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A Comparison of Estimates of Cost-Effectiveness of Alternative Fuels and Vehicles for Reducing Emissions

G. R. Hadder

MANAGED BY
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A COMPARISON OF ESTIMATES OF COST-EFFECTIVENESS OF ALTERNATIVE FUELS AND VEHICLES FOR REDUCING EMISSIONS

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ACRONYMS AND ABBREVIATIONS

AF	Alternative fuel
AFV	Alternative fuel vehicle
API	American Petroleum Institute
ASTM	American Society for Testing and Materials
BTU	British thermal unit
CAAA	Clean Air Act Amendments of 1990
Cal	California
CARB	California Air Resources Board
CER	Cost-effectiveness ratio
CG	Conventional gasoline
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
ded	Dedicated fuel vehicle
df	Dual-fueled vehicle
DOE	Department of Energy
EPA	Environmental Protection Agency
EPACT	Energy Policy Act of 1992
EV	Electric vehicle
E85	Mixture of 85 percent ethanol in gasoline
E95	Mixture of 95 percent ethanol in gasoline
E200	The cumulative volume percent evaporated at 200°F in ASTM test D86-87: Distillation of Petroleum Products

E300	The cumulative volume percent evaporated at 300°F in ASTM test D86-87: Distillation of Petroleum Products
F	Fahrenheit
ffv	Flexible-fueled vehicle
gal	Gallon
GAO	Government Accounting Office
GHG	Greenhouse gas
gm/mi	Grams per mile
HC	Hydrocarbon
LNG	Liquified natural gas
LPG	Liquified petroleum gas
M85	Mixture of 85 percent methanol in gasoline
M100	Neat methanol
NAS	National Academy of Sciences
NMOG	Non-methane organic gas
NOx	Oxides of nitrogen
NPC	National Petroleum Council
NPRA	National Petroleum Refiners Association
ORNL	Oak Ridge National Laboratory
PADD	Petroleum Administration for Defense District
psi	Pounds per square inch
Reg-Neg	Negotiated rule making
RFG	Reformulated gasoline
RVP	Reid vapor pressure
RYM	Refinery Yield Model

S. Cal	Southern California
SO_2	Sulfur dioxide
TAP	Toxic air pollutant
TMC	Turner, Mason and Company
ULEV	Ultra low emission vehicle
VOC	Volatile organic compound
ZEV	Zero emission vehicle
ϕ	Phase

ABSTRACT

The cost-effectiveness ratio (CER) is a measure of the monetary value of resources expended to obtain reductions in emissions of air pollutants. Properly used, the CER can lead to selection of the most effective sequence of pollution reduction options. Derived with different methodologies and technical assumptions, CER estimates for alternative fuel vehicles (AFVs) have varied widely among previous studies. In one of several explanations of CER differences, this report uses a consistent basis for fuel price to re-estimate CERs for AFVs in reduction of emissions of criteria pollutants, toxics, and greenhouse gases. The re-estimated CERs for a given fuel type have considerable differences due to non-fuel costs and emissions reductions, but the CERs do provide an ordinal sense of cost-effectiveness. The category with CER less than $5,000 per ton includes compressed natural gas and liquified petroleum gas vehicles; and E85 flexible-fueled vehicles (with fuel mixture of 85 percent cellulose-derived ethanol in gasoline). The E85 system would be much less attractive if corn-derived ethanol were used. Furthermore, the CER for E85 (corn-derived) is higher with higher values placed on the reduction of greenhouse gas emissions. CER estimates are relative to conventional vehicles fueled with Phase 1 California reformulated gasoline (RFG). The California Phase 2 RFG program will be implemented before significant market penetration by AFVs. CERs could be substantially greater if they are calculated incremental to the Phase 2 RFG program. Regression analysis suggests that different assumptions across studies can sometimes have predictable effects on the CER estimate of a particular AFV type. However, the relative differences in cost and emissions reduction assumptions can be large, and the effect of these differences on the CER estimate is often not predictable. Decomposition of CERs suggests that methodological differences can make large contributions to CER differences among studies. Resolution of CER differences could require the community of analysts and policy makers to establish methodological ground rules and to agree on premises for determination of critically important technical characteristics such as vehicle emissions profiles.

A COMPARISON OF ESTIMATES OF COST-EFFECTIVENESS OF ALTERNATIVE FUELS AND VEHICLES FOR REDUCING EMISSIONS

1. INTRODUCTION

The development of alternative transportation fuels is driven by national concerns about growing U.S. dependence on imported oil, declining urban air quality, and a negative U.S. trade balance (DOE, 1993/1994).

The transportation sector accounts for about two-thirds of total petroleum use and one-fourth of total energy consumption in the U.S. There is nearly a one-to-one relationship between additional gasoline consumption and increased use of imported oil by the U.S. At $60 billion per year, U.S. oil import expenditures account for about 60 percent of the merchandise trade deficit. Displacing imported oil by using domestically-produced alternative fuels (AFs) could reduce the trade deficit, create jobs, and promote economic activity (Tierney, 1994). With regard to air quality concerns, motor vehicles are responsible for about two-thirds of all carbon monoxide and at least one-third of all emissions of hydrocarbons and nitrogen oxides. Hydrocarbons and nitrogen oxides react to form ozone, an ingredient of urban smog. Motor vehicles also emit about half of the nation's toxic air pollutants (GAO, 1994).

Congress has enacted several laws to promote the use of AFs, including the Alternative Motor Fuels Act of 1988, the Clean Air Act Amendments of 1990 (CAAA), and the Energy Policy Act of 1992 (EPACT). These statutes provide for regulatory, incentive and voluntary actions to increase the use of AFs (Tierney, 1994). The alternative fuel vehicle (AFV) purchase requirements of affected vehicle fleets under EPACT are summarized in Table 1 (DOE, 1993b). In Executive Order 12844 (April 21, 1993), President Clinton directed federal agencies to exceed by 50 percent the EPACT requirements related to federal purchase of AFVs. This would mean an additional 33,750 AFVs entering the federal fleet between fiscal years 1993 and 1995. The Order also established the Federal Fleet Conversion Task Force to develop and to recommend a coordinated public and private sector plan for accelerating the commercialization and market acceptance of AFVs (Tierney, 1994). A chief recommendation of the Task Force was the establishment of a presidential Clean Cities Program which seeks to involve federal, state, local, and private interests in promoting AFs. This program aims to accelerate and expand the use of AFVs in urban communities and to provide refueling and maintenance facilities for their operation. By involving vehicle users, fuel suppliers and various levels of government, the program can more readily address the barriers to construction of AFV refueling facilities and can enhance public awareness of AFVs. The Department of Energy hopes that 50 cities will be involved in the program by 1996 (GAO, 1994).

Several AFs can potentially replace gasoline and diesel fuel, the fuels most vehicles now use. These AFs include electricity, alcohols, natural gas, and propane. AFs can be used in AFV configurations that have different fuel flexibility, emissions, and costs. In the development of policies to promote AFs, cost-effectiveness can be useful in identifying attractive AF/AFV configurations. With a properly used measure of costs to obtain air quality improvements, the cost-effectiveness concept can lead to selection of the most effective sequence of pollution reduction options. Derived with different methodologies and technical assumptions (i.e., assumptions about emissions and costs for fuel, vehicle, and maintenance), cost-effectiveness estimates have varied widely among previous studies. In one of several explanations of cost-effectiveness differences, this report uses a consistent basis for fuel price to re-estimate cost-effectiveness for fuels and AFVs in reduction of emissions of criteria pollutants (hydrocarbons,[1] nitrogen oxides, and carbon monoxide), toxic air pollutants, and greenhouse gases.

The following section describes some of the alternative fuel and vehicle options. Section 3 discusses key issues in the estimation of AFV cost-effectiveness, converts the cost-effectiveness results of other studies into a comparable metric, and identifies the factors that contribute to differences in cost-effectiveness estimates. Section 4 makes adjustments in the cost-effectiveness measure to account for the benefits of greenhouse gas reduction in certain AFV systems. The cost-effectiveness of reformulated gasoline and replacement fuel ("low petroleum gasoline") is discussed in Section 5. Recent emissions test data are used to estimate cost-effectiveness for "best-designed" systems in Section 6. Section 7 compares the cost-effectiveness of AFVs and gasolines with other measures to control mobile source emissions and presents key observations of this review.

[1]In subsequent references, "hydrocarbons" will refer to reactivity-adjusted non-methane organic gases. (NMOG = nonmethane hydrocarbons + carbonyls + alcohols).

Table 1. Alternative fuel vehicle purchase requirements of affected vehicle fleets under the Energy Policy Act of 1992					
Year	Number of Federal AFVs	Percent of AFVs			
		Federal	State	Fuel Provider	Municipal/ Private
1993	5,000				
1994	7,500				
1995	10,000				
1996		25	10	30	
1997		33	15	50	
1998		50	25	70	
1999		75	50	90	0-20
2000		75	75	90	0-20
2001		75	75	90	0-20
2002		75	75	90	20-30
2003		75	75	90	40
2004		57	75	90	50-60
2005		75	75	90	60-70
2006		75	75	90	70

2. ALTERNATIVE FUELS AND VEHICLES

Compared to conventional liquid transportation fuels, AFs have properties which are sufficiently different to require major changes in physical infrastructure, industry practice, consumer behavior, or regulatory conventions. Differences in AF properties may require minor to complete changes in engines, fuel storage systems, refueling and fuel distribution systems, production technologies, and resource bases (Interagency Commission on Alternative Motor Fuels, 1990). Potential near-term AFs include electricity, methanol, ethanol, natural gas, and propane. AFVs can fall into several categories:

- Dedicated (ded) vehicles can operate on only one type of AF. Generally, dedicated vehicles have superior emissions and performance because their design has been optimized for operation on only one fuel.

- Dual-fueled (df) or bi-fueled vehicles can operate on two different fuels, typically one AF and one conventional fuel, but not at the same time.[2] Two separate fuel systems are required in dual-fueled vehicles. These vehicles are advantageous for drivers who do not always have access to an AF fueling station.

- Flexible-fueled vehicles (ffv) can operate on a varying mixture of two fuels, stored in a single tank. Expensive fuel sensors and controllers are required in ffvs to identify and respond to the type of fuel coming to the engine. As with df vehicles, ffvs are advantageous for drivers who do not always have access to an AF (GAO, 1994; DOE, 1994b).

2.1 ELECTRICITY

Interest in electricity as an AF is high because of (1) the potential for improving energy security and air quality, (2) a California mandate requiring automobile manufacturers to offer zero emission vehicles (ZEVs) for sale beginning in 1998, and (3) the possibility that other states may adopt the California ZEV mandate. Since the electricity generating source produces emissions, the actual air quality benefits of electric vehicles (EVs) will vary (GAO, 1994). In an EV, gasoline and internal combustion engine are replaced with battery and electric motor. In comparison to gasoline, batteries are extremely poor energy storage devices, with low energy density. The battery's reduced energy and power account for reduced EV range, acceleration, and speed. On the other hand, electric motors are light weight, efficient, small, quiet, contain few moving parts, are rated for continuous performance, and can double or triple output for short periods, such as during passing (Henderson and Rusin, 1994).

Batteries are the most expensive items in an EV. Battery pack replacement could be required every 30,000 miles or three years. Each battery replacement could cost 15 to 20 percent of the original vehicle cost. Some of the features for use of electricity as an alternative fuel are shown in Table 2 (DOE, 1994b).

[2]In recent DOE definitions, bi-fueled still refers to vehicles that can use either of two fuels, but not at the same time. In the new definitions, dual-fueled vehicles are defined as those that have fuel tanks for two separate fuels, but burn both fuels simultaneously.

2.2 ALCOHOLS

The AFs which most closely resemble gasoline are methanol and ethanol. Both alcohols can be combined with gasoline. Methanol has a higher octane rating than gasoline, which can result in greater fuel efficiency with proper adjustment of the engine's compression ratio. Methanol's high heat of vaporization results in lower peak flame temperatures than gasoline and lower emissions of nitrogen oxides. Its greater tolerance to lean combustion (higher air-to-fuel equivalence ratio) results in generally lower overall emissions and higher energy efficiency. Disadvantages include methanol's lower energy density (about half of gasoline's), which reduces the range a vehicle can travel on an equivalent volume of fuel. Current-technology vehicles using neat methanol (M100) at temperatures below 45°F are difficult to start because of methanol's lower vapor pressure. M85, a mixture of 85 percent methanol and 15 percent gasoline, solves the cold start difficulties because of its gasoline component (NREL, 1992). Methanol can be corrosive, and stainless steel is required in areas where wet fuel is in continuous contact with metals. Conventional elastomers must be replaced by materials compatible with methanol. Ethanol is less corrosive than methanol and has about 35 percent greater energy content, so that ethanol could require less severe modifications to conventional vehicle designs (Interagency Commission on Alternative Motor Fuels, 1990).

Tables 3 and 4 show some of the characteristics of alcohol-based AFs (DOE, 1994b). The incremental costs of dedicated alcohol-based AFVs will be negligible. Dedicated alcohol vehicles do not need a fuel sensor, the most expensive item required for fuel flexibility.

2.3 NATURAL GAS AND PROPANE

At normal temperatures, natural gas and propane have lower volumetric energy contents than liquid fuels. Pressurized storage is needed to provide adequate driving range in vehicles that use natural gas or propane. Because these fuels are used in closed systems, they can significantly reduce or eliminate evaporative fuel emissions. Exhaust emissions, particularly hydrocarbons, could be lower for natural gas and propane than for gasoline.

Natural gas can be used as compressed natural gas (CNG) or liquified natural gas (LNG). CNG is stored on the vehicle in cylinders pressurized to 2,400 to 3,600 pounds per square inch (psi). Because of CNG's lower energy density, the size and weight of the storage cylinders make it difficult to store enough fuel to provide a satisfactory driving range in light duty vehicles. LNG requires large, heavy, insulated storage cylinders, and would be used in larger vehicles, such as long-haul trucks. Natural gas is less expensive on a cost-per-mile basis, and there are substantial domestic reserves. Storage cylinders are high cost items for CNG vehicles. Other items include high-pressure fuel lines and pressure regulators. In the df configuration, gasoline fuel components and a fuel selection switch are needed. Table 5 summarizes some of the characteristics of CNG and LNG fuels (DOE, 1994b).

Propane (liquified petroleum gas, LPG) is a by-product of natural gas production and petroleum refining. Propane has greater driving range than CNG and often costs less than gasoline. The supply of propane is limited, and its costs are sensitive to the demand for propane in building heating service. Storage cylinders are high cost items for the LPG vehicle. Other items include vaporizers (or regulators) and gas/air mixers. In the df configuration, gasoline fuel components and a fuel selection switch are needed. Table 6 summarizes the characteristics of LPG transportation fuel (DOE, 1994b)

Table 2. Electricity as an alternative fuel (DOE, 1994b)	
Fuel description	• Onboard rechargeable batteries power an electric motor.
Domestic content of fuel	• Over 95 percent.
Fueling	• Onboard charger. Full charging takes 4 to 8 hours.
Fuel availability	• Home/business outlets. Special hookups may be required. • Public charging networks under development in California.
Vehicle experience and availability	• Fleets with over 500 vehicles have operated for several years in California, Arizona, and local utilities. • Chrysler and Ford minivans available. • Conversions available in larger metropolitan areas.
Operational performance	• 50 mile range with current technology. • Payload, range, and accessories limited by battery weight. • More energy efficient than conventional fuels. • Acceleration, speed equivalent to comparable conventional fuel system.
Maintenance and reliability	• Battery pack replacement every 30,000 miles or three years. • Low component wear, less maintenance. • No tune-ups or oil changes. • Tire replacement more frequent due to vehicle weight. • Unsealed batteries need daily water check.
Safety	• Training needed to operate and maintain vehicles.
Costs	• Each battery replacement equals 15-20 percent or more of original vehicle cost. • New vans costs four to five times more than conventional van. • Electricity likely to cost less than gasoline. • Charging facility may require only minimal costs. • Auto manufacturers, utilities, and converters may assist with technician training. • May need to purchase service and diagnostic equipment if access to commercial electric vehicle maintenance facilities is not available.

Table 3. Methanol as an alternative fuel (DOE, 1994b)	
Fuel description	• Odorless clear liquid, produced from natural gas, coal, or biomass. M85 is for light-duty applications. M100 is for heavy duty applications now; light duty applications are under development.
Domestic content of fuel	• At least 90 percent, depending on price.
Fueling	• Same as with gasoline or diesel fuel.
Fuel availability	• Fueling stations are sparse, with increasing availability in California, New York, Atlanta, Denver, Houston, Detroit and other locations. • M100 available through bulk suppliers in most major cities.
Vehicle experience and availability	• More than 15,000 ffvs are in operation. • Ford, Chrysler offer M85 flexible-fuel sedans. • Heavy-duty compression-ignition engines are available for M100 from Detroit Diesel.
Operational performance	• Provides a little over half the driving range of comparable gasoline vehicle. • Power, acceleration, and payload are comparable to conventional fuel system.
Maintenance and reliability	• Use special lubricants with slight cost premium. • Use M85-compatible replacement parts.
Safety	• Training needed to operate and maintain vehicles.
Costs	• M85 fuel cost is about 1.5 times that of gasoline under current taxing structure. • M85 vehicle costs up to $250 greater than gasoline-fueled vehicle, due to special fittings.

Table 4. Ethanol as an alternative fuel (DOE, 1994b)	
Fuel description	• Liquid produced from grain or agricultural waste. E85 is for light-duty applications, while E95 is for heavy-duty applications.
Domestic content of fuel	• As high as 100 percent, depending on price.
Fueling	• Same as with gasoline or diesel fuel.
Fuel availability	• Fueling stations are sparse, primarily in the upper Midwest, DC, and California. • E95 is available only through bulk suppliers.
Vehicle experience and availability	• More than 400 vehicles are in use. Methanol-compatible vehicles can be modified to use ethanol. • Ford offers E85 flexible-fuel sedans. • Two conversions are available: M85 to E85, only after fuel metering system and sensor are adjusted; and heavy-duty compression-ignition engines to E95.
Operational performance	• Has slightly lower driving range than comparable gasoline vehicle. • Power, acceleration, payload, and cruise speed are comparable to conventional fuel system.
Maintenance and reliability	• Use special lubricants with slight cost premium. • Use E85-compatible replacement parts. • Maintenance assistance is available from local dealers; practices are similar to those for conventional fuels.
Safety	• Training needed to operate and maintain vehicles.
Costs	• E85 fuel costs about twice what gasoline costs. • E85 vehicle costs up to $250 greater than gasoline-fueled vehicle, due to special fittings.

Table 5. Natural gas as an alternative fuel (DOE, 1994b)	
Fuel description	• Extracted from underground reserves, composed primarily of methane • For CNG vehicle, gas is compressed to 2,400-3,600 psi in special cylinders. In LNG vehicle, gas is liquified by cooling to -259 °F and stored in insulated tanks.
Domestic content of fuel	• 100 percent.
Fueling	• "Slow" fill (up to 8 hours) and "quick" fill (3 to 5 minutes) are available for CNG. LNG is dispensed like liquified petroleum gas; refueling times are comparable to those for gasoline or diesel fuel.
Fuel availability	• Fueling stations are located in most major cities and in many rural areas. • LNG is only available through suppliers of cryogenic liquids.
Vehicle experience and availability	• Over 30,000 vehicles in U.S. and nearly one million worldwide. • Dual fuel and dedicated vans, minivans, and light trucks are available from Ford and Chrysler. • CNG- or LNG-specialty buses, service vehicles are available from at least 15 manufacturers.
Operational performance	• Range of CNG vehicle is at least one-half that of comparable gasoline-fueled vehicle. LNG fuel tank range is just under two-thirds that of gasoline. • Power, acceleration, payload, and cruise speed are comparable to conventional fuel system.
Maintenance and reliability	• Most CNG fleets report good reliability, longer useful lifetimes, longer time between tune-ups and engine rebuilds. • High-pressure tanks require periodic inspection and certification.
Safety	• Pressurized tanks have been designed to withstand severe impact and high external temperatures; they are as safe as gasoline tanks. • Adequate training is required to operate and maintain vehicles.
Costs	• Fuel cost is about three-fourths that of gasoline. • Conversion costs about $2,700 to $5,000 per vehicle. Manufacturer's extra price premium can be $3,500 to $7,500. • May need to purchase service and diagnostic equipment if access to commercial CNG/LNG vehicle maintenance facilities is not available.

Table 6. Propane as an alternative fuel (DOE, 1994b)	
Fuel description	• Liquified petroleum gas (LPG; commonly called propane) is a liquid mixture (at least 90 percent propane, 2.5 percent butane and higher hydrocarbons, and the balance ethane and propylene). LPG is a by-product of natural gas processing or petroleum refining.
Domestic content of fuel	• Between 95 and 98 percent.
Fueling	• Similar to filling gas grill tank; time comparable to that needed for gasoline or diesel fuel. • Tank should be filled to 80 percent capacity to allow for liquid expansion as ambient temperature rises.
Fuel availability	• 5,000 to 10,0000 publicly accessible fueling stations exist in all states.
Vehicle experience and availability	• Over 350,000 on- and off-road propane-powered units in U.S., and about 3.5 million worldwide. • Currently available as conversions. • Ford offers factory-installed conversion package option for medium-duty trucks.
Operational performance	• Range is almost equivalent to that of comparable gasoline vehicle. • Power, acceleration, payload, and cruise speed are comparable to conventional fuel system.
Maintenance and reliability	• Fleets generally report good reliability, slightly longer engine lifetime, and reduced maintenance costs.
Safety	• Adequate training is required to operate and maintain vehicles.
Costs	• Bulk purchases provide a one-fifth saving in fuel cost compared to gasoline. • Ford factory-installed truck conversion costs about $1,000 over the conventional vehicle base price; nonfactory conversions average about $2,500. • Cost for fueling station is similar to, or lower than, comparably sized gasoline dispensing system. • Service and diagnostic equipment would probably be required if access to commercial propane vehicle maintenance facilities is not available.

2.4 PUBLIC ACCEPTANCE OF ALTERNATIVE FUEL VEHICLES

To achieve their anticipated benefits, AFs must enjoy widespread public use. Surveys have determined that the fuel and vehicle characteristics listed in Table 7 are among the factors important in a motorist's vehicle choice (Greene, 1994). The table suggests that to gain public acceptance, AFs must be competitive with conventional fuels in availability, cost, and performance. A critical barrier to widespread acceptance of AFVs has been the interdependency between vehicle manufacturers and fuel providers that makes each hesitant to expand first. Manufacturers hesitate to produce large numbers of AFVs until AFs are widely available, but fuel providers are reluctant to invest in new facilities without a market provided by a large number of vehicles that use AFs (GAO, 1994).

Table 7. Fuel and vehicle choices
Fuel Characteristics
1. Cost
2. Fuel availability
3. Refueling difficulty
Range (frequency)
Refueling time and convenience
4. Fuel quality
Performance (acceleration and power)
Effect on vehicle reliability and maintenance
Health and safety
Aesthetics
5. Social benefits
Emissions
Oil dependence
Vehicle Characteristics
1. Cost
2. Reliability and maintenance
3. Performance (acceleration and power)
4. Health and safety
5. Capacity (passenger and cargo)
6. Value of multi-fuel options
7. Combined effects of fuel characteristics

3. COST-EFFECTIVENESS OF ALTERNATIVE FUEL VEHICLE SYSTEMS

3.1 COST-EFFECTIVENESS ESTIMATION

The cost-effectiveness ratio (CER) is a measure of the monetary value of resources expended to obtain reductions in emissions of air pollutants. Properly used, CERs can lead to the selection of the least expensive and most effective sequence of AF/AFV options. Selection of options without regard to cost-effectiveness could squander scarce resources (Krupnick and Walls, 1992).

The CER estimate can be based on damage value or on control costs. Damage values directly represent the value of emissions reductions by certain control measures. Estimation of damage value involves (1) identification of emission sources; (2) estimation of emissions; (3) simulation of air pollutant concentrations in the atmosphere; (4) estimation of exposure of humans and objects to air pollutants; (5) identification of physical effects of air pollutants on humans and objects; and (6) economic valuation of physical effects. Estimation of damage value suffers from necessary assumptions and simplifications and from great uncertainties involved in each estimating step. The cumulative effect of the uncertainties is a decrease in the accuracy of the estimated damage value. Damage values are underestimated because it is not practical to account for all potentially adverse air pollution effects. Some scientists have disputed the reliability of methods that are applied to air quality modeling and economic valuation of air pollution effects, and there has been philosophical uneasiness with attempts to place dollar values on human comfort and life. Given these drawbacks and the high resource-intensity of damage value estimation, many researchers base their CER estimate on control costs rather than damage value.

The control cost estimating method assumes that the cost required to satisfy air quality standards imposed by legislators reveals the value society places on the emissions being controlled. If the assumption is true, the estimated marginal control cost equals the marginal damage value of air pollution when air quality standards are met. Calculation of the CER, in dollars per ton of emissions controlled, requires information on the cost and emissions reduction of the marginal control measure over its lifetime. Cost estimation must include initial capital cost, operation and maintenance costs, and other pollutant-specific cost components. Estimates of emission reductions need to account for emission control deterioration over the lifetime of the equipment. If a control measure reduces emissions of more than one pollutant, the cost of the technology needs to be allocated among the reduced pollutants. Although it is generally agreed that discounting should be applied to the cost estimates, researchers differ as to whether discounting should be applied to emissions estimates. Depending on whether discounting is applied to emissions and whether the lifetime of the control technologies is considered, different techniques can be used in calculation of control costs. Table 8 illustrates four techniques, each of which results in different CER estimates with different meanings for the same control technology (Wang et al, 1994).

Table 8. Emission control cost calculation techniques (Wang et al, 1994)			
	Calculation method	Units	Meaning
Technique 1: Lifetime costs divided by annual emission reductions			
a: Discount costs and emissions:	(lifetime present value of cost)/(levelized tons reduced per year)	($/lifetime)/(ton/year)	Cost to reduce one ton each year throughout lifetime
b: Discount costs only:	(lifetime present value of cost)/(straight average of tons reduced per year)		
Technique 2: Annual costs divided by annual emissions reductions			
a: Discount costs and emissions:	(levelized costs per year)/(levelized tons reduced per year)	$/ton	Cost to reduce one ton
b: Discount costs only:	(levelized costs per year)/(straight average of tons reduced per year)		
Technique 3: Lifetime costs divided by lifetime emission reductions			
a: Discount costs and emissions:	(lifetime present value of costs)/(lifetime present value of tons reduced)	$/ton	Cost to reduce one ton
b: Discount costs only:	(lifetime present value of costs)/straight sum of lifetime tons reduced)		
Technique 4: Annual costs divided by lifetime emissions reductions			
a: Discount costs and emissions:	(levelized costs per year)/(lifetime present value of tons reduced)	($/year)/(ton/lifetime)	Annual cost throughout lifetime to reduce one ton
b: Discount costs only:	(levelized costs per year)/(straight sum of lifetime tons reduced)		

A number of studies have estimated the CERs of AFVs in the reduction of emissions of ozone forming pollutants, toxic air pollutants, and carbon monoxide. Table 9 shows the CER estimates of these studies, indicates which calculation technique is used, and summarizes the extent of treatment of key issues in CER estimation (Lareau, 1994):

Baseline emissions: Cost-effectiveness depends on what policies precede the option under consideration. As more efforts are undertaken to reduce emissions, the baseline from which a new option is evaluated shrinks, and cost-effectiveness deteriorates. The baseline should include only emissions from programs already implemented or required by law. When program order makes a difference, the order should be determined that provides the lowest cost means of reaching air quality objectives.

Incremental derivation: Marginal cost-effectiveness (the value of the last ton of reduced emissions) is the preferred basis for comparison. Average cost-effectiveness can hide the typically increasing cost of emission reduction and does not reveal which components of a program pass a cost-effectiveness test.

Regionality: The benefits of emissions reduction are greater in nonattainment areas than in attainment areas. Unless emission control benefits are important in attainment areas, then cost-effectiveness of national control policies should be computed by dividing national costs by nonattainment tonnage reductions. The distinction between attainment and nonattainment tons can be further refined, since the value of reducing a ton of emissions varies with nonattainment areas. Emissions reductions could have some value in attainment areas because:

Dose-response functions may increase smoothly from the origin. Without a threshold type dose-response function, there is some benefit for control below the standard.

There could be residual impacts such as ozone damage to crops, forests, or building materials.

Precursor emissions and ozone might be transported by weather patterns from attainment into nonattainment areas.

Some hydrocarbons can be carcinogenic. To the extent that these emissions are not regulated to harmless levels, some residual damage is possible.

Seasonality: When emissions reductions occur all year, society could be paying for some reductions that have little value. For example, the length of the ozone season varies, partly depending on whether an area is a northern or southern city, and partly due to the differences in emission inventories.

Cost discounting: The cost of a pollution control measure should include costs that can be attributed to that measure, discounted to a present value. Discounting cost items reflects the fact that future dollars are worth less than present dollars, because of the lack of investment opportunity for future dollars and because of inflation.

Benefit discounting: There are three different arguments on benefit discounting:

One, because emissions are not in monetary terms, they should never be discounted.

Two, benefits should be discounted at a negative rate, with future emissions worth more than present emissions. While the current generation has control of emissions for future generations, future generations have no control over the current generation's actions. Assigning a higher value to future emissions helps limit the consequences of the current generation's actions (Wang, 1994).

Three, benefits should be discounted at a positive rate with future emissions worth less than present emissions. Using the simplifying assumption that the effect on air quality of a ton of emissions reduction is the same over time, some argue that the health benefits associated with the air quality improvement would also be expected to be the same. Whatever economic value is assigned to improved health, there is an advantage in accelerating the time when the benefits are realized. Discounting at a positive rate may be further justified by the fact that air quality is improving in almost all areas of the country. Emissions reductions now are reducing public exposure to higher levels of pollution than will exist ten years from now (Austin and Lyons, 1994).

Emissions denomination: Dividing total costs by total tons of all emissions reductions can lead to errors, since emission tons are generally not alike. Changing the mix, but not the total tons, changes the damage caused by the emissions. Similarly, if the emissions contribute to formation of a different compound, changing the mix of emissions species can lead to a different level of pollution. Other complications can include the fact that most toxic emissions are volatile hydrocarbons. Also, a ton of hydrocarbon control may not may not have the same impact on ozone as a ton of nitrogen oxide (NOx) control. NOx control may not even contribute to the reduction of ozone. Carbon monoxide (CO) control is being solved by vehicle turnover and winter use of oxygenated fuel. By 2000, it is likely that only a handful of cities will still be out of attainment for CO. Thus, reductions in CO should not be valued as highly as reductions in hydrocarbons. Using an unweighted sum of hydrocarbons, NOx, and CO as a measure of effectiveness may be misleading.

While it is preferable to compare policies using CERs denominated in the control species (e.g., ozone) rather than precursor emission units, this is generally not practical. The relationship between precursor emissions and the controlled species has to be established, accounting for reactivity variability and differences in precursor composition across cities (Lareau, 1994).

Vehicle technology advances: Emissions profiles determined by standard testing of prototype or converted gasoline vehicles may lead to emissions overestimates for advanced-technology future fleets of AFVs, equipped with optimized emissions control. On the other hand, it may be inappropriate to compare the emissions behavior of developmental and prototype AFVs with current-technology gasoline vehicles.

Table 9. Alternative fuel vehicle cost-effectiveness and issue treatment

AFV type	Study/ calculation technique	CER (thousand $/ton, 1993)	Pollutant	Issue treatment							
				Baseline emissions	Incremental derivation	Regionality	Seasonality	Cost discounting	Benefit discounting	Emissions denomination	Vehicle technology advancement
M85 ffv	Wang, 1993/3a	8.05 (S. Cal)	HC,CO, NOx,TAP	●		●		●	●	●	○
	Fraas and McGartland, 1990/2b	9.6 to 36	HC	○				○		●	
M85 ded	Hahn, 1993/3b	76.5 (S. Cal)	HC	○	●	●				●	
	Hahn, 1993/3b	11.9 (S. Cal)	HC	○		●				●	
	Wang, 1993/3a	1.45 (S. Cal)	HC,CO, NOx,TAP	●		●		●	●	●	○
	Krupnick and Walls, 1992/2b	40.8	HC	●		●				●	○
	Fraas and McGartland, 1990/2b	4.1 to 29	HC	○				○		●	
	Congress, 1989/2b	10 to 78	HC	○		●		○		●	○
M100 ffv	Wang, 1993/3a	9.02 (S. Cal)	HC,CO, NOx,TAP	●		●		●	●	●	○
M100 ded	Wang, 1993/3a	2.33 (S. Cal)	HC,CO, NOx,TAP	●		●		●	●	●	○
	Krupnick and Walls, 1992/2b	73.3	HC	●		●				●	○
	Lareau, 1990/2b	2 to 1116	HC	●		●				○	
	Fraas and McGartland, 1990/2b	-4.7 to 9.6	HC	○				○		●	
	Congress, 1990/2b	3.7 to 26	HC	○		●		○		●	○

● → ○ → blank cell: indicates decreasing degree of treatment

Table 9 (continued). Alternative fuel vehicle cost-effectiveness and issue treatment

AFV type	Study/ calculation technique	CER (thousand $/ton, 1993)	Pollutant	Issue treatment: Baseline emissions	Incremental derivation	Regionality	Seasonality	Cost discounting	Benefit discounting	Emissions denomination	Vehicle technology advancement
E85 ffv (corn-derived)	Wang, 1993/3a	16.2 (S. Cal)	HC,CO, NOx,TAP	●		●		●	●	●	○
LPG df	Wang, 1993/3a	7.36 (S. Cal)	HC,CO, NOx,TAP	●		●		●	●	●	○
CNG df	Wang, 1993/3a	0.65 (S. Cal)	HC,CO, NOx,TAP	●		●		●	●	●	○
	Congress, 1989/2b	4.6 to 26	HC	○		●		○		●	○
CNG ded	Sierra, 1994/3a	24.2 to 24.6 (Cal)	HC,NOx, CO	●		●	●	○	●		
	Sierra, 1994/3a	76.8 to 78.1 (Nation)	HC,NOx, CO	●		●	●	○	●		
	Wang, 1993/3a	-0.72 (S. Cal)	HC,CO, NOx,TAP	●		●		●	●	●	○
	Fraas and McGartland, 1990/2b	-13.7 to 1.88	HC,CO	○				○		●	○
	Congress, 1989/2b	1.9 to 17	HC	○		●		○		●	○
EV	Wang, 1993/3a	4.60 (S. Cal)	HC,CO, NOx,TAP	●		●		●	●	●	
ULEV to ZEV	Sierra, 1994/3a	109 (Cal)	HC,NOx, CO	●	●	●	●	●	●		
	Sierra, 1994/3a	194 (Nation)	HC,NOx, CO	●	●	●	●	●	●		
EVs and AFVs	DRI/McGraw-Hill, 1994/2b	44 to 265 (Cal)	HC,NOx	●	●	○				○	○

● → ○ → blank cell: indicates decreasing degree of treatment

3.2 CONSISTENT METRIC FOR COST-EFFECTIVENESS ESTIMATES

Using different calculation techniques and different assumptions about costs and emissions reductions, as shown in Table 10, CER estimates for the same AFV type can be substantially different. In an attempt to reduce the differences underlying CER estimates, adjustments are made in two variables:

Fuel price -

> Several studies present results for multiple fuel price assumptions and demonstrate that CER is quite sensitive to the price of the AF relative to the price of gasoline. For a given AFV type in Table 11, CER estimates are based on identical fuel price assumptions. The assumptions, adopted from Wang (1993), are shown in Table 12. CERs and prices are expressed in 1993 dollars.
>
> The price adjustment can differ for each study, depending on the information reported in a study. As an example, Appendix A discusses adjustment of a CER reported by Congress (1989). The example shows that the adjusted price is near the center of the price range considered in the Congress report.

Pollutant denomination -

> All studies report reductions in hydrocarbon emissions, but many studies do not report reductions in emissions of CO, NOx, and toxic air pollutants (TAPs). Table 11 places CER estimates on the comparable pollutant denomination of hydrocarbons. Reactivity adjustment corrections have been applied to results of Congress (1989) and Sierra (1994). The reactivity adjustment factor assumptions, reported by Wang et al (1993) are shown in Table 13. Reactivity adjustment for a Congress CER is discussed in Appendix A.
>
> Table 11 reports CER estimates derived on the average basis, because all studies report average CER estimates or provide sufficient information for estimation of average CERs. Only a few studies report incremental CER estimates.

Table 10. Alternative fuel vehicle cost-effectiveness and assumptions						
AFV type	Study/ calculation technique	CER (thousand $/ton, 1993)	Pollutant	Assumptions		
				Fuel price ($, 1993)[a]	Incremental non-fuel cost ($, 1993)[c]	Emissions reduction (percent)
M85 ffv	Wang, 1993/3a	8.05 (S. Cal)	HC,CO, NOx,TAP	1.47 (G) 1.04 (M)	339	17[d]
	Fraas and McGartland, 1990/2b	9.6 to 36	HC	0.81 to 1.17 (G)[b] 0.65 to 0.77 (M)[b]	368	35
M85 ded	Hahn, 1993/3b	11.9 (S. Cal)	HC	1.47 (G) 1.03 to 1.07 (M)	277	93
	Wang, 1993/3a	1.45 (S. Cal)	HC,CO, NOx,TAP	1.47 (G) 1.04 (M)	113	24[d]
	Krupnick and Walls, 1992/2b	40.8	HC	1.33 (G)[b] 1.17 (M)[b]	0	50
	Fraas and McGartland, 1990/2b	4.1 to 29	HC	0.81 to 1.17 (G)[b] 0.65 to 0.77 (M)[b]	368	35
	Congress, 1989/2b	10 to 78	HC	1.21 (G) 0.75 to 0.99 (M)	589	30
M100 ffv	Wang, 1993/3a	9.02 (S. Cal)	HC,CO, NOx,TAP	1.47 (G) 1.04 (M)	339	20[d]
M100 ded	Wang, 1993/3a	2.33 (S. Cal)	HC,CO, NOx,TAP	1.47 (G) 1.04 (M)	113	29[d]
	Krupnick and Walls, 1992/2b	73.3	HC	1.66 (G)[b] 1.17 (M)[b]	0	42
	Lareau, 1990/2b	2 to 1116	HC	1.13 (G) 0.63 to 0.94 (M)	365	6.9 to 75
	Fraas and McGartland, 1990/2b	-4.7 to 9.6	HC	0.81 to 1.17 (G)[b] 0.65 to 0.77 (M)[b]	0	80
	Congress, 1990/2b	3.7 to 26	HC	1.21 (G) 0.75 to 0.99 (M)	589	90

Table 10. (continued). Alternative fuel vehicle cost-effectiveness and assumptions						
AFV type	Study/ calculation technique	CER (thousand $/ton, 1993)	Pollutant	Assumptions		
				Fuel price ($, 1993)[a]	Incremental non-fuel cost ($, 1993)[c]	Emissions reduction (percent)
E85 ffv (corn-derived)	Wang, 1993/3a	16.2 (S. Cal)	HC,CO, NOx,TAP	1.47 (G) 1.70 (E)	339	14[d]
LPG df	Wang, 1993/3a	7.36 (S. Cal)	HC,CO, NOx,TAP	1.47 (G) 1.07 (L)	1,131	36[e]
CNG df	Wang, 1993/3a	0.65 (S. Cal)	HC,CO, NOx,TAP	1.47 (G) 10.7 (C)	931	37[d]
	Congress, 1989/2b	4.6 to 26	HC	1.21 (G) 9.2 to 10.2 (C)	1,178	56
CNG ded	Sierra, 1994/3a	24.2 to 24.6 (Cal)	HC,NOx, CO	NA	2,734	17[d]
	Wang, 1993/3a	-0.72 (S. Cal)	HC,CO, NOx,TAP	1.47 (G) 10.7 (C)	336	45[d]
	Fraas and McGartland, 1990/2b	-13.7 to 1.88	HC,CO	1.77 (G) 8.8 to 12.1 (C)	1,998	60
	Congress, 1989/2b	1.9 to 17	HC	1.21 (G) 9.2 to 10.2 (C)	1,178	90
EV	Wang, 1993/3a	4.60 (S. Cal)	HC,CO, NOx,TAP	1.47 (G) 7.3 (K)	13,260	87[d]
ULEV to ZEV	Sierra, 1994/3a	109 (Cal)	HC,NOx, CO	NA	21,034	54[d]

[a]Prices include taxes unless otherwise noted
(G): conventional gasoline gallon
(M): methanol gallon
(E): ethanol gallon price does not include renewable tax credit
(L): LPG gallon
(C): compressed natural gas price in $ per million BTUs
(K): electricity price in cents per kilowatt hour
NA: study assumed no fuel cost effects
[b]Taxes not included
[c]Present value of vehicle and maintenance costs incremental to gasoline vehicle
[d]Discounted life-cycle emissions reduction

Table 11. Alternative fuel vehicle cost-effectiveness for comparable fuel price and pollutant denomination assumptions

AFV type	Study	CER (thousand $/ton hydrocarbon, 1993 dollars)
M85 ffv	Wang, 1993	22.1 (S. Cal)
	Fraas and McGartland, 1990	28.0
M85 ded	Hahn, 1993 (average)	11.9 (S. Cal)
	Wang, 1993	7.85 (S. Cal)
	Krupnick and Walls, 1992	12.4
	Fraas and McGartland, 1990	18.9
	Congress, 1989	14.1
M100 ffv	Wang, 1993	25.8 (S.Cal)
M100 ded	Wang, 1993	12.4 (S. Cal)
	Krupnick and Walls, 1992	61.8
	Lareau, 1990	40.5
	Fraas and McGartland, 1990	3.90
	Congress, 1989	13.2
E85 ffv (corn-derived)	Wang, 1993	67.6 (S. Cal)
LPG df	Wang, 1993	12.1 (S. Cal)
CNG df (75 percent CNG operation)	Wang, 1993	4.44 (S. Cal)
	Congress, 1989	9.0
CNG ded	Sierra, 1994	20.9 (Cal)
	Wang, 1993	-5.29 (S. Cal)
	Fraas and McGartland, 1990	9.02
	Congress, 1989	3.7
EV	Sierra, 1994	283 (Cal)
	Wang, 1993	93.2 (S. Cal)

Table 12. Reference motor fuel prices (Wang, 1993)	
Fuel	Price (in 1993 dollars per physical gallon, or as noted)
Conventional gasoline	1.47
Methanol	1.04
Ethanol (corn-derived)	1.70
LPG	1.07
CNG	10.7 per million BTUs
Electricity	7.3 cents per kilowatt hour (2.9 cents per mile)

Table 13. Reactivity adjustment factors (Wang et al, 1993)	
Fuel type	Reactivity adjustment factor (ratio of ozone grams to reactive hydrocarbon grams for a fuel type)
Conventional gasoline	1.00
Reformulated gasoline	0.98
M85	0.41
M100	0.37
CNG	0.18

Figs. 1 and 2 compare the adjusted AFV CER estimates for hydrocarbon reduction. With one exception,[3] the studies agree with the order of increasing CER estimates:

CNG ded < CNG df < M85 ded < M100 ded < M85 ffv < EV.

There are large differences in CERs for hydrocarbon reduction, with range overlaps for all AFV options except E85 ffv (corn-derived) and EV.

[3]The Fraas and McGartland (1990) CER for M100 ded is the exception.

To place CER estimates in a metric based on a more inclusive emission set, assumptions have to be made for expanding the emissions denomination to a composite total for hydrocarbons (HC) + NOx + CO + TAP. Only Wang (1993) expresses CER in terms of a composite total of these emissions, and only he describes an algorithm that could be used to expand the emissions denomination from partial emissions to the composite total.[4] Using the Wang algorithm to expand the pollutant denomination results in the CERs of Table 14. The expansion includes extension of the CO season in Sierra (1994) to an annual basis. Figs. 3 and 4 compare the AFV CER estimates for the expanded pollutant set. With the exception of M100 ded,[5] the studies appear to agree with the previously cited order of increasing CER estimates.

The CER estimates for HC+NOx+CO+TAP reduction differ greatly, with range overlaps for all AFV options. Contributors to CER variability include differences in non-fuel costs,[6] emissions baselines and emissions reduction paths, discounting, and other assumptions. EV provides an example of different perceptions about non-fuel costs. Sierra (1994) estimates the present value of non-fuel costs for its California scenario to be about \$21,000, but the Wang (1993) estimate appears to be about \$13,300. The non-fuel cost difference accounts for 35 percent of the difference in the two EV CERs.

---

[4]In the Wang algorithm, life-cycle emissions reductions and life-cycle costs are estimated for vehicles using reformulated gasoline, methanol, ethanol, LPG, CNG, and electricity. Vehicle emission estimates include exhaust and evaporative emissions for hydrocarbons, CO, NOx, and toxic air pollutants (benzene, formaldehyde, 1,3-butadiene, and acetaldehyde). Pollutants are weighted according to relative damage factors. Emissions and emissions reductions credits (for the Los Angeles area) are not seasonalized. Prices are mid-range values derived from other studies. The present value of vehicle life-cycle costs is calculated as:

$$PV_{cost} = IP + \sum_{i=1}^{n} [(FC_i + MC_i + Misc_i)/(1 + r)^i]$$

where

PV_{cost} =	present value of vehicle life-cycle costs
IP =	initial price of a new vehicle
n =	vehicle lifetime
i =	vehicle age
FC_i =	annual fuel cost
MC_i =	annual vehicle maintenance cost
$Misc_i$ =	annual miscellaneous cost
r =	real-term discount rate

A composite tonnage of emissions reductions is calculated from emissions reductions of the seven pollutants. Relative damage values are used to calculate the weighting factor for each pollutant. For CO, the damage value is assumed to equal the control cost. The present value of life-cycle emissions reductions is calculated by discounting annual vehicle emission reductions.

[5]Estimates by Fraas and McGartland (1990) and Congress (1989) are the exceptions.

[6]"Non-fuel costs" are vehicle and maintenance costs incremental to a gasoline vehicle.

With the assumption of constant present value of fuel costs, CER differences might be explained by differences in the non-fuel cost and emissions components of CER cost estimation. Table 15 and Figs. 5 and 6 show the broad range of relative non-fuel costs and emissions reductions among the studies.[7] With few exceptions, non-fuel costs are higher, emissions reductions are lower, and CER values are higher, compared with Wang (1993). Correlation analysis suggests that region and year of study (i.e., a learning curve effect) do not account for differences in CER values.

3.3 COMPONENTS OF DIFFERENCES FOR COST-EFFECTIVENESS ESTIMATES

3.3.1 Cost and Emissions Reduction Components

If it is assumed that non-fuel costs are constant within an AFV type, CER differences might be explained by differences in fuel costs and emissions reductions. Table 16 and Figs. 7 and 8 show the broad range of relative fuel costs and emissions among the studies.[8]

If it is assumed that emissions reductions costs are constant within an AFV type, CER differences might be explained by differences in fuel and non-fuel costs. Table 17 and Figs. 9 and 10 show the broad range of relative costs among the studies.[9]

[7]With constant fuel cost equal to the Wang assumption: the relative value of non-fuel costs is known, and the relative value of emissions reductions is derived so that the study CER value equals the CER value of Wang. Suppose a study reports that CER = cer. To derive the relative emissions reduction for that study, the present value of that study's non-fuel costs is used in the Wang algorithm to compute CER = cer′. The relative emissions reduction is the factor f by which the denominator must be multiplied to match the study's CER: $cer = cer'/f$.

[8]With constant non-fuel cost equal to the Wang assumption: the relative value of emissions reductions is known, and the relative value of fuel costs is derived so that the study CER value equals the CER value of Wang.

[9]With constant emissions reductions equal to the Wang assumption: the relative value of fuel costs is known, and the relative value of non-fuel costs is derived so that the study CER value equals the CER value of Wang.

3.3.2 Regression Analysis

Regression analysis has been used to examine the predictability of CERs.[10] Figs. 11 through 16 suggest that the effects of costs and emissions reductions might sometimes be predictable across studies for a given AFV type. Assume, for example, that a study of M85 ded uses the same fuel cost and emissions reduction of Wang (1993). If that study's non-fuel costs are twice the non-fuel costs of Wang, then Fig. 12 shows that the study's estimated CER would be about $400 per ton higher than the CER estimate of Wang. The problem in Fig. 12 is that two outliers are for CERs predicted with *reported values of* independent variables (Krupnick and Walls, 1992; Lareau, 1990); all but three of the remaining points in Fig. 12 are based on independent variables which have been manipulated as described in footnotes 7-9. With reported independent variable values, the models in Figs. 11 through 16 are poor predictors of CERs for half the study cases.[11]

3.3.3 Methodological and Other Components

The CERs for a given AFV type can be expressed in a form similar to a truncated Taylor series, providing estimates of components of differences. Let:

f = fuel costs relative to Wang
n = non-fuel costs relative to Wang
e = emissions reductions relative to Wang
i = a particular study for a given AFV type, with $i = 0$ for the Wang estimate
$CER_i(f_i,n_i,e_i)$ = the cost-effectiveness ratio for a particular study for a given AFV type, expressed as a function of the costs and emissions reductions of that study relative to Wang

Then

$$CER_i(f_i,n_i,e_i) = CER_0(f_0,n_0,e_0) + (\partial CER_0/\partial f_0)(f_i - f_0) + (\partial CER_0/\partial n_0)(n_i - n_0) + (\partial CER_0/\partial e_0)(e_i - e_0) + R_i.$$

[10]The analysis used relative CERs for the originally reported costs and emissions reductions, plus the relative CERs in Tables 15, 16, and 17.

[11] The models are poor predictors for M85 ded CER estimates reported by Krupnick and Walls (1992) and Hahn (1993); for M100 ded estimates of Krupnick and Walls (1992) and Lareau (1990); for CNG df estimates of Wang (1993) and Congress (1989); for CNG ded estimates of Wang (1994) and Sierra (1994); and for EV estimates of Sierra (1994).

The preceding equation expresses the CER for a study in terms of the $CER_0(f_0,n_0,e_0)$ estimate of Wang and four components:

$(\partial CER_0/\partial f_0)(f_i - f_0)$: the fuel cost component of difference;

$(\partial CER_0/\partial n_0)(n_i - n_0)$: the non-fuel cost component of difference;

$(\partial CER_0/\partial e_0)(e_i - e_0)$: the emissions reduction component of difference; and

R_i: differences due to study methodologies, higher order terms which have been truncated, and other approximations.

Appendix B illustrates the decomposition of CERs, and Fig. 17 shows the components of difference for all studies. CER differences are explained largely by cost and emissions reduction differences in only a few cases: M85 ded by Fraas and McGartland (1990); M85 ded by Congress (1990); and M100 ded by Congress (1990). In most cases, differences due to methodologies and other approximations make large contributions to CER differences.

3.3.4 Application Precautions

Given the considerable effects of differences in costs, emissions reductions, and methodologies, caution should be used in the application of CERs. Among AFVs, the CERs might provide an ordinal sense of cost-effectiveness. For example, using Wang's fuel cost assumptions, the average CERs fall into the four groups shown in Table 18, with CNG ded/ CNG df/ LPG df/ M85 ded options in the group with CERs less than \$5,000 per ton.[12] For quantitative analysis, upper and lower range values or the average CER values might be used, but conservative and cautious interpretation of results is advisable.

[12]The transportation fuel price assumptions of Wang are different from the reference case forecast prices of the *Annual Energy Outlook 1995* (DOE, 1995). Appendix C shows how CER estimates for CNG and EV systems differ with AEO prices. The Appendix also shows that the relative groupings in Table 18 for CNG vehicles and EVs are not changed with use of the DOE price forecasts.

Table 14. Annualized alternative fuel vehicle cost-effectiveness for comparable fuel price and total pollutant denomination

AFV type	Study	CER (thousand $/ton HC+NOx+CO+TAP, 1993 dollars)
M85 ffv	Wang, 1993	8.50 (S. Cal)
	Fraas and McGartland, 1990	11.1
M85 ded	Hahn, 1993 (average)	4.22 (S. Cal)
	Wang, 1993	3.32 (S. Cal)
	Krupnick and Walls, 1992	4.40
	Fraas and McGartland, 1990	6.70
	Congress, 1989	5.00
M100 ffv	Wang, 1993	10.2 (S.Cal)
M100 ded	Wang, 1993	4.63 (S. Cal)
	Krupnick and Walls, 1992	19.3
	Lareau, 1990	12.6
	Fraas and McGartland, 1990	1.22
	Congress, 1989	4.12
E85 ffv (corn-derived)	Wang, 1993	17.8 (S. Cal)
LPG df	Wang, 1993	3.03 (S. Cal)
CNG df (75 percent CNG operation)	Wang, 1993	1.3 (S. Cal)
	Congress, 1989	3.6
CNG ded	Sierra, 1994	4.3 (Cal)
	Wang, 1993	-1.44 (S. Cal)
	Fraas and McGartland, 1990	5.60
	Congress, 1989	0.91
EV	Sierra, 1994	36.4 (Cal)
	Wang, 1993	11.5 (S. Cal)

Table 15. Cost and emissions differences in alternative fuel vehicle CER studies (Constant present value of fuel costs)

AFV type	Study	Relative to Wang value for AFV type:				
		Region	CER	Present value of fuel costs	Present value of non-fuel costs	Emissions reductions
M85 ffv	Wang, 1993	S. Cal	1	1	1	1
	Fraas and McGartland, 1990		1.31	1	1.09	0.80
M85 ded	Hahn, 1993 (average)	S. Cal	1.27	1	2.45	0.82
	Wang, 1993	S. Cal	1	1	1	1
	Krupnick and Walls, 1992		1.32	1	0	0.52
	Fraas and McGartland, 1990		2.02	1	3.26	0.58
	Congress, 1989		1.57	1	5.21	.96
M100 ffv	Wang, 1993	S. Cal	1	1	1	1
M100 ded	Wang, 1993		1	1	1	1
	Krupnick and Walls, 1992		4.16	1	0	0.18
	Lareau, 1990		2.72	1	3.23	0.38
	Fraas and McGartland, 1990		0.26	1	0	2.85
	Congress, 1989		0.89	1	5.21	1.35
E85 ffv (corn-derived)	Wang, 1993	S. Cal	1	1	1	1
LPG df	Wang, 1993	S. Cal	1	1	1	1
CNG df (75 percent CNG operation)	Wang, 1993		1	1	1	1
	Congress, 1989		2.77	1	1.26	0.69
CNG ded	Sierra, 1994	Cal	-2.99	1	7.47	.93
	Wang, 1993	S. Cal	1	1	1	1
	Fraas and McGartland, 1990		-3.89	1	5.46	0.42
	Congress, 1989		-0.63	1	3.22	0.55
EV	Sierra, 1994	Cal	3.2	1	1.59	0.59
	Wang, 1993	S. Cal	1	1	1	1

Table 16. Cost and emissions differences in AFV CER studies
(Constant present value of non-fuel costs)

AFV type	Study	Relative to Wang value for AFV type:				
		Region	CER	Present value of fuel costs	Present value of non-fuel costs	Emissions reductions
M85 ffv	Wang, 1993	S. Cal	1	1	1	1
	Fraas and McGartland, 1990		1.02	0.61	1	0.62
M85 ded	Hahn, 1993 (average)	S. Cal	1.03	1.95	1	1.31
	Wang, 1993	S. Cal	1	1	1	1
	Krupnick and Walls, 1992		4.50	4.32	1	0.70
	Fraas and McGartland, 1990		1.02	0.52	1	0.49
	Congress, 1989		1.29	1.66	1	1.01
M100 ffv	Wang, 1993	S. Cal	1	1	1	1
M100 ded	Wang, 1993		1	1	1	1
	Krupnick and Walls, 1992		5.31	3.86	1	0.56
	Lareau, 1990		1.71	2.14	1	0.99
	Fraas and McGartland, 1990		0.30	0.32	1	1.08
	Congress, 1989		0.65	1.0	1	1.30
E85 ffv (corn-derived)	Wang, 1993	S. Cal	1	1	1	1
LPG df	Wang, 1993	S. Cal	1	1	1	1
CNG df (75 percent CNG operation)	Wang, 1993		1	1	1	1
	Congress, 1989		2.84	-0.19	1	0.77
CNG ded	Sierra, 1994	Cal	-3.19	-0.62	1	0.47
	Wang, 1993	S. Cal	1	1	1	1
	Fraas and McGartland, 1990		14.6	12.9	1	1.26
	Congress, 1989		-0.31	0.49	1	2.06
EV	Sierra, 1994	Cal	0.68	3.32	1	0.65
	Wang, 1993	S. Cal	1	1	1	1

Table 17. Cost and emissions differences in AFV CER studies
(Constant present value of emissions reductions)

AFV type	Study	Relative to Wang value for AFV type:				
		Region	CER	Present value of fuel costs	Present value of non-fuel costs	Emissions reductions
M85 ffv	Wang, 1993	S. Cal	1	1	1	1
	Fraas and McGartland, 1990		0.65	0.60	0.74	1
M85 ded	Hahn, 1993 (average)	S. Cal	1.64	1	6.55	1
	Wang, 1993	S. Cal	1	1	1	1
	Krupnick and Walls, 1992		3.00	3.27	5.05	1
	Fraas and McGartland, 1990		0.77	0.56	2.67	1
	Congress, 1989		1.99	1.72	5.54	1
M100 ffv	Wang, 1993	S. Cal	1	1	1	1
M100 ded	Wang, 1993		1	1	1	1
	Krupnick and Walls, 1992		2.78	1.18	22.0	1
	Lareau, 1990		2.22	0.75	19.2	1
	Fraas and McGartland, 1990		0.66	0.63	-2.53	1
	Congress, 1989		1.23	1.12	4.53	1
E85 ffv (corn-derived)	Wang, 1993	S. Cal	1	1	1	1
LPG df	Wang, 1993	S. Cal	1	1	1	1
CNG df (75 percent CNG operation)	Wang, 1993		1	1	1	1
	Congress, 1989		4.03	0.63	6.23	1
CNG ded	Sierra, 1994	Cal	-11.1	0	19.5	1
	Wang, 1993	S. Cal	1	1	1	1
	Fraas and McGartland, 1990		3.71	2.63	0.30	1
	Congress, 1989		-2.96	0.50	6.49	1
EV	Sierra, 1994	Cal	0.72	0	0.56	1
	Wang, 1993	S. Cal	1	1	1	1

Table 18. CER groups for pollutant reduction options	
Cost-effectiveness range (per ton HC+NOx+CO+TAP, 1993 dollars)	Option
Less than $5,000	CNG ded CNG df LPG df M85 ded
$5,000 to $10,000	M100 ded M85 ffv
$10,000 to $20,000	M100 ffv E85 ffv (corn-derived)
Greater than $20,000	EV Low petroleum gasoline

4. GREENHOUSE GAS EMISSIONS REDUCTIONS

Greenhouse gases (GHGs) impede the outward flow of infrared radiation more effectively than they impede incoming solar radiation, causing the earth to be warmer than it would be in the absence of GHGs. Some of the major GHGs which can be emitted by evaporation or combustion of fuels used by light duty vehicles are water vapor, carbon dioxide, nitrous oxide, and methane. Human activity has contributed to increased atmospheric concentrations of GHGs, which may increase average global temperatures. The atmospheric concentration of carbon dioxide is about 25 percent greater than it was prior to the Industrial Revolution (1750), and the concentration of carbon dioxide is increasing at about 0.5 percent per year. The concentration of methane is more than twice what it was in 1750, and rising at a rate of 0.9 percent per year. Climatic models predict that an increase in GHG concentrations equivalent to a doubling of the preindustrial level of carbon dioxide would cause global average temperatures to increase by 1.9° to 5.2°C. Some of the radical changes that could result from increases in global temperatures include:

As high-latitude tundra melts, methane could be released, accelerating greenhouse warming.

Increased runoff of fresh water in high latitudes and a reduced temperature differential from equator to pole could result in changes in major ocean currents, leading to altered weather patterns.

There could be significant melting of polar ice, resulting in a sea level several meters higher than it is today (NAS, 1992).

GHG emissions reductions can be among the benefits of AF use. Using the approach of Wang et al (1993), a composite tonnage of emissions reductions has been calculated for HC, NOx, CO, TAP, and GHG.[13] Weighting factors are based on the relative damage and control values shown in Table 19.

The damage value for GHGs is uncertain. Therefore, the weighting factors for GHGs are based on a range of costs to control GHG emissions. Table 19 shows GHG weighting factors for two control cost assumptions. A control cost of $10 per ton of CO_2 equivalent is at the upper end of the range associated with halocarbon usage reduction. A control cost of $100 per ton of CO_2 equivalent is at the upper end of the range associated with reforestation (NAS, 1992).

[13]Alternately, monetary benefits of GHG emissions reductions could be subtracted from AFV costs. CER would be then be calculated without including GHG emissions reductions in the composite tonnage.

Fig. 18 shows that, relative to gasoline vehicles, GHG benefits are provided by the CNG ded, M85 ded, M100 ded, E85 (cellulosic ethanol), and EV systems (Finizza, 1991, and Singh, 1995). GHG emissions are higher with the use of E85 (corn-derived ethanol). GHG emissions of cellulosic ethanol are low because much CO_2 released during biomass conversion to ethanol and ethanol combustion will be absorbed during the growth of new biomass materials to replace those used during conversions (DOE, 1993b). Other factors that could contribute to lower emissions of GHGs in the use of cellulosic ethanol include reduced use of fertilizers, pesticides, tillage, and labor. Table 20 shows that CERs decrease for E85 (cellulosic) and electric vehicles, while there is a CER increase for E85 (corn-derived).

Fig. 18 shows that GHGs other than CO_2 account for a small (7 percent) fraction of gasoline vehicle emissions. Since emissions of HCs and NOx increase over the life of a gasoline vehicle, emissions of GHGs other than CO_2 could increase with time. Because of the apparently small contribution of vehicle GHG emissions other than CO_2 and uncertainty about its time profile, it has been assumed that total GHG emissions per mile are constant over the life of the vehicle. Discounting is applied to GHG emissions reductions, as for the reduction of other pollutants.

In addition to the damage values for GHGs, the future cost and availability of cellulosic ethanol is uncertain. Fig. 19 presents CERs for E85 (with both corn-derived and cellulosic ethanol) for a range of GHG damage values, and over a range of cellulosic ethanol prices (Perlack, 1995). CERs increase as the CO_2 value increases for E85 (corn-derived). However, CERs for E85 (cellulosic) fall below $5,000 per ton at the intermediate price assumption of $1.00 per gallon of ethanol, and benefits increase as the CO_2 value increases. The cellulosic results are speculative because they assume that cellulosic ethanol (a long-term technology possibility) is available for the nearer-term emissions evaluation period of 1995 to 2007.

Table 19. Pollutant weighting factors

Pollutant	Value	Weighting factor	Weighting factor derivation
HC	$18,600/ton	1	Value (damage) relative to HC
CO	$9,300/ton	0.49	
NOx	$24,400/ton	1.4	
Greenhouse gas (carbon dioxide equivalent)	$10/ton	5.38×10^{-4}	Value (control cost) relative to HC
	$100/ton	5.38×10^{-3}	

Pollutant	Unit risk	Residence time (hour)	Weighting factor	Weighting factor derivation
Benzene	8.3×10^{-6}	198	10	Wang assumption
1,3-Butadiene	2.8×10^{-4}	5.5	9.37	Product of Unit risk and residence time, relative to product for benzene
Formaldehyde	1.3×10^{-5}	16.5	1.31	
Acetaldehyde	2.2×10^{-6}	22.5	0.31	

Table 20. Alternative fuel vehicle cost-effectiveness impact of greenhouse gas emissions reductions[a]

AFV type	CER (thousand $/ton HC+NOx+CO+TAP, 1993 dollars)	CER (thousand $/ton HC+NOx+CO+TAP+GHG, 1993 dollars)	
		GHG at $10/ton	GHG at $100/ton
M85 ded	3.3	3.3	3.3
M100 ded	4.6	4.6	4.6
CNG ded	-1.4	-1.4	-1.3
E85 (corn-derived ethanol @ $1.50/gal)	17.8	18.2	23.5
E85 (cellulosic ethanol @ $1.00/gal))	4.5	4.0	2.0
EV	11.5	11.4	10.5

[a]CERs calculated with algorithm of Wang (1993), modified to include provision for GHG benefits

5. REFORMULATED GASOLINE

5.1 THE CLEAN AIR ACT AMENDMENTS OF 1990

The CAAA mandate the use of Phase I reformulated gasolines (RFGs) beginning January 1, 1995, in nine areas with extreme or severe ozone pollution problems. Other cities with less-than-severe ozone problems may "opt-in" to the RFG program. The law specifies RFG formulas with restrictions for oxygen, benzene, and additives; and regional performance standards for emissions of NOx, volatile organic compounds (VOCs),[14] and TAPs, as shown in Table 21 (DOE, 1994a). Phase II RFGs will be required beginning in year 2000.

Table 21. Emissions performance standards for federal reformulated gasolines

Pollutant	Phase I CAAA standards	Phase II EPA final rule standards
Volatile Organic Compounds	Must be reduced by at least 15 percent during the summer high-ozone season, compared with the calculated VOC emissions from the use of the statutory baseline gasoline.	Must be reduced during the summer by 25.9 percent on a per-gallon basis or by 27.4 percent on an averaged basis.[a] A greater percentage reduction is required in Southern states.
Toxic Air Pollutants	Must be reduced by at least 15 percent during the entire year, compared with calculated TAP emissions from the use of the statutory baseline gasoline.	Must be reduced year-round by 20 percent on a per-gallon basis or by 21.5 percent on an averaged basis.
Nitrogen Oxides	Must not increase relative to the emissions of the statutory baseline gasoline.	Must be reduced during the summer by 5.5 percent on a per-gallon basis or by 6.8 percent on an averaged basis. Must not increase during the winter on a per-gallon basis and must be reduced by 1.5 percent on an averaged basis.

[a]For the per-gallon standard, every gallon of every batch of RFG produced at the refinery must meet the same emissions-performance requirements. For the averaged standard, different batches may vary within limits, as long as the refinery's total RFG output meets the specified average emissions performance requirement.

[14]VOCs are hydrocarbons (including or excluding methane and ethane, depending on definition) and oxyhydrocarbon compounds. This reports assumes that VOCs are NMOGs, which are converted to HCs by the reactivity adjustment factors in Table 13.

The Environmental Protection Agency (EPA) used the negotiated rule making (Reg-Neg) process to allow parties who would be affected by the CAAA gasoline programs to negotiate an approach to the Phase I RFG requirements. The CAAA require a formal fuel certification procedure for demonstrating the emissions performance of a fuel. During the Reg-Neg workshop on fuel certification, the concept of emissions modeling was discussed. Emissions modeling provides a means for predicting the emissions performance of a gasoline, given other physical and chemical properties of the gasoline. In August, 1991, an agreement in principle established two emissions models: the Simple Model and the Complex Model.

The Simple Model is a set of equations that predicts emissions of VOCs and TAPs in terms of a gasoline's Reid vapor pressure (RVP), benzene, oxygen by type of oxygen source, and aromatics contents. EPA's final Complex Model is a set of equations that predicts emissions in terms of a gasoline's RVP, E200, E300, benzene, oxygen by type of oxygen source, sulfur, aromatics, and olefins contents. Gasoline producers may use either the Simple Model or the Phase I Complex Model to certify the emissions performance of RFGs manufactured between January 1, 1995, and December 31, 1997. After December 31, 1997, only the Complex Model will be used.

The areas in the extreme and serious ozone nonattainment categories currently comprise about 25 percent of the nation's gasoline market. Besides requiring RFG in the covered ozone nonattainment areas, the CAAA requires that gasoline in all other areas not be any more polluting than it was in 1990. Without this "anti-dumping" provision, the potential exists for emissions from conventional gasoline to worsen as polluting fuel components are removed from gasoline to be sold as RFG (Hadder, 1994).

5.2 THE ENERGY POLICY ACT OF 1992

EPACT was enacted to provide a comprehensive national energy policy. With a goal to increase U.S. energy security in ways that are both cost-effective and environmentally prudent, one EPACT objective is to decrease U.S. dependence on foreign oil. To meet this objective, Section 502 of EPACT requires the Secretary of Energy to determine the feasibility of reducing imported oil by 30 percent by the year 2010.

Reductions in foreign oil dependence could be achieved by reducing the consumption of petroleum fuels by light duty motor vehicles, through the use of alternative and replacement fuels. A replacement fuel is substantially not petroleum, but it replaces only a portion of a petroleum-derived motor fuel. For example, ethanol is a replacement fuel in a gasoline containing 10 percent ethanol (but ethanol mixed with less than 20 percent gasoline is an alternative fuel). EPACT requires the Secretary of Energy to determine the feasibility of producing sufficient replacement fuels to replace at least 30 percent of the projected consumption of motor fuels by light duty vehicles in the year 2010. In its marriage with petroleum-derived fuels, the replacement fuel concept depends on the continuing existence and technical development of the petroleum refining infrastructure. Replacement gasolines are referred to as "low petroleum gasolines." Like all highway gasolines, low petroleum gasolines must comply with CAAA requirements for reformulation and anti-dumping.

5.3 COST-EFFECTIVENESS OF REFORMULATED GASOLINES

A number of studies have estimated the CERs of regional RFGs. Other studies have not reported CERs but have presented cost and emissions results from which CERs can be derived. RFG production costs are typically estimated with refinery linear programs. For example, the Oak Ridge National Laboratory Refinery Yield Model (ORNL-RYM) is a refinery linear program which tracks octane, RVP, oxygen content, sulfur, benzene, aromatics, total olefins, distillation points, VOC, TAP, and NOx on more than 200 gasoline component streams. The regional refinery representations in ORNL-RYM can include up to 50 refining processes, which can be used to produce 40 different products from more than 100 crude oils. The ORNL-RYM investment module provides for the addition of processing capacity.

Table 22 shows that there can be substantial differences in reported CERs for RFG. The differences in the CERs of Table 22 are due partly to inconsistencies in (1) pollutant denomination; (2) the increment of derivation (average or incremental); and (3) the baseline gasoline (for example, cost and pollutant reduction effects may be calculated relative to conventional gasoline or to Phase I gasoline). Where possible, average Phase II CERs have been recomputed relative to Phase I emissions of HC + NOx + CO + TAP. The recomputed Phase II CERs are shown in Table 23, which also includes CERs derived from cost and emissions results of recent studies which do not explicitly report average CER estimates (DOE, 1994a; API, 1993; and NPRA, 1992). Table 23 and Fig. 20 show close agreement for RFG CERs in Petroleum Administration for Defense Districts I (U.S. East Coast) and III (U.S. Gulf Coast). There are substantial differences in RFG CERs for California.

CER variability for California RFG can be explained by differences in reformulation costs and the emissions reductions. Figs. 21 and 22 show the range of relative reformulation costs and emissions reductions among studies of California RFG. Given the considerable differences in the relative reformulation costs and emissions reductions, caution should be used in the application of these California CERs. RFG CERs are shown with AFV CERs in Fig. 23. For consistency, the CERs in Fig. 23 have are expressed relative to Phase I gasoline.[15] In the CER groups of Table 24, RFGs for PADDs I and III fall between the dedicated methanol AFVs; the CER for California RFG is slightly less than the CER for E85 ffv (corn-derived); and low petroleum gasoline has the highest CER of all options.

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[15]Studies with conventional gasoline baselines are Fraas and McGartland (1990), Hahn (1993), and Congress (1989). Given the comparable fuel price change (the fuel price change is relative to Phase I gasoline), Phase I gasoline air pollutants are assumed to be about 15 percent less than conventional gasoline. Therefore, the CERs for these studies are further adjusted by dividing by 0.85.

Table 22. RFG cost-effectiveness issue treatment

Study	CER (thousand $/ton, 1993)	Pollutant	Comments	Issue treatment: Baseline emissions	Incremental derivation	Regionality	Seasonality	Cost discounting	Benefit discounting	Emissions denomination	Vehicle technology advancement
DOE, 1994a, by ORNL	0 to 120 (PADDs I and III)	NOx	Incremental summer ton	●	●	●	●	○		○	○
Lareau, 1994	11.8 to 24.5	VOC,CO,NOx	Average summer ton, year 2005	●	●	○	●	○	○	●	
Sierra, 1994	7.4 (Cal)	HC,NOx,CO	Cal RFG	●		●	○	●	●	●	
	5.2 (Cal)	HC,NOx,CO	Federal RFG	●		●	○	●	●	●	
API, 1993	7 to 80 (PADD I)	VOC	Incremental summer ton	●	●	●	●	○		○	○
	13 to 20 (PADD I)	NOx	Incremental summer ton	●	●	●	●	○		○	○
	6 to 40 (PADD III)	VOC	Incremental summer ton	●	●	●	●	○		○	○
	7 to 26 (PADD III)	NOx	Incremental summer ton	●	●	●	●	○		○	○

● → ○ → blank cell: indicates decreasing degree of treatment

Table 22 (continued). RFG cost-effectiveness issue treatment											
Study	CER (thousand $/ton, 1993)	Pollutant	Comments	Issue treatment: Baseline emissions	Incremental derivation	Regionality	Seasonality	Cost discounting	Benefit discounting	Emissions denomination	Vehicle technology advancement
NPC, 1993	7.6 to 18 (PADD I)	VOC,NOx	Average summer ton, relative to CG	●		●	●	○		○	○
	4.8 to 47 (PADD I)	VOC,NOx	Incremental summer ton	●	●	●	●	○		○	○
	9.4 to 16 (PADD II)	VOC,NOx	Average summer ton, relative to CG	●		●	●	○		○	○
	6 to 62 (PADD II)	VOC,NOx	Incremental summer ton	●	●	●	●	○		○	○
	8.1 to 26 (PADD IV)	VOC,NOx	Average summer ton, relative to CG	●		●	●	○		○	○
	17 to 56 (PADD IV)	VOC,NOx	Incremental summer ton	●	●	●	●	○		○	○

● → ○ → blank cell: indicates decreasing degree of treatment

Table 22 (continued). RFG cost-effectiveness issue treatment											
Study	CER (thousand $/ton, 1993)	Pollutant	Comments	Issue treatment: Baseline emissions	Incremental derivation	Regionality	Seasonality	Cost discounting	Benefit discounting	Emissions denomination	Vehicle technology advancement
Wang, 1993	4.09 (Cal)	HC,CO, NOx,TAP		●		●		●	●	●	○
Sierra, 1991	61 (Cal)	HC,NOx	Federal RFG, incremental to Cal ϕ 1	●	○	●	○			●	
	65 (Cal)	HC,NOx	RFG cost knee, incremental to Cal ϕ 1	●	○	●	○			●	
	76 (Cal)	HC,NOx	CARB ϕ 2, incremental to Cal ϕ 1	●	○	●	○			●	
	91 (Cal)	HC,NOx	CARB ϕ 2 actual, incremental to Cal ϕ 1	●	○	●	○			●	
	71 (Cal)	HC,NOx	EC-X, incremental to Cal ϕ 1	●	○	●	○			●	
CARB, 1991	8 to 18.2 (Cal)	VOC,NOx, CO,SO_2	Cal ϕ 2, incremental to Cal ϕ 1	●	○	●	○			●	

● → ○ → blank cell: indicates decreasing degree of treatment

Table 23. Phase 2 RFG cost-effectiveness, incremental to Phase 1, with comparable pollutant denomination

Region	Study	Comments	CER (thousand $/ton HC+NOx+CO+TAP, 1993 dollars)
PADD I	DOE, 1994a, by ORNL	6.8 percent NOx reduction in ϕ 2	6.3
	API, 1993, by TMC[a]	6.8 percent NOx reduction in ϕ 2	7.2
PADD III	DOE, 1994a, by ORNL	6.8 percent NOx reduction in ϕ 2	5.2
	API, 1993, by TMC[a]	6.8 percent NOx reduction in ϕ 2	5.9
	DOE, 1994a, by ORNL	Low petroleum gasoline with 31 percent non-petroleum	26.7
California	Sierra, 1994		6.7
	Wang, 1993		4.1
	NPRA, 1992, by TMC	CARB-2	5.4
	Sierra, 1991	Federal RFG	26
	Sierra, 1991	RFG cost knee	30
	Sierra, 1991	CARB ϕ 2	36
	Sierra, 1991	CARB ϕ 2 actual	51
	Sierra, 1991	EC-X	36
	CARB, 1991		15.9
Cross-regional	Lareau, 1994	Year 2005	17.2

[a]NPC (1993) reports on work completed before Phase II emissions requirements were defined. The contractor who performed the NPC refinery analysis subsequently estimated the cost and pollutant reduction impacts of the final Phase II standards in work for the American Petroleum Institute (API, 1993). Instead of the NPC results, the API results are reported in this table because of the latter work's treatment of the Phase II NOx requirement.

Table 24. CER groups for RFG and AFV pollutant reduction options (relative to Phase I gasoline)

Cost-effectiveness range (per ton HC+NOx+CO+TAP, 1993 dollars)	Option
Less than $5,000	CNG ded CNG df LPG df E85 ffv (cellulosic)[a]
$5,000 to $10,000	M85 ded PADD III RFG PADD I RFG M100 ded
$10,000 to $20,000	M100 ffv M85 ffv Cal RFG E85 ffv (corn-derived)[a]
Greater than $20,000	EV Low petroleum gasoline

[a]Cellulosic ethanol: $1.00/gallon. Corn-derived ethanol: $1.50/gallon.

6. COST-EFFECTIVENESS OF BEST-DESIGNED ALTERNATIVE FUEL VEHICLES

AFV CERs could be lower if AFV technologies evolve with greater-than-anticipated emissions reductions, relative to the evolving conventional vehicle technologies. Some recent test programs have observed reported emissions reductions somewhat greater than the reductions assumed by Wang (1993). Southwest Research Institute (SWRI) reports E85 exhaust emissions for standard Ford Taurus ffvs (Dodge et al, 1994). These vehicles were designed to run as M85 ffvs, but they run well on E85 without modifications. Table 25 compares SWRI test emissions with the emissions profile assumed by Wang. If the Wang algorithm is used to calculate the CER for the E85 ffv with SWRI emissions reductions, the CER is 12 percent lower than the original CER. Further reduction of emissions in the SWRI test vehicles may be achieved at additional cost with proposed aftertreatment devices and engine modifications.

Table 25. E85 exhaust emissions and CER

	Wang	SWRI
Reactivity adjustment factor (RAF)	0.63	0.67
HC = NMOG x RAF (gm/mi) in year 1	0.160	0.107
Reduction of HC (percent)	-30	-53
Formaldehyde (weight percent in NMOG emissions)	1.86	0.96
Acetaldehyde (weight percent in NMOG emissions)	7.82	8.04
CER per Wang algorithm (thousand $/ton HC+NOx+CO+TAP, 1993 dollars)	17.8	15.6

Emissions characteristics of "best-designed" AFVs and gasoline vehicles have been summarized by Wang et al (1993). Table 26 shows the exhaust emissions reductions of best-designed AFVs relative to counterpart gasoline vehicles. These AFVs were configured to minimize pollutant emissions, whereas the counterpart gasoline vehicles were designed simply to satisfy emissions standards. Therefore, emissions reductions for the best-designed AFVs may be overstated, and the incremental costs may be understated. The Wang algorithm has been used to calculate CERs for the tabulated emissions reductions of the best-designed AFVs. Best-design CERs are compared in Fig. 24.

Table 26. Exhaust emissions of best-designed vehicles					
AFV option	Emissions basis	Emissions reductions (percent)			CER (thousand $/ton HC+NOx+CO+TAP, 1993 dollars)
		HC	CO	NOx	
CNG ded	Average, Wang, 1993	-90	-40	-10	-1.44[a]
	Best-design, Wang et al, 1993	-98.5	-65.8	-86.7	-0.79[a]
M85 ded	Average, Wang, 1993	-65	-15	-10	3.32
	Best design, Wang et al, 1993	-86.3	-20.8	-63.9	1.79

[a]With a cost savings, the CER is greater with greater reduction of emissions (-.79 > -1.44). Therefore, the greater CER is more cost-effective.

AFV CERs could be substantially lower than estimated if on-road emissions of conventional vehicles have been underestimated (Wang, 1993). Measurements of VOC concentrations near roadways and in tunnels, as well as ambient measurements of specific VOCs in urban areas indicate that VOC emissions from mobile sources have been underestimated. The discrepancy in mobile-source emissions is probably a result of several factors in current emissions models. It is likely that the fleets used in dynamometer testing to determine emissions factors are not representative of on-road vehicles, that speed correction factors and estimates of evaporative emissions are inaccurate, and that the Federal Test Procedure does not adequately simulate actual driving behavior (NRC, 1991).

7. COST-EFFECTIVENESS IN CONTEXT

AFVs, RFG, low petroleum gasoline and other measures to control mobile source emissions are grouped by CER categories in Table 27. Pollutant control options are listed in order of increasing CER in the table. CERs for the other measures (shown in bold in the table) have been derived from Sierra (1994) for California control programs relative to vehicles with emissions that satisfy Phase I gasoline standards.

The category with CER less than $5,000 per ton (not counting GHG benefits) includes measures for evaporative control of gasoline emissions, and four AFVs: CNG ded, CNG df, LPG df, and E85 ffv (with cellulosic ethanol at an intermediate price). If a $10/ton credit is given for GHG reduction benefits for the AFVs in this category, the CERs would change very little, and the listing order would not change.

The E85 ffv system CER is much less attractive (in the $10,000 to $20,000 per ton category) if corn-derived ethanol is used. Furthermore, the CER for E85 (corn-derived) is higher with higher damage values for GHG emissions.

Total potential benefits and relative costs are important in selection of an option. Table 27 suggests that programs to encourage scrappage of high emitter vehicles could be more cost effective than EVs, California RFG and several alcohol-based AFVs. Of course, the incremental benefits of vehicle scrappage programs would be exhausted when all high emitter vehicles had been scrapped.

The California Phase 2 RFG program will be implemented before significant market penetration by AFVs. CERs could be substantially greater if they are calculated incremental to the Phase 2 RFG program, instead of the Phase 1 RFG program. Relative to Phase 2 RFG, the Wang algorithm shows that the incremental CER for EV is 25 percent higher than the CER relative to Phase 1 RFG. Relative to Phase 2 RFG, E85 ffv (corn-derived) emissions increase, and E85 ffv (corn-derived) is an unreasonable option.

This report has attempted to explain the differences among CER study results by estimating the effects of different assumptions for costs, emissions reductions and methodologies. For example, the fuel price difference has been removed to reveal the relative differences in non-fuel costs and emissions reductions of AFVs. Different assumptions across studies can sometimes have predictable effects on the CER estimate for a particular AFV type. However, the relative differences in cost and emissions reduction assumptions can be large, and the effect of these differences on the CER estimate is often not predictable. Decomposition of CERs suggests that methodological differences can make large contributions to CER differences among studies.[16] Resolution of differences might require the community of analysts and policy makers to establish methodological ground rules and to agree on specific premises for determination of critically important characteristics such as vehicle emissions profiles. Consistent premises for analysis of refinery operations may underlie the close agreement between DOE and API CERs for RFGs. In these RFG cases, DOE and API used very specific study premises that had been developed by committee in a lengthy government-industry evaluation process (NPC, 1993).

[16]Wang (1994) has identified methodological differences that create CER results which cannot be compared.

Table 27. Cost-effectiveness groups for pollutant reduction options (relative to Phase I gasoline)

Cost-effectiveness range (per ton HC+NOx+CO+TAP, 1993 dollars)	Option (in order of increasing CER)
Less than $5,000	**Enhanced Inspection/Maintenance** **Stage II vapor recovery** **Fuel volatility control/ Enhanced evaporative controls**[a] **Onboard refueling vapor recovery** CNG ded[b] CNG df[b] LPG df[b] E85 ffv (cellulosic)[b,c]
$5,000 to $10,000	M85 ded[b] PADD III RFG PADD I RFG **Vehicle scrappage** M100 ded[b]
$10,000 to $20,000	M100 ffv[b] M85 ffv[b] **Onboard diagnostics**[d] Cal RFG E85 ffv (corn-derived)[b,c]
Greater than $20,000	EV[b] Low petroleum gasoline **Transportation control measures**[e]

[a]The CAAA directed EPA to promulgate new evaporative standards and test procedures to control running loss emissions and multi-day diurnal emissions under summer ozone-forming conditions.

[b]Assumes constant present value of AFV fuel costs

[c]Cellulosic ethanol: $1.00/gallon. Corn-derived ethanol: $1.50/gallon.

[d]On-board diagnostics systems will identify and cause to be repaired all those vehicles that are capable of being identified with an enhanced Inspection/Maintenance test.

[e]Transportation control measures include trip reduction ordinance; parking management; flexible/staggered work hours; telecommunications; park and ride lots; and off-peak goods movement.

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APPENDIX A
ADJUSTMENT OF COST-EFFECTIVENESS RATIO ESTIMATES

The process of adjustment of price and pollutant denomination differs for each study. For example, the adjustment approach for M100 reported by Congress (1989) follows. The information provided by Congress (1989) is:

General cost-effectiveness is CER_1 = \$3,200 to CER_2 = \$22,000 per ton.

The levelized (annualized) added cost for the vehicle is C_1 = \$0 to C_2 = \$150.

The price of M85 is \$1.15 to \$1.51 per gasoline gallon equivalent.

The price of gasoline is \$1.025 per gallon.

The vehicle averages 10,000 miles per year and 26.2 miles per gasoline equivalent gallon.

A 90 percent reduction in emissions of volatile organic compounds can be achieved with M100.

With the above information, the cost-effectiveness equation can be solved for the annual tons of HC emissions reductions (ΔT), assuming that HCs = volatile organic compounds:

CER = (levelized added cost for vehicle + annual added fuel cost)/ΔT

CER_1 = \$3,200/ton = [0 + (10,000 miles)/26.2 miles/gallon)(\$1.15/gallon - \$1.025/gallon)]/ΔT

Therefore, ΔT = 0.0149 tons.

The Price Adjustment

In 1990 dollars, Wang's price increase for M100 versus gasoline is:

(Physical price of methanol)*(energy content of gasoline/energy content of methanol)*(mpg benefit) - price of gasoline =

(\$0.92/gallon)*[(115,000 BTU/gallon)/(56,800 BTU/gallon)]*(.85) - \$1.30/gallon = 0.283/gallon in 1990 dollars or \$0.272/gallon in 1989 dollars of the Congress study. **This price increase is within the sensitivity range of the Congress study** (\$0.125 < \$0.27 < \$0.49).

With the revised pricing, the price-adjusted CERs become:

CER_{p1} = [0 + (10,000 miles)/26.2 miles/gallon)(\$0.272/gallon)]/0.0149 tons = \$6,970/ton

CER_{p2} = [150 + (10,000 miles)/26.2 miles/gallon)(\$0.272/gallon)]/0.0149 tons = \$17,000/ton

Converted to 1993 dollars with the factor (1.0418),[4] the adjusted CER range is:

$8,210/ton to $20,000/ton

The Reactivity Adjustment

Congress assumes that a 90 percent reduction in HC emissions can be achieved with M100. Therefore, the HC emissions of M100 = (0.1)*(HC emissions of gasoline).

From Table 13, the reactivity adjustment factor (RAF) for gasoline is 1.00, and the RAF for M100 is 0.37. So reactivity adjusted HC emissions of M100 = (0.37)*(0.1)*(HC emissions of gasoline) = 0.037*(HC emissions of gasoline).

Therefore, relative to gasoline, the reactivity adjusted emissions reduction for M100 is (1 - 0.037)*100 percent = 96.3 percent. CER_{p1} and CER_{p2} were calculated for a 90 percent reduction in HCs, without reactivity adjustment. With the reactivity adjustment, the emissions reductions are greater by a factor of (0.963)/(0.9) = 1.07. The reactivity and price adjusted CERs become:

CER_{rp1} = CER_{p1}/1.07 = $8,210/ton/1.07 = $7,670/ton.

CER_{rp2} = CER_{p2}/1.07 = $20,000/ton/1.07 = $18,700/ton.

In Table 11, the average of CER_{rp1} and CER_{rp2} is reported = $13,200/ton.

Total Pollutant Denomination

In the Wang (1993) algorithm for M100, the present value of the reduction of HC emissions is 0.0883 tons. For Wang's conditions, the present value of the reduction in composite emissions of HC+NOx+CO+TAP is 0.2830 tons. For each ton of HC reduction, there are 0.2830/0.0883 = 3.205 tons of reduction of composite emissions. If it is assumed that the ratio of composite emissions reduction to HC reduction is about the same for both studies, then the estimated CER based on composite emissions is $13,200/ton/3.205 = $4,120/ton, as shown in Table 14.

The ratio (3.205) of composite emissions reduction to HC reduction is somewhat in error because baseline gasolines differ in Congress and Wang. This error cannot be corrected with confidence because gasoline properties are not sufficiently reported. In a sensitivity examination for which RVP is the major difference in baseline gasolines (9 psi RVP is reported by Congress; 7.8 psi is assumed for Wang; and emissions reductions are computed with the EPA final Complex Model), the ratio of composite emissions reduction to HC reduction is 2.75, and the estimated CER based on composite emissions is $13,200/ton/2.75 = $4,800/ton.

APPENDIX B
DECOMPOSITION OF COST-EFFECTIVENESS RATIO

Decomposition of the cost-effectiveness ratio is illustrated for the M85 ffv estimate of Fraas and McGartland (1990).

The CERs for a given AFV type can be expressed in a form similar to a truncated Taylor series, providing estimates of components of differences. Let:

f = fuel costs relative to Wang
n = non-fuel costs relative to Wang
e = emissions reductions relative to Wang
i = a particular study for a given AFV type, with i = 0 for the Wang estimate
$CER_i(f_i,n_i,e_i)$ = the cost-effectiveness ratio for a particular study for a given AFV type, expressed as a function of the costs and emissions reductions of that study relative to Wang

Then

$$CER_i(f_i,n_i,e_i) = CER_0(f_0,n_0,e_0) + (\partial CER_0/\partial f_0)(f_i - f_0) + (\partial CER_0/\partial n_0)(n_i - n_0) + (\partial CER_0/\partial e_0)(e_i - e_0) + R_i$$

The preceding equation expresses the CER for a study in terms of the $CER_0(f_0,n_0,e_0)$ estimate of Wang and four components:

$(\partial CER_0/\partial f_0)(f_i - f_0)$: the fuel cost component of difference;

$(\partial CER_0/\partial n_0)(n_i - n_0)$: the non-fuel cost component of difference;

$(\partial CER_0/\partial e_0)(e_i - e_0)$: the emissions reduction component of difference; and

R_i: differences due to study methodologies, higher order terms which have been truncated, and other approximations.

The algorithm of Wang (1993) is used to construct Tables B-1 and B-2. Partial derivatives are estimated with the values in these tables.

Table B-1. Data for estimation of partial derivatives for M85 ffv (Costs and CERs in 1990 dollars)				
Case	Present value of fuel costs, $	Present value of non-fuel costs, $	Present value of emissions reductions, tons	CER per algorithm of Wang (1993), $/ton
Base	1,012	300	0.1698	7,724
Increase AF cost by 10 percent	1,513	300	0.1698	10,675
Increase non-fuel cost by 10 percent	1,012	330	0.1698	7,901
Increase AF emissions by 10 percent	1,012	300	0.08848	14,823

Table B-2. Converted data for estimation of partial derivatives for M85 ffv (CERs in 1993 dollars)				
Case	Relative to Base			CER per algorithm of Wang (1993), $/ton
	Present value of fuel costs	Present value of non-fuel costs	Present value of emissions reductions	
Base	1	1	1	8,734
Increase AF cost by 10 percent	1.495	1	1	12,071
Increase non-fuel cost by 10 percent	1	1.1	1	8,934
Increase AF emissions by 10 percent	1	1	0.5211	16,761

From Table B-2:

$(\partial CER_0/\partial f_0) = (12{,}071 - 8{,}734)/(1.495 - 1) = 6{,}736$

$(\partial CER_0/\partial n_0) = (8{,}934 - 8{,}734)/(1.1 - 1) = 1{,}998$

$(\partial CER_0/\partial e_0) = (16{,}761 - 8{,}734)/(0.5211 - 1) = -16{,}761$
The Frass and McGartland CER function for M85 ffv is:

$$CER_i(f_i,n_i,e_i) = CER_i(0.6,1.09,0.62) = \$8{,}840/\text{ton}$$

The Wang CER function for M85 ffv is:

$$CER_0(f_0,n_0,e_0) = CER_0(1,1,1) = \$8{,}500/\text{ton}$$

The fuel cost component of difference is:

$$(\partial CER_0/\partial f_0)(f_i - f_0) = (6{,}736)(0.6 - 1) = -\$2{,}695/\text{ton}$$

The non-fuel cost component of difference is:

$$(\partial CER_0/\partial n_0)(n_i - n_0) = (1{,}998)(1.09 - 1) = \$180/\text{ton}$$

The emissions reduction component of difference is:

$$(\partial CER_0/\partial e_0)(e_i - e_0) = (-16{,}761)(0.62 - 1) = \$6{,}369/\text{ton}$$

The difference due to study methodologies, higher order terms which have been truncated, and other approximations is:

$$R_i = 8{,}840 - 8{,}500 + 2{,}695 - 180 - 6{,}369 = -\$3{,}514/\text{ton}$$

Fig. 17 shows the decomposition of the M85 ffv CER estimate of Fraas and McGartland.

APPENDIX C
COST-EFFECTIVENESS RATIO ESTIMATES BASED ON DOE FUEL PRICE FORECAST

CERs have been recomputed with transportation fuel price forecasts reported in DOE (1995). Price assumptions are shown in Table C-1. Table C-2 shows the CER estimates for the price assumptions of Table C-1. With DOE prices, the CERs are lower. However, CERs based on DOE price forecasts would not change the relative positions for CNG vehicles and EVs in Table 27. DOE (1995) does not provide price forecasts for methanol, ethanol, and LPG.

Table C-1. Transportation fuel prices

Fuel	1995 Price (in 1993 dollars per physical gallon, or as noted)		
	Wang (1993)	DOE (1995) Reference Case	
		Year 1995	Year 2000
Conventional gasoline	1.47	1.17	1.38
CNG	$10.7 per million BTUs	$5.14 per million BTUs	$8.67 per million BTUs
Electricity	7.3 cents per kilowatt hour	5.1 cents per kilowatt hour	5.4 cents per kilowatt hour

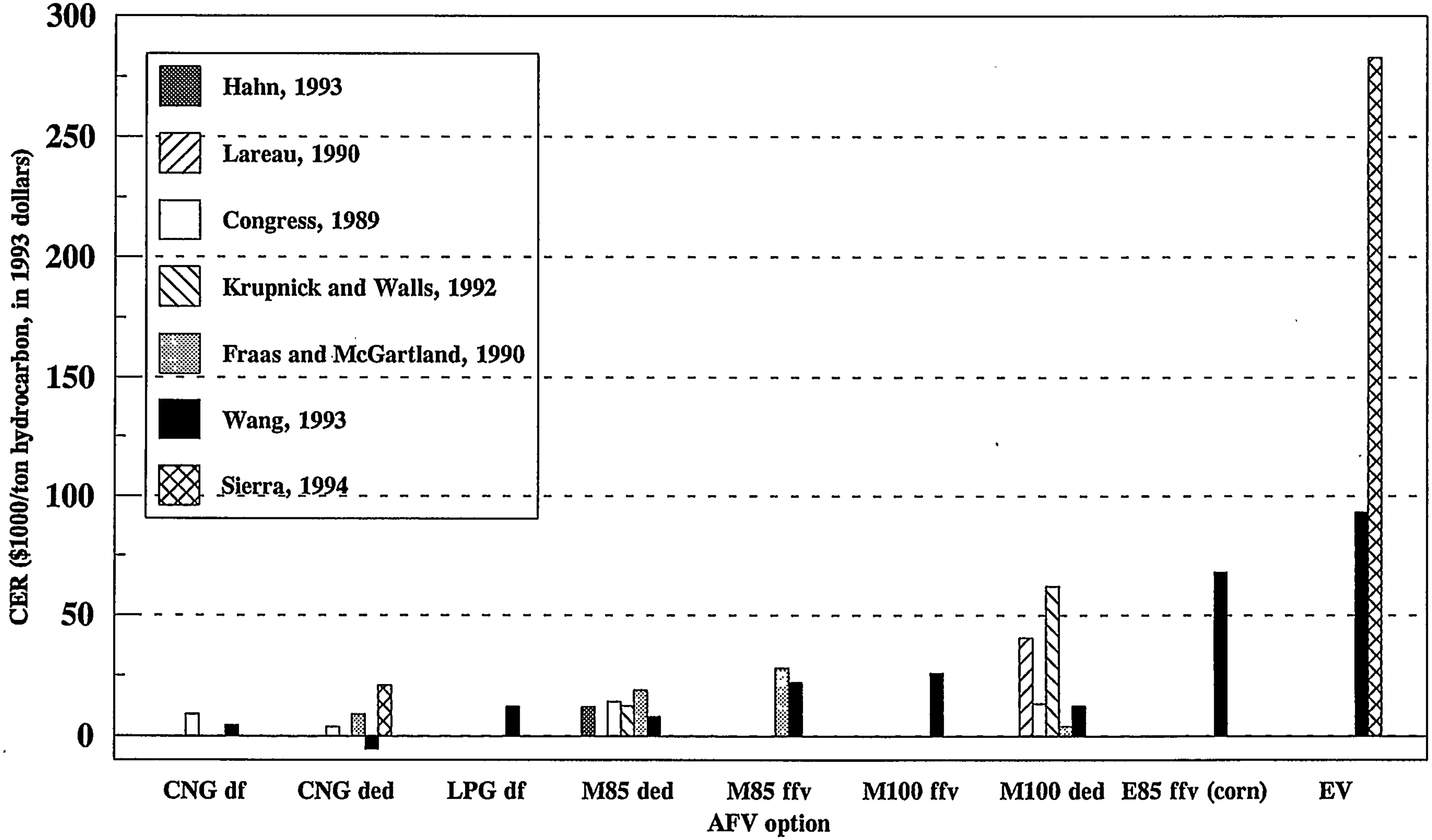
Table C-2. Annualized alternative fuel vehicle cost-effectiveness for different fuel price assumptions

AFV type	CER (thousand $/ton HC+NOx+CO+TAP, 1993 dollars)	
	Wang price assumption	DOE price assumption
CNG df (75 percent CNG operation)	1.3 (S. Cal)	-2.78
	3.6	0.24
CNG ded	4.3 (Cal)	0.48
	-1.44 (S. Cal)	-4.86
	5.60	-1.45
	0.91	-0.92
EV	36.4 (Cal)	33.9
	11.5 (S. Cal)	11.2

FIGURES

Fig. 1. AFV CER for hydrocarbon reduction

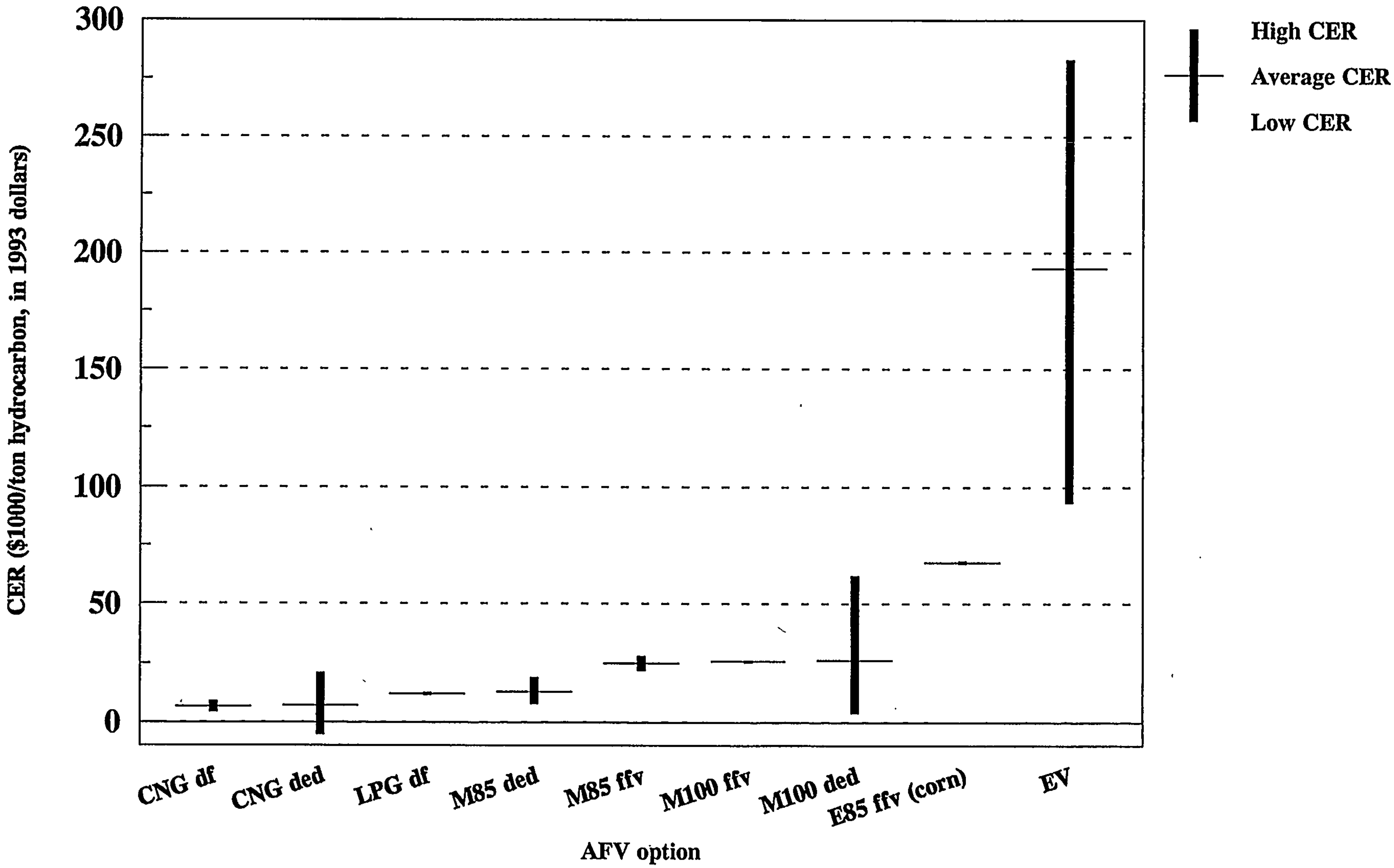
(Constant present value of fuel costs)



Annualized CER, derived on average basis.
Some studies do not report CER for all AFVs.
No zero CER values are shown.

Fig. 2. AFV CER range for hydrocarbon reduction

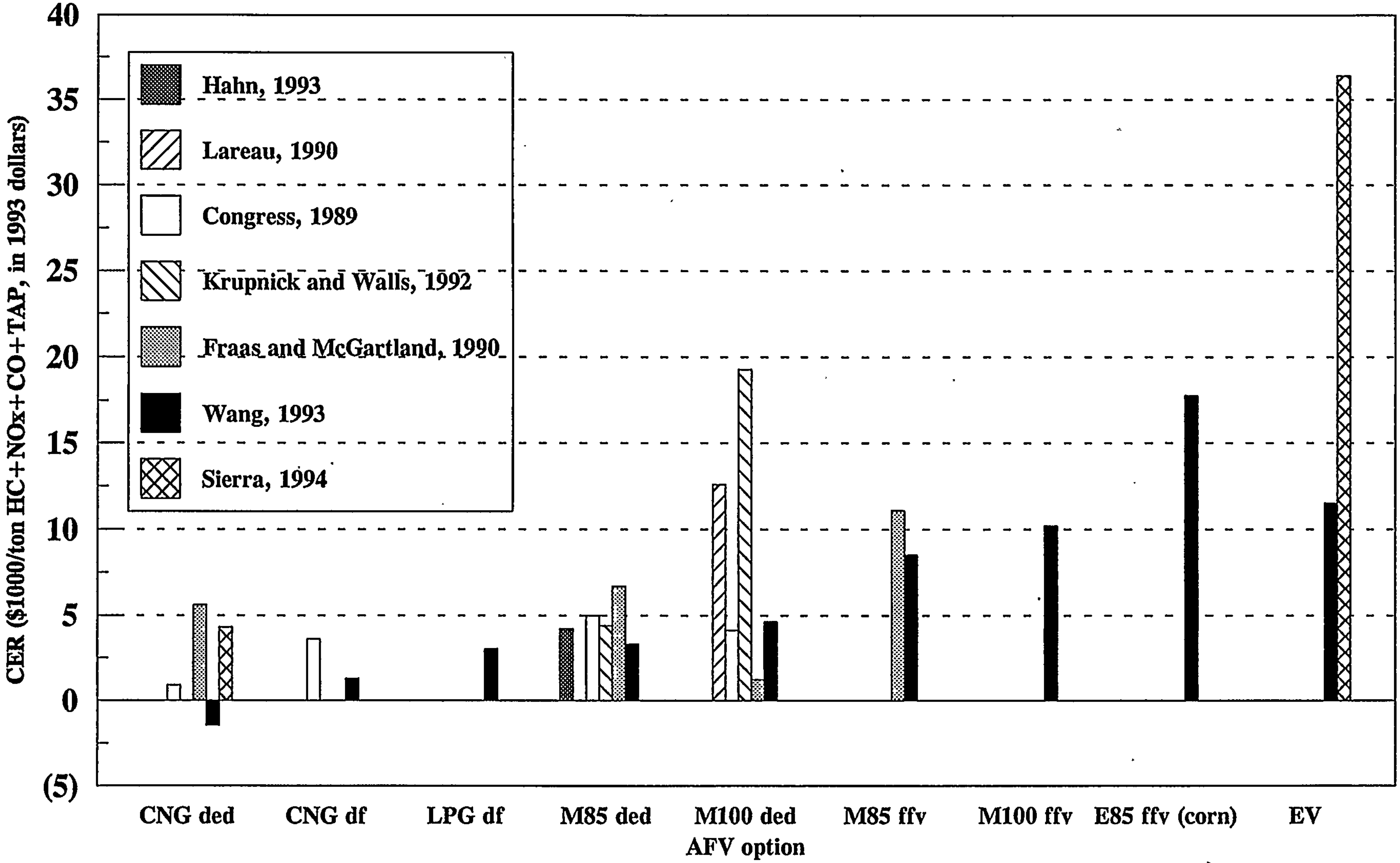
(Constant present value of fuel costs)



Annualized CER, derived on average basis.
Narrow range for some AFVs due to small number
of studies and does not imply greater certainty.

Fig. 3. AFV CER for HC+NOx+CO+TAP reduction

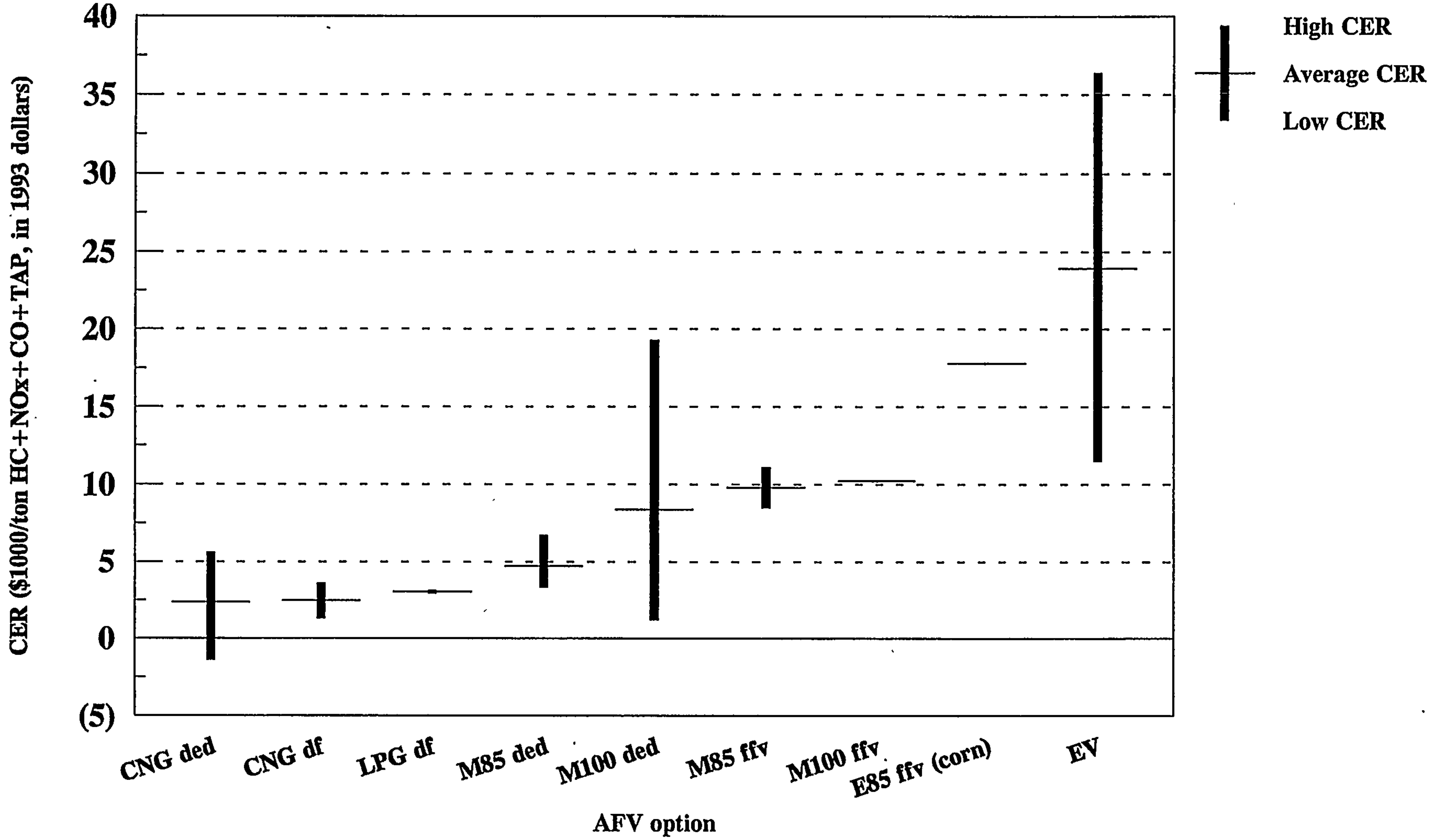
(Constant present value of fuel costs)



Annualized CER, derived on average basis.
Some studies do not report CER for all AFVs.
No zero CER values are shown.

Fig. 4. AFV CER range for HC+NOx+CO+TAP reduction

(Constant present value of fuel costs)



Annualized CER, derived on average basis.
Narrow range for some AFVs due to small number of studies and does not imply greater certainty.

Fig. 5. Non-fuel cost differences in CER estimates

(Constant present value of fuel costs)

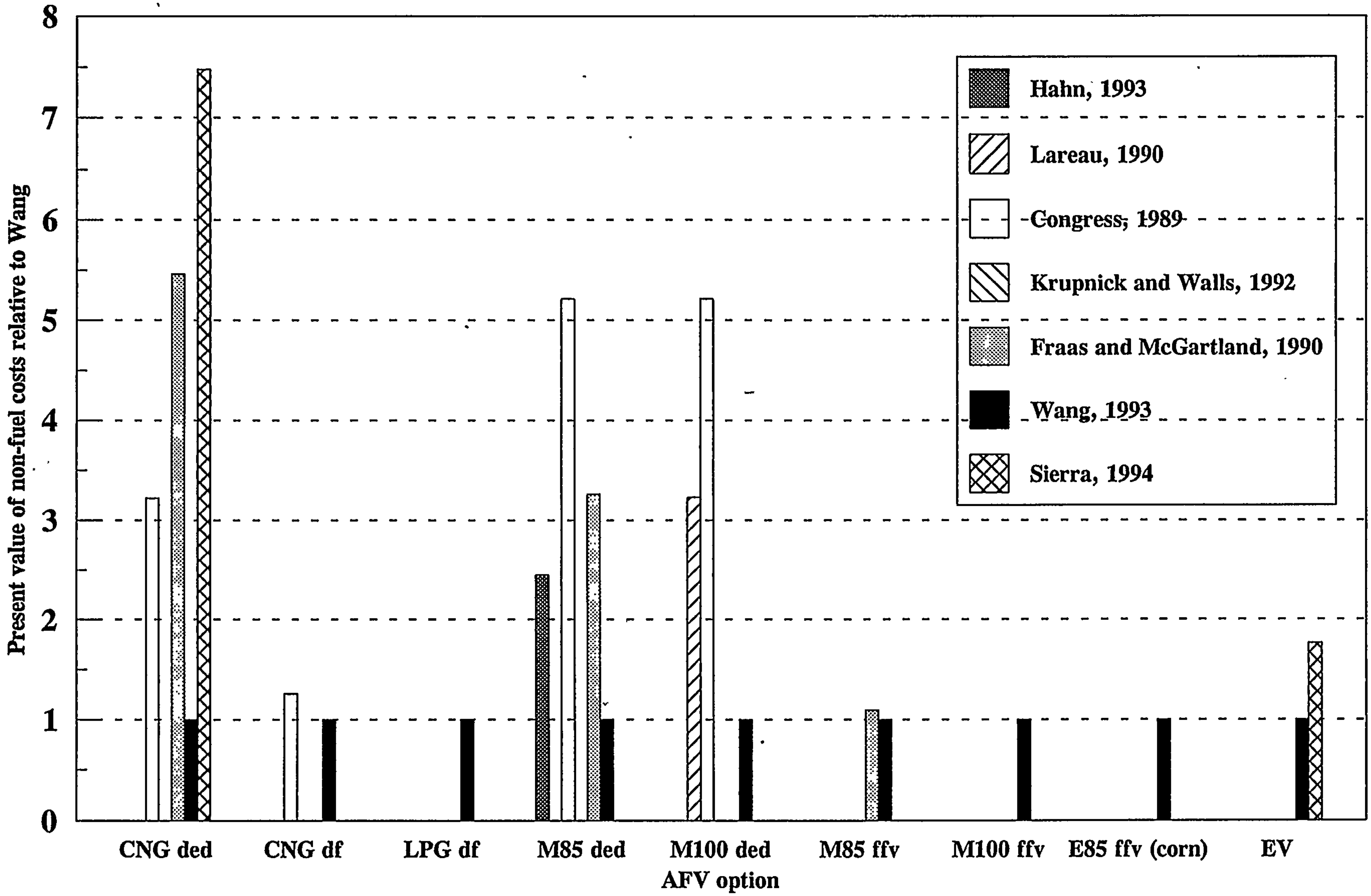


Fig. 6. Emissions reduction differences in CER estimates

(Constant present value of fuel costs)

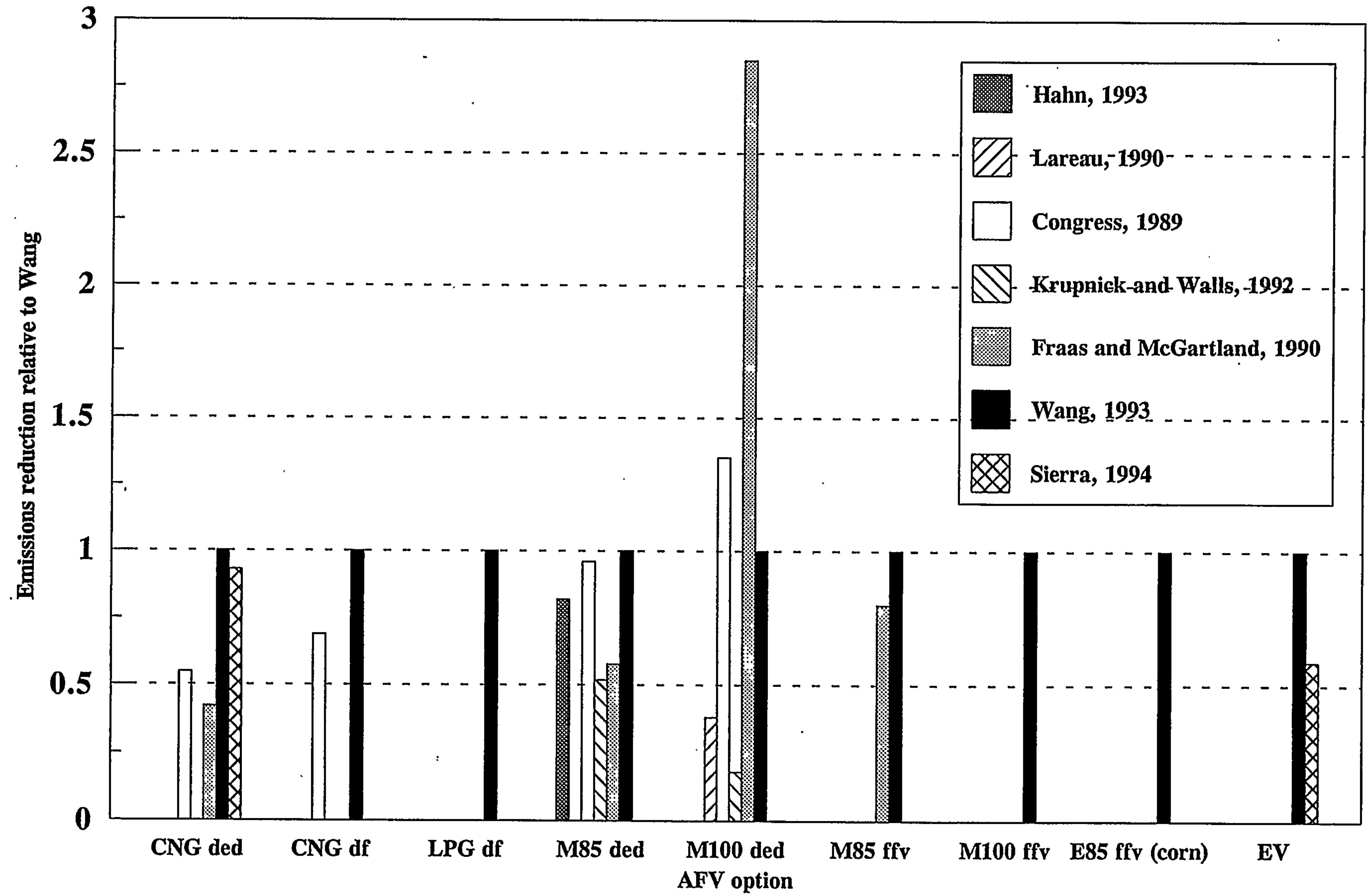


Fig. 7. Emissions reduction differences in CER estimates

(Constant present value of non-fuel costs)

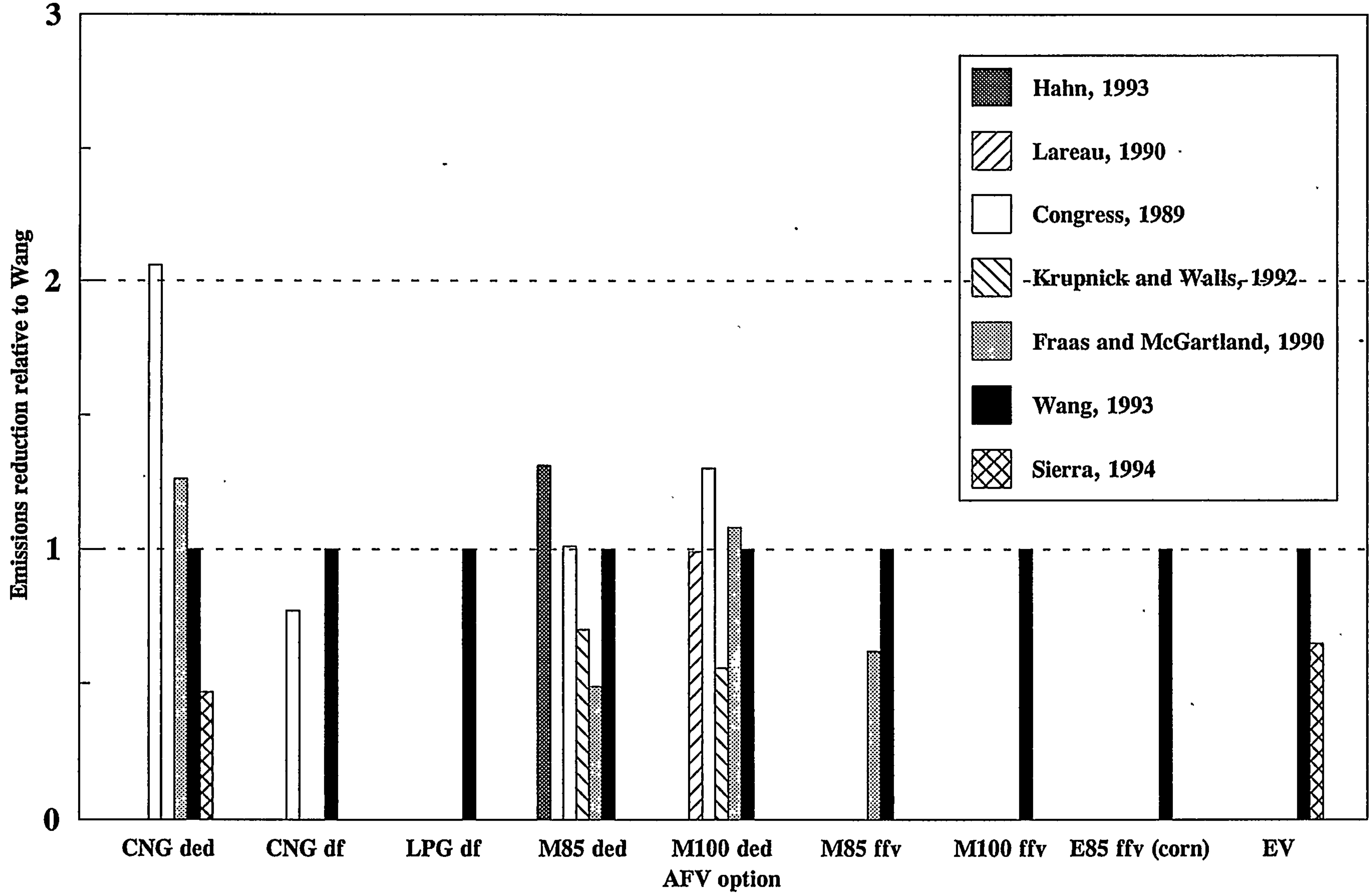


Fig. 8. Fuel cost differences in CER estimates

(Constant present value of non-fuel costs)

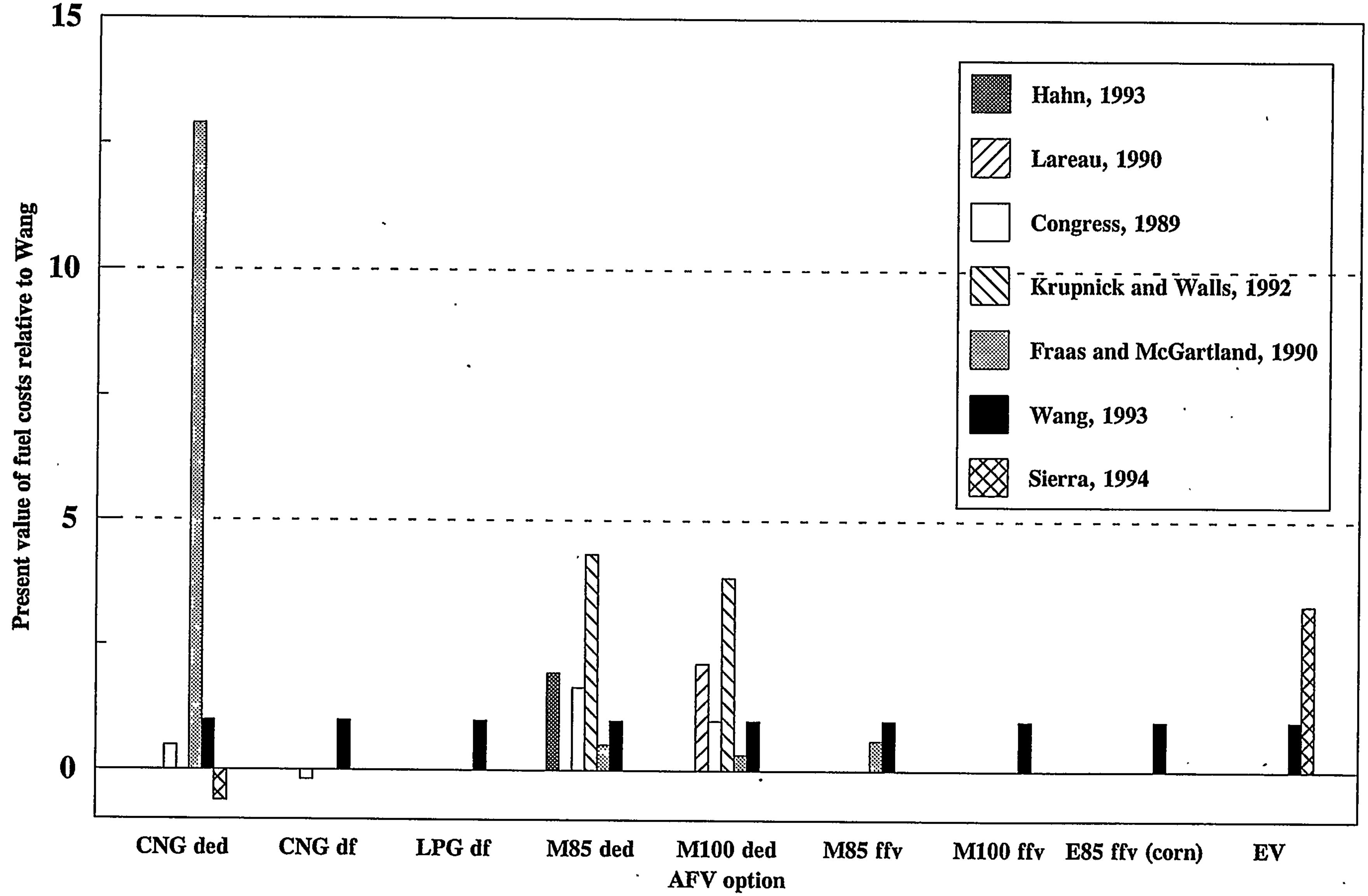


Fig. 9. Fuel cost differences in CER estimates

(Constant present value of emissions reductions)

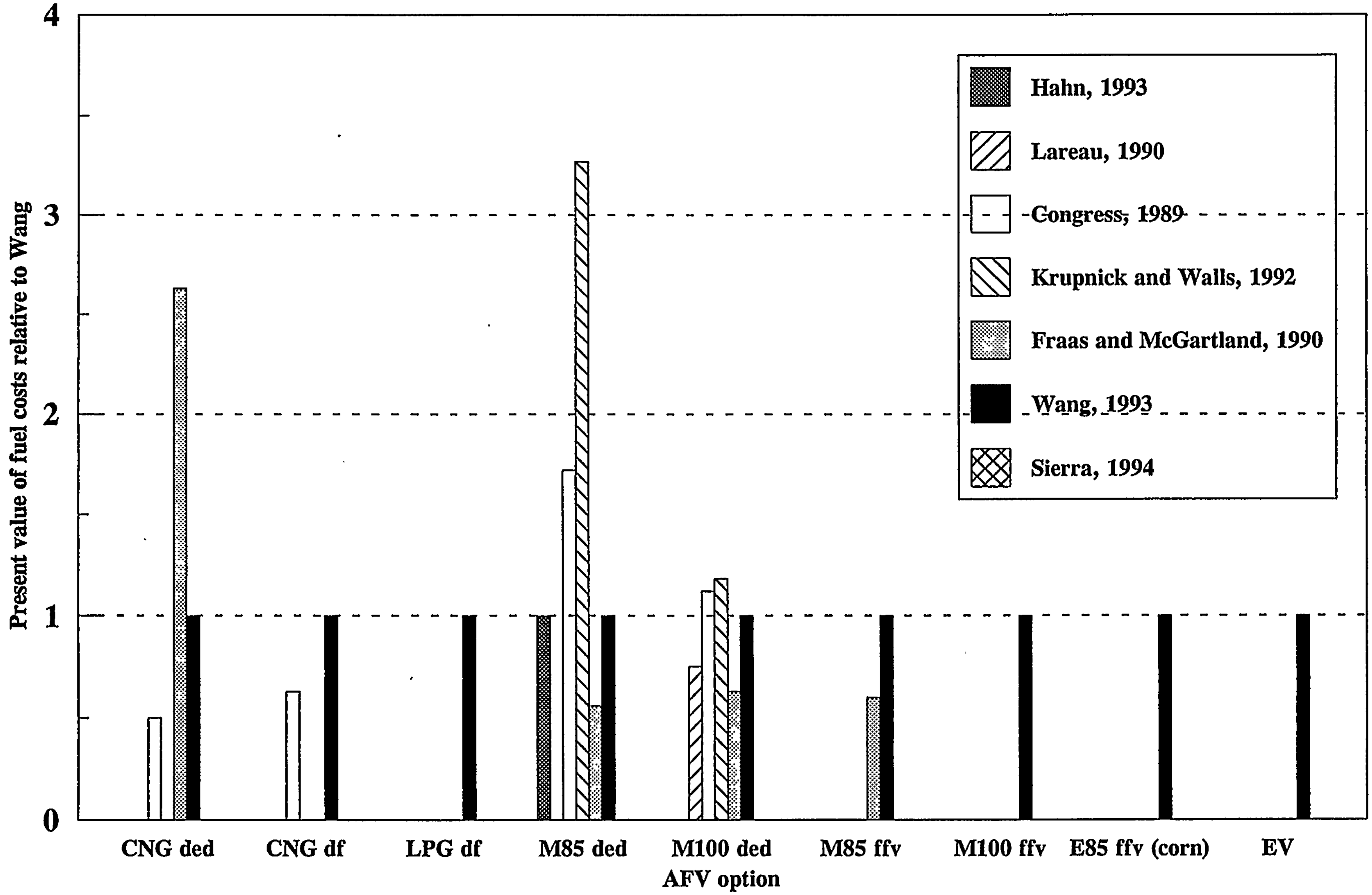


Fig. 10. Non-fuel cost differences in CER estimates

(Constant present value of emissions reductions)

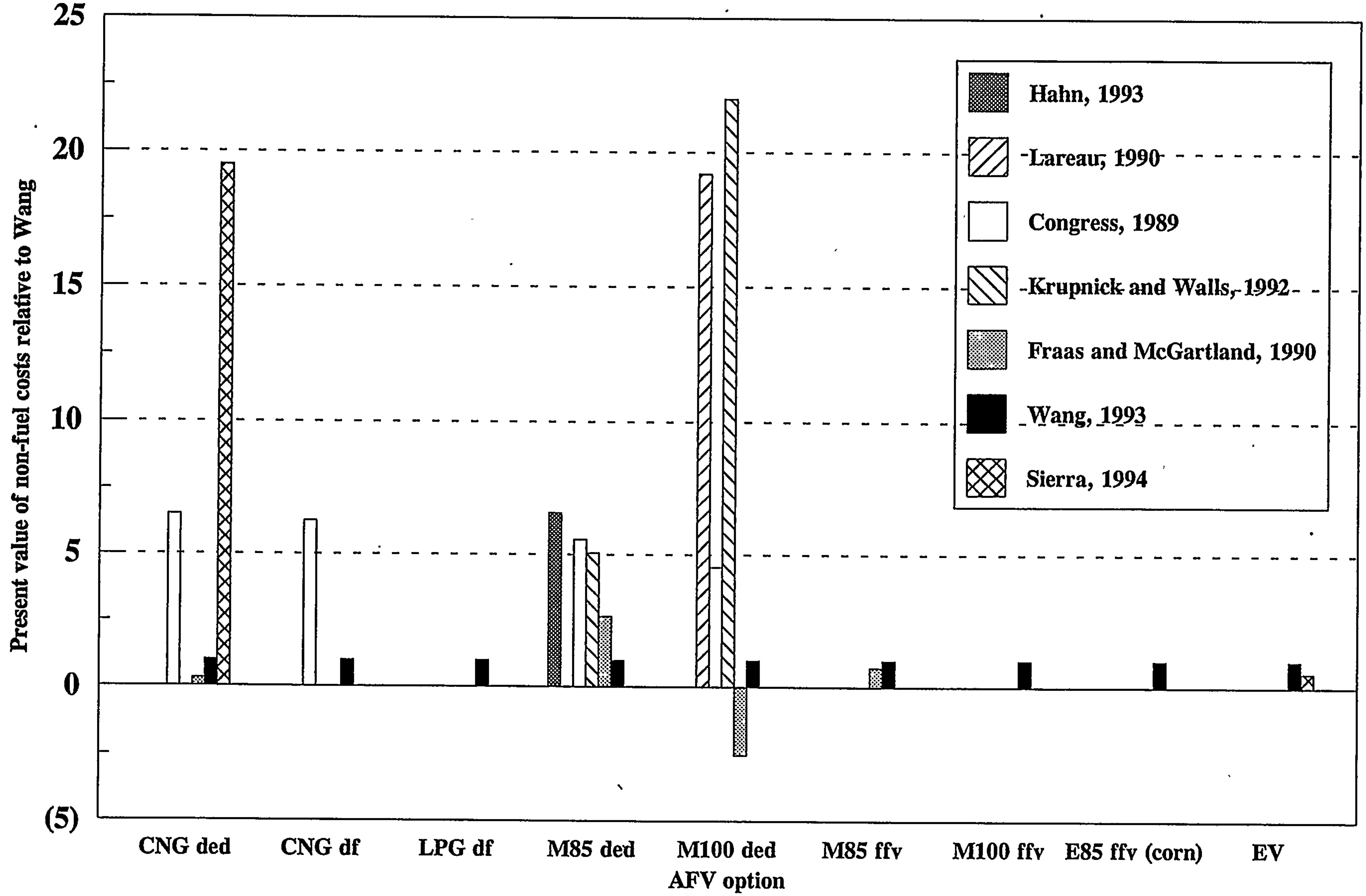
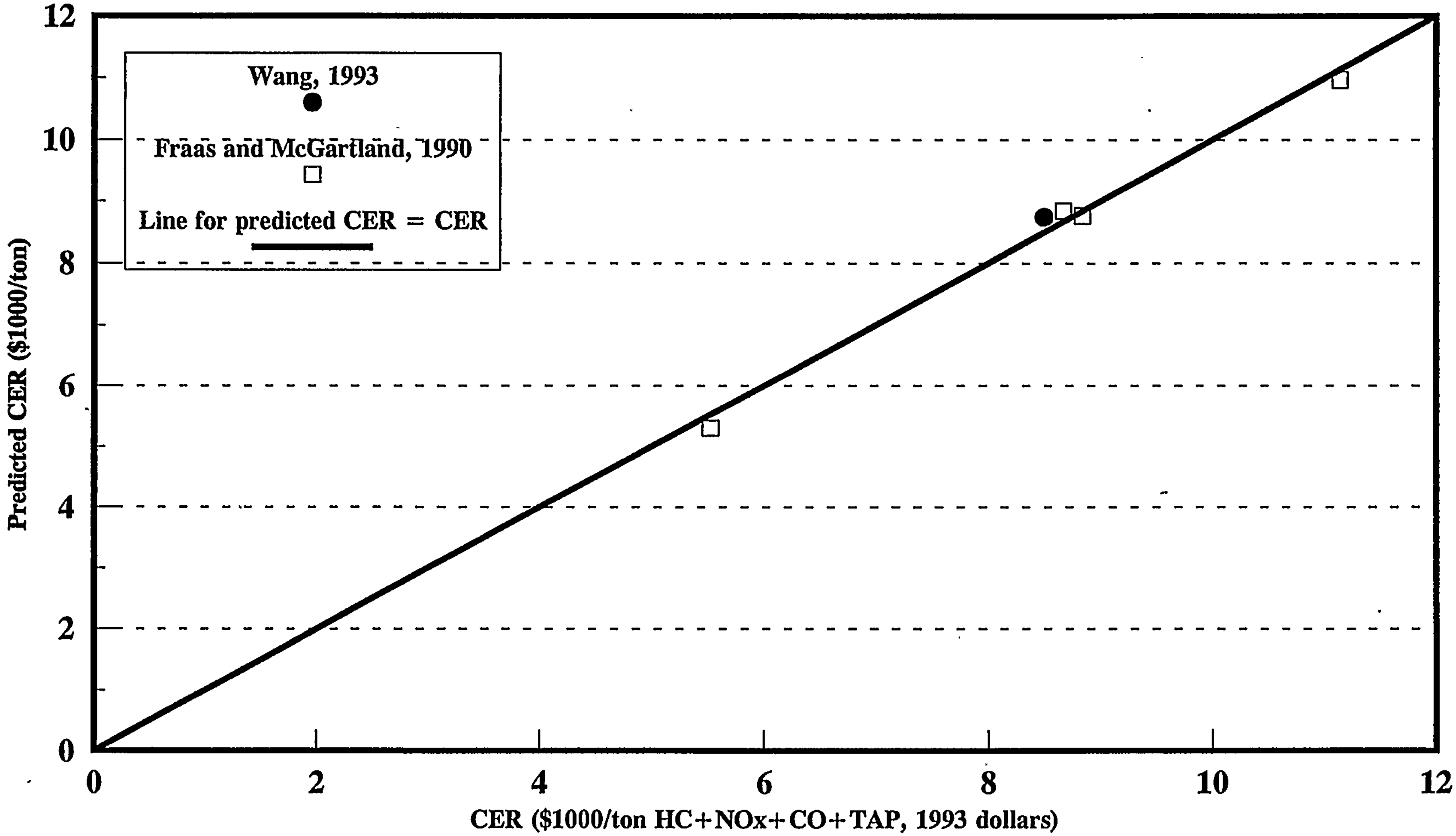


Fig. 11. CER prediction for M85 ffv

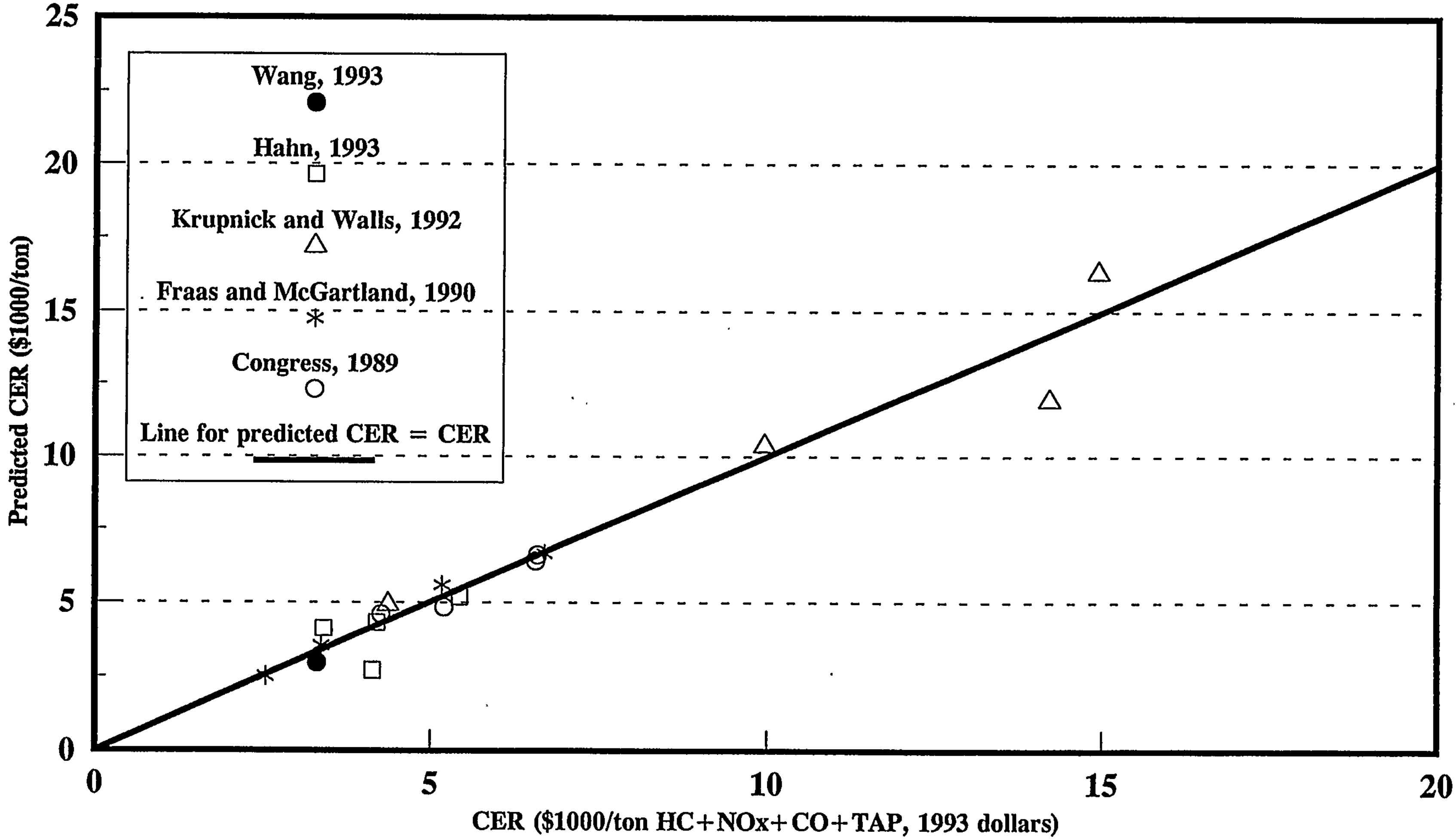
Predicted CER = a*(fuel cost/emission reduction)
+ b*(non-fuel cost/emission reduction)



a = 8.36 and b = 0.386.
Equation costs and emission reduction are relative to Wang, 1993.

Fig. 12. CER prediction for M85 ded

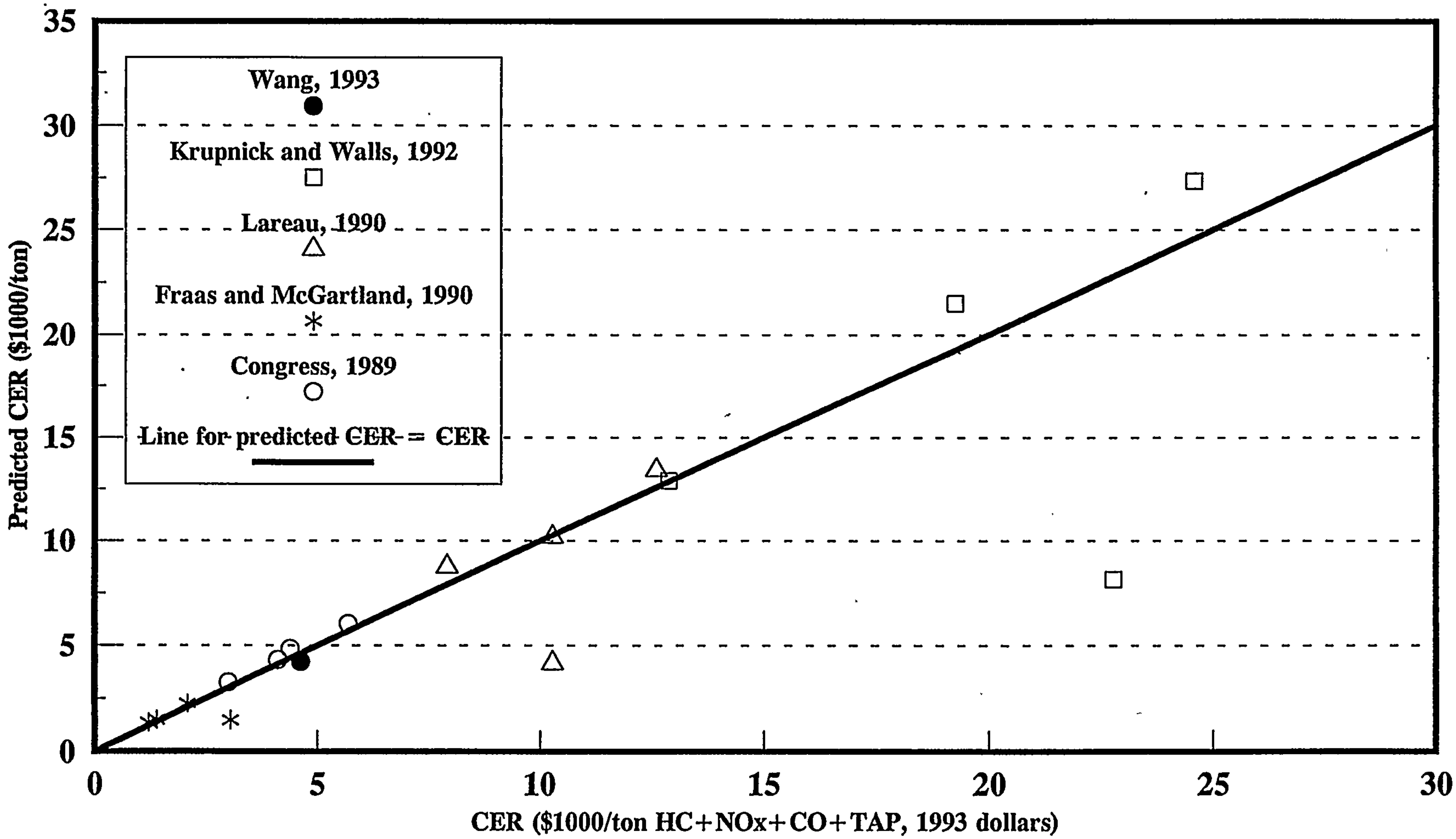
Predicted CER = a*(fuel cost/emission reduction) + b*(non-fuel cost/emission reduction)



a = 2.55 and b = 0.401.
Equation costs and emission reduction are relative to Wang, 1993.

Fig. 13. CER prediction for M100 ded

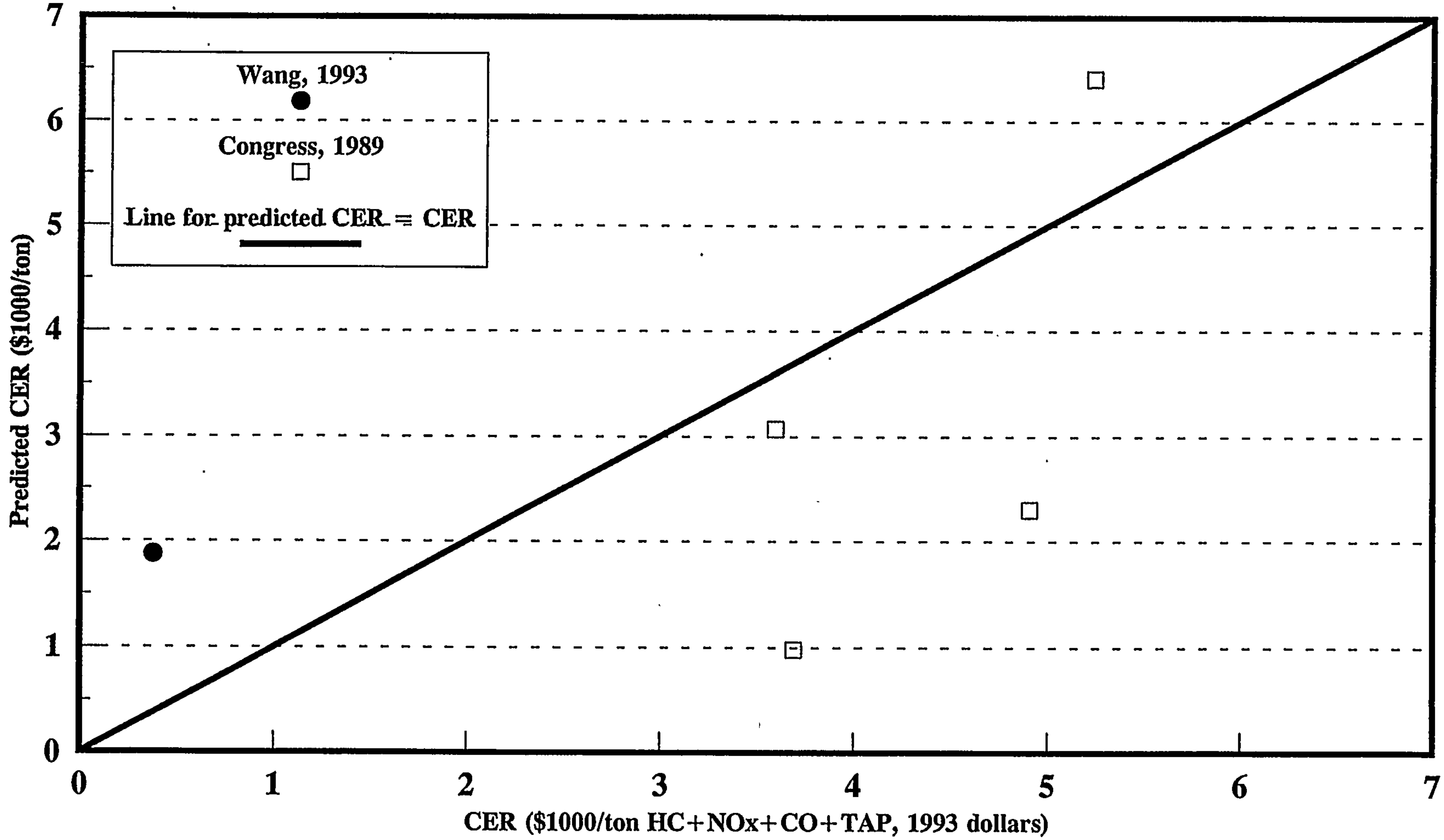
Predicted CER = a*(fuel cost/emission reduction)
+ b*(non-fuel cost/emission reduction)



a = 3.87 and b = 0.379.
Equation costs and emission reduction are relative to Wang, 1993.

Fig. 14. CER prediction for CNG df

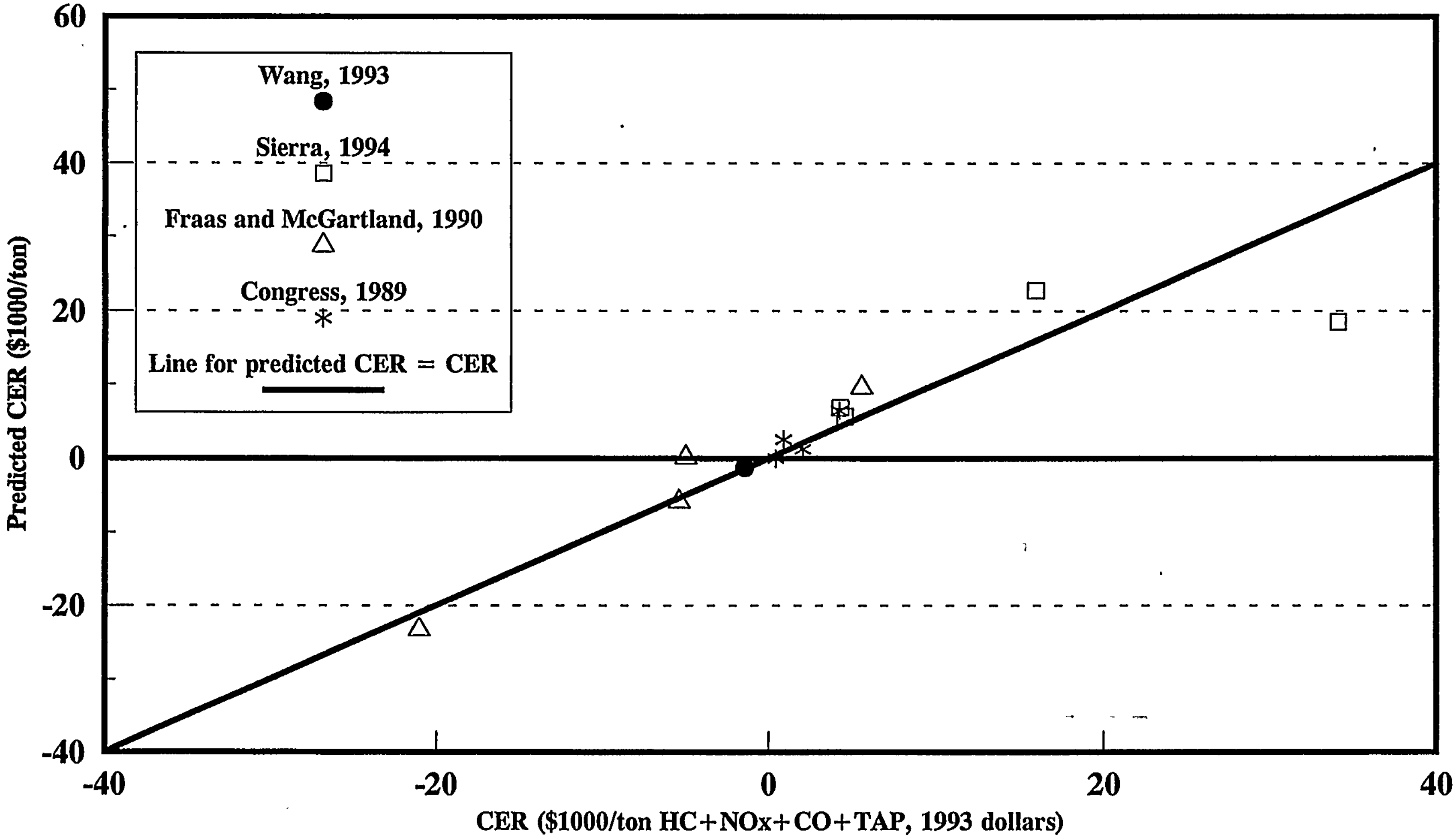
Predicted CER = a*(fuel cost/emission reduction)
+ b*(non-fuel cost/emission reduction)



a = 0.943 and b = 0.934
Equation costs and emission reduction are relative to Wang, 1993.

Fig. 15. CER prediction for CNG ded

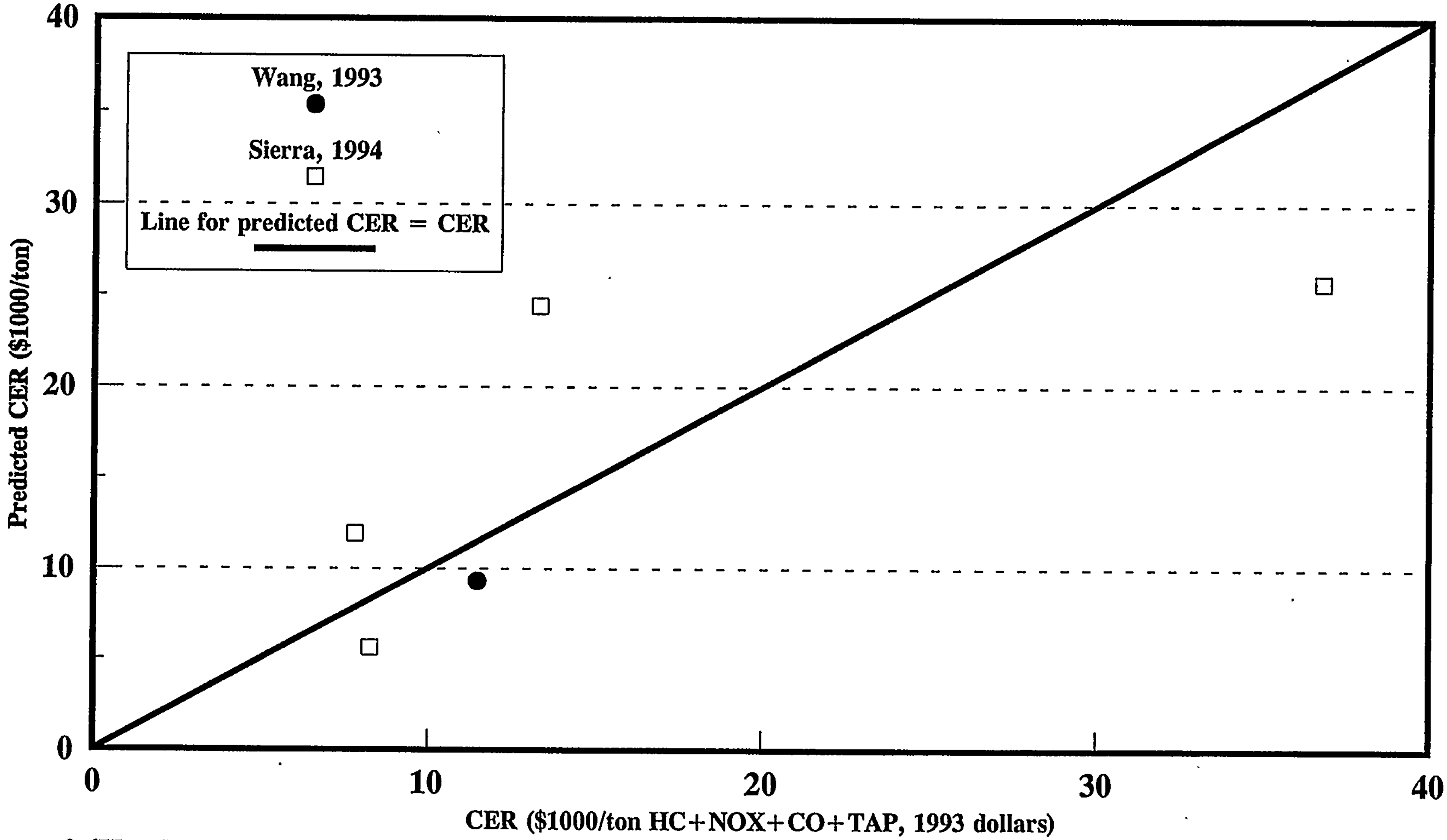
Predicted CER = a*(fuel cost/emission reduction) + b*(non-fuel cost/emission reduction)



a = -2.37 and b = 1.17.
Equation costs and emission reduction are relative to Wang, 1993.

Fig. 16. CER prediction for EV

Predicted CER = a*(fuel cost/emission reduction) + b*(non-fuel cost/emission reduction)



a = -0.677 and b = 9.99.
Equation costs and emission reduction are relative to Wang, 1993.

Fig 17. Decomposition of cost-effectiveness ratio

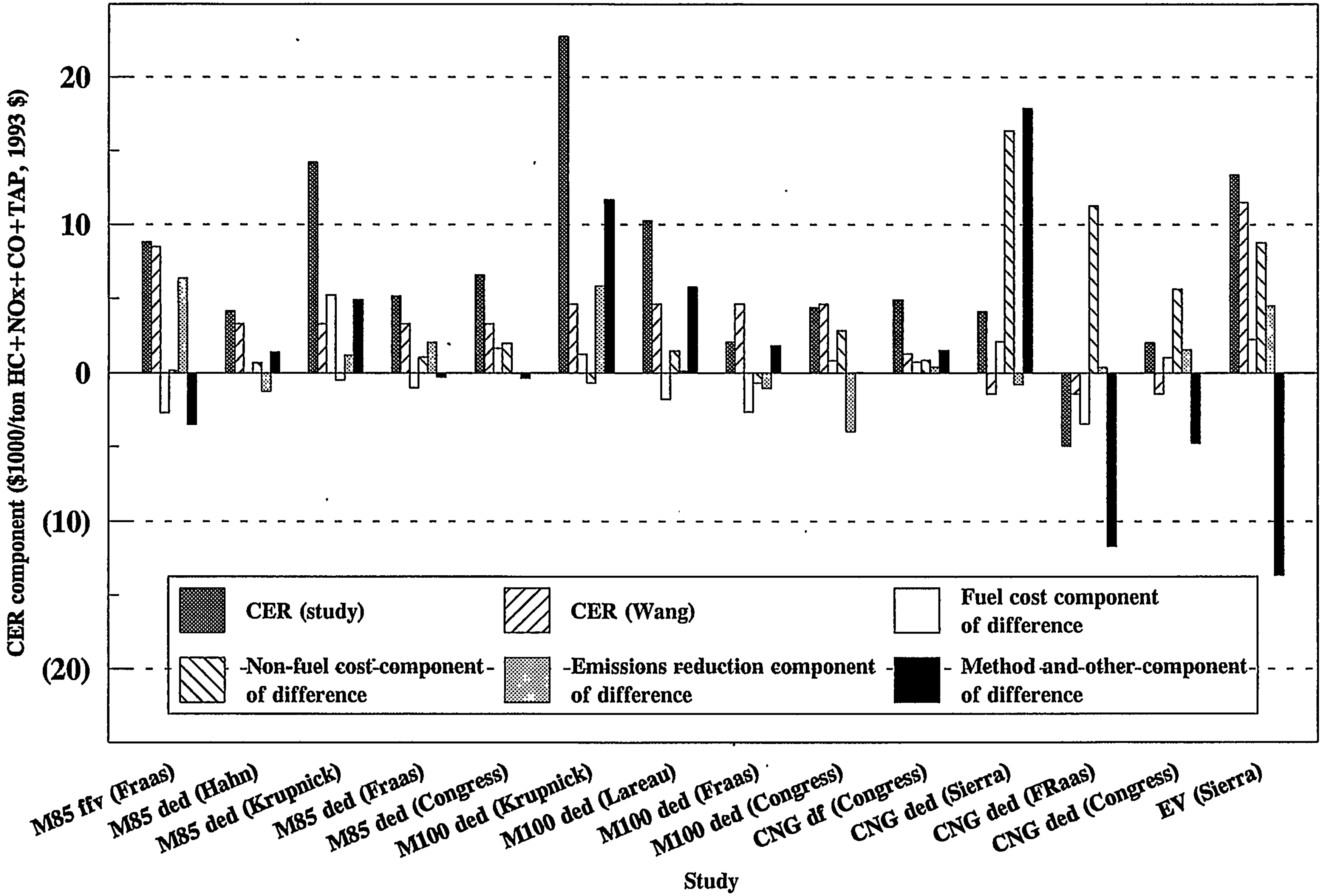
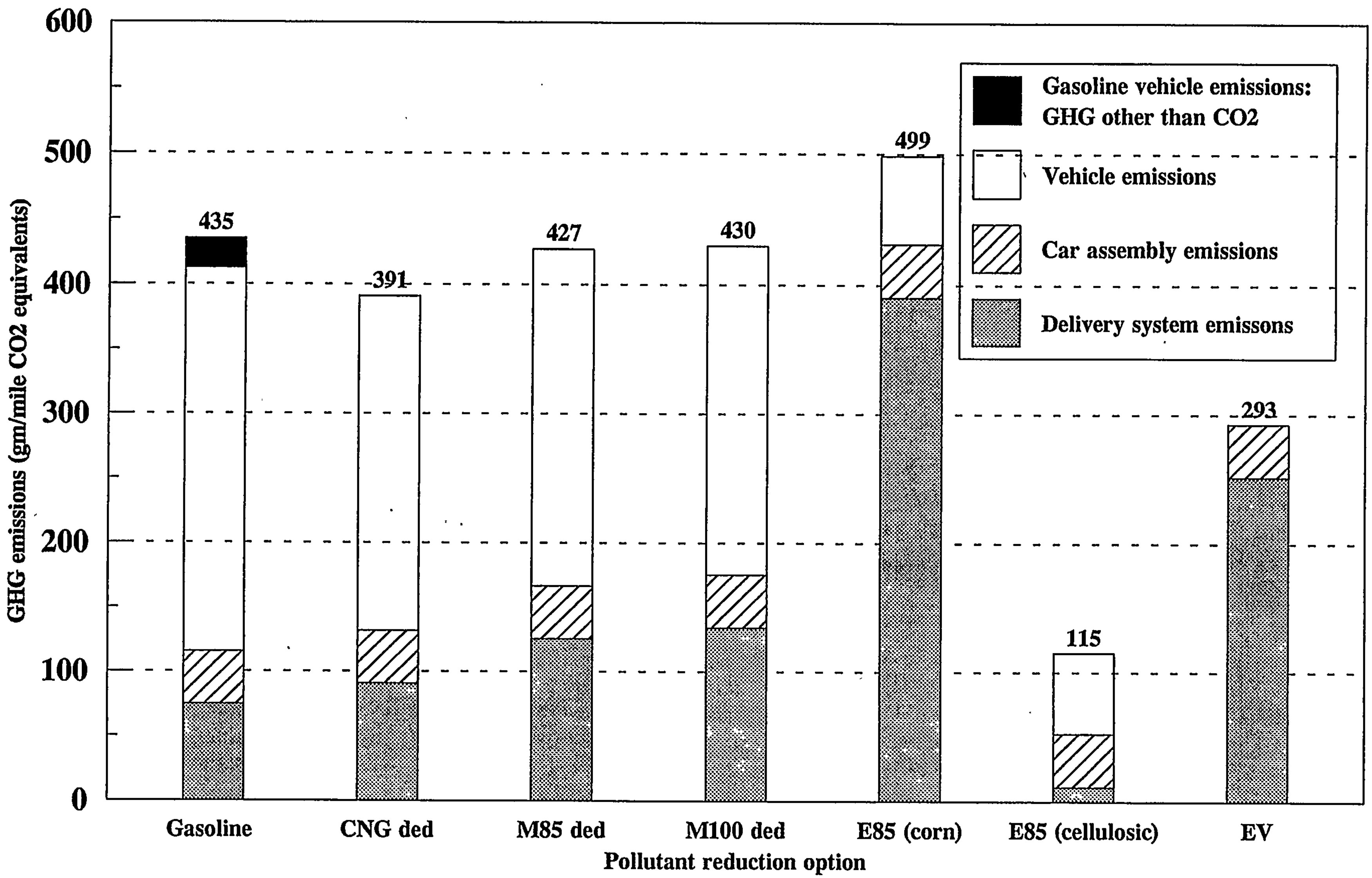


Fig. 18. Greenhouse gas emissions of vehicle systems



Only gasoline vehicle emissions disaggregated into CO2 and other GHG components.

Fig. 19. E85 AFV CER for HC+NOx+CO+TAP+GHG

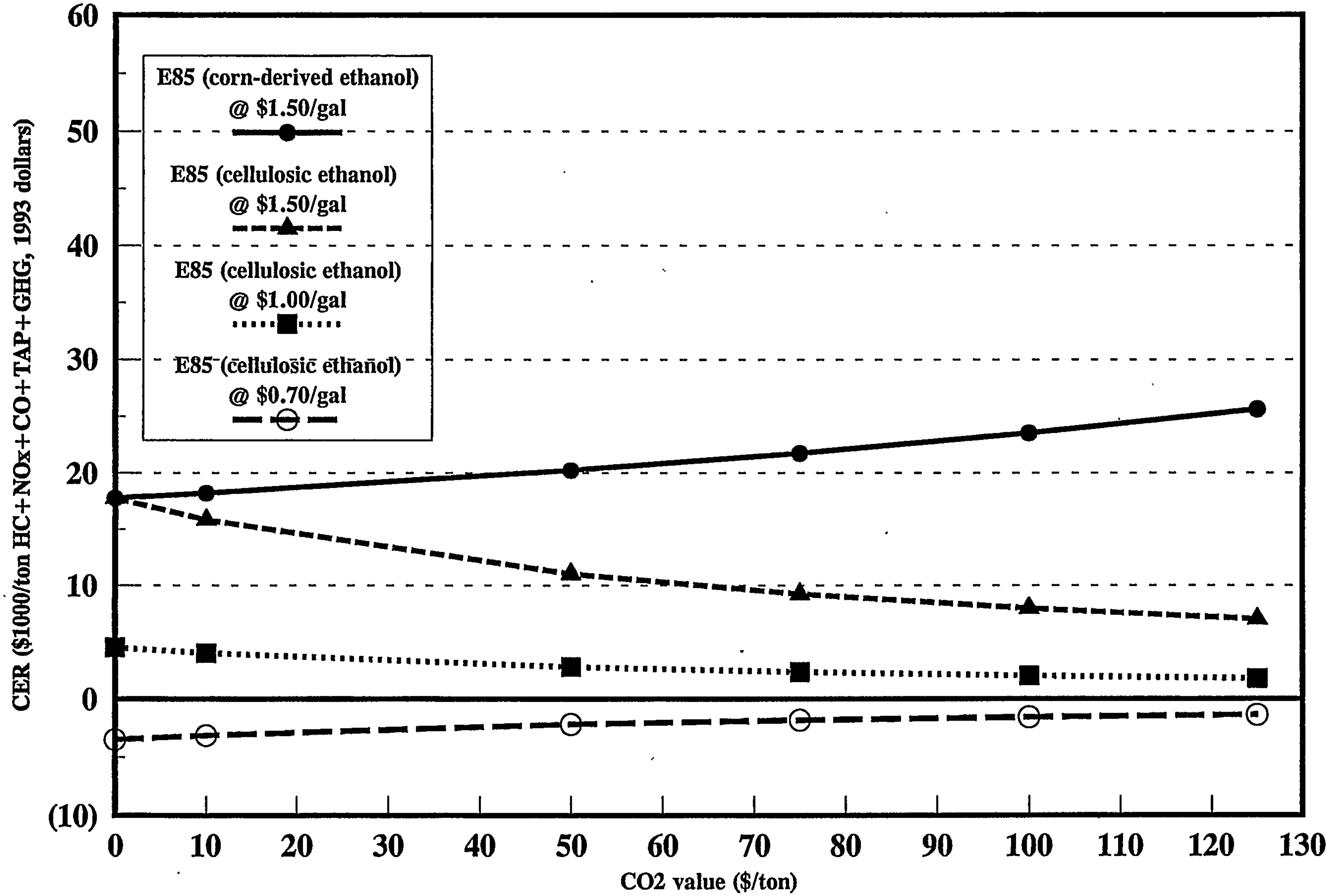
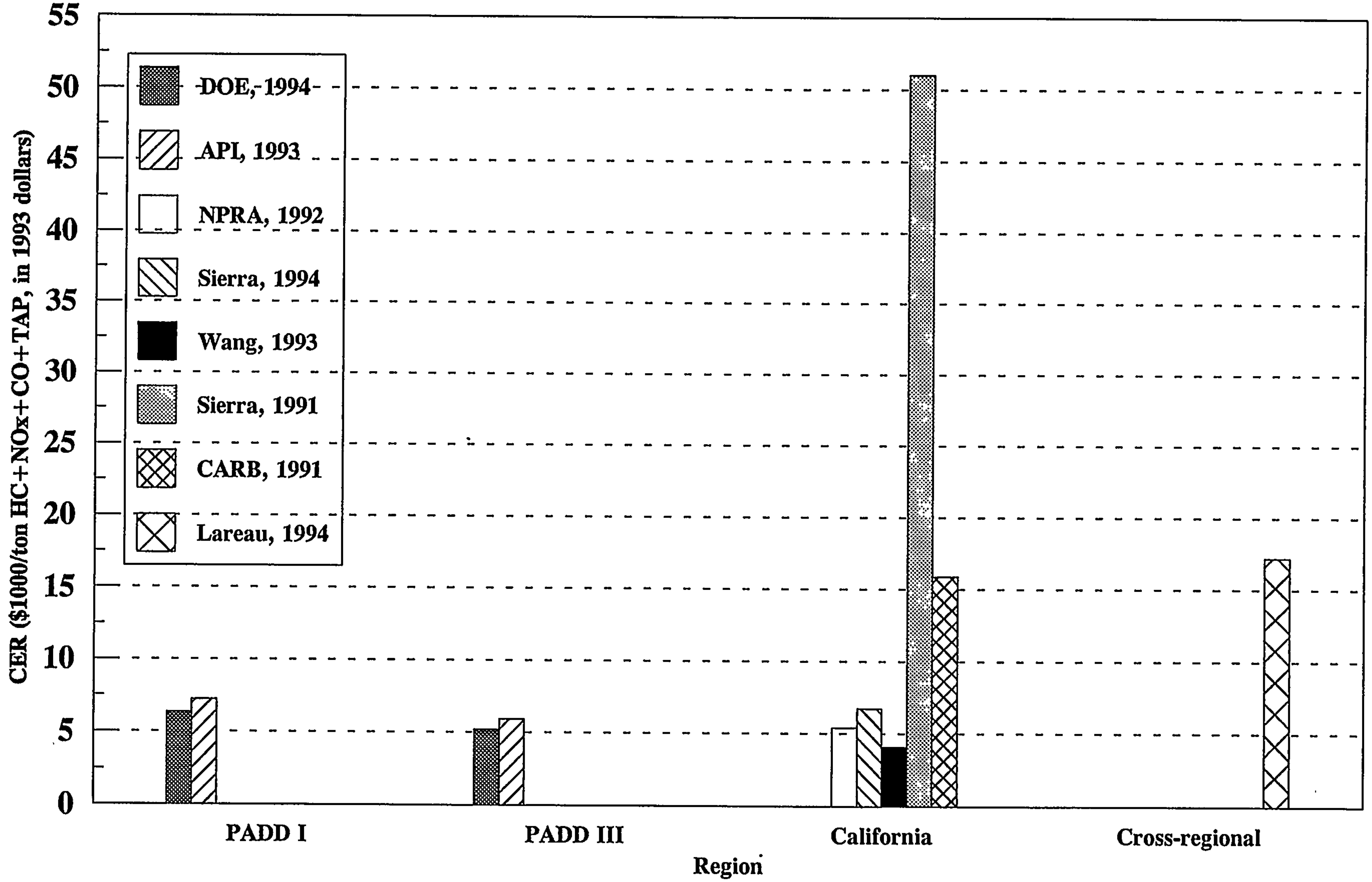


Fig. 20. Phase 2 reformulated gasoline CER



CER annualized; averaged, Phase 1 to Phase 2.
Studies do not report CER for all regions.
No zero CER values are shown.

Fig. 21. Reformulation cost differences in RFG CER estimates

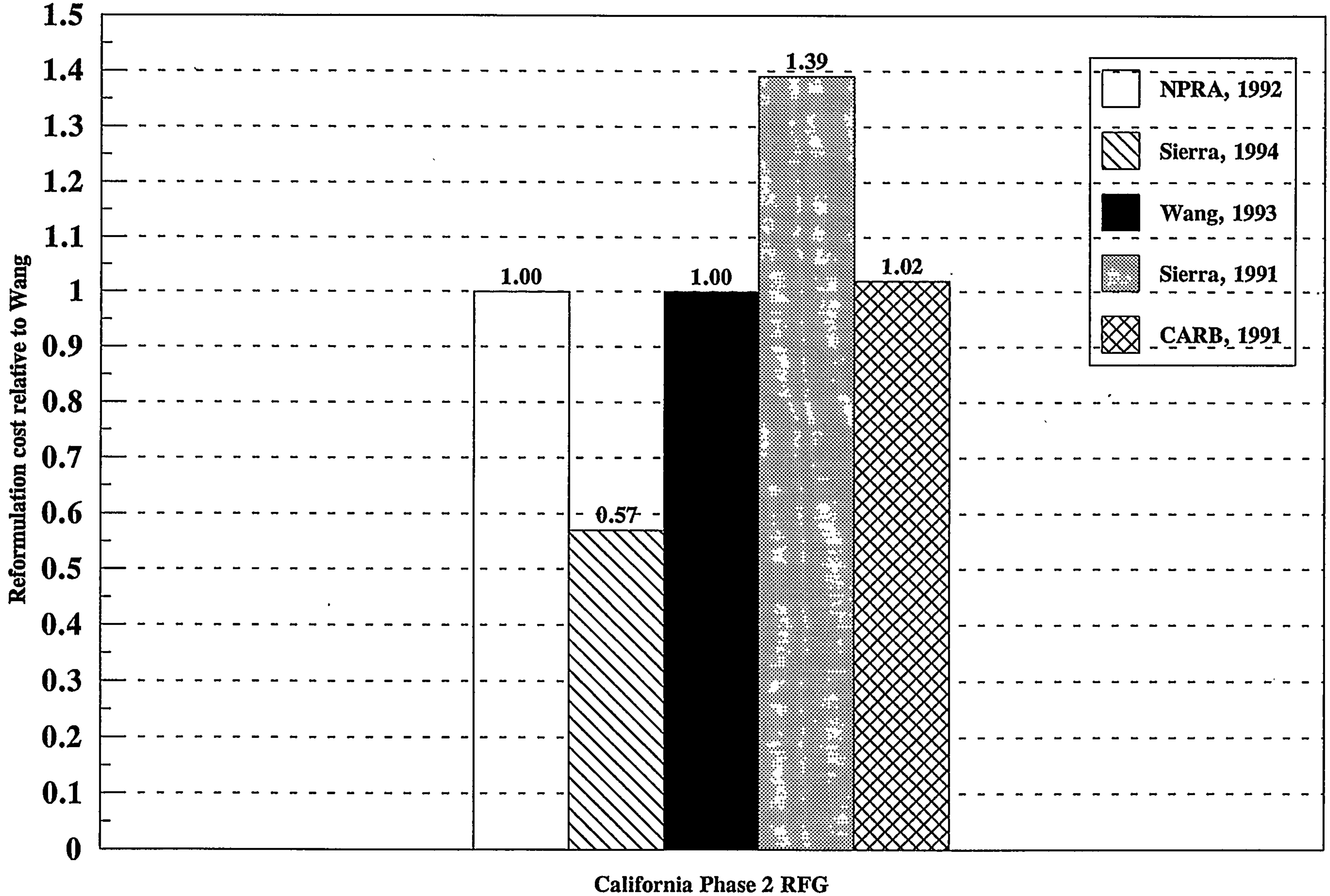


Fig. 22. Emissions reduction differences in RFG CER estimates

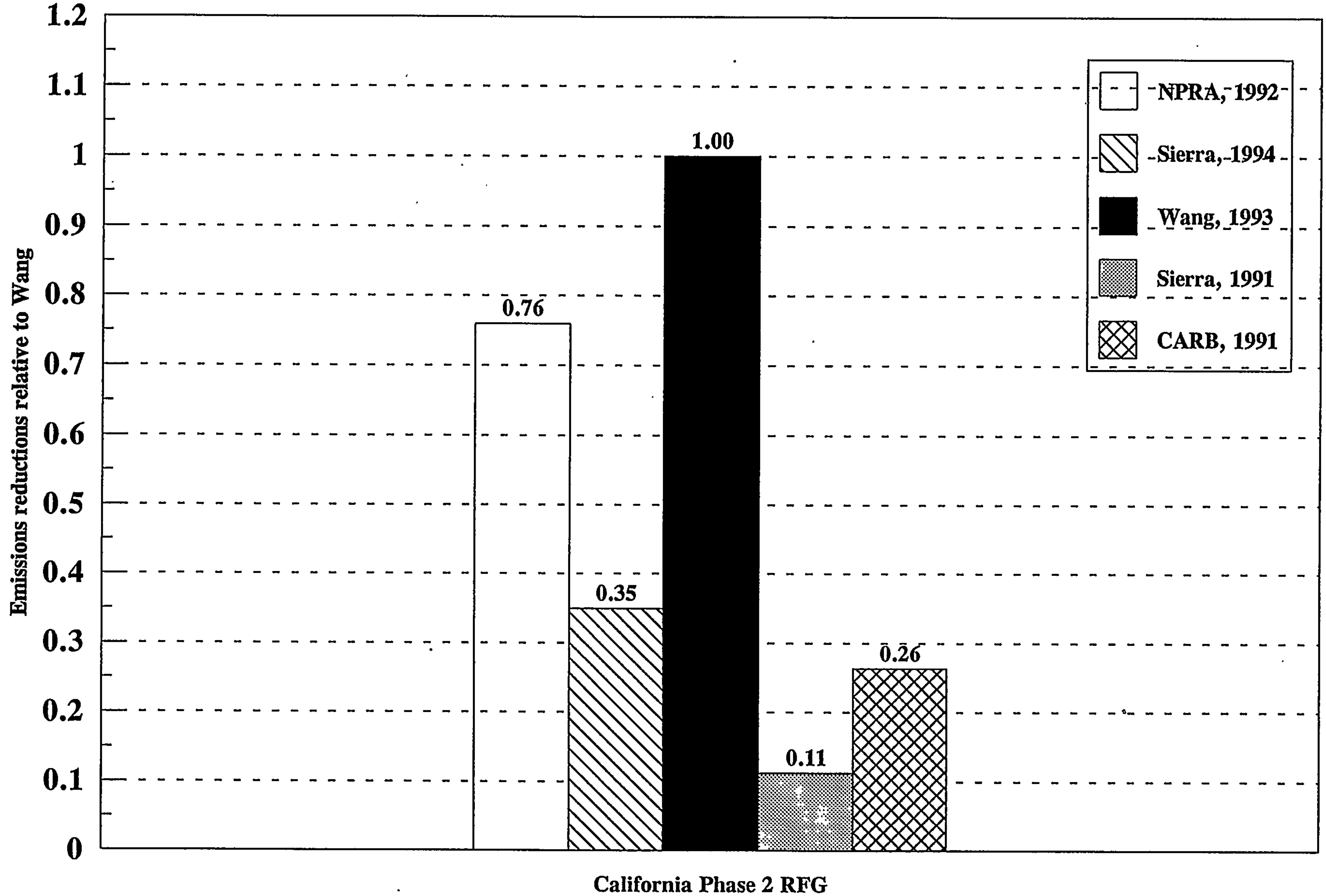
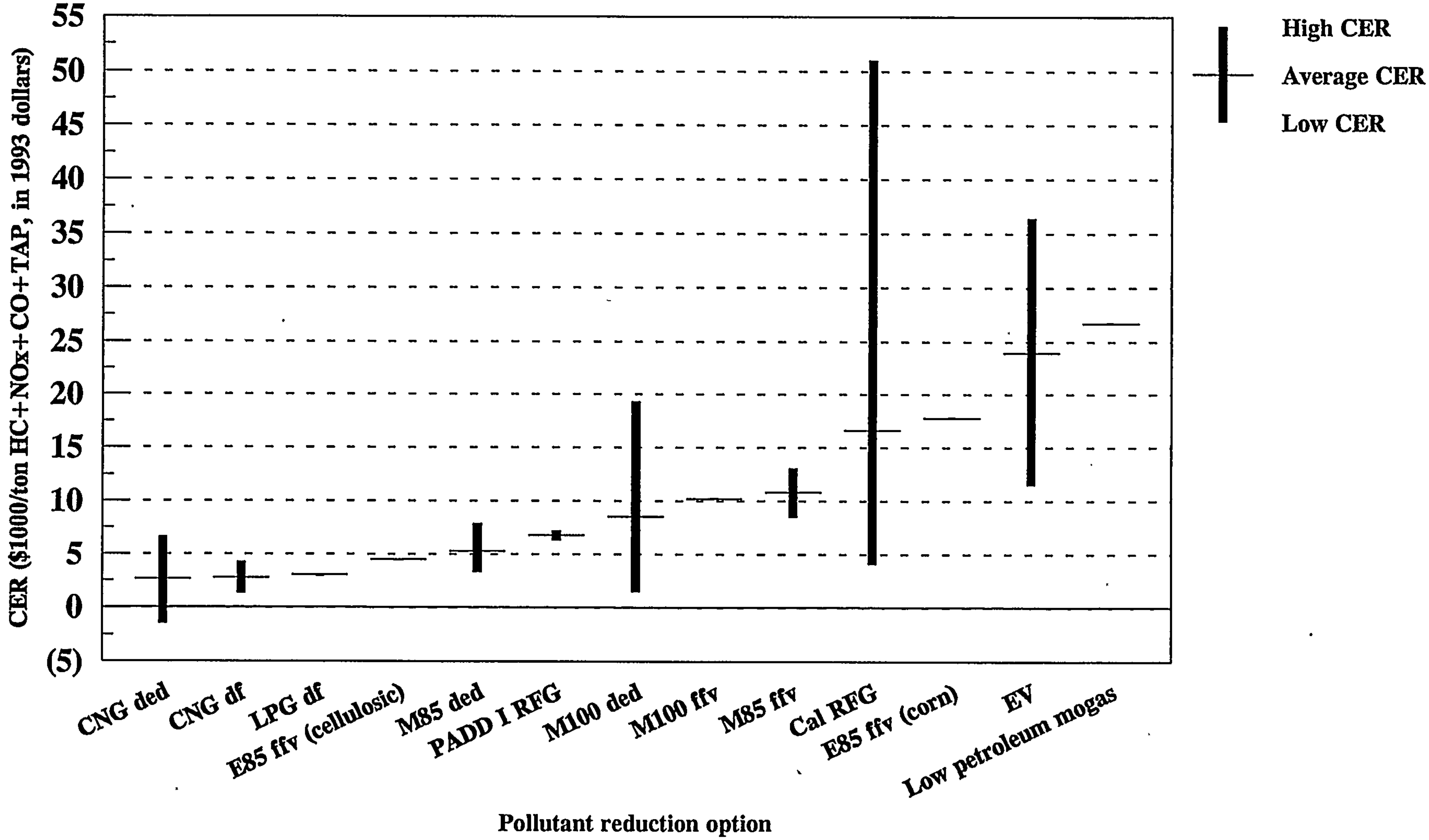


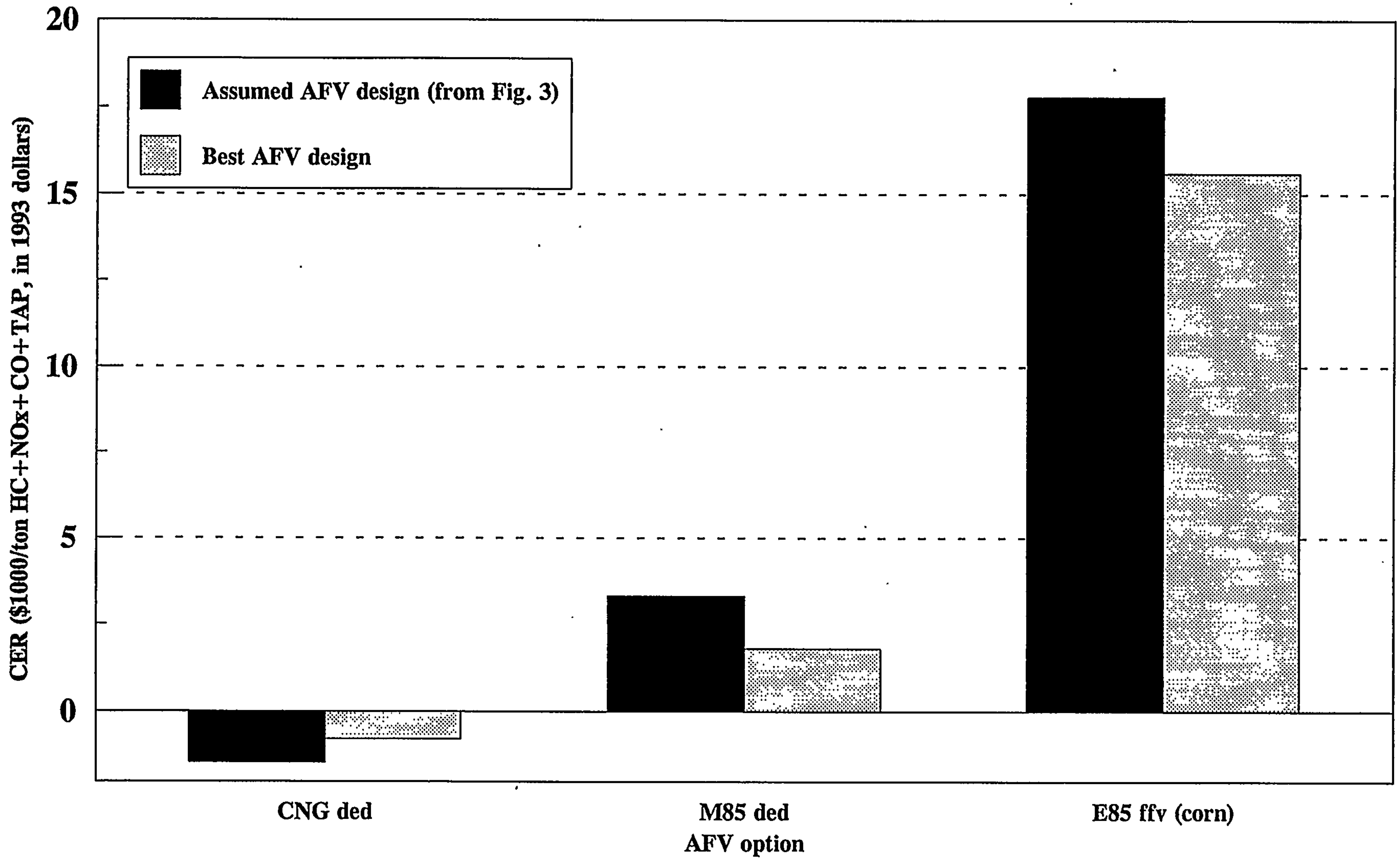
Fig. 23. CER range for HC+NOx+CO+TAP reduction

(Constant present value of AFV fuel costs)



Annualized CER, derived on average basis.
Cellulosic ethanol: $1/gal. Narrow range does not imply greater certainty.

Fig. 24. Best AFV design CER for HC+NOx+CO+TAP reduction



Annualized CER, derived on average basis.
For negative CERs, less negative CER has greater emissions reduction.

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