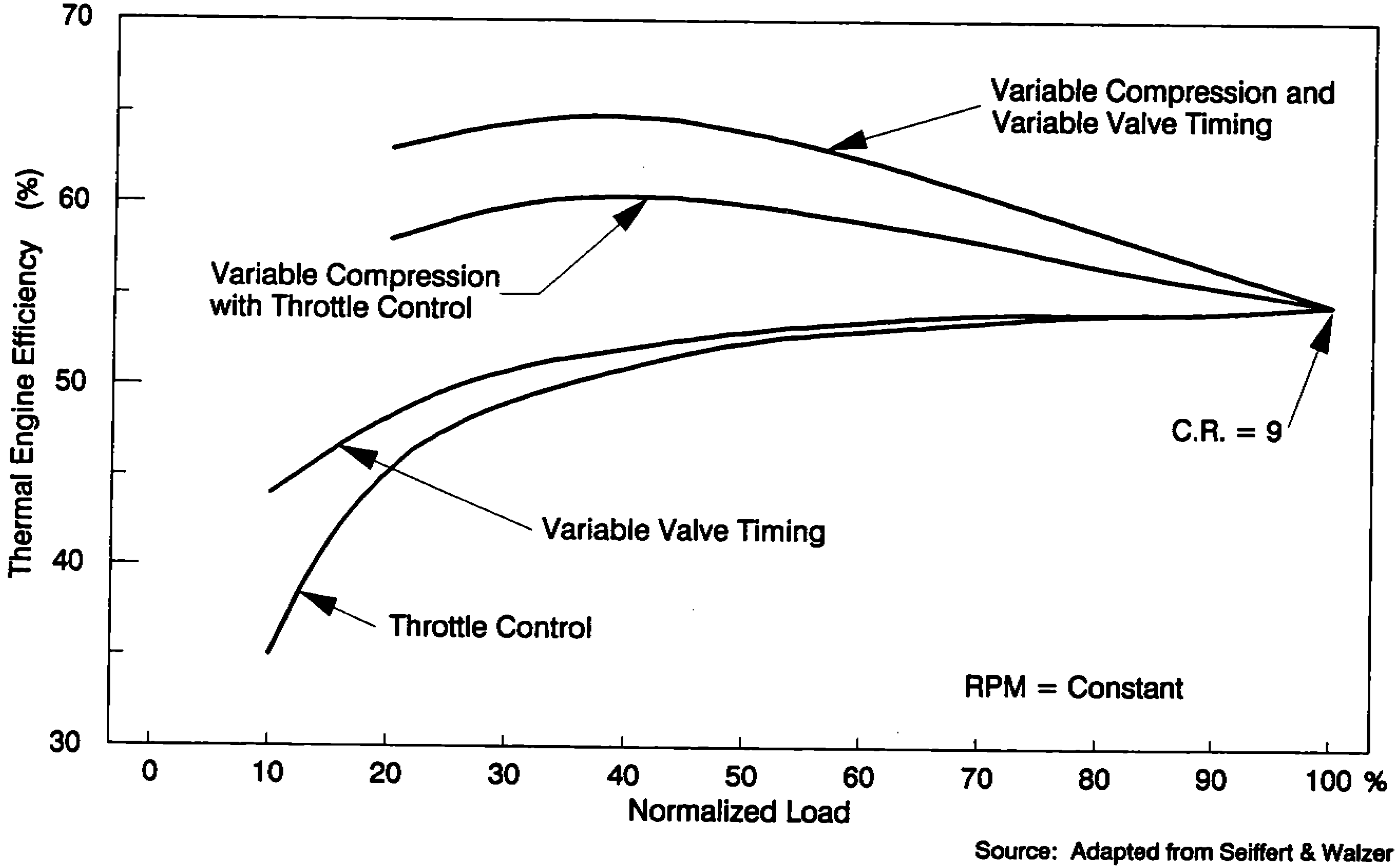
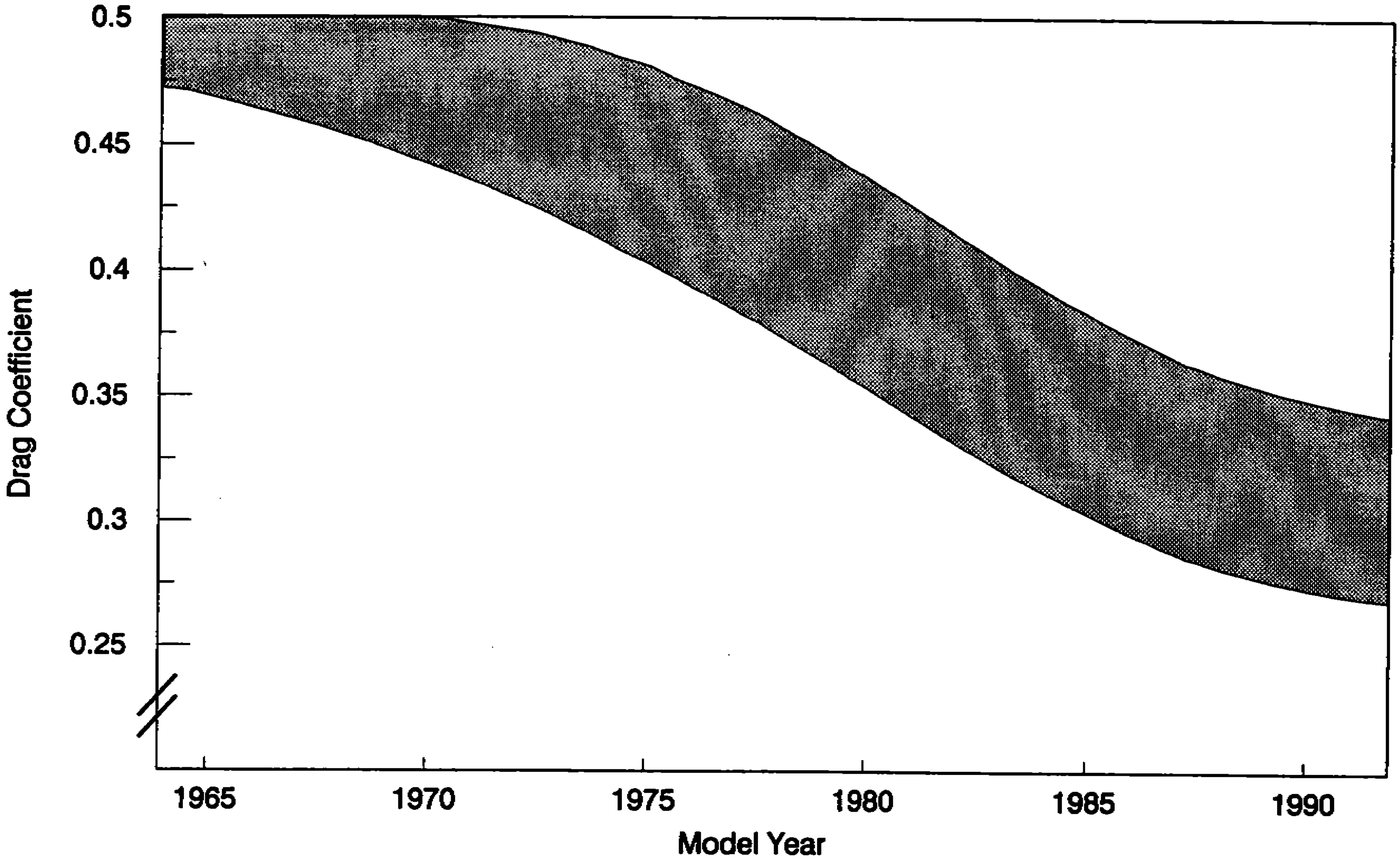


Figure E-13. Thermal Engine Efficiency vs. Engine Load at Constant Engine Speed



Source: Adapted from Seiffert & Walzer

Figure E-14. Drag Coefficients of Automobiles Manufactured by Volkswagen

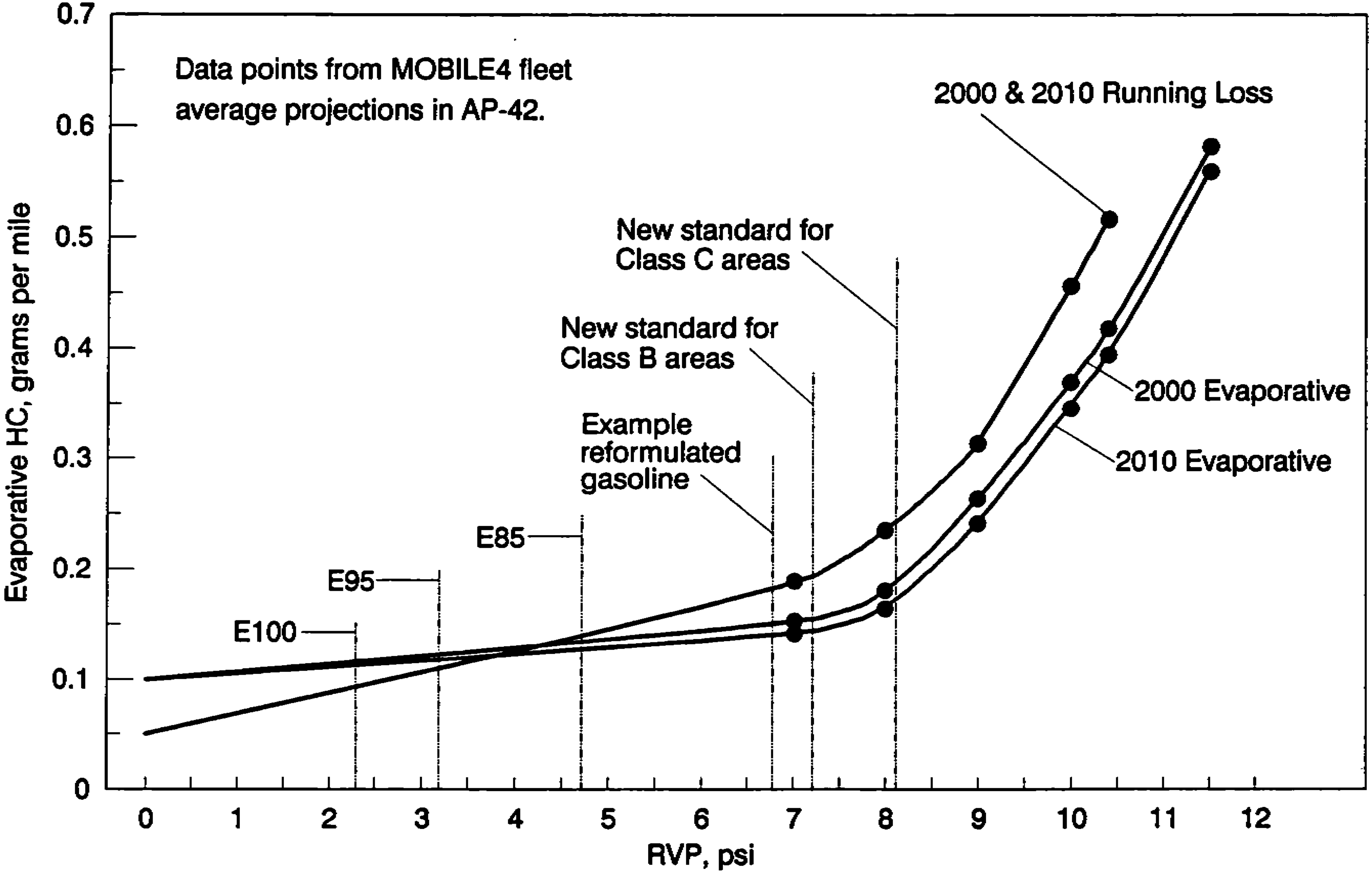


Figure E-15. Evaporative and Running Losses as a Function of RVP

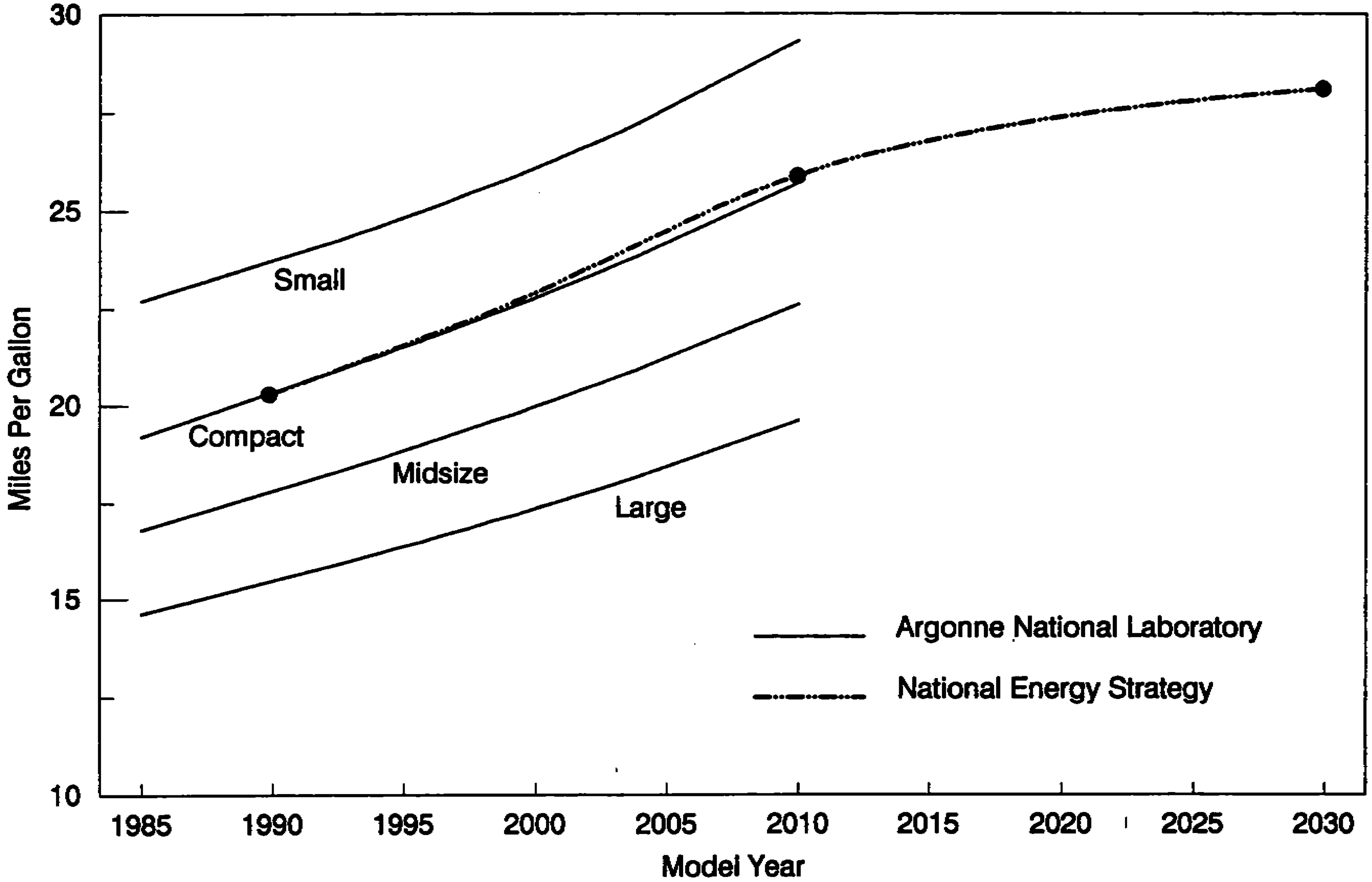


Figure E-16. Projection of Auto Efficiency

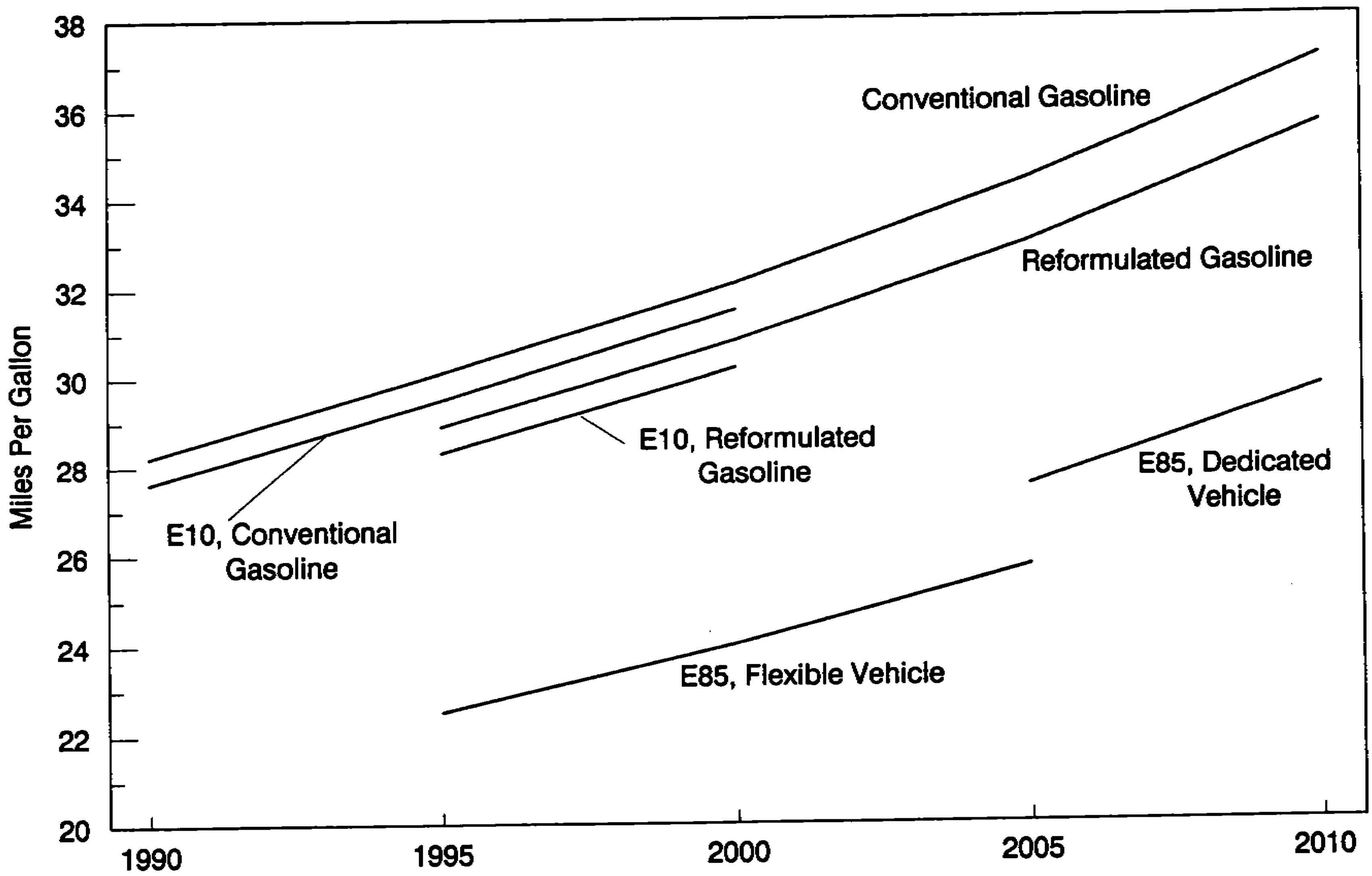


Figure E-17. Achievable New Car mpg Efficiencies

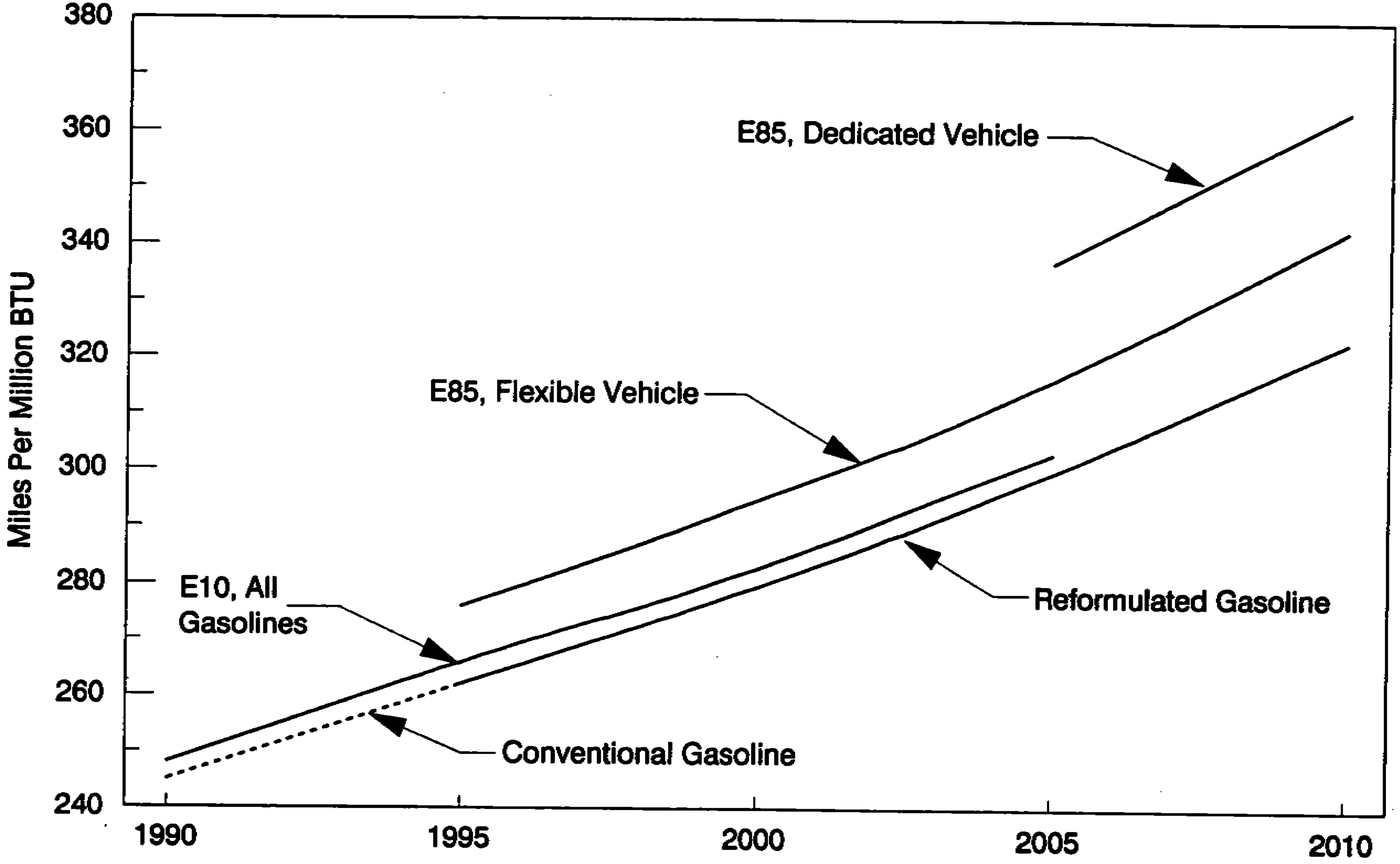
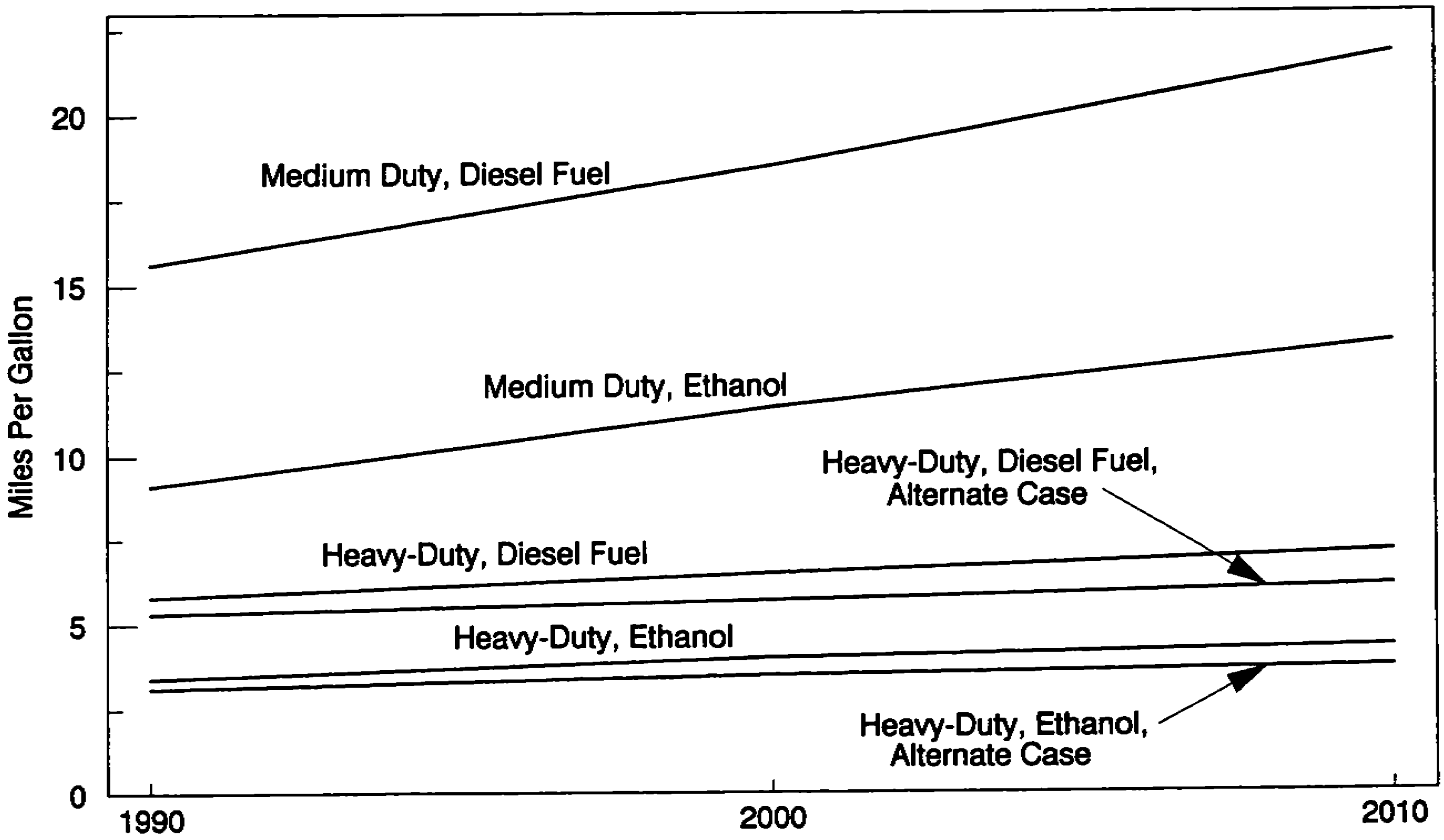
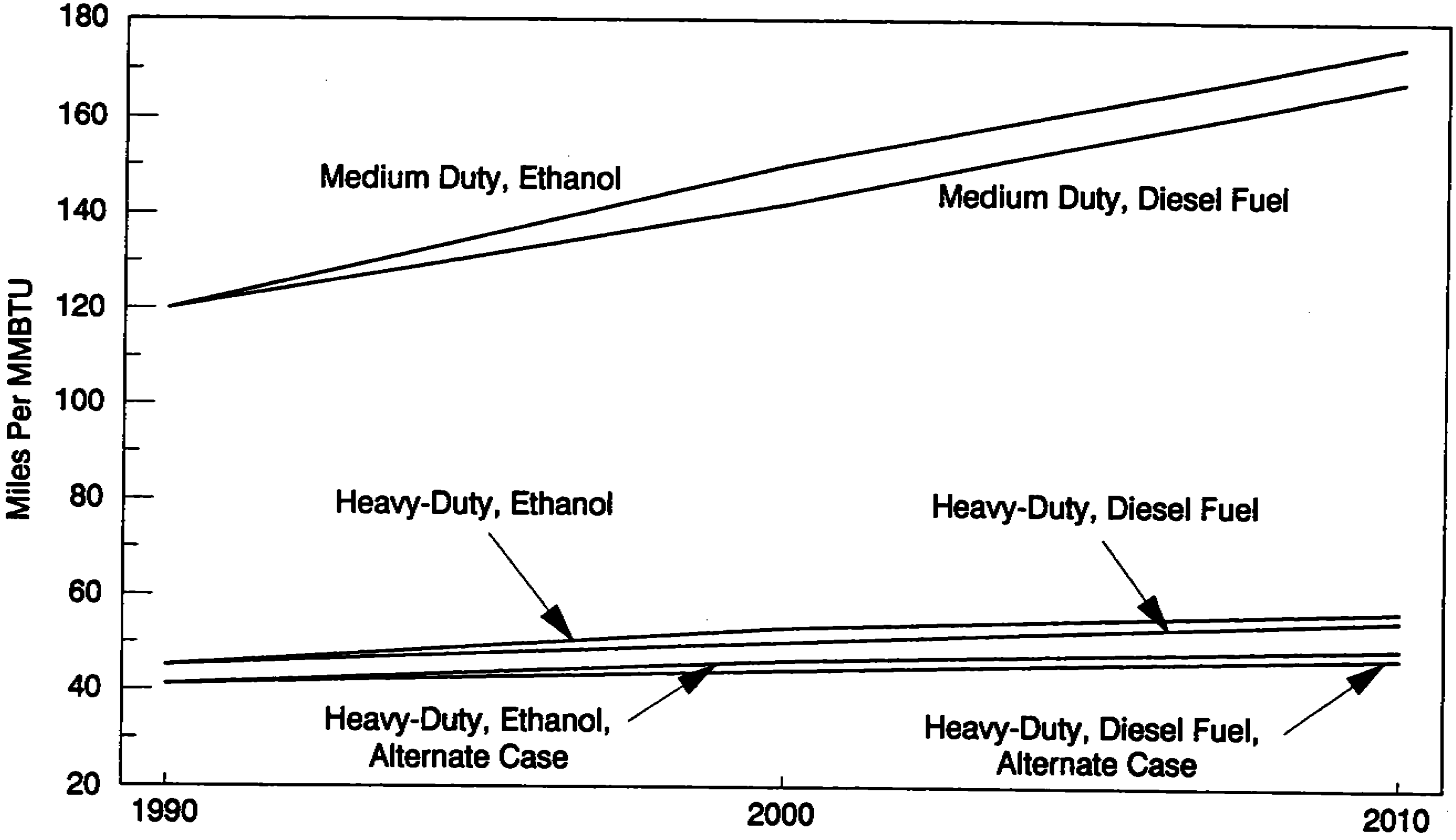


Figure E-18. Achievable New Car Energy Efficiencies



Source: Diesel efficiency forecasts from National Energy Strategy

Figure E-19. Potential Diesel Truck Mileage Efficiencies



Source: Diesel efficiency forecasts from National Energy Strategy

Figure E-20. Potential Diesel Truck Energy Efficiencies for Ethanol and Diesel Fuel

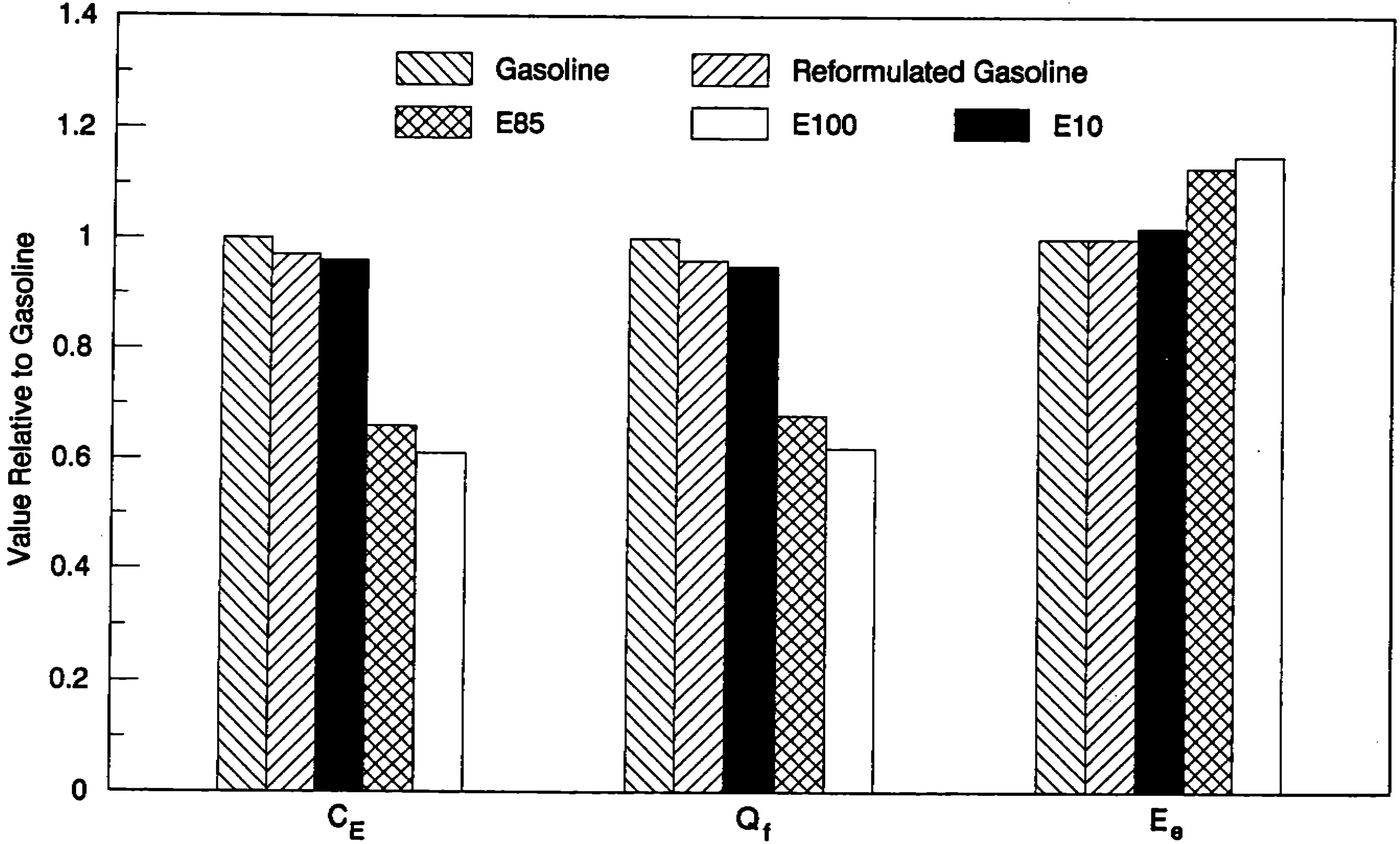


Figure E-21. Relative Values of Carbon Dioxide Emission Factors for Different Fuels

Table E-1.
Comparative Fuel Properties

FUEL PARAMETER	UNITS											
REFERENCE NUMBER		27	27	27	27	27	27	4	4	4	7	7
FUEL TYPE		MeOH	EtOH	Gasoline	Diesel	Low-S Diesel	M-85	MeOH	EtOH	Gasoline	EtOH	MeOH
Boiling Point	degrees C	65	78.5	27-210	188-340							
Boiling Point	degrees F							149	172	80-437		
Specific Gravity		0.791	0.789	0.73-0.75	0.81-0.88			0.796	0.794	0.72-0.78		
Density	lb/gallon							6.63	6.61	6.0-6.5		
RVP	kPa	32	15	50-100	0.1-1.5							
RVP	psi							4.6	2.3	8.0-15		
Blending RVP	kPa											
Blending RVP	psi											
Heat of Vaporization	kJ/kg	1167	920	275-365	225-280			1170	930	180	904	1110
Heat of Vaporization	BTU/lb							506	396	150		
Autoignition Point	degrees C	385	365	220	225							
Autoignition Point	degrees F							867	793	495		
Flammability limit	%	6.7-36	3.3-19	1.4-7.6	0.6-5.5			7.3-36	4.3-19	1.4-7.6		
Stoichiometric A/F, Weight	kg/kg	6.45	9	14.7	15			6.45	9	14.6		
Flame Temperature	degrees C	1886	1930	1977	2054							
Flame Temperature	degrees F											
Heat of Combustion, HHV	kJ/kg	22700	29700	47000	45600							
Heat of Combustion, HHV	kJ/liter	17960	23400	35200	38800							
Heat of Combustion, LHV	kJ/kg	20090	26970	43800	42800			19900	26800	42700	26800	19700
Heat of Combustion, LHV	kJ/liter	15890	21280	32400	36400							
Heat of Combustion, LHV	BTU/lb							8570	11500	18000-19000		
Heat of Combustion, LHV	BTU/gallon				130000	130000	65500	56800	76000	109000-119000		
Volume Equivalent to Diesel, LHV		2.29	1.71	1.12	1							
Volume Equivalent to Gasoline, LHV												
RON								109	109	90-100		
MON								89	90	80-90		
(R+M)/2								99	99.5	85-95		
Blending RON								115-130	112-120			
Blending MON								95-103	95-106			
Specific Energy, LHV/AF	MJ/kg							3.08	3	2.92		
Carbon Dioxide	lb/lb Fuel											
Carbon Dioxide	lb/MMBTU-LHV											

Table E-1.
Comparative Fuel Properties (Cont'd)

FUEL PARAMETER	UNITS												
REFERENCE NUMBER		5	5	5	5	8	8	8	8	9	9	9	9
FUEL TYPE		MeOH	EtOH	E-10	Gasoline	Gasoline	MeOH	EtOH	Diesel	Gasoline	Diesel	MeOH	EtOH
Boiling Point	degrees C												
Boiling Point	degrees F	149	172										
Specific Gravity						0.7502			0.843				
Density	lb/gallon												
RVP	kPa												
RVP	psi												
Blending RVP	kPa												
Blending RVP	psi	58-62	18-22										
Heat of Vaporization	kJ/kg									310	285	1100	904
Heat of Vaporization	BTU/lb												
Autoignition Point	degrees C									232-482	204-260	464-470	420
Autoignition Point	degrees F												
Flammability limit	%									1.0-8.0	0.7-5.0	6.7-36	4.3-19
Stoichiometric A/F, Weight	kg/kg												
Flame Temperature	degrees C												
Flame Temperature	degrees F												
Heat of Combustion, HHV	kJ/kg												
Heat of Combustion, HHV	kJ/liter												
Heat of Combustion, LHV	kJ/kg									43500	45300	19600	26900
Heat of Combustion, LHV	kJ/liter												
Heat of Combustion, LHV	BTU/lb												
Heat of Combustion, LHV	BTU/gallon		76000	110300	114100								
Volume Equivalent to Diesel, LHV													
Volume Equivalent to Gasoline, LHV													
RON		133	130			92.9	114	102		90-100		106	106
MON		99	98			83.2	94	89		80-90		92	91
(R+M)/2		116	113			88	104	96		85-95		99	98.5
Blending RON													
Blending MON													
Specific Energy, LHV/AF	MJ/kg												
Carbon Dioxide	lb/lb Fuel												
Carbon Dioxide	lb/MMBTU-LHV												

Table E-1.
Comparative Fuel Properties (Cont'd)

FUEL PARAMETER	UNITS												
REFERENCE NUMBER		10	10	10	10	11	11	12	12	12	12	12	12
FUEL TYPE		#2 Oil	Gasoline	MeOH	EtOH	EtOH	Gasoline	Gasoline	#1 Diesel	#2 Diesel	EtOH	MeOH	Gasohol
Boiling Point	degrees C							30-225	190-280	210-325	78.3	65	25-210
Boiling Point	degrees F							85-437	360-530	375-630	173	149	77-410
Specific Gravity								0.72-0.75	0.82	0.85	0.79	0.79	0.73-0.76
Density	lb/gallon												
RVP	kPa							62-90	0.34	0.27	17	32	55-110
RVP	psi							9.0-13	0.05	0.04	2.5	4.6	8.0-16
Blending RVP	kPa												
Blending RVP	psi												
Heat of Vaporization	kJ/kg					842	330	400	600	600	900	1110	465
Heat of Vaporization	BTU/lb							170	250	250	390	500	200
Autoignition Point	degrees C												
Autoignition Point	degrees F												
Flammability limit	%												
Stoichiometric A/F, Weight	kg/kg					9	14.5	14.6	14.6	14.6	9	6.4	14
Flame Temperature	degrees C												
Flame Temperature	degrees F												
Heat of Combustion, HHV	kJ/kg												
Heat of Combustion, HHV	kJ/liter											20100	41900
Heat of Combustion, LHV	kJ/kg					26860	43000	43500	43000	43000	27000		
Heat of Combustion, LHV	kJ/liter							32000	35300	36600	21300	15900	
Heat of Combustion, LHV	BTU/lb	18400	18800	8600	11500			18700	18500	18400	11600	8600	18000
Heat of Combustion, LHV	BTU/gallon							117000	126000	130000	76000	57000	
Volume Equivalent to Diesel, LHV													
Volume Equivalent to Gasoline, LHV													
RON						108	92	91-100			111	112	
MON						90	83	82-92			92	91	
(R+M)/2						99	87.5	86.5-96			101.5	101.5	
Blending RON													
Blending MON													
Specific Energy, LHV/AF	MJ/kg												
Carbon Dioxide	lb/lb Fuel	3.2	3.18	1.38	1.91								
Carbon Dioxide	lb/MMBTU-LHV	174	169	160	166								

Table E-1.
Comparative Fuel Properties (Cont'd)

FUEL PARAMETER	UNITS						
REFERENCE NUMBER		31	64	1	1	1	1
FUEL TYPE		EtOH	EtOH	EtOH	Gasohol	Gasoline	Diesel
Boiling Point	degrees C		78.5				
Boiling Point	degrees F						
Specific Gravity		0.794	0.79				
Density	lb/gallon						
RVP	kPa						
RVP	psi						
Blending RVP	kPa						
Blending RVP	psi						
Heat of Vaporization	kJ/kg		839				
Heat of Vaporization	BTU/lb	396					
Autoignition Point	degrees C		425				
Autoignition Point	degrees F						
Flammability limit	%						
Stoichiometric A/F, Weight	kg/kg	8.97					
Flame Temperature	degrees C						
Flame Temperature	degrees F						
Heat of Combustion, HHV	kJ/kg						
Heat of Combustion, HHV	kJ/liter			23580	33700	34840	38660
Heat of Combustion, LHV	kJ/kg		26945				
Heat of Combustion, LHV	kJ/liter			21091	31334	22166	35873
Heat of Combustion, LHV	BTU/lb	11550					
Heat of Combustion, LHV	BTU/gallon			75670	112417	115400	128700
Volume Equivalent to Diesel, LHV							
Volume Equivalent to Gasoline, LHV							
RON		112	191				
MON		95	97				
(R+M)/2		103.5	109				
Blending RON							
Blending MON							
Specific Energy, LHV/AF	MJ/kg						
Carbon Dioxide	lb/lb Fuel						
Carbon Dioxide	lb/MMBTU-LHV						

Table E-2.
Stoichiometric Amounts of Air Required and Gases Produced for Different Fuels
(Standard Cubic Fee Per Million BTU Burned)

Fuel	Atomic Ratios	SCF of Air Required Per MMBTU	SCF of Reaction Products Per MMBTU	SCF of Exhaust Gas Per MMBTU	Ratio of ACF to Ethanol
Ethanol	$CH_3O_{0.5}$	9,800	3,713	11,600	--
Methanol	CH_4O	9,300	3,920	11,500	0.97
Gasoline	$CH_{1.85}$	9,700	2,650	10,600	0.93
Diesel	$CH_{1.73}$	10,200	2,650	10,900	0.99

Basis: (Ho 1990)

Table E-3.
Summary of Tier 1 Tailpipe Certification Standards

Vehicle Type and GVWR (lbs)	Fuel	LVW (lbs)	ALVW (lbs)	Half Life Standards (g/mi)*				Full Life Standards (g/mi)**			
				NMHC	CO	NO_x	PM	NMHC	CO	NO_x	PM
LDV	[1]Non-diesel	All	All	0.25	3.4	0.4	0.08	0.31	4.2	0.60	0.10
All	[1]Diesel	All	All	0.25	3.4	1.0	0.08	0.31	4.2	1.25	0.10
Light	[1]Non-diesel	0-3750	All	0.25	3.4	0.4	N/A	0.31	4.2	0.60	N/A
LDT	[1]Diesel	0-3750	All	0.25	3.4	1.0	N/A	0.31	4.2	1.25	N/A
0-6,000	[1]Non-diesel	3751-5750	All	0.32	4.4	0.7	N/A	0.40	5.5	0.97	N/A
	[1]Diesel	3751-5750	All	0.32	4.4	N/A	N/A	0.40	5.5	0.97	N/A
	[2]All	All	All	N/A	N/A	N/A	0.08	N/A	N/A	N/A	0.10
Heavy	[3]Non-diesel	All	3751-5750	0.32	4.4	0.7	N/A	0.46	6.4	0.98	0.10
LDT	[3]Diesel	All	3751-5750	0.32	4.4	N/A	N/A	0.46	6.4	0.98	0.10
>6,000	[3]Non-diesel	All	>5750	0.39	5.0	1.1	N/A	0.56	7.3	1.53	0.12
	[3]Diesel	All	>5750	0.39	5.0	N/A	N/A	0.58	7.3	1.53	0.12

- * Half life is 5 years or 50,000 miles
- ** Full life is 10 years, 100,000 miles for LDV and Light LDT, 11 years and 120,000 miles for Heavy LDT

GVWR = Gross vehicle weight rating
LVW = Loaded vehicle weight = curb weight + 300 lbs
ALVW = Adjusted loaded vehicle weight = (curb weight + GVWR)/2
[1]Phase-in schedule starts in 1994
[2]Phase-in schedule starts in 1995
[3]Phase-in schedule starts in 1996
[4]Phase-in schedule starts in 1998

Source: EPA (June 1991)

Table E-4.
Summary of Tier 1 In-Use Tailpipe Standards

Vehicle Type and GVWR (lbs)	Fuel	LVW (lbs)	ALVW (lbs)	Half Life Standards (g/mi)*				Full Life Standards (g/mi)**			
				NMHC	CO	NO_x	PM	NMHC	CO	NO_x	PM
LDV All	[1]Non-diesel	All	All	0.32	3.4	0.4	0.08	N/A	N/A	N/A	0.10
	[1]Diesel	All	All	0.32	3.4	1.0	0.08	N/A	N/A	N/A	0.10
	[3]Non-diesel	All	All	0.25	3.4	0.4	0.08	0.31	4.2	0.60	0.10
	[3]Diesel	All	All	0.25	3.4	1.0	0.08	0.31	4.2	1.25	0.10
Light LDT <=6,000	[1]Non-diesel	0-3750	All	0.32	5.2	0.4	N/A	N/A	N/A	N/A	N/A
	[1]Diesel	0-3750	All	0.32	5.2	1.2	N/A	N/A	N/A	N/A	N/A
	[1]Non-diesel	3751-5750	All	0.41	6.7	0.7	N/A	N/A	N/A	N/A	N/A
	[1]Diesel	3751-5750	All	0.41	6.7	1.7	N/A	N/A	N/A	N/A	N/A
	[3]Non-diesel	0-3750	All	0.25	3.4	0.4	N/A	0.31	4.2	0.60	N/A
	[3]Diesel	0-3750	All	0.25	3.4	1.0	N/A	0.31	4.2	1.25	N/A
	[3]Non-diesel	3751-5750	All	0.32	4.4	0.7	N/A	0.40	5.5	0.97	N/A
	[3]Diesel	3751-5750	All	0.32	4.4	0.97	N/A	0.40	5.5	0.87	N/A
	[2]All	0-5750	All	N/A	N/A	N/A	0.08	N/A	N/A	N/A	0.10
Heavy LDT >6,000	[3]Non-diesel	All	3751-5750	0.40	5.5	0.88	0.10	N/A	N/A	N/A	0.10
	[3]Diesel	0-3750	3751-5750	0.40	5.5	1.2	0.1	N/A	N/A	N/A	0.10
	[3]Diesel	3751-5750	3751-5750	0.40	5.5	1.7	0.10	N/A	N/A	N/A	0.10
	[3]Non-diesel	All	>5750	0.49	6.2	1.38	0.12	N/A	N/A	N/A	0.12
	[3]Diesel	0-3750	>5750	0.49	6.2	1.2	0.12	N/A	N/A	N.A	0.12
	[3]Diesel	3750-5750	>5750	0.49	6.2	1.7	0.12	N/A	N/A	N/A	0.12
	[4]Non-diesel	All	3751-5750	0.32	4.4	0.7	0.10	0.46	6.4	0.98	0.10
	[4]Diesel	All	3751-5750	0.32	4.4	0.98	0.10	0.46	6.4	0.98	0.10
	[4]Non-diesel	All	>5750	0.39	5.0	1.1	0.12	0.56	7.3	1.53	0.12
	[4]Diesel	All	>5750	0.39	5.0	1.53	0.12	0.56	7.3	1.53	0.12

Footnotes: See Table E-3

Source: EPA (June 1991)

Table E-5.
Urban Bus Particulate Standards

Model Year	Standard (g/BHP-hr)	Percent Reduction From Uncontrolled
1987 and Earlier	No Std.	N/A
1988-1990	0.60	14%
1991-1992	0.25	64%
1993	0.10	86%
1994 and Later	0.05	93%

Table E-6. Summary of Standards for Heavy-Duty Diesel Engines

Year Effective	HC	CO	NO_x	PM
	Grams/BHP-Hour			
1991	1.3	15.5	5.0	0.25
1994	1.3	15.5	5.0	0.10
1998	1.3	15.5	4.0	0.10

Table E-7. Baseline Gasoline Fuel Properties (Summer Months)

API Gravity	57.4
Sulfur, ppm	339
Benzene, Vol. %	1.53
RVP, psi	8.7
Octane, (R+M)/2	87.3
IBP, °F	91
10%, °F	128
50%, °F	218
90%, °F	330
End Point, °F	415
Aromatics, Vol. %	32.0
Olefins, Vol. %	9.2
Saturates, Vol. %	58.8

Table E-8. Baseline Gasoline Fuel Properties (Winter Months)

Benzene, Vol. %	1.64
Aromatics, Vol. %	26.3
Olefins, Vol. %	11.9
T_{90}, °F	332
T_{50}, °F	199
Sulfur, ppm	340
RVP, psi	12.3

Table E-9. Properties of ARCO EC-X

Fuel	Industry Average	EC-X
Vapor Pressure, psi	8.6	6.7
Benzene, Vol. %	1.6	0.8
Aromatics, Vol. %	34.4	21.6
Olefins, Vol. %	9.7	5.5
Oxygen, Wt. %	0.0	2.7
T_{50}, °F	213	201
T_{90}, °F	323	293
Sulfur, ppm	349	41

Table E-10. Fleet Average HC Emissions for Light-Duty Vehicles (9.0 psi RVP Gasoline) (Grams Per Mile)

	1990	2000	2010
Exhaust NMHC	1.76	0.84	0.81
Evaporative HC	0.52	0.26	0.24
Refueling Loss	0.22	0.20	0.20
Running Loss	0.36	0.30	0.30
Combined NMHC	2.87	1.60	1.55

Table E-11.
Year 2000 Comparison of Emissions
Between Standard and Reformulated Gasoline
(Zero-Miles Light-Duty Vehicles)

	Conventional Gasoline 8.0 RVP*	Reformulated Gasoline 6.7 RVP
Evaporative VOC, grams/mile	0.27	0.20
Exhaust VOC, grams/mile	0.28	0.21
CO, grams/mile	2.91	2.19
NO_x, grams/mile	0.63	0.63

*Requirement is 8.1 in Class C areas and 7.2 in Class B areas

Table E-12.
Current Technology-Specific Exhaust Effects
of Oxygenated Blends
(Percent Change From Gasoline)

	3.7% Oxygen (10% Ethanol)			2.0% Oxygen (11% MTBE)		
Technology	CO	NO_x	VOC	CO	NO_x	VOC
Non-Catalyst	-18.0	+4.8	-8.5	-9.7	+2.6	-4.6
Open-Loop Catalyst (Carbureted)	-30.0	+4.8	-8.5	-16.6	+2.6	-4.6
Closed-Loop (Carbureted)	-10.0	+6.3	-4.4	-5.4	+3.4	-2.4
Closed-Loop (Fuel Injected)	-10.0	+6.3	-4.4	-5.4	+3.4	-2.4

Source: EPA (1987)

Table E-13.
Year 2000 Comparison of Emissions
Between Reformulated Gasoline and Ethanol Blends
(Zero-Mile New Light-Duty Vehicles)

	Reformulated Gasoline	Splash E10 (% Change)	RVP Adjusted E10 (% Change)	E85 (% Change)	E95 (% Change)
Evaporative VOC, g/mile	0.204	+30	+0	-15	-28
Exhaust VOC, g/mile	0.208	-2	-2	-2	-2
Total VOC, g/mile	0.412	+15	-1	-8	-15
CO, g/mile	2.19	-4.6	-4.6	-4.6	-4.6
NO_x, g/mile	0.635	+2.9	+2.9	-20.0	-22.0

Table E-14.
Projection of Emissions for Spark Ignited Engines
(Zero-Mile New Light-Duty Vehicles)

Fuel/Pollutant	Units	1990	2000	2010
	BASE CASE, EXISTING REGULATIONS			
Gasoline, 8 psi RVP				
Evaporative VOC	grams/mile	0.27	0.27	0.27
Exhaust VOC	grams/mile	0.27	0.28	0.28
CO	grams/mile	2.81	2.91	2.91
NO_x	grams/mile	0.64	0.63	0.63
CO_2	grams/mile	317	278	241
SO_2	mg/mile	70	61	53
Benzene	mg/mile	1.7	1.7	1.7
1-3 Butadiene	mg/mile	0.13	0.13	0.13
Formaldehyde	mg/mile	0.27	0.27	0.27
Acetaldehyde	mg/mile	0.19	0.19	0.19
Reformulated Gasoline, 6.7 psi RVP				
Evaporative VOC	grams/mile		0.20	0.20
Exhaust VOC	grams/mile		0.21	0.21
CO	grams/mile		2.19	2.19
NO_x	grams/mile		0.63	0.63
CO_2	grams/mile		280	243
SO_2	mg/mile		52	45
Benzene	mg/mile		0.79	0.79
1-3 Butadiene	mg/mile		0.10	0.10
Formaldehyde	mg/mile		0.20	0.20
Acetaldehyde	mg/mile		0.14	0.14
E10, Splash Blended		**Conv. Base**	**Reform. Base**	
Evaporative VOC	grams/mile	0.36	0.26	
Exhaust VOC	grams/mile	0.26	0.20	
CO	grams/mile	2.53	2.09	
NO_x	grams/mile	0.68	0.65	
CO_2	grams/mile	314	278	
SO_2	mg/mile	64	50	
Benzene	mg/mile	1.53	1.21	
1-3 Butadiene	mg/mile	0.12	0.12	
Formaldehyde	mg/mile	0.54	0.54	
Acetaldehyde	mg/mile	0.47	0.47	
E10, RVP Adjusted				
Evaporative VOC	grams/mile		0.20	0.20
Exhaust VOC	grams/mile		0.20	0.20
CO	grams/mile		2.09	2.09
NO_x	grams/mile		0.65	0.65
CO_2	grams/mile		278	241
SO_2	mg/mile		50	43
Benzene	mg/mile		1.21	1.21
1-3 Butadiene	mg/mile		0.12	0.12
Formaldehyde	mg/mile		0.54	0.54
Acetaldehyde	mg/mile		0.47	0.47

Table E-14.
Projection of Emissions for Spark Ignited Engines (Cont'd)

Fuel/Pollutant	Units	1990	2000	2010
E85				
Evaporative VOC	grams/mile		0.17	0.17
Exhaust VOC	grams/mile		0.20	0.20
CO	grams/mile		2.09	2.09
NO_x	grams/mile		0.52	0.52
CO_2	grams/mile		259	209
SO_2	mg/mile		12	10
Benzene	mg/mile		0.43	0.43
1-3 Butadiene	mg/mile		0.06	0.06
Formaldehyde	mg/mile		0.40	0.40
Acetaldehyde	mg/mile		1.14	1.14
E95				
Evaporative VOC	grams/mile		0.15	0.15
Exhaust VOC	grams/mile		0.20	0.20
CO	grams/mile		2.09	2.09
NO_x	grams/mile		0.51	0.51
CO_2	grams/mile		259	209
SO_2	mg/mile		4.3	3.5
Benzene	mg/mile		0.38	0.38
1-3 Butadiene	mg/mile		0.05	0.05
Formaldehyde	mg/mile		0.40	0.40
Acetaldehyde	mg/mile		1.14	1.14
ALTERNATE CASE, TIER I AND TIER II STANDARDS				
Gasoline, 8 psi RVP				
Evaporative VOC	grams/mile	0.27	0.25	0.125
Exhaust VOC	grams/mile	0.27	0.25	0.125
CO	grams/mile	2.81	2.81	1.70
NO_x	grams/mile	0.64	0.4	0.2
CO_2	grams/mile	317	278	241
SO_2	mg/mile	70	61	52
Benzene	mg/mile	1.7	1.6	0.79
1-3 Butadiene	mg/mile	0.13	0.12	0.06
Formaldehyde	mg/mile	0.27	0.25	0.12
Acetaldehyde	mg/mile	0.19	0.18	0.09
Reformulated Gasoline, 6.7 psi RVP				
Evaporative VOC	grams/mile		0.19	0.09
Exhaust VOC	grams/mile		0.19	0.09
CO	grams/mile		2.19	1.70
NO_x	grams/mile		0.4	0.2
CO_2	grams/mile		280	243
SO_2	mg/mile		52	45
Benzene	mg/mile		0.74	0.37
1-3 Butadiene	mg/mile		0.09	0.05
Formaldehyde	mg/mile		0.19	0.09
Acetaldehyde	mg/mile		0.13	0.06

Table E-14.
Projection of Emissions for Spark Ignited Engines (Cont'd)

Fuel/Pollutant	Units	1990	2000	2010
E10, Splash Blended		Conv. Base	Reform. Base	
Evaporative VOC	grams/mile	0.36	0.24	
Exhaust VOC	grams/mile	0.26	0.18	
CO	grams/mile	2.53	2.09	
NO_x	grams/mile	0.68	0.4	
CO_2	grams/mile	314	278	
SO_2	mg/mile	64	50	
Benzene	mg/mile	1.53	0.86	
1-3 Butadiene	mg/mile	0.12	0.11	
Formaldehyde	mg/mile	0.54	0.48	
Acetaldehyde	mg/mile	0.47	0.42	
E10, RVP Adjusted				
Evaporative VOC	grams/mile		0.19	0.09
Exhaust VOC	grams/mile		0.19	0.09
CO	grams/mile		2.09	1.70
NO_x	grams/mile		0.4	0.2
CO_2	grams/mile		278	241
SO_2	mg/mile		50	43
Benzene	mg/mile		0.86	0.42
1-3 Butadiene	mg/mile		0.11	0.05
Formaldehyde	mg/mile		0.48	0.24
Acetaldehyde	mg/mile		0.42	0.21
E85				
Evaporative VOC	grams/mile		0.16	0.08
Exhaust VOC	grams/mile		0.18	0.09
CO	grams/mile		2.09	1.70
NO_x	grams/mile		0.4	0.2
CO_2	grams/mile		259	209
SO_2	mg/mile		12	10
Benzene	mg/mile		0.38	0.19
1-3 Butadiene	mg/mile		0.05	0.03
Formaldehyde	mg/mile		0.36	0.18
Acetaldehyde	mg/mile		1.02	0.51
E95				
Evaporative VOC	grams/mile		0.14	0.07
Exhaust VOC	grams/mile		0.18	0.09
CO	grams/mile		2.09	1.70
NO_x	grams/mile		0.4	0.2
CO_2	grams/mile		259	209
SO_2	mg/mile		4.3	3.5
Benzene	mg/mile		0.34	0.17
1-3 Butadiene	mg/mile		0.04	0.02
Formaldehyde	mg/mile		0.36	0.18
Acetaldehyde	mg/mile		1.02	0.51

Table E-15.
Estimated Energy Density of Reformulated Gasoline

Component	Original Vol %	Original BTU/Gal	Reformulated Vol %	Reformulated BTU/Gal
Aromatics	34.4	43,707	21.6	27,440
Olefins	9.7	9,900	5.5	5,610
Benzene	1.6	2,040	0.8	1,020
Other	54.3	59,353	54.3	59,353
MTBE	0	0	15.0	14,034
Added Alkylate	0	0	2.8	3,131
Total	**100.0**	**115,000**	**100.0**	**110,588**

Table E-16.
Estimated Heating Values of Ethanol Blends
(BTU/Gallon, Lower Heating Value)

	Using Current Gasoline		Using Year-2000 Gasoline	
	BTU/Gal	Ratio E-Blend/Gasoline	BTU/Gal	Ratio E-Blend/Gasoline
Gasoline	115,000	--	110,600	--
Ethanol	76,000	0.66	76,000	0.69
E10	111,100	0.97	107,140	0.97
E85	81,850	0.71	81,190	0.73
E95	77,950	0.68	77,730	0.70

Table E-17.
Achievable New-Car Mileage Efficiencies
(Miles Per Gallon)

Fuel/Vehicle	1990	1995	2000	2005	2010
Conventional Gasoline	28.2	30.1	32.1	34.4	37.1
E10, Conventional Gasoline	27.6	29.5	31.5		
Reformulated Gasoline		28.9	30.8	33.0	35.6
E10, Reformulated Gasoline		28.3	30.2	32.3	
E85, Flexible Fuel Vehicle		22.5	24.0	25.7	
E85, Dedicated Vehicle				27.5	29.7

Table E-18.
Achievable New-Car Energy Efficiencies
(Miles Per Million BTU)

Fuel/Vehicle	1990	1995	2000	2005	2010
Conventional Gasoline	245	262	279	299	323
E10, Conventional Gasoline	248	266	282		
Reformulated Gasoline		262	279	299	323
E10, Reformulated Gasoline		266	282	303	
E85, Flexible Fuel Vehicle		276	294	315	
E85, Dedicated Vehicle				337	364

Table E-19.
Potential Diesel Truck Efficiencies for Ethanol and Diesel Fuel

	1990	2000	2010
BASE CASE			
Medium-Duty Trucks, Miles/Gallon			
Diesel Fuel	15.6	18.5	21.8
Ethanol*	9.1	11.4	13.3
Heavy-Duty Trucks, Miles/Gallon			
Diesel Fuel	5.8	6.5	7.1
Ethanol*	3.4	4.0	4.3
Medium-Duty Trucks, Miles/MMBTU			
Diesel Fuel	120	142	168
Ethanol*	120	150	175
Heavy-Duty Trucks, Miles/MMBTU			
Diesel Fuel	45	50	55
Ethanol*	45	53	57
ALTERNATE HEAVY-DUTY CASE			
Heavy-Duty Trucks, Miles/Gallon			
Diesel Fuel	5.3	5.7	6.1
Ethanol*	3.1	3.5	3.7
Heavy-Duty Trucks, Miles/MMBTU			
Diesel Fuel	41	44	47
Ethanol*	41	46	49

*E100

Table E-20.
Carbon Dioxide Emission Factors for Light-Duty Vehicles

Fuel	MPG	Sp. Gr.	Grams C Per Gram Fuel	gm CO_2 Per Mile
Gasoline				
1990	28.2	0.74	.866	317
2000	32.1	0.74	.866	278
2010	37.1	0.74	.866	241
Reformulated Gasoline				
2000	30.8	0.74	.838	280
2010	35.6	0.74	.838	243
E10, Conventional Gasoline				
1990	27.6	0.75	.830	314
2000	31.5	0.75	.830	275
E10, Reformulated Gasoline				
2000	30.2	0.75	.804	278
2010	34.9	0.75	.804	241
E85				
2000	24.0	0.78	.572	259
2010	29.7	0.78	.572	209
E95				
2000	22.9	0.79	.538	259
2010	28.3	0.79	.538	209

Table E-21.
Carbon Dioxide Emission Factors for Diesel Type Medium and Heavy-Duty Trucks

Vehicle/Fuel	Year	MPG	gm CO_2 Per Mile
	BASE CASE		
Medium Duty			
Diesel Fuel	1990	15.6	657
Diesel Fuel	2000	18.5	554
Diesel Fuel	2010	21.8	470
Ethanol*	1990	9.1	629
Ethanol*	2000	11.4	502
Ethanol*	2010	13.3	437
Heavy Duty			
Diesel Fuel	1990	5.8	1,760
Diesel Fuel	2000	6.5	1,580
Diesel Fuel	2010	7.1	1,440
Ethanol*	1990	3.4	1,680
Ethanol*	2000	4.0	1,430
Ethanol*	2010	4.3	1,330
	ALTERNATE HEAVY-DUTY CASE		
Heavy Duty			
Diesel Fuel	1990	5.3	1,940
Diesel Fuel	2000	5.7	1,800
Diesel Fuel	2010	6.1	1,710
Ethanol*	1990	3.1	1,840
Ethanol*	2000	3.5	1,630
Ethanol*	2010	3.7	1,550

*E100

REF. NO.	TEST PROCEDURE	NO. of CARS	FUEL TYPE	FUEL CONSUM. MPG	FUEL CONSUM. l/100 km	ENERGY ECONOMY miles/MMBTU	EtOH/GAS. RATIO miles/MMBTU
24		1	E95	11.90		152.65	1.027
24		1	E85	12.30		150.27	1.011
24		1	Gasoline	17.10		148.70	
25			E100		20.4	151.73	1.072
25			E100		20.4	151.73	1.072
25			Gasoline		14.3	143.05	
33	ECE	1	E100	23.54		309.77	1.067
33	ECE	1	Gasoline	33.39		290.34	
32	Non-FTP		E10 (190proof)		6.94	306.15	1.046
32	Non-FTP		E15 (190proof)		7.35	294.77	1.007
32	Non-FTP		E20 (190proof)		7.24	305.26	1.043
32	Non-FTP		E25 (190proof)		7.25	311.10	1.063
32	Non-FTP		Gasoline		6.99	292.65	
32	Non-FTP		E10 (190proof)		10.76	197.46	0.933
32	Non-FTP		E15 (190proof)		10.63	203.81	0.963
32	Non-FTP		E20 (190proof)		11.77	187.77	0.888
32	Non-FTP		E25 (190proof)		11.64	193.77	0.916
32	Non-FTP		Gasoline		9.67	211.55	
32	Non-FTP		E10 (190proof)		12.09	175.74	0.870
32	Non-FTP		E15 (190proof)		10.86	199.50	0.988
32	Non-FTP		E20 (190proof)		10.18	217.10	1.075
32	Non-FTP		E25 (190proof)		13.55	166.45	0.824
32	Non-FTP		Gasoline		10.13	201.94	
37		1 one cyl.	E14				1.114
37		1 one cyl.	Gasoline				
22	ECE		E25		10.73	208.29	1.110
22	ECE		Gasoline		10.9	187.67	
22	FTP-75	4	E95			164.35	1.099
22	FTP-75	4	Gasoline			149.57	
49		1	E85		8.4	342.13	1.154
49		1	Gasoline		6.9	296.47	
23		7	E100				1.110
47	Actual		E85				0.980
51	FTP-75	12	E95				1.074
51	FTP-75	1	Gasoline				
51	Actual	2	E100	8.75	.	115.13	1.051
51	Actual		Gasoline				
22	ECE City		E100		22.8	135.76	1.115
22	ECE 90km/h		E100		13.9	222.68	1.023
22	ECE 120 km/h		E100		17	182.07	1.041
22	ECE City		Gasoline		16.8	121.76	
22	ECE 90km/h		Gasoline		9.4	217.62	
22	ECE 120 km/h		Gasoline		11.7	174.84	

Exhibit E-1. Relative Efficiency of Spark Ignited Engines With Ethanol Fuels

REF. NO.	TEST PROCEDURE	NO. of CARS	FUEL TYPE	FUEL CONSUM. MPG	FUEL CONSUM. l/100 km	ENERGY ECONOMY miles/MMBTU	EtOH/GAS. RATIO miles/MMBTU
43		2	E10	12.10		108.912	0.935
43		2	Gasoline	13.40		116.526	
42	FTP City	5	E10	17.90		161.118	0.996
42	FTP City	5	Gasoline	18.60		161.746	
42	FTP City	3	E10	18.00		162.018	1.007
42	FTP City	3	Gasoline	18.50		160.876	
40	FTP City	3	E10	14.95		134.565	1.002
40	FTP City	3	Gasoline	15.44		134.266	
44	FTP-75	47	E10	21.67		195.052	1.027
44	FTP-75	47	Gasoline	21.83		189.834	
44	HFET	47	E10	30.13		271.200	1.021
44	HFET	47	Gasoline	30.55		265.663	
26	Actual	41	E10				0.995
26	Actual	197	E10				1.025
26	Actual	17	E10				0.983
53	Actual	5	E10	16.24		146.176	0.985
53	Actual	5	Gasoline	17.07		148.441	
53	Actual	5	E10	17.64		158.778	0.976
53	Actual	5	Gasoline	18.71		162.702	
53	Actual	5	E10	21.03		189.291	0.988
53	Actual	5	Gasoline	22.03		191.573	
54	UDDS	4	E8	27.88		249.191	1.003
54	UDDS	4	Gasoline	28.56		248.358	
57	FTP-75	1	E10	10.80		97.211	0.998
57	FTP-75	1	Gasoline	11.20		97.395	
57	FTP-75	1	E10	12.70		114.313	1.019
57	FTP-75	1	Gasoline	12.90		112.178	
57	FTP-75	1	E10	19.00		171.019	1.003
57	FTP-75	1	Gasoline	19.60		170.442	
57	FTP-75	1	E10	23.10		207.923	0.996
57	FTP-75	1	Gasoline	24.00		208.704	
57	FTP-75	1	E10	18.30		164.718	0.987
57	FTP-75	1	Gasoline	19.20		166.963	
58	FTP-75	1	E10	22.03		198.292	1.005
58	FTP-75	1	Gasoline	22.69		197.312	
58	FTP-75	1	E10	22.23		200.092	1.010
58	FTP-75	1	Gasoline	22.79		198.182	
58	FTP-75	1	E10	19.27		173.449	1.006
58	FTP-75	1	Gasoline	19.82		172.355	
58	FTP-75	1	E10	19.35		174.169	1.012
58	FTP-75	1	Gasoline	19.79		172.094	
58	FTP-75	1	E10	16.00		144.016	1.000
58	FTP-75	1	Gasoline	16.56		144.006	
58	FTP-75	1	E10	15.86		142.756	1.002
58	FTP-75	1	Gasoline	16.39		142.527	
58	FTP-75	1	E10	27.11		244.017	1.006
58	FTP-75	1	Gasoline	27.89		242.531	
58	FTP-75	1	E10	18.77		168.949	1.007
58	FTP-75	1	Gasoline	19.29		167.746	
60	Actual	53	E10				1.019

Exhibit E-2. Relative Efficiency of Spark Ignited Engines With E10 Fuels

REF. NO.	TEST PROCEDURE	NO. of ENGINES	FUEL TYPE	THERMAL EFFICIENCY %	EFFIC. therm. EtOH/DIES. RATIO	FUEL CONSUM. MPG	FUEL CONSUM. l/100 km	ENERGY ECONOMY miles/MMBTU	EtOH/DIES. RATIO miles/MMBTU
21		1	E100	38	1.086				
21		1	Diesel	35					
16	Actual	3 Buses	E100					76.24	1.057
16	Actual	3 Buses	Diesel					72.13	
35	Actual	1 PID	E100				70.9	43.55	1.050
35	Actual	1	Diesel				43.5	41.50	
35		1 PID	E100						1.042
46	Actual	30 Cars	E25			28		266.03	1.081
46	Actual	30 Cars	Diesel			32		246.14	
46	FTP-75	1	E25			32.73		310.97	1.076
46	FTP-75	1	Diesel			37.58		289.07	
34		1 Tractor	E100						1.020
50		1	E100		0.930				

Exhibit E-3. Relative Efficiency of Compression Ignition Engines With Ethanol Fuels

REF. NO.	TEST PROCEDURE	NO. of CARS	FUEL TYPE	CO g/mile	CO g/test	CO Vol. %	EtOH/GAS. RATIO
8	FTP-75	1	E100				0.160
8	FTP-75	1	E100				0.490
25	ECE 15/04		E100		82.00		1.281
25	ECE 15/04		E100		48.50		0.758
25	ECE 15/04		Premium		64.00		
24	FTP-75		E95	1.90			1.357
24	FTP-75		E85	1.80			1.286
24	FTP-75		Gasoline	1.40			
33	FTP-75		E100				0.660
37		1 one cyl.	E14			1.7	0.567
37		1 one cyl.	Gasoline			3	
22	ECE		E25		50.90		0.749
22	ECE		Gasoline		68.00		
22	ECE	1	E23	20.97			1.206
22	ECE	1	Gasoline	17.38			
22	ECE	1	E23	12.71			1.717
22	ECE	1	Gasoline	7.40			
22	FTP-75	4	E95	3.17			0.667
22	FTP-75	4	Gasoline	4.75			
22	ECE		E100		82.00		0.948
22	ECE		Gasoline		86.50		
23	FTP-75	8	E100	23.10			0.344
23	FTP-75	6	Gasoline	67.10			
23	FTP-75	7	E100	41.00			0.488
23	FTP-75	7	Gasoline	84.00			
23	FTP-75	1	E100	5.27			2.558
23	FTP-75	1	Gasoline	2.06			
23	FTP-75	1	E85	1.83			0.763
23	FTP-75	1	Gasoline	2.40			

Exhibit E-4. Carbon Monoxide Emissions From SI Engines

REF. NO.	TEST PROCEDURE	NO. of CARS	FUEL TYPE	NOx g/mile	NOx g/test	NOx ppm	EtOH/GAS. RATIO
8	FTP-75	1	E100				0.580
8	FTP-75	1	E100				0.800
25	ECE 15/04		E100		8.10		1.052
25	ECE 15/04		E100		4.10		0.532
25	ECE 15/04		Gasoline		7.70		
24	FTP-75	1	E95	0.50			0.758
24	FTP-75	1	E85	0.61			0.924
24	FTP-75	1	Gasoline	0.66			
33	FTP-75	1	E100				0.640
37		1 one cyl.	E14			2900	1.318
37		1 one cyl.	Gasoline			2200	
22	ECE		E25		12.70		1.095
22	ECE		Gasoline		11.60		
22	ECE	1	E23	2.94			0.729
22	ECE	1	Gasoline	4.04			
22	ECE	1	E23	2.96			0.974
22	ECE	1	Gasoline	3.04			
22	FTP-75	4	E95	0.49			0.700
22	FTP-75	4	Gasoline	0.70			
22	ECE		E100		8.10		0.648
22	ECE		Gasoline		12.50		
23	FTP-75	8	E100	2.08			1.137
23	FTP-75	6	Gasoline	1.83			
23	FTP-75	7	E100	3.10			0.756
23	FTP-75	7	Gasoline	4.10			
23	FTP-75	1	E100	1.83			0.330
23	FTP-75	1	Gasoline	5.55			
23	FTP-75	1	E85	7.87			0.970
23	FTP-75	1	Gasoline	8.11			

Exhibit E-5. Nitrogen Oxide Emissions From SI Engines

Draft Report: Do not cite, copy, or quote.

REF. NO.	TEST PROCEDURE	NO. of CARS	FUEL TYPE	VOC g/mile	HC g/mile	HC ppm	HC g/test	ROG g/mile	EtOH/GAS. RATIO (ORG.)	EtOH mg/mile	EtOH/GAS RATIO (EtOH)	MeOH mg/mile	EtOH/GAS RATIO(MeOH)
8	FTP-75	1	E100						0.450				
8	FTP-75	1	E100						0.690				
25	ECE 15/04		E100				8.1		0.794				
25	ECE 15/04		E100				4.8		0.471				
25	ECE 15/04		Gasoline				10.2						
24	FTP-75	1	E95					0.94	2.686	742.70			
24	FTP-75	1	E85					1.02	2.914	783.40			
24	FTP-75	1	Gasoline					0.35					
33	FTP-75		E100						0.400				
37		1 one cyl.	E14			185			0.771				
37		1 one cyl.	Gasoline			240							
22	ECE		E25				8.4		1.024				
22	ECE		Gasoline				8.2						
22	ECE	1	E23		1.96				0.819	205.95		9.33	1.758
22	ECE	1	Gasoline		2.40							5.31	
22	ECE	1	E23		2.62				1.264	363.63		11.75	2.433
22	ECE	1	Gasoline		2.08							4.83	
22	FTP-75	4	E95		0.22				0.647				
22	FTP-75	4	Gasoline		0.34								
22	ECE		E100				8.1		0.942				
22	ECE		Gasoline				8.6						
22	FTP-75	1	E30	0.22					0.759	30.00			
22	FTP-75	1	E70	0.3					1.034	50.00			
22	FTP-75	1	E100	0.8					2.759	650.00			
22	FTP-75	1	Gasoline	0.29									
23	FTP-75	8	E100		1.98				0.315				
23	FTP-75	6	Gasoline		6.29								
23	FTP-75	7	E100		3.90				0.368				
23	FTP-75	7	Gasoline		10.60								
23	FTP-75	1	E100		0.71				1.868				
23	FTP-75	1	Gasoline		0.38								
23	FTP-75	1	E85		0.14				0.737				
23	FTP-75	1	Gasoline		0.19								

Exhibit E-6. Exhaust VOC Emissions From SI Engines

REF. NO.	TEST PROCEDURE	NO. of CARS	FUEL TYPE	VOC g/test	EtOH/GAS RATIO(VOC)	ROG g/mile	EtOH/GAS RATIO (ROG)	EtOH g/test	EtOH/GAS RATIO(EtOH)
24	FTP SHED	1	E95			0.03	0.075		
24	FTP SHED	1	E85			0.05	0.125		
24	FTP SHED	1	Gasoline			0.4			
51		2	E95	1.78					
51		4	E95	1.99					

Exhibit E-7. Evaporative VOC Emissions From SI Engines

REF. NO.	TEST PROCEDURE	NO. of CARS	FUEL TYPE	ACETALDE-HYDE mg/mile	EtOH/GAS RATIO (ACET.)	FORMALDE-HYDE mg/mile	EtOH/GAS RATIO (FORM.)	TOTAL ALDEHYDE mg/mile	EtOH/GAS. RATIO (TOT.)
24	FTP-75	1	E95	60.97	40.112	12.26	1.596		
24	FTP-75	1	E85	52.51	34.546	10.64	1.385		
24	FTP-75	1	Gasoline	1.52		7.68			
22	ECE	1	E23	25.74		38.78	1.030		
22	ECE	1	Gasoline			37.65			
22	ECE	1	E23	36.36		73.53	1.242		
22	ECE	1	Gasoline			59.21			
51	FTP-75	8	E100					253	5.383
51	FTP-75	6	Gasoline					47	

Exhibit E-8. Aldehyde Emissions From SI Engines

REF. NO.	TEST	NO. of	FUEL	EHTYL-	ETH/GAS		ETH/GAS		ETH/GAS		ETH/GAS		ETH/GAS
	PROCEDURE	CARS	TYPE	BENZ.	(ETHYL-	BENZ.	(BENZ)	TOLU.	(TOLU.)	PAH	(PAH)	BaP	(Bap)
				mg/mile	BENZ.)	mg/mile		mg/mile		ug/mile		ug/mile	
22	ECE	1	E23	186.64	0.678	129.20	0.730	240	0.714	101.37	0.656	2.57	0.941
22	ECE	1	Gasoline	275.14		176.99		336.28		154.46		2.74	
22	ECE	1	E23	270.31	1.302	147.06	0.992	325.02	1.154	75.62	1.343	1.38	1.720
22	ECE	1	Gasoline	207.56		148.19		281.58		56.32		0.80	
24			E95	0.80	0.297	3.10	0.440	4.85	0.090				
24		1	E85	1.74	0.647	3.42	0.486	16.28	0.301				
24		1	Gasoline	2.69		7.04		54.11					

Exhibit E-9. Other Emissions From SI Engines

REF. NO.	TEST PROCEDURE	NO. of ENGINES	FUEL TYPE	CO g/mile	CO g/kWh	RANGE g/kWh	EtOH/DIES. RATIO
18	Hot Transient	1	E160		7.92		2.859
18	Hot Transient	1	E160		10.02		3.617
18	Hot Transient	1	E180		8.45		3.051
18	Hot Transient	1	E95		6.2		2.238
18	Hot Transient	1	E85		8.65		3.123
18/19	Hot Transient	1	Diesel		2.77		
19	Hot Transient	1	E95		8.13		2.935
19	Hot Transient	1	Diesel		2.77		
21			E100		0.06	0-0.12	0.008
21			Diesel		15	2.0-28	
30	ECE R49	4 Buses	E95		0.1		
46	FTP-75	1	E25	0.84			1.024
46	FTP-75	1	Diesel	0.82			
50		1 SAD	E100				1.450

Exhibit E-10. Carbon Monoxide Emissions From CI Engines

REF. NO.	TEST PROCEDURE	NO. of ENGINES	FUEL TYPE	NOx g/kWh	RANGE g/kWh	NOx g/mile	NOx ppm	EtOH/DIES. RATIO
18	Hot Transient	1	E160	2.37				0.369
18	Hot Transient	1	E160	1.44				0.224
18	Hot Transient	1	E180	2.67				0.415
18	Hot Transient	1	E95	4.81				0.748
18	Hot Transient	1	E85	4.49				0.698
18/19	Hot Transient	1	Diesel	6.43				
19	Hot Transient	1	E95	4.21				0.655
19	Hot Transient	1	Diesel	6.43				
21		1	E100	12	8.0-16			1.043
21		1	Diesel	11.5	7.0-16			
30	ECE R49	4 Buses	E95	4.5				
46	FTP-75	1	E25			1.08		0.982
46	FTP-75	1	Diesel			1.10		
50		1 SAD	E100				525.00	0.875
50		1 SAD	Diesel				600.00	

Exhibit E-11. Nitrogen Oxide Emissions From CI Engines

REF. NO.	TEST PROCEDURE	NO. of ENGINES	FUEL TYPE	HC ppm	HC g/mile	HC g/kWh	HC RANGE	OMHE g/kWh	EtOH/GAS. RATIO (ORG.)	EtOH g/kWh	EtOH ppm
18	Hot Transient	1	E160					2.29	4.164	3.22	
18	Hot Transient	1	E160					3.46	6.291	5.19	
18	Hot Transient	1	E180					2.71	4.927	4.09	
18	Hot Transient	1	E95					2.71	4.927	4.1	
18	Hot Transient	1	E85					2.44	4.436	2.86	
18/19	Hot Transient	1	Diesel					0.55			
19	Hot Transient	1	E95					1.78	3.236		
19	Hot Transient	1	Diesel					0.55			
21		1	E100			0.6	0.1-1.1		0.300		
21		1	Diesel			2	0.3-3.7				
30	ECE R49	4 Buses	E95			0.2					
46	FTP-75	1	E25		0.3				1.500		
46	FTP-75	1	Diesel		0.2						
50		1 SAD	E100	200					1.176		45
50		1 SAD	Diesel	170							0

Exhibit E-12. VOC Emissions From CI Engines

REF. NO.	TEST PROCEDURE	NO. of ENGINES	FUEL TYPE	ACETALDE-HYDE g/kWh	FORMALDE-HYDE g/kWh	TOTAL ALDEHYDE g/kWh	TOTAL ALDEHYDE mg/mile	EtOH/DIES. RATIO (TOT.)
18	Hot Transient	1	E160	0.14	0.09	0.23		
18	Hot Transient	1	E160	0.22	0.13	0.37		
18	Hot Transient	1	E180	0.19	0.1	0.3		
18	Hot Transient	1	E95	0.21	0.11	0.33		
18	Hot Transient	1	E85	0.19	0.12	0.33		
46	FTP-75	1	E25				71	1.578
46	FTP-75	1	Diesel				45	

Exhibit E-13. Aldehyde Emissions From CI Engines

REF. NO.	TEST PROCEDURE	NO. of ENGINES	FUEL TYPE	PM-10 g/kWh	PM-10 g/mile	EtOH/DIES. RATIO (PM)
18	Hot Transient	1	E160	0.13		0.394
18	Hot Transient	1	E160	0.11		0.333
18	Hot Transient	1	E180	0.12		0.364
18	Hot Transient	1	E95	0.18		0.545
18	Hot Transient	1	E85	0.41		1.242
18/19	Hot Transient	1	Diesel	0.33		
19	Hot Transient	1	E95	0.167		0.506
19	Hot Transient	1	Diesel	0.33		
30	ECE R49	4 Buses	E95	0.05		
46	FTP-75	1	E25		0.13	0.650
46	FTP-75	1	Diesel		0.20	

Exhibit E-14. Particulate Emissions From CI Engines

REF. NO.	TEST PROCEDURE	NO. of ENGINES	FUEL TYPE	PAH ug/mile	ETH/DIES (PAH)	BaP ug/mile	ETH/DIES (Bap)
46	FTP-75	1	E25	80.00	0.615		0.270
46	FTP-75	1	Diesel	130.00			

Exhibit E-15. Other Emissions From CI Engines

REF. NO.	TEST PROCEDURE	NO. of CARS	FUEL TYPE	CO g/mile	CO Vol. %	EtOH/GAS. RATIO
20	FTP-75	14	E10	3.62		0.743
20	FTP-75	14	E10 RVPadj	2.70		0.554
20	FTP-75	14	E10 RVPadj	3.70		0.760
20	FTP-75	14	Gasoline	4.87		
37		1 one cyl	E10		2.20	0.733
37		1 one cyl.	Gasoline		3.00	
41	FTP-75	1	E10	12.40		0.488
41	FTP-75	1	Gasoline	25.40		
40	FTP-75	1	E10	6.13		0.739
40	FTP-75	1	Gasoline	8.52		
40	FTP-75	1	E10	0.91		0.867
40	FTP-75	1	Gasoline	1.05		
40	FTP-75	1	E10	2.99		1.128
40	FTP-75	1	Gasoline	2.65		
42	FTP-75	5	E10	4.66		0.544
42	FTP-75	5	Gasoline	8.56		
42	FTP-75	3	E10	4.55		0.730
42	FTP-75	3	Gasoline	6.23		
43	FTP-75	1	E10	25.50		0.955
43	FTP-75	1	Gasoline	26.70		
43	FTP-75	1	E10	7.80		0.614
43	FTP-75	1	Gasoline	12.70		
26	FTP-75	2	E10	2.00		0.571
26	FTP-75	2	Gasoline	3.50		
26	FTP-75	1	E10	2.30		0.657
26	FTP-75	1	Gasoline	3.50		
44	FTP-75	5	E10	29.50		0.727
44	FTP-75	5	Gasoline	40.60		
44	FTP-75	7	E10	19.10		0.586
44	FTP-75	7	Gasoline	32.60		
44	FTP-75	8	E10	11.70		0.560
44	FTP-75	8	Gasoline	20.90		
44	FTP-75	11	E10	11.10		0.750
44	FTP-75	11	Gasoline	14.80		
44	FTP-75	12	E10	9.20		0.748
44	FTP-75	12	Gasoline	12.30		
44	FTP-75	4	E10	5.50		0.640
44	FTP-75	4	Gasoline	8.60		
54	UDDS	4	E10	7.11		0.992
54	UDDS	4	Gasoline	7.17		

Exhibit E-16. Carbon Monoxide, E10 In SI Engines

REF. NO.	TEST PROCEDURE	NO. of CARS	FUEL TYPE	CO g/mile	CO Vol. %	EtOH/GAS. RATIO
57	FTP-75	1	E10	138.00		0.958
57	FTP-75	1	Gasoline	144.00		
57	FTP-75	1	E10	1.14		0.462
57	FTP-75	1	Gasoline	2.47		
57	FTP-75	1	E10	5.94		0.834
57	FTP-75	1	Gasoline	7.12		
57	FTP-75	1	E10	1.95		0.759
57	FTP-75	1	Gasoline	2.57		
57	FTP-75	1	E10	2.94		0.689
57	FTP-75	1	Gasoline	4.27		
58	FTP-75	1	E10	0.692		0.925
58	FTP-75	1	Gasoline	0.748		
58	FTP-75	1	E10	0.787		0.778
58	FTP-75	1	Gasoline	1.012		
58	FTP-75	1	E10	0.881		0.999
58	FTP-75	1	Gasoline	0.882		
58	FTP-75	1	E10	0.768		0.956
58	FTP-75	1	Gasoline	0.803		
58	FTP-75	1	E10	1.156		1.157
58	FTP-75	1	Gasoline	0.999		
58	FTP-75	1	E10	1.527		0.988
58	FTP-75	1	Gasoline	1.545		
58	FTP-75	1	E10	1.985		0.886
58	FTP-75	1	Gasoline	2.240		
58	FTP-75	1	E10	0.626		0.906
58	FTP-75	1	Gasoline	0.691		
62	UDDS	1	E10	1.30		0.448
62	UDDS	1	Gasoline	2.90		
62	UDDS	1	E10	0.90		0.563
62	UDDS	1	Gasoline	1.60		
62	UDDS	1	E10	5.97		1.053
62	UDDS	1	Gasoline	5.67		
60	FTP-75	53	E10			0.737
60	FTP-75	23	E10			0.607
60	FTP-75	6	E10			0.799
60	FTP-75	3	E10			0.755
60	FTP-75	7	E10			0.806
69	FTP-75	20	E10			0.870

Exhibit E-16. Carbon Monoxide, E10 In SI Engines (Cont'd)

REF. NO.	TEST PROCEDURE	NO. of CARS	FUEL TYPE	NOx g/mile	NOx ppm	EtOH/GAS. RATIO
20	FTP-75	14	E10	1.18		1.146
20	FTP-75	14	E10 RVPadj	1.26		1.223
20	FTP-75	14	E10 RVPadj	1.24		1.204
20	FTP-75	14	Gasoline	1.03		
37	1 one cyl.	1 one cyl.	E10		2700.00	1.227
37	1 one cyl.	1 one cyl.	Gasoline		2200.00	
41	FTP-75	1	E10	1.50		0.789
41	FTP-75	1	Gasoline	1.90		
40	FTP-75	1	E10	1.39		0.777
40	FTP-75	1	Gasoline	1.79		
40	FTP-75	1	E10	0.53		0.930
40	FTP-75	1	Gasoline	0.57		
40	FTP-75	1	E10	0.89		1.085
40	FTP-75	1	Gasoline	0.82		
42	FTP-75	5	E10	1.63		1.000
42	FTP-75	5	Gasoline	1.63		
42	FTP-75	3	E10	0.59		1.229
42	FTP-75	3	Gasoline	0.48		
43	FTP-75	1	E10	1.48		
43	FTP-75	1	Gasoline			
43	FTP-75	1	E10	2.10		1.544
43	FTP-75	1	Gasoline	1.36		
26	FTP-75	2	E10	1.10		0.917
26	FTP-75	2	Gasoline	1.20		
26	FTP-75	1	E10	0.20		1.333
26	FTP-75	1	Gasoline	0.15		
44	FTP-75	5	E10	2.20		1.100
44	FTP-75	5	Gasoline	2.00		
44	FTP-75	7	E10	2.20		0.957
44	FTP-75	7	Gasoline	2.30		
44	FTP-75	8	E10	1.40		1.167
44	FTP-75	8	Gasoline	1.20		
44	FTP-75	11	E10	0.90		1.286
44	FTP-75	11	Gasoline	0.70		
44	FTP-75	12	E10	0.90		1.125
44	FTP-75	12	Gasoline	0.80		
44	FTP-75	4	E10	0.60		1.000
44	FTP-75	4	Gasoline	0.60		
54	UDDS	4	E8	0.57		0.905
54	UDDS	4	Gasoline	0.63		

Exhibit E-17. Nitrogen Oxides, E10 In SI Engines

REF. NO.	TEST PROCEDURE	NO. of CARS	FUEL TYPE	NOx g/mile	NOx ppm	EtOH/GAS. RATIO
57	FTP-75	1	E10	2.82		0.986
57	FTP-75	1	Gasoline	2.86		
57	FTP-75	1	E10	1.81		1.084
57	FTP-75	1	Gasoline	1.67		
57	FTP-75	1	E10	1.88		1.000
57	FTP-75	1	Gasoline	1.88		
57	FTP-75	1	E10	0.26		1.000
57	FTP-75	1	Gasoline	0.26		
57	FTP-75	1	E10	1.38		1.243
57	FTP-75	1	Gasoline	1.11		
58	FTP-75	1	E10	0.545		0.949
58	FTP-75	1	Gasoline	0.574		
58	FTP-75	1	E10	0.424		0.918
58	FTP-75	1	Gasoline	0.462		
58	FTP-75	1	E10	0.326		1.045
58	FTP-75	1	Gasoline	0.312		
58	FTP-75	1	E10	0.366		0.971
58	FTP-75	1	Gasoline	0.377		
58	FTP-75	1	E10	0.692		0.977
58	FTP-75	1	Gasoline	0.708		
58	FTP-75	1	E10	0.640		0.904
58	FTP-75	1	Gasoline	0.708		
58	FTP-75	1	E10	0.576		1.063
58	FTP-75	1	Gasoline	0.542		
58	FTP-75	1	E10	0.540		0.917
58	FTP-75	1	Gasoline	0.589		
62	UDDS	1	E10	0.88		8.800
62	UDDS	1	Gasoline	0.10		
62	UDDS	1	E10	0.77		1.013
62	UDDS	1	Gasoline	0.76		
62	UDDS	1	E10	0.64		0.889
62	UDDS	1	Gasoline	0.72		
60		53	E10			0.943
69	FTP-75	20	E10			1.050

Exhibit E-17. Nitrogen Oxides, E10 In SI Engines (Cont'd)

REF. NO.	TEST PROCEDURE	NO. of CARS	FUEL TYPE	VOC g/mile	HC g/mile	HC ppm	EtOH/GAS. RATIO (ORG.)	EtOH mg/mile	EtOH/GAS RATIO (EtOH)	MeOH mg/mile	EtOH/GAS RATIO(MeOH)
20	FTP-75	14	E10	0.31			1.107	8.02	4.051		
20	FTP-75	14	E10 RVPadj	0.25			0.893	6.19	3.126		
20	FTP-75	14	E10 RVPadj	0.28			1.000	5.43	2.742		
20	FTP-75	14	Gasoline	0.28				1.98			
37	1 one cyl.	1 one cyl.	E10			205.00	0.854				
37	1 one cyl.	1 one cyl.	Gasoline			240.00					
40	FTP-75	1	E10		0.53		0.815				
40	FTP-75	1	Gasoline		0.65						
40	FTP-75	1	E10		0.20		1.000				
40	FTP-75	1	Gasoline		0.20						
40	FTP-75	1	E10		0.32		1.231				
40	FTP-75	1	Gasoline		0.26						
41	FTP-75	1	E10		1.40		0.933				
41	FTP-75	1	Gasoline		1.50						
42	FTP-75	5	E10		0.58		0.682				
42	FTP-75	5	Gasoline		0.85						
42	FTP-75	3	E10		0.39		0.907				
42	FTP-75	3	Gasoline		0.43						
43	FTP-75	1	E10		2.66		0.695				
43	FTP-75	1	Gasoline		3.83						
43	FTP-75	1	E10		0.55		1.100				
43	FTP-75	1	Gasoline		0.50						
26	FTP-75	2	E10		0.50		1.000				
26	FTP-75	2	Gasoline		0.50						
26	FTP-75	1	E10		0.17		0.680				
26	FTP-75	1	Gasoline		0.25						
44	FTP-75	5	E10		2.11		0.946				
44	FTP-75	5	Gasoline		2.23						
44	FTP-75	7	E10		1.68		0.753				
44	FTP-75	7	Gasoline		2.23						
44	FTP-75	8	E10		0.90		0.667				
44	FTP-75	8	Gasoline		1.35						
44	FTP-75	11	E10		0.68		0.895				
44	FTP-75	11	Gasoline		0.76						
44	FTP-75	12	E10		0.62		0.838				
44	FTP-75	12	Gasoline		0.74						
44	FTP-75	4	E10		0.37		1.000				
44	FTP-75	4	Gasoline		0.37						
54	UDDS	4	E8		0.41		1.061	17.48			
54	FTP-75	4	Gasoline		0.39						

Exhibit E-18. VOC, E10 In SI Engines

REF. NO.	TEST PROCEDURE	NO. of CARS	FUEL TYPE	VOC g/mile	HC g/mile	HC ppm	EtOH/GAS. RATIO (ORG.)	EtOH mg/mile	EtOH/GAS RATIO (EtOH)	MeOH mg/mile	EtOH/GAS RATIO(MeOH)
57	FTP-75	1	E10		7.86		0.978	44.80			
57	FTP-75	1	Gasoline		8.04						
57	FTP-75	1	E10		1.07		1.189	3.00			
57	FTP-75	1	Gasoline		0.90						
57	FTP-75	1	E10		0.78		1.026	18.10			
57	FTP-75	1	Gasoline		0.76						
57	FTP-75	1	E10		0.14		0.737				
57	FTP-75	1	Gasoline		0.19						
57	FTP-75	1	E10		0.20		0.741	8.50			
57	FTP-75	1	Gasoline		0.270						
58	FTP-75	1	E10		0.101		0.944				
58	FTP-75	1	Gasoline		0.107						
58	FTP-75	1	E10		0.098		0.838				
58	FTP-75	1	Gasoline		0.117						
58	FTP-75	1	E10		0.215		0.995				
58	FTP-75	1	Gasoline		0.216						
58	FTP-75	1	E10		0.185		0.995				
58	FTP-75	1	Gasoline		0.186						
58	FTP-75	1	E10		0.208		1.078				
58	FTP-75	1	Gasoline		0.193						
58	FTP-75	1	E10		0.194		1.016				
58	FTP-75	1	Gasoline		0.191						
58	FTP-75	1	E10		0.142		0.953				
58	FTP-75	1	Gasoline		0.149						
58	FTP-75	1	E10		0.155		1.069				
58	FTP-75	1	Gasoline		0.145						
62	UDDS	1	E10		0.18		1.000	6.10			
62	UDDS	1	Gasoline		0.18						
62	UDDS	1	E10		0.21		0.724	38.00			
62	UDDS	1	Gasoline		0.29						
62	UDDS	1	E10		0.48		1.021	18.80			
62	UDDS	1	Gasoline		0.47						
60		53	E10				0.955				
69	FTP-75	20	E10				0.950				

Exhibit E-18. VOC, E10 In SI Engines (Cont'd)

REF. NO.	TEST PROCEDURE	NO. of CARS	FUEL TYPE	VOC g/test	EtOH/GAS RATIO(VOC)	ROG g/mile	EtOH/GAS RATIO (ROG)	EtOH g/test	EtOH/GAS RATIO(EtOH)	THC grams	EtOH\GAS RATIO (THC)
20	FTP SHED	14	E10	9.51	1.651			0.8	13.333		
20	FTP SHED	14	E10 RVPadj	7.02	1.219			0.85	14.167		
20	FTP SHED	14	E10 RVPadj	10.12	1.757			0.95	15.833		
20	FTP SHED	14	Gasoline	5.76				0.06			
40	SHED	1	E10	3.28	1.090						
40	SHED	1	Gasoline	3.01							
40	SHED	1	E10	3.96	1.338						
40	SHED	1	Gasoline	2.96							
42	SHED	5	E10	4.00	1.429						
42	SHED	5	Gasoline	2.80							
42	SHED	3	E10	2.30	1.150						
42	SHED	3	Gasoline	2.00							
43	SHED	1	E10					6.510	130.200	23.41	2.124
43	SHED	1	Gasoline					0.050		11.02	
43	SHED	1	E10					0.910	30.333	6.08	3.948
43	SHED	1	Gasoline					0.030		1.54	
44	SHED	4	E10		1.368						
52	SHED	11	E10		1.550						
52	SHED	1	E10			0.19	1.583				
52	SHED	1	Gasoline			0.12					
54	Diurnal	1	E10	0.70	0.636						
54	Diurnal	1	Gasoline	1.10							
57	SHED	1	E10					0.280	25.455	6.06	1.018
57	SHED	1	Gasoline					0.011		5.95	
57	SHED	1	E10					1.500	13.043	26.5	1.373
57	SHED	1	Gasoline					0.115		19.3	
57	SHED	1	E10					0.300	30.000	2.84	1.315
57	SHED	1	Gasoline					0.010		2.16	
57	SHED	1	E10					0.040	8.000	0.67	1.523
57	SHED	1	Gasoline					0.005		0.44	
57	SHED	1	E10					0.112	9.333	0.42	1.235
57	SHED	1	Gasoline					0.012		0.34	
69	Diurnal	20	E10								1.300
69	Hot Soak	20	E10								1.500

Exhibit E-19. Evaporative VOC, E10 In SI Engines

REF. NO.	TEST PROCEDURE	NO. of CARS	FUEL TYPE	ACETALDE-HYDE mg/mile	EtOH/GAS RATIO (ACET.)	FORMALDE-HYDE mg/mile	EtOH/GAS RATIO (FORM.)	TOTAL ALDEHYDE mg/mile	EtOH/GAS. RATIO (TOT.)
20	FTP-75	14	E10					12.62	1.462
20	FTP-75	14	E10 RVPadj					11.26	1.305
20	FTP-75	14	E10 RVPadj					12.99	1.505
20	FTP-75	14	Gasoline					8.63	
42		5	E10					18	1.000
42		5	Gasoline					18	
42		3	E10					8	2.000
42		3	Gasoline					4	
44	FTP-75	15	E10					12.59	1.204
44	FTP-75	15	Gasoline					10.46	
54	UDDS	4	E8	3.09	2.006	4.08	1.020	8.86	1.170
54	UDDS	4	Gasoline	1.54		4.00		7.57	
52		1	E10	3.56	2.000	13.51	1.499		
52		1	Gasoline	1.78		9.01			
57	FTP-75	1	E10	26.60	1.364	80.30	0.955	144	0.947
57	FTP-75	1	Gasoline	19.50		84.10		152	
57	FTP-75	1	E10	22.40	2.055	44.40	1.401	84.2	1.493
57	FTP-75	1	Gasoline	10.90		31.70		56.4	
57	FTP-75	1	E10	7.00	3.043	5.90	1.054	16.1	1.626
57	FTP-75	1	Gasoline	2.30		5.60		9.9	
57	FTP-75	1	E10	2.60	1.857	4.10	1.323	8.7	1.426
57	FTP-75	1	Gasoline	1.40		3.10		6.1	
57	FTP-75	1	E10	2.20	2.750	3.80	1.152	6.4	1.422
57	FTP-75	1	Gasoline	0.80		3.30		4.5	
62	UDDS	1	E10			7.00	1.842		
62	UDDS	1	Gasoline			3.80			
62	UDDS	1	E10			18.00	1.837		
62	UDDS	1	Gasoline			9.80			
62	UDDS	1	E10			17.00	0.850		
62	UDDS	1	Gasoline			20.00			
69	FTP-75	20	E10		2.590		1.190		

Exhibit E-20. Aldehydes, E10 In SI Engines

REF. NO.	TEST PRO-CEDURE	NO. of CARS	FUEL TYPE	ETHYL-BENZ. mg/mile	TH/GAS (ETHYL-BENZ.)	BENZ. mg/mile	ETH/GAS (BENZ)	TOLU. mg/mile	ETH/GAS (TOLU.)	XYLENE mg/mile	ETH/GA (XYL.)	1,3BUTA-DIENE mg/mile	TH/GAS (1,3BUT.)
52		1	E10	3.04	0.965	7.96	0.964	61.17	0.964	11.87	0.964		
52		1	Gasoline	3.15		8.26		63.48		12.31			
54		4	E8			16.01	0.841	17.30	0.825	13.57	0.868	0.76	0.905
54		4	Gasoline			19.03		20.97		15.64		0.84	
57		1	E10			332.00	0.789	489.00	0.496	341.20	0.519	68	1.126
57		1	Gasoline			421.00		986.00		658.00		60.4	
57		1	E10			13.20	0.763	23.80	0.464	22.50	0.618	1.7	1.133
57		1	Gasoline			17.30		51.30		36.40		1.5	
57		1	E10			21.20	0.797	32.10	0.413	25.20	0.509	1.1	0.846
57		1	Gasoline			26.60		77.80		49.50		1.3	
57		1	E10			6.10	0.570	9.20	0.391	4.50	0.349	0.8	1.000
57		1	Gasoline			10.70		23.50		12.90		0.8	
57		1	E10			8.00	0.571	14.10	0.379	13.00	0.421	0.8	1.000
57		1	Gasoline			14.00		37.20		30.90		0.8	
69	FTP	20	E10				0.880						0.940

Exhibit E-21. Other Emissions, E10 In SI Engines