

Reducing Car Fleet Emissions through Fuel Technology

Policy Alternatives for Sweden

by

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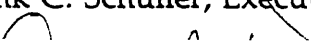
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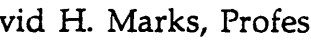
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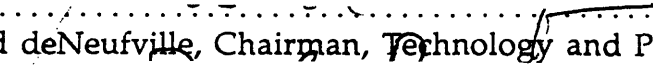
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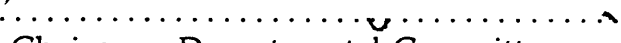
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Abstract

Fuel changes offer the possibility to further reduce automotive emissions of carbon monoxide, hydrocarbons and nitrous oxides. This study investigates oxygenated and reformulated fuel, including detergent additives. These relatively small modifications of the fuel composition could be introduced in the existing car fleet and within a short time frame.

The study applies the technological facts to the policy environment of Sweden, which will have to harmonize its traditionally strict environmental regulations with the standards in the European Union. The examination of technology and policy leads to a computer model that makes it possible to forecast emissions under different scenarios.

The use of an inlet valve detergent proved more cost effective than that of gasoline with 2.7 wt% of oxygen. While oxygenated gasoline offers higher reductions of the emission of carbon monoxide, it slightly increases emissions of nitrous oxides. The impact of buy back programs is limited to the short term, their cost effectiveness is low.

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This
thesis used
approx. 15 lb
of paper, 20 kWh
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of courier mail, 10 hours
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international calls and uncounted
gallons of orange juice. It is my sincere
hope that it will save as much pollution as it
caused.

Table of Contents

Abbreviations	10
Conversion Factors	11
1 Introduction	12
1.1 Objective	13
1.2 Scope	14
2 Effects of Pollution	15
2.1 Acid Rain	15
2.2 Ground Level Ozone	16
2.3 Toxic and Carcinogenic Substances	17
2.4 Climate Changes	18
2.5 Contribution of Road Vehicles	18
3 Emission Targets for Sweden	19
4 Principles of Hydrocarbon Combustion	22
5 Reformulated Gasoline	25
5.1 Methanol Production	25
5.2 Ethanol Production	26
5.3 Comparison of Methanol and Ethanol Production	27
5.4 Characteristics of Alcohol Fuels	28
5.4.1 Driveability	28
5.4.2 Safety	30
5.5 Ether Production	30
5.6 Characteristics of Ethers	31
5.7 Experience with Reformulated Gasoline	32
5.8 Emissions from Reformulated Gasoline	34
5.8.1 Lead	34
5.8.2 Benzene	34
5.8.3 Evaporative VOG - Reduction of RVP, Increase of Volatility	34
5.8.4 Exhaust VOG - Reduction of Aromatics	36
5.8.5 Carbon Monoxide - Reduction of Aromatics	36
5.8.6 Carbon Monoxide and Hydrocarbons - Introduction of Oxygenates	37
5.8.7 PAH - Reduction of Aromatics	39
5.8.8 Overall Improvements - Reductions of Sulfur	39

6 Gasoline with Additives	40
6.1 Types and Functions of Additives	40
6.2 Emissions from Gasoline with Detergent Additives	41
6.3 Cost of Detergent Additive	43
7 Political Background	44
7.1 Structure of Naturvårdsverket	44
7.2 Development of Emission Standards	45
7.3 Gasoline Infrastructure	49
7.4 Development of Gasoline Standards	49
8 Analysis	52
8.1 Analysis of Swedish Car Fleet	52
8.2 Forecast of Swedish Car Fleet	55
8.3 Forecast of Emissions of Swedish Car Fleet	66
8.3.1 Present Emissions	66
8.3.2 Emissions with New Gasoline Blends	67
8.3.3 No Action Scenario	68
8.3.4 Oxygenated Gasoline Scenario	70
8.3.5 Detergent Gasoline Scenario	72
8.4 Methodology of Policy Comparison	74
8.5 Introduction of Catalytic Converter as Reference Policy	75
8.6 Comparison of Oxygenated Gasoline and Detergent Gasoline	77
8.6.1 Comparison in Terms of Emissions Reduction	77
8.6.2 Comparison in Terms of Cost	81
8.6.3 Comparison in Terms of Cost Effectiveness	83
8.7 Alternatives	85
8.7.1 Buy Back Program	85
8.7.2 Changes of the Driving Pattern	86
8.8 Comparison with Swedish Emission Targets	88
9. Conclusions	89
10. Critical Issues for Further Research	91
Bibliography	92

List of Figures

Fig. 2.1	Ozone reactivities of some HC molecules	16
Fig. 2.2	U.S. Ambient Air Quality Standards	18
Fig. 3.1	Total emissions of SO _x and NO _x in Sweden	19
Fig. 3.2	Emitters of NO _x in Sweden	19
Fig. 3.2	Emitters of SO _x in Sweden	20
Fig. 3.3	Preliminary objectives for the road traffic sector	20
Fig. 4.1	Qualitative relationship between air/fuel ratio and exhaust emissions	23
Fig. 4.2	Influence of driving mode on emissions	24
Fig. 5.1	Comparison of processes for methanol production	26
Fig. 5.2	Economies of scale in ethanol production	26
Fig. 5.3	Prices of alcohol and petroleum fuels	27
Fig. 5.4	Properties of different fuels	29
Fig. 5.5	Comparison of different oxygenated gasolines	31
Fig. 5.6	Global use of gasoline and alternative fuels	32
Fig. 5.7	Maximum allowable concentration of oxygenates under the EPA "substantially similar rule"	33
Fig. 5.8	Emissions of VOG from 1981 and newer model passenger cars	35
Fig. 5.9	Influence of fuel aromatics content on CO emissions relative to a standard fuel with 30% aromatics	36
Fig. 5.10	Influence of fuel oxygen content on emissions of CO and HC	37
Fig. 5.11	Emission reductions of 2.0 wt% oxygen blend	38
Fig. 5.12	Emission reductions of 2.7 wt% oxygen blend	38
Fig. 6.1	Characteristics of reformulated gasoline test fuel and reference fuel	41
Fig. 6.2	Emission reductions by test gasoline (oxygenated, with detergent)	42
Fig. 6.3	Emission reductions expected of a fuel comparable to the test fuel, but without detergent	42
Fig. 6.4	Expected emission reduction by use of detergent only	43
Fig. 7.1	1993/94 appropriations for SNV in million SEK	44
Fig. 7.2	Development of Swedish emission standards	47
Fig. 7.3	Planned future Swedish emission standard (voluntary)	48
Fig. 7.4	Specification for environmental classes for gasoline	50

Fig. 8.1	Composition of Swedish car fleet by manufacturer	52
Fig. 8.2	The ten most sold car models in 1991 and 1992 and their respective share of total sales	53
Fig. 8.3	Sales of diesel cars in percent of total car sales	54
Fig. 8.4	Proportion of diesel cars in the car fleet	54
Fig. 8.5	"Raw" survival rate	56
Fig. 8.6	Raw survival rate and adjusted survival rate	57
Fig. 8.7	Adjusted survival rate, extended to incorporate cars of up to 23 years of age	58
Fig. 8.8	Basic structure of spreadsheet FLEET FORECAST	59
Fig. 8.9	Number of cars in use in the Swedish car fleet	60
Fig. 8.10	Number of newly registered cars in the Swedish car fleet	61
Fig. 8.11	Average age of the Swedish car fleet over time	62
Fig. 8.12	Forecast of the composition of the Swedish car fleet	63
Fig. 8.13	"Raw" mileage of different groups of model years	64
Fig. 8.14	Adjusted mileage of different groups of model years	65
Fig. 8.15	Representative emissions and energy use of cars with and without catalytic converters	66
Fig. 8.16	Expected emissions with the use of 15 vol% MTBE only	67
Fig. 8.17	Expected emissions with the use of inlet valve detergent only	67
Fig. 8.18	No Action Scenario: emissions of CO over time	68
Fig. 8.19	No Action Scenario: emissions of HC over time	69
Fig. 8.20	No Action Scenario: emissions of NO _x over time	69
Fig. 8.21	Oxygenated Gasoline Scenario: expected reduction of CO emissions over time	70
Fig. 8.22	Oxygenated Gasoline Scenario: expected reduction of HC emissions over time	71
Fig. 8.23	Oxygenated Gasoline Scenario: expected INCREASE of NO _x emissions over time	71
Fig. 8.24	Detergent Gasoline Scenario: expected reduction of CO emissions over time	72
Fig. 8.25	Detergent Gasoline Scenario: expected reduction of HC emissions over time	73
Fig. 8.26	Detergent Gasoline Scenario: expected reduction of NO _x emissions over time	73
Fig. 8.27	Emissions of cars without and with catalytic converter	75
Fig. 8.28	Pollution reductions by catalytic converters as a function of discount rate	76
Fig. 8.29	Pollution reduction with catalytic converter per dollar invested	76

Fig. 8.30	Oxygenated Fuel Scenario: Cumulative reductions of CO, discounted to 1995	77
Fig. 8.31	Oxygenated Fuel Scenario: Cumulative reductions of HC, discounted to 1995	78
Fig. 8.32	Oxygenated Gasoline Scenario: cumulative INCREASES of NO _x , discounted to 1995	78
Fig. 8.33	Detergent Gasoline Scenario: Cumulative reductions of CO, discounted to 1995	79
Fig. 8.34	Detergent Gasoline Scenario: Cumulative reductions of HC, discounted to 1995	79
Fig. 8.35	Detergent Gasoline Scenario: Cumulative reductions of HC, discounted to 1995	80
Fig. 8.36	Fuel consumptions used to calculate the cost of fuel programs	81
Fig. 8.37	Cumulative costs of oxygenated gasoline scenario and detergent gasoline scenario, discounted to 1995	82
Fig. 8.38	Cost effectiveness of oxygenated gasoline	84
Fig. 8.39	Cost effectiveness of detergent gasoline	84
Fig. 8.40	Buy back of model years 1980 and older, pollution savings over time	86
Fig. 8.41	Annual mileage reduction of 2%: pollution savings over time	87
Fig. 8.42	Cumulative emission reductions of different policies, discounted to 1995	87

Abbreviations

ACEA	Association des Constructeurs Européens d'Automobiles
API	American Petroleum Institute
ASB	Aktiebolaget Svensk Bilprovning - Swedish Car Inspection
A10	Swedish automotive emission standard of 1983, cars without catalytic converters that are subject to the standard
BIL	Association of Swedish Automobile Manufacturers and Wholesalers
CEN	Comité Européen de Normalisation, European Standardization Committee
CCAPD	Clark County Air Pollution Control Division
CCD	Combustion Chamber Deposit
CRC	Coordinating Research Council
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
EC	European Community (since 1992 EU)
ECMT	European Conference of Ministers of Transport
EGR	Exhaust Gas Recirculation
ETBE	Ethyl Tertiary-Butyl Ether
EU	European Union (up to 1992 EC)
Europaia	European Petroleum Industry Association
FBP	Final Boiling Point, temperature where all gasoline has evaporated
FTP	Federal Test Procedure
GAO	U.S. General Accounting Office
HC	Hydrocarbons, basically identical to VOG, see also NMOG
IVD	Intake Valve Deposit
MBGE	Million Barrels of Gasoline Equivalent
MTBE	Methyl Tertiary Butyl Ether
MTC	Motortestcentern - Swedish entity that tests engines
NMOG	Non-Methane Organic Gases, similar to HC and VOC, but excludes methane emissions
NPV	Net Present Value
OC	Oxydizing Catalyst (without oxygen sensor, cannot reduce NO _x)
OECD	Organization for Economic Cooperation and Development
ORI	Octane Requirement Increase
PAH	PolyAromatic Hydrocarbons - solid particles made up of "clumps" of aromatic compounds
PFI	Port Fuel Injector - as opposed to direct injection

ppm	parts per million
ppb	parts per billion
ROG	Reactive Organic Gases, essentially identical to HC and VOG, see also NMOG
RPM	Revolutions Per Minute
RVP	Reid Vapor Pressure, measure in psi or kPa
SAE	Society of Automotive Engineers
SEK	Svenska Kronor - Swedish Crowns
SFS	Svensk Författningssamling - Swedish Constitutional Law
SNV	Statens Naturvårdsverket - Swedish Environmental Protection Agency
SwEPA	Swedish Environmental Protection Agency
TBA	Tertiary Butyl Alcohol
TWC	Three Way Catalyst (with oxygen sensor, also called closed loop catalyst, can reduce NO _x)
T50	Temperature at which 50% of the fuel has evaporated
T90	Temperature at which 90% of the fuel has evaporated
U.S.	United States
VOC	Volatile Organic Compounds, essentially identical to HC and ROG, see also NMOG
VMT	Vehicle Miles Traveled
WHO	World Health Organization

Conversion Factors

length:	1 mi	=	1.61 km
	1 km	=	0.62 mi
volume:	1 gal	=	3.79 l
	1 l	=	0.26 gal
pressure:	1 psi	=	6.84 kPa
	1 kPa	=	0.15 psi

1 Introduction

In the past decade, new motor technology has drastically curbed automotive emissions per distance driven. The introduction of three-way catalytic converters alone reduced emissions by about 90% ¹ [Tolba: 409]. In Sweden, nitrous oxide emissions from cars decreased by 22% between 1986 and 1991, even though car traffic increased by 12% [BIL: 1].

Within all of the industrialized countries combined, however, the increasing number of vehicles and the growing total fleet mileage have outweighed pollution control measures. In OECD countries, total emissions from mobile sources increased between 20 and 75% from 1975 to 1992. ² [ECMT/OECD].

In the United States, about 80 cities are lagging behind compliance with the federal Clean Air Act, affecting close to 60 million people [EPA 1992]. About \$30 billion are spent annually on air pollution control [President's Council on Air Quality].

In the case of Sweden, several studies of urban air suggest that it could be responsible for 100 to 800 cancer deaths per year [Cancer Committee 1984, Institute for Water and Air Conservation 1991, quoted in Norén 1993: 10]. Acid rain continues to harm the natural environment, agriculture and man-made monuments.

Two million Swedes, about a quarter of the population, suffer from allergies and respiratory diseases. This number is continuously increasing, the percentage of children who suffer from asthma tripled over the past forty years. Allergic diseases are significantly more common in urban areas and have been linked to air quality [Norén 1993: 10].

Some of the pollution, especially in the case of Sweden, is swept in from abroad. In the short run, however, it will only be possible to influence the domestic emissions. In the United States, about 6 to 44% of total emissions stem from road traffic [EPA 1990, EPA, 1992]. In urban areas, this increases to 50-80% [Norén 1993: 6]. In Sweden, cars contribute about 15% of total emissions of NO_x and 35% of hydrocarbons [Norén: 1995]. The policy perspective to reduce tailpipe emissions therefore stands out as an important environmental objective.

¹ dependent on the pollutant

² dependent on the pollutant

In general, four venues can be used to reduce road traffic emissions: changes of the driving pattern, the vehicle mix, the technology, and the fuel.

Changes of the driving pattern. A decrease in the total vehicle miles traveled would have the most direct impact on emissions. Possible measures range from public awareness campaigns to high occupancy vehicle lanes, from tax schemes to increased “tele-commuting.”

Changes of the vehicle mix. Aging cars rely on outdated technology, which means disproportionate amounts of pollution as compared to later models. In addition, emission characteristics generally deteriorate over the lifetime of the engine, as wear and lowers the efficiency. Replacing old cars by newer ones can thus significantly reduce fleet emissions.

Changes of technology. Modern motor technology, in combination with catalytic converters, has already curbed emissions. Future technological advances could produce further benefits. The introduction of electric vehicles in California must be seen in this context.

Changes in fuel technology. New fuels could either increase the efficiency of combustion or produce combustion products that cause less environmental impact. Obviously, the introduction of a new fuel could demand drastic changes in technology, as is the case for hydrogen. Other alternative fuels, such as the reformulated gasoline mandated in the clean air act, are based on existing motor technology.

1.1 Objective

As public pressure for environmental protection intensifies, the choice of regulation has become increasingly difficult. The stakes are high: measures that are not cost effective squander economic resources that could be applied in other areas. Inconsistent regulations or constant changes of requirements could be wasteful or ineffective because of loopholes.

Currently, there is no diagnostic tool that systematically evaluates tradeoffs among automotive fuels in Europe. Regulatory and business decisions come about in a process that often reflects political persuasion rather than empirical foundation.

This research effort proposes to develop a diagnostic tool whose parameters, derived from independent scientific test results, allow policy makers and business managers to evaluate economic and political tradeoffs among several variables affecting tail pipe emissions.

This diagnostic offers several advantages. It is meant to aid regulators in determining which variable to modify, the appropriate levels of resources to apply, and the most effective regulation method. In turn, business managers may allocate research and development funds more efficiently to create new technologies in fuels and engines that can meet the regulatory requirements of the future.

1.2 Scope

This study is limited to gasoline changes in passenger cars. In technologically advanced countries, reformulated gasolines could further reduce emissions while avoiding costly infrastructure changes as they are necessary for electric or liquid natural gas vehicles. In addition, gasoline changes offer an almost instantaneous effect while other approaches might take decades to implement.

Experience has shown that aging and therefore highly pollutant cars are often exported to the less affluent countries, e.g. Eastern Europe, where there is less environmental control. Here, reformulated gasoline might offer a relatively inexpensive means to limit pollution.

Pollution will be measured in terms of release of carbon monoxide, hydrocarbons, and nitrous oxides. The fuels of interest are gasoline with improved additive packages and reformulated gasoline. Reformulated gasoline encompasses gasoline with changed properties (e.g. vapor pressure, aromatics content) or blends of gasoline and oxygenates (e.g. MTBE, methanol, ethanol).

These fuels offer the benefit to require only standard technology (piston engine; non-pressurized, non-insulated gas tank). As the cars need no adjustments, the changes can be incorporated inexpensively in the existing vehicle fleet, allowing a much faster market introduction.

The geographic scope is limited to Sweden. However, as it has traditionally taken stringent measures to curb pollution, Sweden could emerge as a leader in environmental protection. The Swedish potential to influence environmental policy abroad further increased when it joined the European Union. For this reason, the analytic tool has the flexibility to be adapted to other countries.

2 Effects of Pollution

Air pollution affects the health of human beings, harms ecosystems and causes property damages. While it is difficult to quantify these effects it is helpful to summarize the most important pollution mechanisms and air quality standards that are in place today.

2.1 Acid Rain (SO_x , NO_x)

SO_x and NO_x in the air can be oxidized to form sulfuric acid (H_2SO_4) and nitrate (HNO_3). These compounds in turn reduce the pH value of rainwater below its natural equilibrium of 5 - 5.6. Below a threshold of 4.7, biological damage is likely to occur [Seinfeld: 703].

Acid rain affects trees and fish populations in lakes. Damages are less severe where the precipitation filters through soil that is chemically basic (pH greater than 7) [Seinfeld: 702]. In the case of Sweden, these mitigating conditions are absent. Its shallow lakes collect a high proportion of direct precipitation. In spring, the melting snow releases great quantities of water that overwhelm the buffering capabilities of the thin layer of soil.

In very high concentrations, sulfur dioxide can cause respiratory problems that can be life threatening. In 1952, for instance 4000 inhabitants of London died from "smog," an acidic fog that contains SO_2 . The U.S. National Ambient Air Standard allows 0.14 ppm of SO_2 , averaged over 24 hours [Seinfeld: 70]. The WHO recommends an almost identical value, but uses a stricter 1 hour average [WHO]. Today however the air in most countries, including Sweden are far below the threshold that would cause such serious consequences.

Limestone is a common construction material in Sweden. This type of stone is particularly sensitive and erodes under the influence of acid rain. Already the situation is "precarious" for many objects, especially in the Old City in Stockholm [Norén 1993: 11].

2.2 Ground Level Ozone (VOG, NO_x)

Ozone is naturally produced in the stratosphere where it forms the ozone layer that shields the earth's surface from harmful ultraviolet radiation. Background levels of ozone in the lower atmosphere range from 0.05 ppm to 0.1 ppm [Borek: 327]. However, the combination of sunlight with NO_x (especially NO₂) and VOG can transform the oxygen in the air (O₂) into ozone (O₃). The chemical processes are very complex and depend on the ratio of VOG/NO_x; the molecular composition of the VOG also plays a major role (see figure 2.1) [Seinfeld: 119ff].

VOG Compound	Reactivity [g O ₃ /g VOG]
Methane (CH ₄)	0.0075 - 0.0108
Carbon Monoxide (CO)	0.033 - 0.040
Methanol (CH ₃ OH)	0.22 - 0.39
Isooctane (C ₈ H ₁₈)	0.39 - 0.69
Ethanol (C ₂ H ₅ OH)	0.39 - 0.77
Formaldehyde (CHOH)	2.0 - 6.6

Fig. 2.1 Ozone reactivities of some HC molecules [Carter: 26ff]

Ozone irritates the respiratory tract [Borek: 330]. In dosages above 0.15 ppm, it can cause irritation of the eyes, nausea, and numbness in the extremities within less than an hour [Kagawa: 411, 419]. Children, active persons and those with a preexisting condition such as asthma are particularly affected [Linn: 136, Lippmann: 445]. In addition, ozone has been connected with mutations and the formation of cancers [Linn: 136]. Ozone has been proven to harm vegetation.

In the U.S., the National Ambient Air Standard allows a maximum of 0.12 ppm, averaged over a one hour period [Seinfeld: 70]. The WHO set a standard of 0.075 to 0.1 ppm [WHO].

2.3 Toxic and Carcinogenic Substances (CO, benzene, lead)

Carbon monoxide impairs the ability of the hemoglobin molecules in the red blood cells to provide oxygen to the cells. Concentrations as small as 30 ppm can already produce slight symptoms such as nausea and reduced mental acuity. A concentration of 600 ppm is considered to be lethal.

Urban air typically contains between 5 and 50 ppm of CO, on congested highways concentrations can reach 100 ppm [Seinfeld: 54f]. However, it takes several hours of carbon monoxide inhalation for the full effect to develop [Seinfeld: 54f].

Measurements in the US have shown that during the wintertime, automobiles can contribute more than 80% of the CO emissions. Another important sources is wood burning [CCAPCD, GAO]

The U.S. National Ambient Air Standard allows 35 ppm of CO [Seinfeld: 70], the WHO recommends 26 ppm as an upper limit [WHO]. Both figures apply to a one hour average of the CO concentration.

Benzene and many other aromatic compounds that are components of gasoline have been linked with leukemia [Seinfeld: 60f].

Combustion of leaded gasoline is the by far dominant source of lead in the environment. Lead is sometimes added to gasoline in order to increase the octane number and to lubricate the valve seats of older cars.

Lead accumulates in the body. It inhibits enzymes and neurological functions. Half of the lead that is released settles out less than 100m from the road, making lead poisoning a very localized problem [Seinfeld: 63]. Also, leaded gasoline forms deposits that permanently disable catalytic converters .

The U.S. Environmental Protection Agency set a standard of ambient air of $1.5 \mu\text{g}/\text{m}^3$ [Seinfeld: 63, 70]. The WHO standard is 0.5 to $1.0 \mu\text{g}/\text{m}^3$ [WHO]. Both refer to an annual average.

2.4 Climate Changes (CO₂, VOG)

Carbon dioxide is a natural component of the atmosphere and thus neither toxic nor carcinogenic. However, combustion of fossil fuels has steadily increased the carbon dioxide concentration in the air. This is known to contribute to the greenhouse effect, altering the climate of the earth. Carbon dioxide is still the preferred outcome of any combustion and there are no limits on CO₂ per se. However carbon dioxide can be minimized through increased fuel efficiency or the use of biologically generated alcohols.

Volatile Organic Gases, such as methane, are known to have an even stronger effect on global warming than carbon dioxide, measured per kg emitted. However, internal combustion engines release much smaller quantities of VOG than of CO₂.

CO	8 hour average	9 ppm
	1 hour average	35 ppm
O ₃	1 hour average	0.12 ppm
NO ₂	annual average	0.053 ppm
SO ₂	annual average	0.03 ppm
	24 hour average	0.14 ppm
Pb	quarterly average	1.5 µg/m ³
PM-10	annual average	50 µg/m ³
	24 hour average	150 µg/m ³

Fig. 2.2 U.S. Ambient Air Quality Standards [EPA 1992]

2.5 Contribution of Road Vehicles

In industrialized countries, 70 to 90% of all man-made CO emissions stem from the transport sector, practically all coming from road vehicles. In Sweden, 43% of the emissions of nitrous oxides originate from motor vehicles³ [SNV 1994b: 12], 2/3 of which comes from trucks [Norén: 1995]. On the other hand, it is cars which produce the overwhelming portion of transport related hydrocarbon emission that makes up about 41% of the entire HC releases. In Sweden, cars hardly contribute to sulfur emissions and ship engines are the predominant source of transport related emissions.

³ About 2/3 of this figure is due to gasoline driven cars [SNV 1994b: 18]

3 Emission Targets in Sweden

In accordance with the most pressing environmental problems for Sweden - acid rain, ground level ozone and global warming [Norén 1993: 1] - the following overall targets have been set by the Swedish EPA or in international treaties [SNVb: 6]:

- Between 1980 and 2000, emissions of sulfur shall be reduced by 80% [SNVb: 6].
- The International Convention on Transboundary Air Pollution requires that by 1998, the emissions of nitrogen oxides are reduced by 30% as compared to the emissions in any of the years between 1980 and 1986 [SNVb: 6].
- SNV set itself the stricter objective to reduce emissions of nitrogen oxides by 30% (compared to the 1980 level) already by the year 1995 [SNVb: 6]. Reductions of 50% are recommended [Norén 1993: 5]
- Carbon dioxide emissions must not exceed current levels. In the long run, they should be reduced to the level that is sustainable to the environment [SNVb: 12].
- HC emissions should be halved between 1988 and the year 2000.
- The emissions of lead are to be reduced by 70% between 1985 and 1995.

It should be noted that much of the SO_x and NO_x that affect the Swedish environment stem from road traffic or sources abroad. The past development of the emission of SO₂ and NO_x in Sweden is shown in figures 3.1, 3.2 and 3.3. While sulfur emissions have been reduced drastically, emissions of nitrous oxide remain at a high level. Here, the contribution of automobile is very significant.

Figure 3.4 presents the targets for emission reduction within the transportation sector, which are even more ambitious. It is clear that NO_x will be critical, which has been affirmed by Alexandra Norén and Titus Kyrklund at the Naturvårdsverket [Norén, Kyrklund]. In a recent publication, SNV states that

"In the case of nitrogen monoxide,⁴ this [reaching the target values] will not be possible without imposing restrictions on traffic." [SNV]

⁴ Most nitrogen oxides are emitted as NO, which is subsequently oxidized to NO₂.

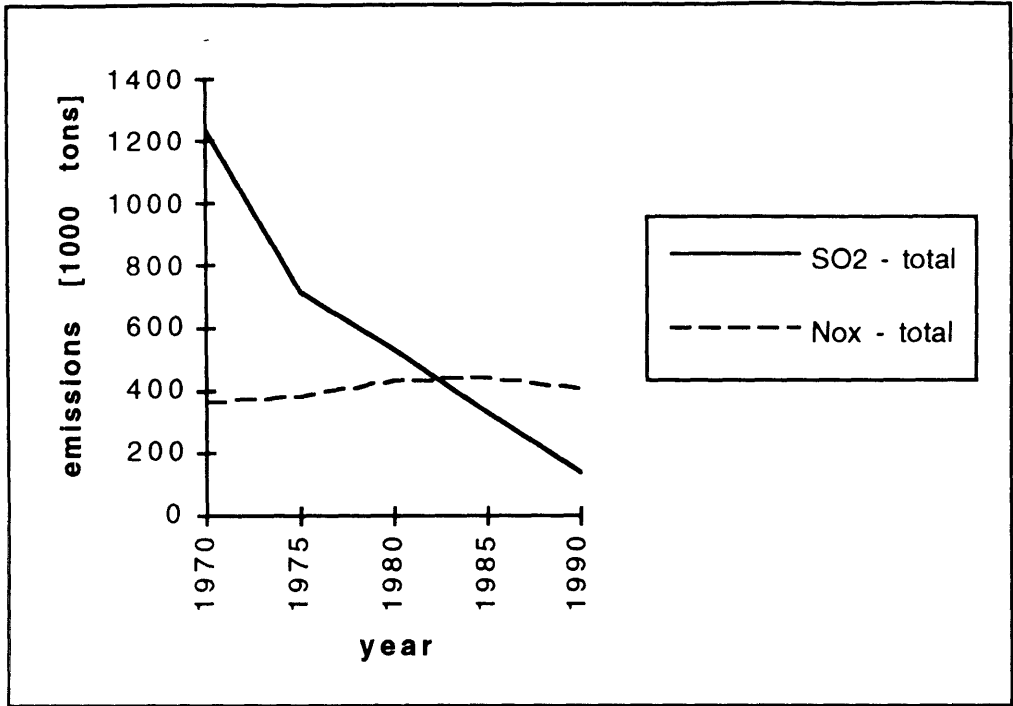


Fig. 3.1 Total emissions of SO_x and NO_x in Sweden [SNVb: 12]

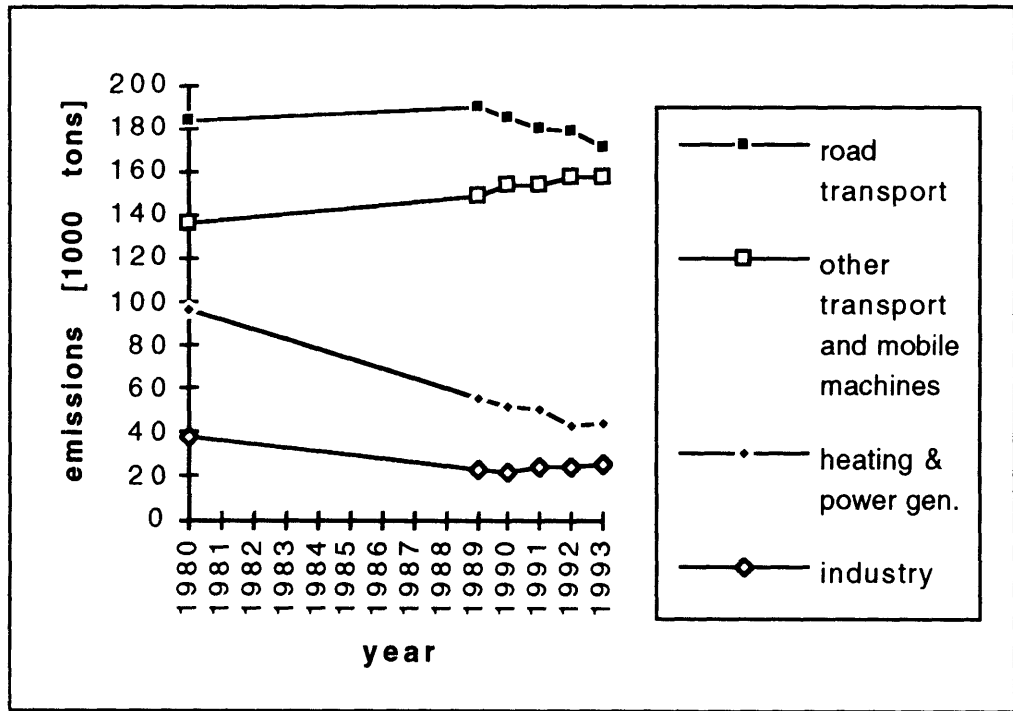


Fig. 3.2 Emitters of NO_x in Sweden [SNV 1994b: 9]

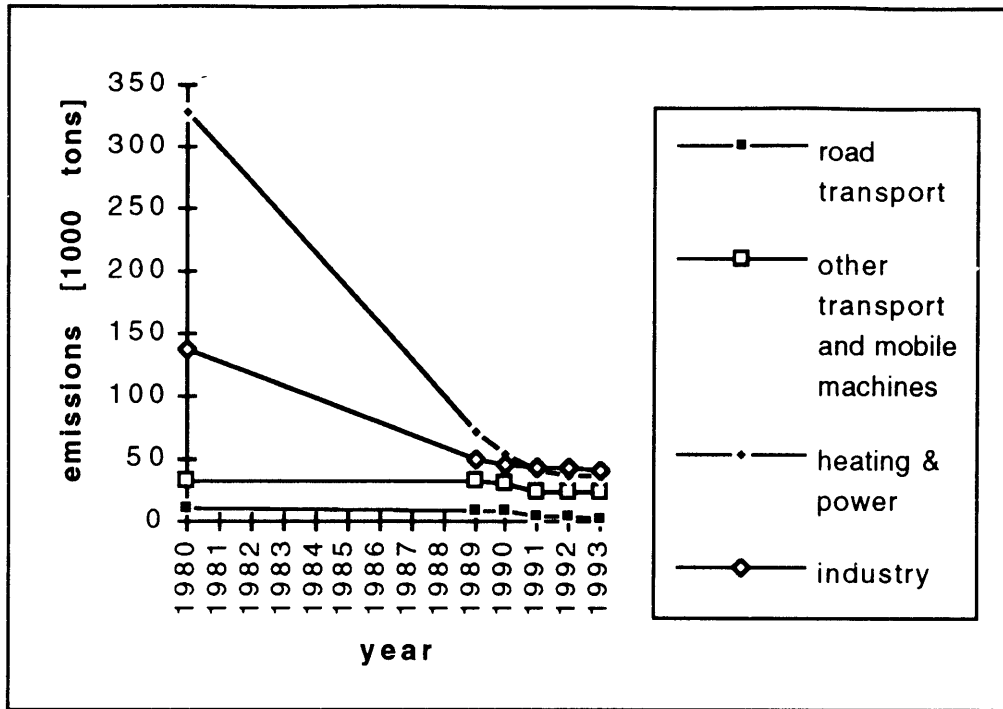


Fig. 3.3 Emitters of SO_x in Sweden [SNV 1994b: 10]

Pollutant	Time frame	Reduction
Sulfur	1980 - 2000	85%
NO _x	1980 - 1995	50%
HC	1988 - 2000	70%
	2000 -	no increase
CO ₂	- 2000	no increase
	2000 -	reduction (unspecified)
Particles	- 2000	50%
Carcinogenic substances	- 2005	50%

Fig. 3.4 Preliminary objectives for the road traffic sector [Norén 1993: 7]

In recent years, the debate has increasingly focused on emissions of particles, carcinogens (such as benzene and other aromatics) and heavy metals, especially lead [SNVb: 10, Norén 1993: 1]. In the long run, these emissions are to be discontinued altogether [Norén 1993: 5].

4 Principles of Hydrocarbon Combustion

All fuels within the scope of this study are composed of a mix of hundreds of different molecules that are essentially made up of carbon and hydrogen atoms. However, the exact chemical structure of these hydrocarbon molecules has a great influence on the combustion behavior of the fuel.

Pure gasoline and diesel mainly contain alkanes, which consist of a hydrogen atoms linked to a chain of carbon atoms - for instance hexane (C_6H_{14}) or octane (C_8H_{18}). Aromatics make up a smaller fraction. Here, the chain of carbon atoms includes some double bonds and forms a ring. Benzene (C_6H_6) is such a molecule.

The mix of different hydrocarbons in standard gasoline can be approximated as $C_7H_{13.02}$ (indolene) [Sein: 78]. However, such a molecule is a statistical construct and does not appear in nature. Diesel has a somewhat heavier composition (C_9H_{20} to $C_{11}H_{24}$) and can be a byproduct of the distillation of other petroleum grades.

Alcohols have a structure very similar to that of alkanes. However, an OH group replaces one of the hydrogen atoms. The two alcohols most relevant as fuels are methyl alcohol or methanol (CH_3OH) and ethyl alcohol or ethanol (C_2H_5OH). They contain 53 wt% and 35% oxygen respectively.

Methyl-tertiary-butyl ether (MTBE, $CH_3OC_4H_9$) and ethyl-tertiary-butyl ether (ETBE, $C_2H_5OC_4H_9$) are heavier than the respective alcohol molecule. As a consequence, they contain only 18 wt% (in the case of MTBE) and 16 wt% (ETBE) of oxygen.

In order for a combustion to take place, the fuel droplets must first be vaporized. The heat of the reaction then breaks up the bonds and the individual elements can react with oxygen and nitrogen in the air. Ideally, the products of this reaction are carbon dioxide and water. However, if not enough oxygen is available, the carbon atoms will only form carbon monoxide. The unoxidized carbon then escapes in the form of soot particles.

Oxides of nitrogen (NO and NO_2 , summarized as NO_x) are formed when the combustion is so hot that nitrogen and oxygen in the air combine⁵. Finally, some of the hydrocarbons (HC) in the fuel might not take part in the combustion. These leak into the environment as volatile organic gases (VOG) sometimes also called reactive organic gases (ROG).

⁵ Nitrogen in the fuel can also contribute to the formation of NO_x .

Figure 4.1 illustrates the typical influence of the air-fuel ratio on the pollutant formation. The arrow marks a stoichiometric mixture, this is to say that the amount of oxygen is precisely sufficient to allow the combustion of the present fuel. Increasing the oxygen from the stoichiometric mixture further reduces carbon monoxide and hydrocarbon emissions. On the other hand, emissions of nitrous oxide increase as oxygen increases.

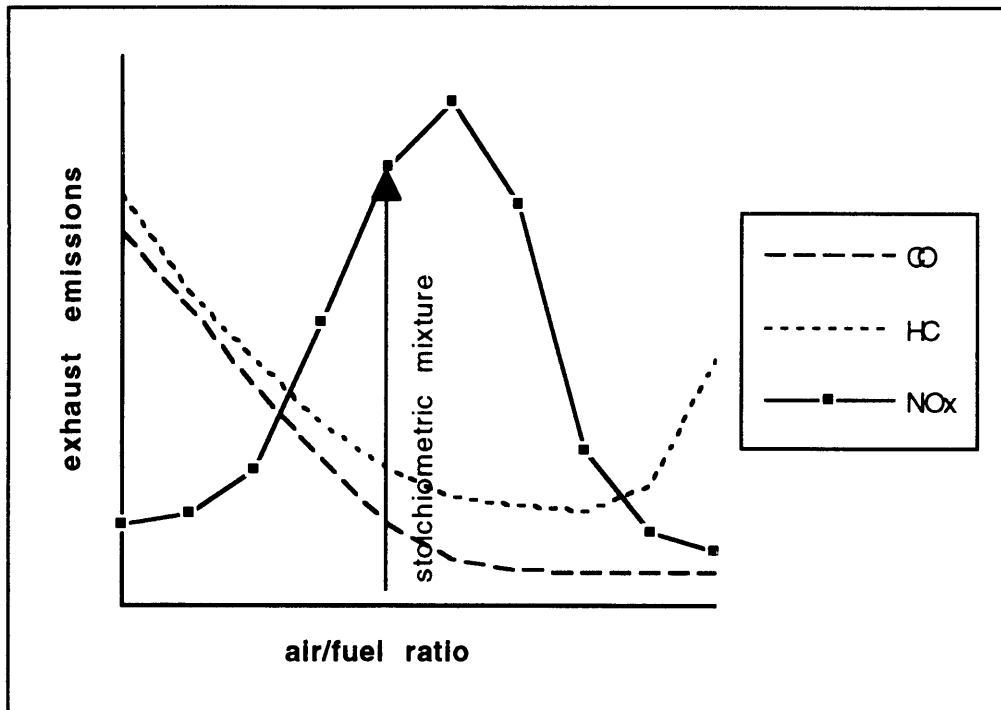


Fig. 4.1 Qualitative relationship between combustion air/fuel ratio and exhaust emissions [Gething 1990: 350]

The chemical makeup of the fuel influences the outcome of the combustion in all of the three mentioned steps: vaporization of droplets, breakup of molecules and reaction of elements.

Vaporization. The Reid Vapor Pressure (RVP) indicates the volatility of a fuel. The higher the RVP is (measured in terms of psi or kPa) the easier the fuel evaporates. Mostly, a high volatility goes along with lighter molecules. While this enhances the cold start capability, it also means higher emissions of VOG.

As diesel is a heavy petroleum distillate, its RVP is about 100 times lower than that of gasoline. For this reason, diesel engines need sophisticated injection systems and fuel preheaters, especially in winter. Additives can reduce the diameter of the injected droplets, which increases the surface area and facilitates the evaporation process.

Breakup. Due to their ring structure and the double bonds, aromatics are more stable. This impedes the combustion. Changed refinement processes can produce fuel with a lower content of aromatics.

Reaction. A critical factor in the combustion is the mixing ratio of air to fuel. However, it is not sufficient to supply the right amount of air to the cylinder. The air has to be present in all zones where the reaction takes place. The high RPM of modern engines allow only very little time for the proper mixing. It has thus been suggested to use fuels that already contain a certain portion of oxygen, i.e. alcohols.

The emission control system in modern cars is highly effective removing pollutants from the exhaust. However, after a cold start, it takes the catalytic converter several minutes to reach its nominal temperature. In addition, the fuel is slow to evaporate in the relatively cool motor. This "cold transient" is responsible for a high proportion of overall emissions.

"Warm transient" means changes of speed with a warmed-up engine. During accelerations, peak power is needed. The engine operates in a fuel rich mode where the catalytic converter is less efficient.

Figure 4.2 illustrates the importance of both cold and warm transients on emissions. It is based on the FTP driving cycle using a 1986 Honda and a 1985 Camber.

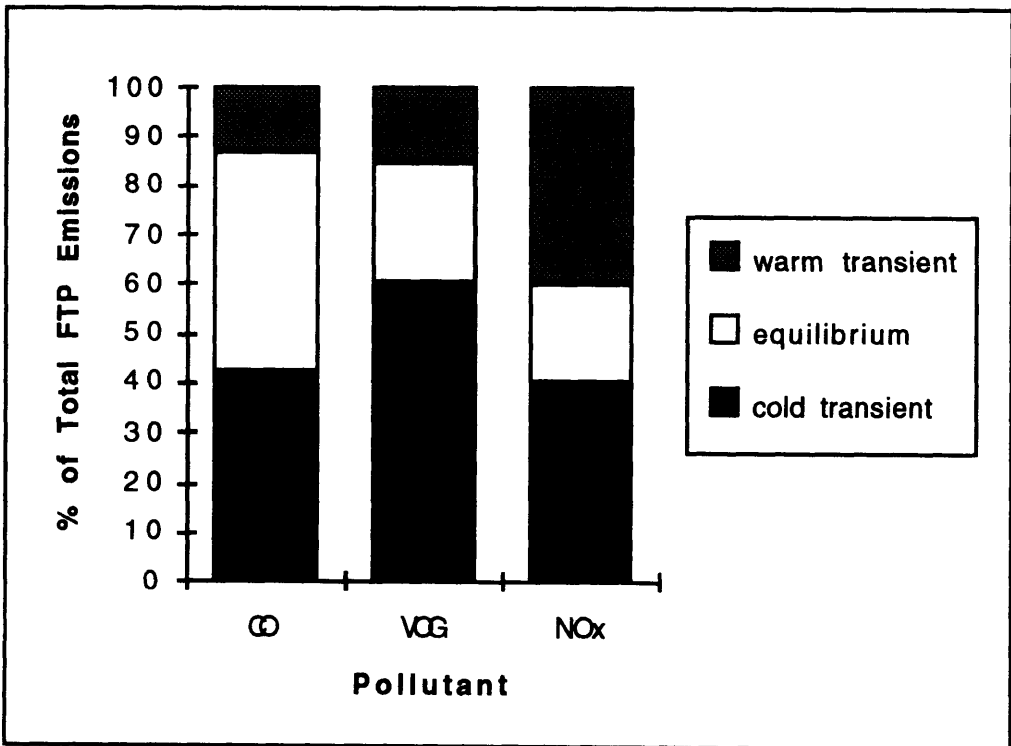


Fig. 4.2 Influence of driving mode on emissions [Piel: 68]

5 Reformulated Gasoline

Similar to gasoline and diesel, alcohol consists of hydrocarbon chains. The difference lies in OH-groups (made up of an oxygen and a hydrogen atom) that are attached to the main molecule. Thus, alcohols are the logical step from traditional fuels to more oxygen rich ones.

Three different types of alcohols lend themselves to use as motor fuels: methanol (CH_3OH), ethanol ($\text{C}_2\text{H}_5\text{OH}$), and ethers, such as MTBE ($\text{CH}_3\text{OC}_4\text{H}_9$) or ETBE ($\text{C}_2\text{H}_5\text{OC}_4\text{H}_9$). Butanol would be another option, but so far it is mostly produced from oil itself, which makes it a less attractive substitute.⁶

The history of alcohol fuel is about as old as the (spark-ignited) internal combustion engine itself. Sauter mentions an alcohol motor as early as 1826 [Sauter, p.67]. On the other hand, it was assumed that diesel engines would not run on alcohol. With modern technology this presumption is no longer valid, however, serious problems persist (see section 5.4).

5.1 Methanol Production

In the commercial process currently used, methane (essentially natural gas) is brought together with steam and CO_2 . The mixture reacts into CO and H_2 . In a second step, this "crude gas" then forms methanol (CH_3OH). Both reactions need high ambient temperature and pressure and the presence of a catalyst [Alternative Fuels Committee of the Engine Manufacturers Association]. The "pump price" of methanol produced this way has been estimated at \$0.18 to \$0.25 per liter ⁷ (\$0.70 to \$1.01 per gallon) [American Institute of Chemical Engineering: 21].

Alternatively, methanol can also be produced from coal or biomass. Partial oxidation of the feed stock results in a crude gas. However, in contrast to the first method, this gas needs to be purified before methanol can form. This explains the increased capital costs and reduced efficiency of the process (figure 5.1).

⁶ N.A. Sauter, "A Technical Assessment of Alcohol Fuels," Paper 820261, presented at the International Congress & Exhibition, Detroit/MI, February 1982, p.66f

⁷ However, the energy content of one liter of methanol is only about 50% of that of a liter of gasoline (see figure 5.4)

feed stock for methanol production	natural gas	coal	wood (biomass)
capital investment (natural gas = 1)	1	3	2.5
efficiency of transformation	0.61	0.59	0.38

Fig. 5.1 Comparison of processes for methanol production
[Alternative Fuels Committee of the Engine Manufacturers Association]

5.2 Ethanol Production

Ethanol forms in the fermentation of any plant matter. The process is used to brew beer and make wine, it is therefore well understood and has been extensively documented [Papazian]. It does not require extreme temperatures or pressures. Distillation easily increases the alcohol content to 95% purity. Figure 5.2 shows considerable cost savings with increased plant size.

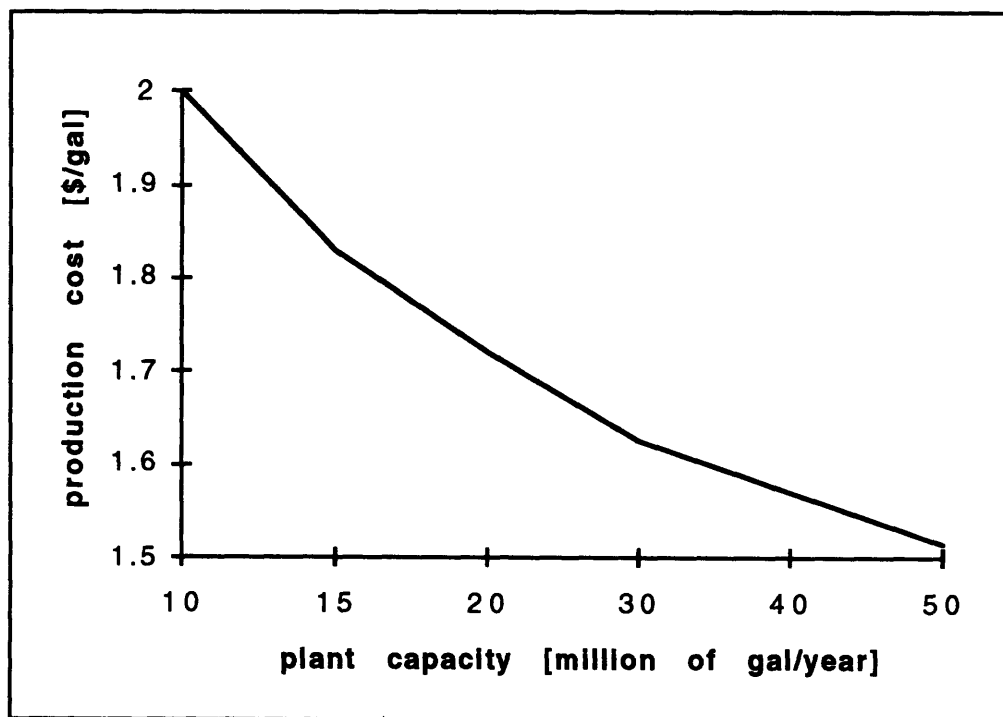


Fig. 5.2 Economies of scale in ethanol production
[Alternative Fuels Committee of the Engine Manufacturers Association]

Hydrolysis converts cellulose (wood) into fermentable sugar. This process was used during World War II, but no plants exist today. In order to produce 50 million gallons of ethanol, 700,000 tons of cellulose would be needed. Such a facility is estimated to cost around \$250 million, almost twice as much as an equivalent fermentation plant [70: 12]. The “pump price” of ethanol produced this way has been estimated at \$0.18 to \$0.27 per liter ⁸ (\$0.70 to \$1.10 per gallon) [American Institute of Chemical Engineering: 21].

5.3 Comparison of Methanol and Ethanol Production

Grains and sugars can only be used to produce ethanol. By contrast, both methanol and ethanol can be manufactured from wood, agricultural residue and solid waste. Here the same material input will produce about four times as much methanol as ethanol [69], with the energy content of both being almost identical [70]. Figure 5.3 shows the 1981 market prices for different fuels.

Fuel	wholesale price [\$/gal]	cost of energy [\$/million BTU]
methanol (from natural gas)	0.8	14.0
ethanol (by fermentation)	1.77	23.3
regular gasoline	1.03	8.8
No. 2 diesel fuel	1.00	7.7

Fig. 5.3 Prices of alcohol and petroleum fuels based on July 1981 wholesale prices, taxes not included) [70]

⁸ However, the energy content of one liter of ethanol is only about 60% of that of a liter of gasoline (see figure 5.4).

5.4 Characteristics of Alcohol Fuels

5.4.1 Driveability

Alcohols have a smaller heating value (energy content) than gasoline. Thus, more mass has to be burned to achieve the same engine output. Due to the lower density of alcohols, this difference is even more pronounced when expressed in terms of volume. This translates into a shorter range for a given fuel tank size.

The low vapor pressure indicates that straight alcohols evaporate only slowly. However, when alcohols are used in blends with gasoline, hydrogen bonding of the hydroxyl group becomes less important and the vapor pressure increases by 7 to 21 kPa⁹ [Dorn: 42, 45]. This can be seen in figure 5.4 for gasohol (90% unleaded gasoline, 10% ethanol). The highest vapor pressures are usually encountered at oxygen concentrations of 3-5 wt% [Dorn: 46].

Straight alcohol and to a lesser degree alcohol/gasoline blends cause problems during cold starts of the engine. This is due not only to the vapor pressure, but also the high heat of vaporization. This means that a small amount of evaporating alcohol consumes so much heat that the temperature of the air drops. It is then even more difficult to vaporize the remaining alcohol.

Alcohol fuels contain some water and organic acids, both of which speed up corrosion. Methanol and ethanol can also cause elastomers to swell and to lose strength [Owen: 245].

Alcohols have a higher octane number than gasoline. This means that the alcohol/air mixture in the cylinder can be compressed more before it autoignites. A higher compression ratio translates into a higher thermodynamic efficiency, which makes alcohols particularly suited for standard spark-ignition engines.

Diesel engines on the other hand depend on the autoignition of the fuel mixture, which makes the use of alcohol very difficult. An additional problem is the higher heat of evaporation of alcohol. As diesel engines inject the fuel in liquid form and it must then evaporate within a very short time frame, this is another argument that speaks against the use of alcohols.

⁹ In the case of methanol, this effect can be reduced by adding TBA as a cosolvent [Dorn: 45].

	gasoline	diesel	methanol	ethanol	gasohol*
density @ 15C [kg/l]	0.73	0.82	0.79	0.79	0.73
viscosity [centistokes]	0.6	1.75	0.58	1.1	0.6
boiling point [C]	30 - 225	190 - 280	65	78	25 - 210
heating value [MJ/kg]	43.5	43	20	27	42
[MJ/l]	32	35	16	21	31
heat of vaporization [MJ/kg]	0.4	0.6	1.1	0.9	0.47
vapor pressure straight ¹⁰ , [kPa]	62 - 90	0.34	17	32	55 - 110
octane number, research	91 - 100	not applicable	112	111	93 - 103
cetane number	< 15	40 - 60	< 15	< 15	< 15
stoichiometric air to fuel ratio [kg/kg]	14.6	14.6	6.4	9	14
flammability limits [vol. %]	0.6 - 8	0.6 - 6.5	5.5 - 26	3.5 - 15	not available
toxicity	moderate irritant, can cause narcosis	moderate irritant, can cause narcosis	irritant, causes narcosis, cumu- lative toxicant	irritant, toxic only in large dosis	moderate irritant, can cause narcosis

Fig. 5.4 Properties of different fuels [Sauter]
* = 90 vol% gasoline, 10 vol% ethanol

¹⁰ at 35°C

5.4.2 Safety

Alcohols have a wide range of flammability. Thus the vapors that take up the empty volume of the fuel tank can explode. In the case of gasoline, which evaporates more readily, these vapors are too fuel rich to ignite. Diesel, on the other hand, hardly evaporates at all, so that the concentration of the fuel vapors stays below the critical threshold. However, once the alcohol is spilled, its higher flammability limit makes it safer.

As alcohol dissolves foam, special equipment is needed to combat an alcohol fire. Also, alcohol burns with a nearly invisible flame that makes it hard to locate the fire.

While gasoline and diesel generally separate from water, alcohols are completely soluble. Thus an alcohol spill could penetrate more easily into the water supply. This also means minute amounts of water (on the order of 400 ppm) can cause an alcohol/gasoline blend to separate [DOE: B-5].

About the toxicity of alcohol, Sauter et al. write:

“Methanol is a cumulative toxin which affects the nervous system, especially the optic nerves. Ingestion of less than four ounces [100 g] is fatal and as little as one ounce [26 g] can cause blindness. Vapors enter the body through lungs and liquid can penetrate the skin, so great care must be used in handling. ... Ethanol, gasoline and diesel must be handled with care, but are not considered so toxic as methanol.

While methanol in its traditional chemical industry uses can cause skin or eye irritation, there is limited understanding of any health effects due to long-term, low-level exposure to methanol vapors typical to fuel use.” [Sauter]

5.5 Ether Production

Methyl-tertiary-butyl ether (MTBE) and ethyl-tertiary-butyl ether (ETBE) today are of main interest as blending stocks for gasoline [Jarsin]. They can be produced from methanol and ethanol. A higher yield of the conversion process from ethanol to ETBE makes this ether more economical even for ethanol prices that are 10 to 30 cents above the price of methanol [Piel: 72].

5.6 Characteristics of Ethers

Shiblom tested blends of gasoline and ETBE up to concentrations of 23.5 vol%. He detected no cold-start problems and reports that the fuel blends do not cause any additional corrosion of metals or swelling of elastomers: 5ff].

Figure 5.5 illustrates the low vapor pressure and the significant increase in octane number that comes with the use of MTBE and especially ETBE.

	Gasoline	Gasoline/ MTBE	Gasoline/ ETBE
Vol% of Ether	0	11	12.7
Wt% of Oxygen	0	2.0	2.0
Octane Number (R+M)/2	87.55	89.45	90.63
Reid Vapor Pressure [kPa]	70	70	65

Fig. 5.5 Comparison of different oxygenated gasolines

5.7 Experience with Reformulated Gasoline

Alcohol was among the first fuels used in internal combustion engines. One of the earliest alcohol motors was patented by Samuel Morey in 1826. In 1933, the "Cooperative Fuel Research Committee" in the U.S. published an extensive report on tests with a 10% alcohol / 90% gasoline mix [Alternative Fuels Committee of the Engine Manufacturer's Association: 67].

In modern times, its property as a coolant has made methanol a fuel of choice for high performance cars, such as in sprint races or the Indianapolis 500. On the other hand, four million cars in Brasilia use methanol [New Scientist]. In contrast, "gasohol," which was pushed in the U.S. after the oil shock, consists of a mixture of 10% ethanol and 90% unleaded gas [Alternative Fuels Committee of the Engine Manufacturers Association: 67]

It should be pointed out that all the above examples refer to spark ignited engines. Even though some important advance have been made, the use of alcohols in compression ignited (i.e. diesel) engines is far from commercial application.

	ethanol	methanol	natural gas	gasoline
global production [MBGE]	74	56	3780	5700
used as fuel [%]	76	13	4	100
how used as fuel	mainly neat	mainly blends	mainly compressed	--
number of vehicles [million]	3.5	0.01	0.7	500

Fig. 5.6 Global use of gasoline and alternative fuels [DOE: I-2]

In the United States, the federal Clean Air Act gave a new boost to oxygenated fuels. One of the most extensive programs was initiated in Colorado, a state plagued by high winter time concentrations of carbon monoxide [Colorado Air Quality Control Commission]. Since 1989, a gasoline blend with MTBE with 2.0 wt% of oxygen is sold from November 1 to February 28. Thus, every year, 1.8 million vehicles run 4.8 billion miles on oxygenated fuel. The fuel consumption during every season is 350 million gallons [Gallagher: 301, 306].

As Denver is situated at an elevation of 1600m, the ambient air contains about 18% less oxygen than at sea level [Gallagher: 302]. The oxygenate in the gasoline is supposed to compensate for this. Oxygenated fuel is estimated to reduce CO emissions at a cost of about \$300/t [Gallagher: 307].

According to Section 211(f) of the Clean Air Act, any fuel used in vehicles must be "substantially similar" to fuels used in emissions certification. In 1981, EPA made it clear that oxygenates fulfill this requirement, provided they do not contain more than 2.0 wt% oxygen [Dorn: 42]. This "substantially similar" rule limits the maximum oxygenate concentrations (see fig. 5.7).

oxygenate	max. allowable concentration [wt%]
methanol	3.0 ¹¹
ethanol	5.4
50% methanol, 50% TBA	5.5
TBA	7.1
MTBE	11.0

Fig. 5.7 Maximum allowable concentration of oxygenates under EPA "substantially similar rule" [Dorn: 42]

For all other fuels it has to be demonstrated that no negative effects on exhaust and evaporative emissions exist. Such waivers have been granted for gasohol (10 vol% ethanol), 9.5 vol% methanol/TBA, and 15.7 vol% TBA, all of which result in an oxygen concentration of about 3.7 wt% [Dorn: 42].

¹¹ In his publication, Dorn quotes "0.3%." As methanol contains 53 wt% oxygen, the correct figure must be 3.0 %.

5.8 Emissions from Reformulated Gasoline

Reformulated gasoline includes gasoline with altered characteristics (such as vapor pressure or content of aromatics) as well as blends of gasoline with oxygenates, as long as the fuel can be burned in a standard engine. The following lists the main variables that are under discussion.

5.8.1 Lead

Lead in European gasoline is being phased out [ACEA/Europa, Norén: 1995]. In the meantime the lead content of leaded gasoline will be lowered as much as is possible without putting at risk the valves of old motors [ACEA/Europa]. However, as long a leaded gasoline is being sold, there will always be a danger of inadvertently using it in cars with catalytic converters. This would permanently destroy the converter.

The low levels of lead normally found in unleaded gasoline can be attributed to the residues of leaded gasoline contaminating the distribution system. Since the introduction of unleaded gasoline, the lead concentration in blood samples has dramatically declined [Kyrklund].

5.8.2 Benzene

Benzene in the fuel contributes to only half of the benzene found in the exhaust. The incomplete combustion of other hydrocarbons and especially the dealkylation of higher aromatics are the other sources. As a consequence, cutting the benzene content in gasoline from 3% to 2%, reduces the benzene emissions by only 17%.

5.8.3 Evaporative VOG - Reduction of RVP, Increase of Volatility

As seen in figure 5.7, hydrocarbons in the exhaust have a relatively small contribution to the overall emissions of VOG of modern passenger cars. Evaporative and running losses are more important and depend strongly on the ambient temperature. In summer, when ozone concentrations are highest and releases of VOG thus need to be minimized, evaporation and running losses contribute up to 92% of overall emissions (RVP 80 kPa, temperature 35

°C). Older cars have both higher exhaust emissions and higher evaporative and running losses¹² so that a similar relation applies.

Reducing the Reid Vapor Pressure to 62 kPa brings down evaporative and running losses to about the same amount as exhaust emissions of VOG. This can be done by removing low boiling olefins (C₄ and C₅) from the gasoline. In winter, a gasoline grade of higher RVP must be used in order for the engine to start promptly.

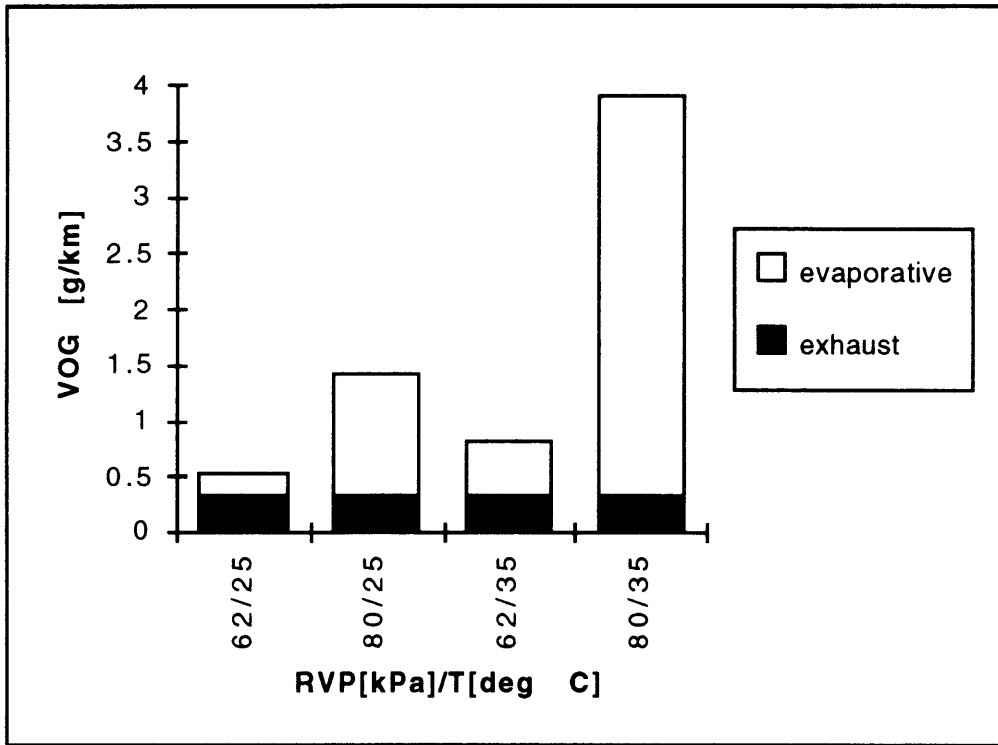


Fig. 5.8 Emissions of VOG from 1981 and newer model passenger cars [Piel: 68]

Changed distillation characteristics offer another venue to curb evaporative emissions of VOG. For non-catalyst cars, increasing the mid-range volatility (E 100) from 45% to 55% reduces VOG emissions by 5% and seems to have no detrimental effect on CO and NO_x [ACEA/Europia].

Other data indicate similar reductions for catalyst equipped cars. A U.S. study suggests increasing the tail-end volatility (E150) to about 90%, and predicts VOG reductions of 22% [ACEA/Europia].

¹² Older cars lack carbon canisters and vacuum pumps that prevent hydrocarbon vapors from escaping.

5.8.4 Exhaust VOG - Reduction of Aromatics

A reduction of aromatics from 30 wt% to 10 wt% has been shown to lead to slight reduction of VOG (on the order of 5%) in the exhaust [Gething 1990]. While its cause is unknown, it can be speculated that it is related to changes of the distillation characteristics associated with the reduction of aromatics. Altered combustion characteristics might offer another explanation [ACEA/Europia].

5.8.5 Carbon Monoxide - Reduction of Aromatics

Figure 5.8 shows that CO emissions increase with the content of aromatics in the fuel. This is backed by numerous studies [Quader, Colucci, de Gobert]. This could be attributed to two properties of aromatic compounds. First, aromatics have a higher proportion of carbon atoms. Second, the double bonds and the ring structure make aromatics harder to break up. As a result, a relatively high amount of carbon does not find enough oxygen to complete the reaction to carbon dioxide and instead ends up in the form of carbon monoxide.

A literature research carried out by ACEA/Europia shows a 7% reduction of CO for catalyst cars only. The emission of non-catalyst cars are not influenced. The same study quotes AQIRP having found reductions of 10-15%. However, none of the figures specifies the exact aromatics content [ACEA/Europia].

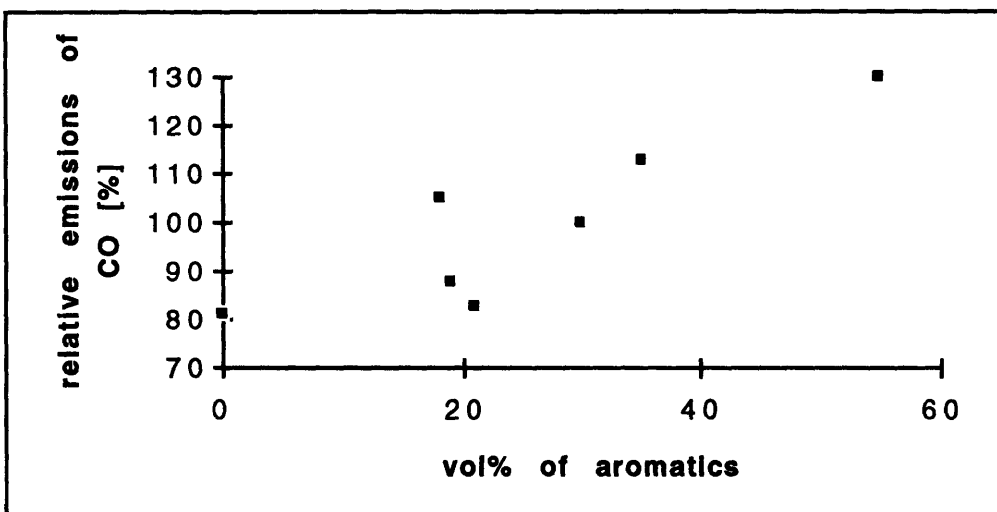


Fig. 5.9 Influence of fuel aromatics content on CO emissions - relative to a standard fuel with 30% aromatics (for 1986 Honda, 1985 Camaro) [Piel: 69]

5.8.6 Carbon Monoxide and Hydrocarbons - Introduction of Oxygenates

Aromatics have the effect to increase the octane rating of the gasoline; they must therefore be replaced by another compound with a similar function. The obvious choice are oxygenates, such as ethers or alcohols. Reducing aromatics has beneficial effects in itself. Replacing aromatics with oxygenates results in a leaner combustion, which brings about additional reductions of CO and VOG, as shown in figure 5.9.

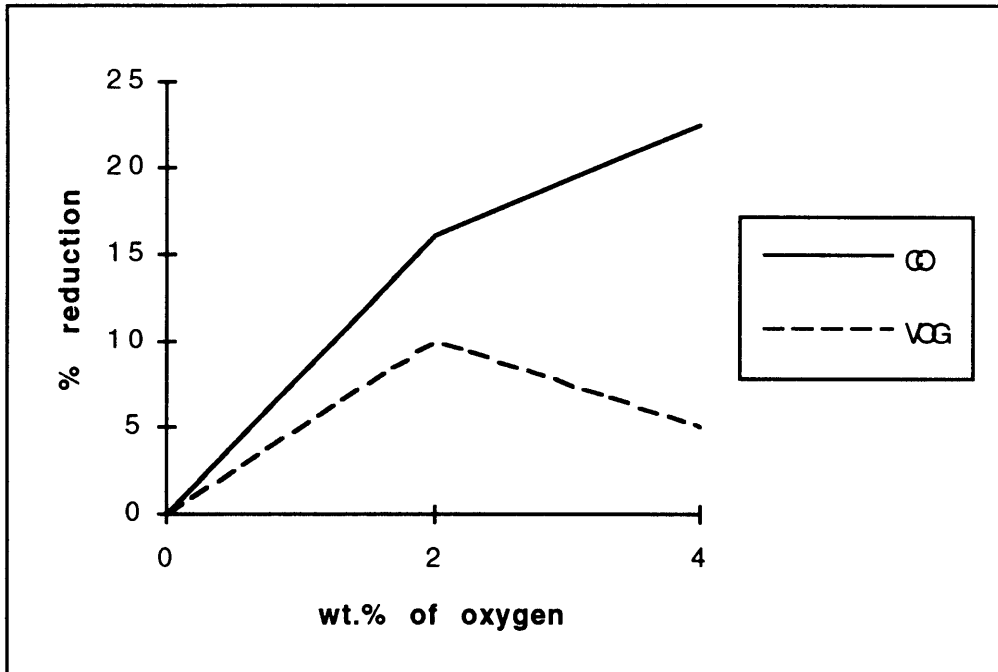


Fig. 5.10 Influence of fuel oxygen content on emissions of CO and HC (average of 137 catalyst car runs)
Due to the testing procedure, this is a conservative estimate.
[Piel: 69]

Piel therefore recommends the use of 2 wt% of oxygen in the fuel. This corresponds to 11 vol% of MTBE or 3 vol% ethanol [Piel: 72].

EPA has compiled emission data from a number of studies. It mandates its data set (shown in figures 5.10 and 5.11) to be used to analyze oxygenated fuels in federally controlled emission programs [EPA 1988b].

	emission reductions of 2.0 wt% oxygen [%] (11 vol.% MTBE)		
	CO	HC	NO _x (increase!)
non-catalyst	13.2	3.0	+ 3.2
catalyst ¹³	11.6	2.8	+ 4.4

Fig. 5.11 Emission reductions of 2.0 wt% oxygen blends [EPA 1988b]

	emission reductions of 2.7 wt% oxygen [%] (10 vol% ethanol or 5 vol% methanol with cosolvent)		
	CO	HC	NO _x (increase!)
non-catalyst	13.2	3.0	+ 3.2
catalyst ¹⁴	11.6	2.8	+ 4.4

Fig. 5.12 Emission reductions of 2.7 wt% [EPA 1988b]

Further studies indicate that the reductions of carbon monoxide emissions are not proportional to the oxygen content in the fuel. For instance a fuel with only 2.0 wt % of oxygenates already exhibits characteristics close to those of a fuel with 3.7 wt% of oxygenates [Gething]. Reductions of hydrocarbon emissions might reach a peak at 2.7 wt% oxygen [API].

The same study notes a small reduction of benzene and a slight increase of formaldehyde. However, one must keep in mind that formaldehyde is also produced by the photo-oxidation of VOG. As VOG is reduced, the overall effect will be a reduction of formaldehyde.

¹³ The reductions for simple oxygenizing converters are generally higher as these converters are less efficient to begin with. However, there are only few such converters in use in Sweden.

¹⁴ The reductions for simple oxygenizing converters are generally higher as these converters are less efficient to begin with. However, there are only few such converters in use in Sweden.

5.8.7 PAH - Reduction of Aromatics

When rings of aromatics molecules clump together, they form polyaromatic hydrocarbons (PAH). These particles have been shown to cause cancer. The content of aromatics in the gasoline should therefore be reduced. However, this is relatively expensive. Reducing aromatics from 30% to 10% is estimated to cost \$0.025 per liter (\$0.1 per gallon) [Center].

5.8.8 Overall Improvements - Reductions of Sulfur

Sulfur in gasoline forms deposits on the catalytic converter and gradually deactivates it. By reducing sulfur levels from 500 to 50 ppm emissions of CO and VOG decline by 18%, while emissions of NO_x decline by 8% [ACEA/Europia]. This effect becomes proportionally stronger the lower the sulfur level is.

6 Gasoline with Additives

6.1 Types and Function of Additives

Lead containing additives¹⁵ were once commonly used to increase the octane rating of a fuel. Due to the health risk associated with heavy metals, these additives are being phased out. More olefins or oxygenates such as ethanol or MTBE are now used to guarantee the octane rating.

Today's gasoline can contain essentially three types of additives. Corrosion inhibitors protect pipelines and storage tanks of the producer as well as fuel lines and fuel pumps of cars. Anti-oxidants keep the short molecules in the gasoline from combining into larger ones that are more difficult to burn ("repolymerization") [Center].

Detergents coat metal surfaces and prevent the build-up of combustion products. Deposits on the cylinder walls reduce the available volume and thus lead to a small but significant increase in the compression ratio. This in turn causes an increase in the octane rating that is required for the car to run smoothly [Center].

The inlet valves are particularly prone to accumulation of deposits, which impair the flow of the fuel-air mixture. Also, the porous deposits absorb gasoline in the start-up phase. As a result, the engine runs rough and hydrocarbon emissions increase. The fuel air ratio of the combustion is disturbed, too, which negatively affects emissions of carbon monoxide and nitrous oxides. Other critical areas include the carburetor or the fuel injectors [Center].

U.S. standards prescribe a maximum deposition of 100 mg after 100,000 miles (160,000 km). In Sweden, a "keep clean performance requirement" for gasoline has been in effect since Jan. 1, 1995, which can only be fulfilled with detergents. In the rest of the EU, there is no legal obligation to use detergents [Center].

¹⁵ tetraalkyl lead

6.2 Emission from Gasoline with Detergent Additive

Southwest Research Laboratories, an independent lab, was recently contracted by an oil company to conduct a fleet test to support advertising claims. The test compared the customer's permium grade gasoline (with an inlet valve detergent - IVD) to Phillips RF-A, which represents an industry average. The main characteristics of both fuels are listed in figure 6.1.

The test vehicles were a 1990 Ford 2.3L with dual spark plugs, a 1990 Buick 3.1L with a V6 engine and a Pontiac 2.3L/Quad 4. The mileage ranged from 31,000 to 44,000 miles. The engines of the test cars have displacements slightly bigger than the typical Swedish car. The test report mentions that all three cars have a history of driveability problems due to intake valve deposits [Center]. It is therefore probable that the emission reductions achieved with an IVD give an upper bound to what can be expected under more realistic conditions.

	test gasoline	reference gasoline
detergent	yes	no
aromatics [wt%]	25.7	28.8
olefins [wt%]	6.6	10.7
sulfur [ppm]	80	300
MTBE [wt.%]	15	0
T50 [deg C]	104	121
T90 [deg C]	158	164

Fig. 6.1 Main characteristics of reformulated gasoline test fuel and reference fuel [Center]

Both fuels differ not only in the detergent content, but also in their oxygen content. (The MTBE content in the test fuel corresponds to about 2.7wt% of oxygen.) It is therefore difficult to separate the influence of the detergent from that of the oxygenate. For this reason, the emission reductions expected of a comparable oxygenated fuel (figure 6.3) are subtracted from the values of the test fuel (figure 6.2).¹⁶ The result, the emission reductions expected from the use of the detergent only, is shown in figure 6.4.

	emission reductions [%] test gasoline (oxygenated, with detergent) vs. reference fuel		
(all catalytic converter)	CO	HC	NO _x
clean valves	26	41	17
dirty valves	23	23	17

Fig. 6.2 Emission reductions by test gasoline (oxygenated, with detergent)

	expected emission reductions [%] of a gasoline comparable to the test gasoline, but without detergent		
	CO	HC	NO _x (increase!)
no converter	18	4.1	+ 4.4
converter	15.8	3.8	+ 6.0

Fig. 6.3 Emission reductions expected of a fuel comparable to the test fuel, but without detergent (based on [EPA 1988b])

¹⁶ As the emission reductions are measured not in absolute terms but in percent, a direct subtraction is technically not correct. Instead the following formula was used:

$$(1 - A) * (1 - B) = (1 - C),$$

where A is the emission reduction by a detergent only (to be determined), B is the reduction by oxygenates only (based on EPA data) and C is the reduction by both (as in the test fuel)

		expected- emission reduction by detergent only [%]		
		CO	HC	NO _x
clean valves	no converter	9.8	38.5	20.5
	converter	12.1	38.7	21.7
dirty valves	no converter	6.1	19.7	20.5
	converter	8.6	20.0	21.7

Fig. 6.4 Expected emission reduction by use of detergent only

For a number of reasons, this method is somewhat speculative:

- There is no data on an identical fuel (without detergent).
- There is no data that was achieved using the same test vehicles.
- There is no data that was achieved using the same reference fuel.
- The effects of oxygenates and additives might not be independent.
- There is no data on the emission reduction of IVD for cars without catalytic converter

6.3 Costs of Detergent Additive

The actual cost of additives is treated as proprietary information and therefore is difficult to obtain. However, one industry expert recently estimated detergent additives to increase the cost of gasoline by 0.2¢/gal or 0.05¢/l [Center].

7 Political Background

7.1 Structure of Naturvårdsverket

Naturvårdsverket (SNV) was established in 1973. It is active in the field of environmental protection and conservation, outdoor leisure activities, research and education [SNVc: 3]. The ministry of the Environment appoints the director-general for a renewable six year term [Bingman]. In total, the agency employs about 500 people [SNVc: 12].

Every year, the government presents a list of proposed measures and projects to SNV. From this list, the Parliament allocates the funds [SNVc: 12]. In 1993/94, the appropriations to SNV totaled SEK 1.2 billion¹⁷ or about \$160 million (see figure 7.1).

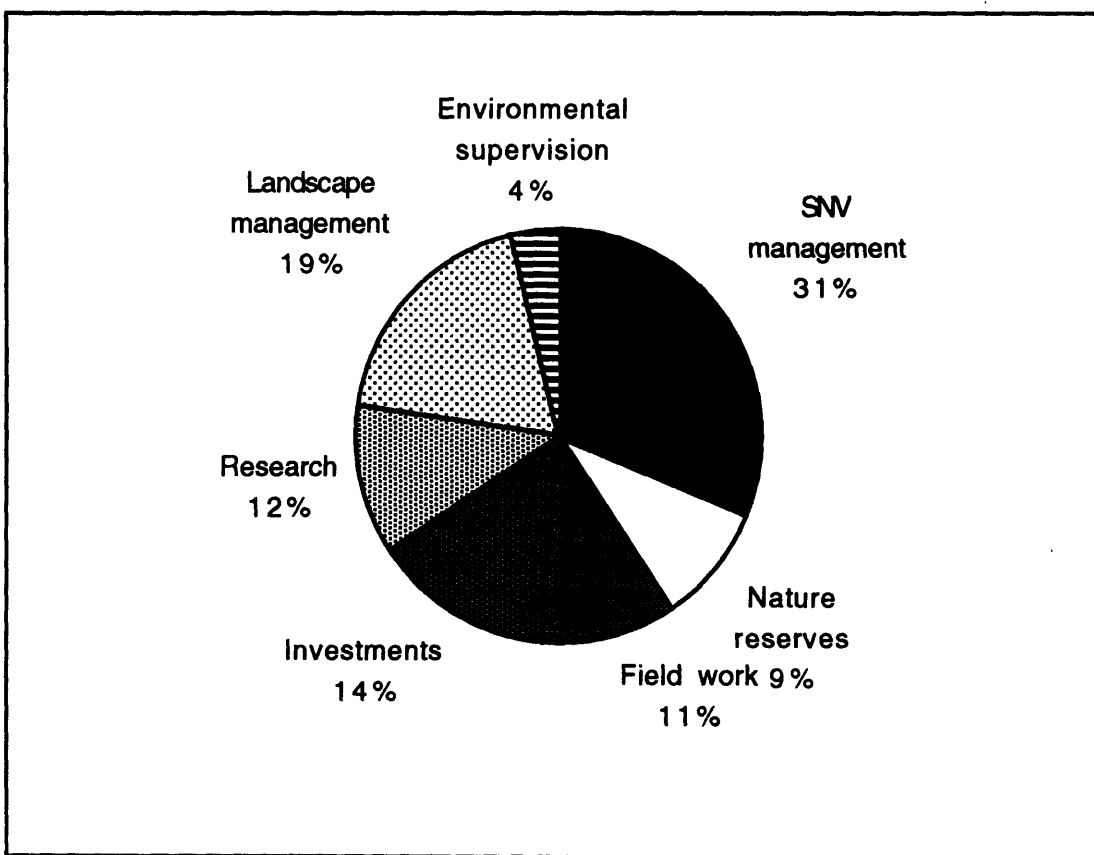


Fig. 7.1 1993/94 appropriations for SNV in million SEK [SNVc]
(Appropriations below SEK 50 million are not shown)

¹⁷ In addition to that, the agency also receives SEK 0.1 billion in external monies (hunting conservation fund, battery fund, environmental technical support etc.) [SNV]

7.2 Development of Swedish Emission Standards

Emission standards were first introduced for the 1971 model year (**F23**, see figure 7.2). These standards basically followed the ECE15 norm that was then used in the EC.

When it became clear that F23 would not bring about the targeted reductions, a new standard was modeled after the 1973 U.S. federal requirements. This new Swedish norm (**F40**) applied to model years 1976 and later. It mandated not only tests on chassis dynamometers, but also extensive documentation before a manufacturer would receive a "Certificate of Conformity."

In the United States, catalytic converters were used to fulfill stricter requirements. By contrast, Sweden lacked unleaded gasoline so that catalytic converters were no option. The most widely used alternatives were exhaust gas recirculation (EGR) systems and controls that avoided abrupt closing of the choke (retardation limiters).

It was not commercially viable to design cars exclusively dedicated to the Swedish market. Instead car manufacturers retrofitted existing engines, which resulted in some cars having worse fuel economy and driveability. Many drivers were dissatisfied with the performance of their cars - mandatory inspections found that 6-15% of the emission systems had been tampered with [MTC9106].

An administrative reform gave the Swedish Environmental Protection Agency (Statens Naturvårdsverket) the power to mandate new standards. Inspections were now to be carried out by the Swedish Motor Vehicle Inspection Company (AB Svensk Bilprovning - ASB). Before that, the Agency for Transportation Safety (Statens Trafiksäkerhetsverket) had the mandate to issue emission requirements based on the government ordinance of exhaust emissions [Norén: 1993].

The **A10** regulation followed the previous standards. Since then however, cars of model year 1983 and later are not only to be tested while factory new. ASB has the authority to measure compliance of privately owned cars which had been in operation. If one brand of cars does generally not fulfill the requirements, the producer can be forced to refit all that have been delivered.

When unleaded gasoline became available in Sweden, Parliament enacted a transitory standard (**A11**) to encourage the voluntary use of catalytic converters. Under this scheme, owners of 1987 and 1988 models with the more sophisticated 3-way catalytic converters had to pay less sales tax. The total amount of this tax break approximately compensated for the additional cost of the converter.

Finally in 1989, the catalytic converter became the standard, as it was the only way to fulfill the emission requirements of regulation A12. In addition to the exhaust standards already mandated in A11, this regulation introduced limits on emissions that previously had been unregulated, such as particles and evaporative losses. Thus it is basically identical with the U.S. federal standards of 1987.

The measure is the result of an international cooperation aimed at harmonizing national regulation. It is now accepted by Norway, Finland, Switzerland, Austria, Taiwan and Brazil. A12 also regulates the acceptance of environmental approvals that had been granted by other countries, especially in Germany and the U.S.

Starting with the 1992 model year, the A12 was extended to small trucks (L-2 vehicles). This A-13 regulation follows the 1990 U.S. standards aimed at the same market.

A-12 and A-13, and Vehicle Emissions Ordinance (1991: 1481) established strict standards for all vehicles except heavy duty trucks, regardless of fuel. In addition to lowering emissions, manufacturer are held responsible for the continued environmental compliance of their cars. If a particular type of engine or car regularly exceeds the emission limits even though its owner has carried out the minimum required maintenance, the manufacturer has to recall all affected vehicles [Vehicle Emission Ordinance (1991: 1481)]. To this end, every producer must establish a representant in Sweden, which is to handle complaints from customers and government agencies [Erlandsson].

In 1991, the Parliament passed a law that defined a system of environmental classifications of cars. Cars of environmental class 1 have the lowest emissions, class 2 vehicles also show significant improvements over the standard automobile. Tax incentives are in place to promote the sale of these cleaner vehicles [Norén: 1995].

Regulation	F23	F40	A10	A11	A12	A13
Equivalent	ECE15	U.S. 73	U.S.73	U.S. 87	U.S. 87	U.S. 90
Description	dynamo-meter tests	CoC*, EGR system	in use control	3-way catalytic converter voluntary	3-way catalytic converter standard, cars	3-way catalytic converter standard, light trucks
model year	71 -	76 - 82	83 - 88	87 - 88	89 -	92 -
CO [g/km]	24.2	24.2	24.2	2.1	2.1	6.2
HC [g/km]	2.1	2.1	2.1	0.25	0.25	0.5
NO _x [g / k m] - overall	1.9	1.9	1.9	0.62	0.62	1.1
NO _x [g/km] -highway	-	-	-	-	0.76	1.4
particles [g/km]	-	-	0.124	0.124	0.124	0.162
compliance [km]	80,000	80,000	80,000	80,000	80,000	200,000

Fig. 7.2 Development of Swedish emission standards [Erlandsson: 3]
 * CoC = Certificate of Conformity

Regulation	environmental class		environmental class		standard (3)
	1	2	2	1	
CO [g/km]	2.1	2.6	2.1	2.6	2.1
methane [g/km]	0.25	-	0.25	-	0.25 (total hydrocarbons)
NMOG [g/km]	0.078	0.097	0.16	0.19	
NO _x [g/km]	0.25	0.37	0.25	0.37	0.62
NO _x [g/km] -highway	0.33	-	0.33	-	-
particles [g/km]	0.05	0.06	0.05	0.06	0.124
compliance [km]	80,000	160,000	80,000	160,000	80,000

Fig. 7.3 Planned future Swedish emission standard (voluntary)
[Vehicle Emissions Ordinance 1991: 1481]

7.3 Gasoline Infrastructure

In Sweden, gasoline is typically transported by sea from the refinery to one of sixty terminals for intermediate storage. Usually terminals store only two different gasoline grades. About half of the gasoline in Sweden passes through storage in underground caverns [Norén 1993: 34, 36]. Water is used to force the gasoline out of the tank. As alcohols and to a lesser extent ethers are sensitive to water (see section 5.4) they would have to be stored separately to be blended in at the pump.

From the intermediate storage site, tank trucks supply the local gas stations. Most of the 4000 gas stations dispense the two gasoline grades that are delivered from the terminal as well as a third, which is a simply blend of the two. Others stock three different grades and sell four [Norén 1993: 36].

If all gas stations were to carry 4 different grades, the necessary upgrades of the terminals would cost SEK200 million (\$28 million). Changing the gas stations themselves would cost around SEK500 million (\$71 million) [Norén 1993: 36].

7.4 Development of Gasoline Standards

On June 4, 1992, the Swedish government commissioned SNV to propose an environmental classification scheme for gasoline. This scheme was to help achieve the emission targets set for the road transportation sector (see section 3). It had to present no additional cost to the state [Norén 1993: 1].

Originally, the SNV proposal included four different environmental classes. However, the scheme was later simplified and environmental class 4 was abolished. The final version entered into effect on December 1, 1994 [Norén: 1995].

Environmental class 3 is the worst grade. It is an unleaded gasoline which fulfills Sweden's obligation as a participant of the European Standardization Committee (CEN) and applicant to the EU to admit "European" gasoline to its market [Norén 1993: 1].

Environmental class 2 has less lead, benzene and sulfur. The maximum vapor pressure in summer is lower. To accommodate the different requirements of cars with and without catalyst, it is further subdivided. The catalyst gasoline has an even lower content of sulfur to protect the converter from deposits.

The characteristics for the environmental classes 2 and 3 are listed in figure 7.4. Environmental class 1 is still under consideration [Norén 1995].

	Environment Class 2		Environment Class 3 (Euro standard EN-228, 1993 ¹⁸)
	no catalyst	catalyst	either
octane rating	98	95 ¹⁹	95
sulfur [wt%]	0.03	0.01	0.1
max. RVP [kPa]	70/95 *	70/95 *	80/95 *
min RVP [kPa]	45/65 *	45/65 *	45/60 *
min E100 [%]	47/50 *	47/50 *	40/43 *
FBP [°C]	200	205	215
max benzene [vol%]	3	3	5
aromatics/13 + benzene [vol%]	6	5.5	-
max oxygen [wt%]	2	2	2.5
max lead [mg/l]	5 **	5 **	13

Fig. 7.4 Specification for environmental classes for gasoline

* The lower number refers to the summer grade (April 15 - Sept. 30), the higher number to the winter grade (Oct. 1 - April 14).

** Sampling shows typical values lower than 2 mg/l [Norén 1993: 3, Norén: 1995]

¹⁸ Only the benzene and lead content are specifically mentioned in the Swedish standard. For the other characteristics a reference to the EN-228 standard is made. However, there exist two EN-228 standards, one passed in 1991, the other passed in 1993. Both differ in their volatility limits. The figures indicated above refer to the 1993 standard, which would be preferable from the Swedish point of view [Noren: 1995].

¹⁹ The law does not prescribe any octane ratings, and catalyst gasoline is also supplied with a 98 octane rating [Jarsin].

In addition to the grades shown, a 96 octane blend can be achieved by using a third pump that automatically mixes catalyst and the non-catalyst gasolines.

All environmental classes limit the amount of oxygenates to 2 wt% of oxygen, less than the 2.7 wt% where the maximum savings of CO are realized. This is done to avoid increasing the emissions of NO_x. Ethers are the preferred oxygenates, as they do not increase the vapor pressure as alcohols do. Furthermore they are not as sensitive to water, which might get in contact with the gasoline during sea transportation [Norén 1993: 16]. Cavern storage, however is impossible for both alcohols and ethers [Jarsin].

In order to stimulate the use of the cleaner environmental class 2, the fuel tax on class 3 gasoline was increased by SEK0.06 (\$0.01) per liter [SFS 1994: 1360]. In addition, the oil companies agreed only to supply class 2 gasoline after July 1, 1995 [Norén 1995].

8.1 Analysis of Swedish Car Fleet

Figure 8.1 shows the composition of the Swedish car fleet at the beginning of 1993. Local manufacturers (Saab, Volvo) contribute about a third of all cars. Another third is produced by Volkswagen/Audi, Opel and Ford, the German mass manufacturers²⁰. Of the remaining third, about 50% are of Japanese origin, 20% are of French origin and 20% are German luxury brands [BIL: 6, 11].

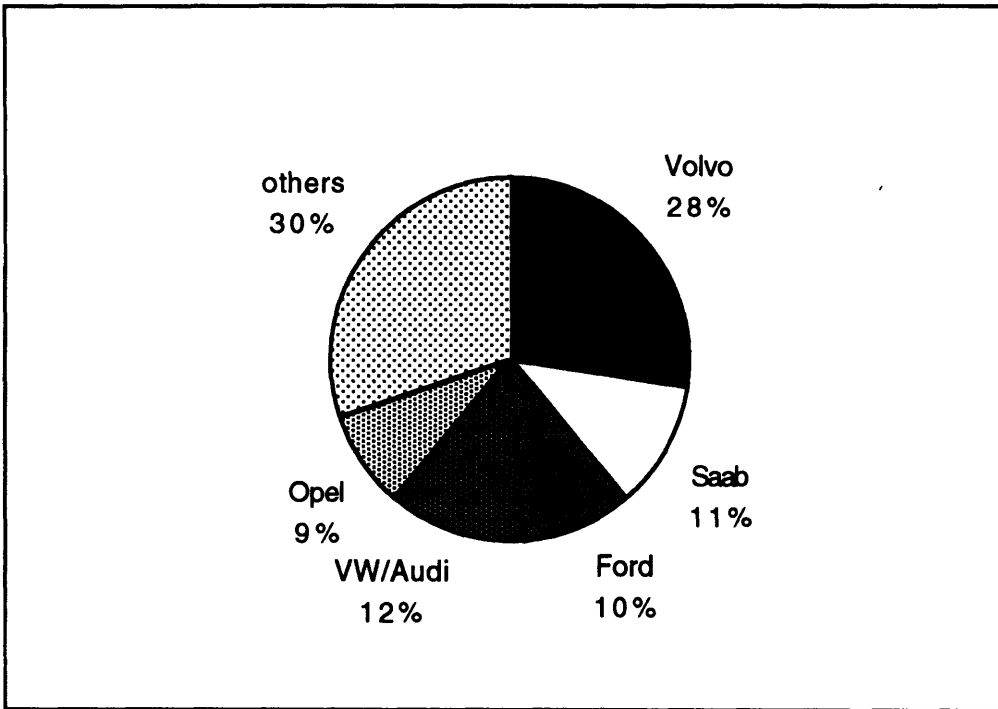


Fig. 8.1 Composition of Swedish car fleet by manufacturer, on 1/1/1993 [BIL: 6]

Figure 8.2 lists the ten most sold models and their share of total sales in the years 1991 and 1992. Taken together, they account for almost half of all car sales. It is noteworthy that five out of the ten models are produced nationally. This means that a few very popular models account for almost the entire market share of Swedish manufacturers.

²⁰ Ford/Europe develops and produces relatively independently, largely in German facilities. Opel is owned by General Motors, but also maintains its own engineering and production in Germany.

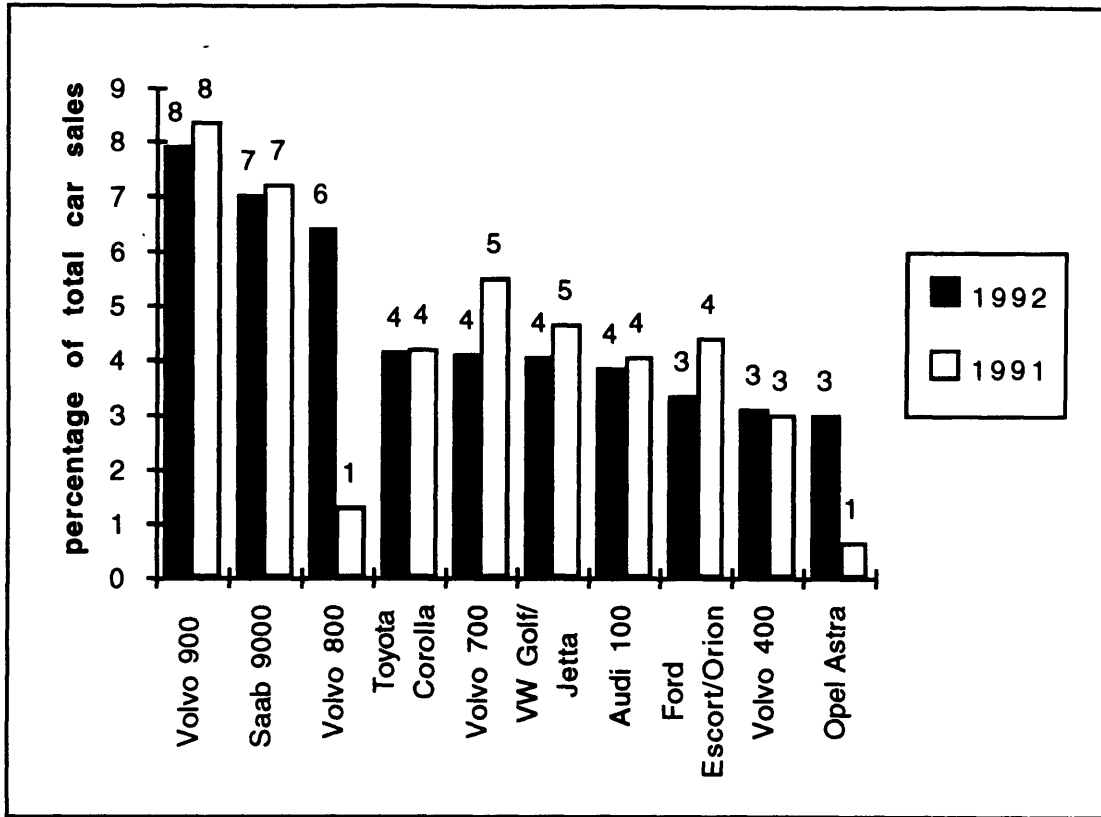


Fig. 8.2 The ten most sold car models in 1991 and 1992 and their respective share of total sales [BIL: 14]

The Swedish car fleet is comparatively old. The proportion of cars 10 years or older is 39%. In the United States, this figure is 34%, in England 26% and in Germany 22% [BIL]. In 1992, the average age of the Swedish car fleet was 9 years [BIL]. In the United States, the average vehicle age is presently 4 years [Christian Science Monitor].

Figure 8.3 shows the percentage of diesel cars relative to total sales. In recent years, less than one percent of the cars sold were diesel driven. This is generally attributed to various problems of diesel cars in extreme winter temperatures, such as difficulty in starting. Another cause are the limitations imposed by the stringent environmental requirements on diesel fuel in Sweden.

As a result of the low sales volume, the share of diesel cars in the car fleet has been declining steadily (figure 8.4). Today, the number of diesel cars is so insignificant as a percentage of total automobile fleet that their contribution to emissions can be neglected.

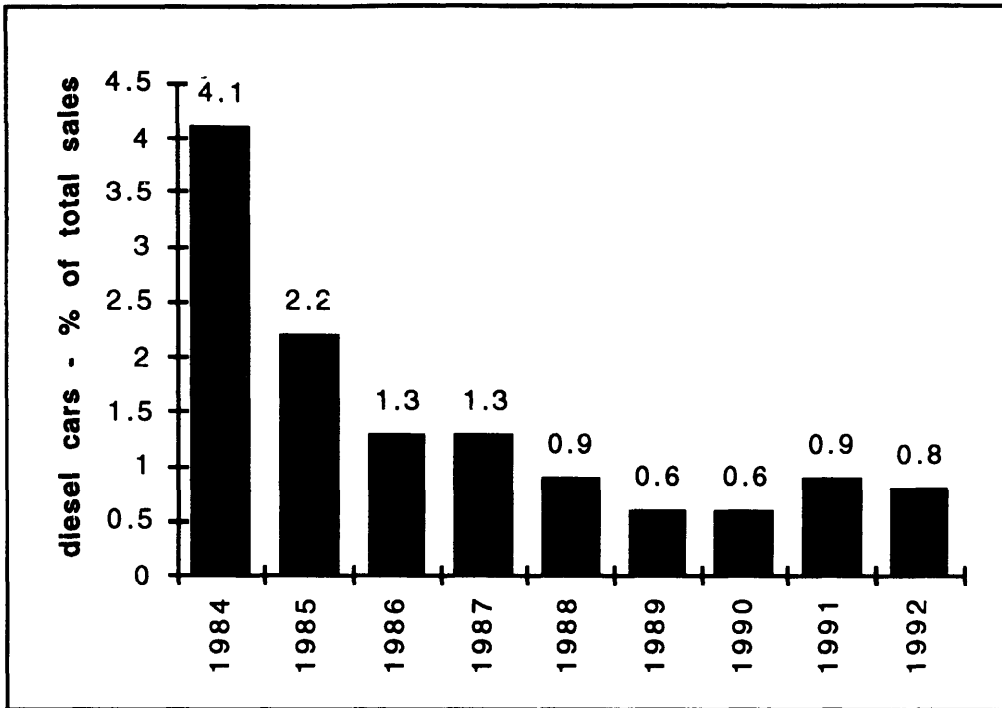


Fig. 8.3 Sales of diesel cars in percent of total car sales [BIL: 5]

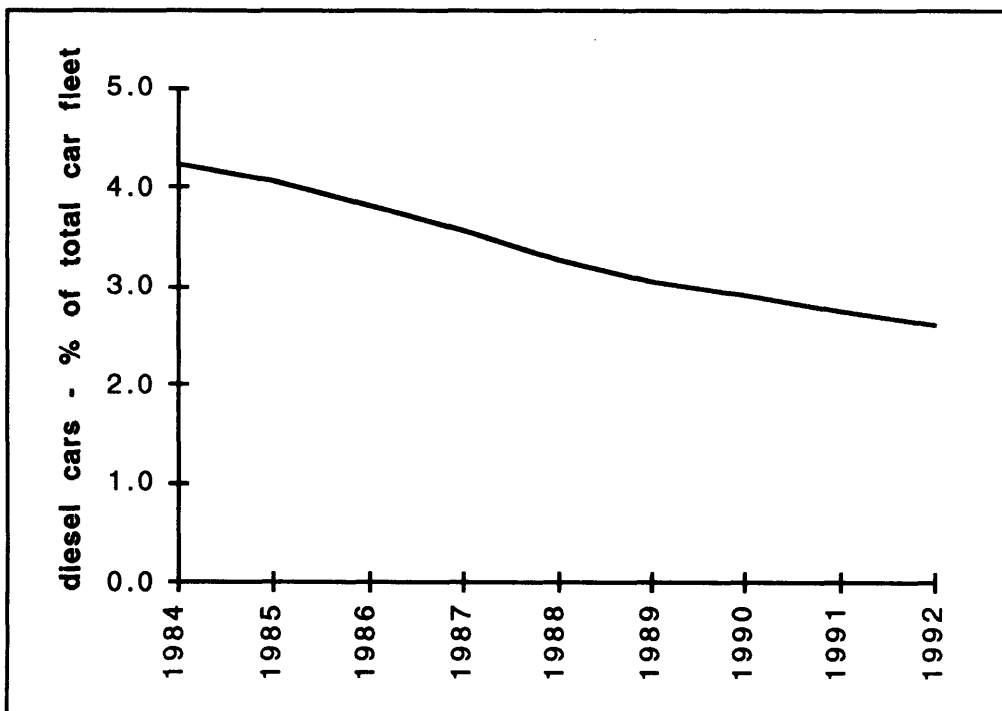


Fig. 8.4 Proportion of diesel cars in the car fleet [BIL: 5]

Diesel does contribute to pollution through trucks, locomotives, off road equipment and ships. This study however, addresses only the passenger car fleet that dominates the Swedish regulations concern.

Of the 3.6 million cars that currently make up the Swedish fleet, 1.3 million (36%) are equipped with catalytic converters [BIL: 1].²¹ generally newer cars are driven more per year. As it is the newer cars (starting with the 1989 model year) that have converters, converter cars account for about half of the total fleet mileage [BIL: 1].

The overwhelming majority of catalyst cars operates with a three-way catalytic converter. The three way design measures the oxygen content in the exhaust and gives a feed back to the engine, adjusting the air to fuel ratio. the catalyst then operates under conditions where it is not only able of oxidizing hydrocarbons and carbon monoxide (to carbon dioxide), but also of reducing nitrogen oxides to molecular nitrogen.

The simple oxidizing converter is found in some 1987 and 1988 models. While it is less expensive the three way catalyst, it lacks the feed back to the engine. It therefore is not capable of reducing NO and NO₂ to N₂.

8.2 Forecast of Swedish Car Fleet

Necessary to forecasting the evolution of the Swedish car fleet is the determination of the rate with which old cars are replaced by new ones. The spreadsheet FLEET FORECAST calculates the "survival rate" of cars, i.e. the proportion of all cars of a model year that is still in operation in a certain calendar year. It is based on 1993 data provided by the Association of Swedish Automobile Manufacturers and Wholesalers [BIL].

The number of vehicles of different model years that was still operational on 1/1/1993 was divided by the number of vehicles that had initially been registered. The result is the "raw" survival rate, presented in figure 8.5. The fact that the raw survival rate sometimes exceeds unity proves that the number of vehicles newly registered in a particular calendar year cannot be identical to the number of car sales of the respective model year.

A slight offset between the two figures was expected, as the model year usually starts in July the previous year [Ljungdahl]. However, for normal years it could have been expected that about as many cars were produced in the previous model year and registered in the relevant calendar year as were produced in the relevant model year and registered in the next calendar year.

²¹ This is considerably less than in the United States, where converter cars make up 90% of the fleet [Norén: 28].

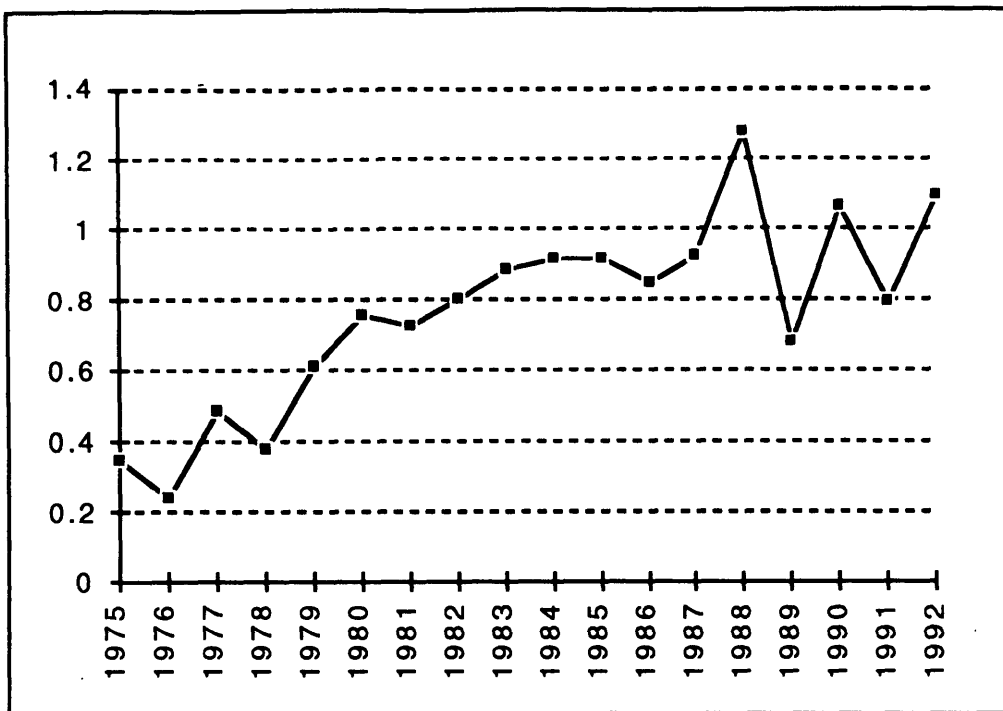


Fig. 8.5 "Raw" survival rate

For the model year 1988, the spreadsheet calculates a survival rate far exceeding unity. This was the last model year before catalytic converters were mandated. In order to speed up the introduction of catalytic converters, the Swedish government lowered the sales tax on those 1988 models that were voluntarily equipped with a converter [Ljungdahl]. This tax incentive did not apply to later model years.

In this transition period, two effects could have taken place. First, those consumers who did not trust the new technology purchased the last of the "real cars" without converter. Second, those consumers who thought about buying a car in the next years took advantage of the tax break and purchased a 1988 model with converter. As a result, the 1988 model was sold in high numbers well into the year 1989. This saturated the market so that the statistic shows a sharp decline in new registrations of 1989 models (figure 8.10).

The survival rate of the 1990 and 1992 model year exceeds unity by a small margin. This could be explained by transient effects of the somewhat erratic car sales.

In terms of a forecast of the car fleet, it is reasonable to assume less abrupt changes in the survivability of cars. This is shown in figure 8.6. A two-segment linear approximation was used for the years 1975-1992, where detailed data existed.

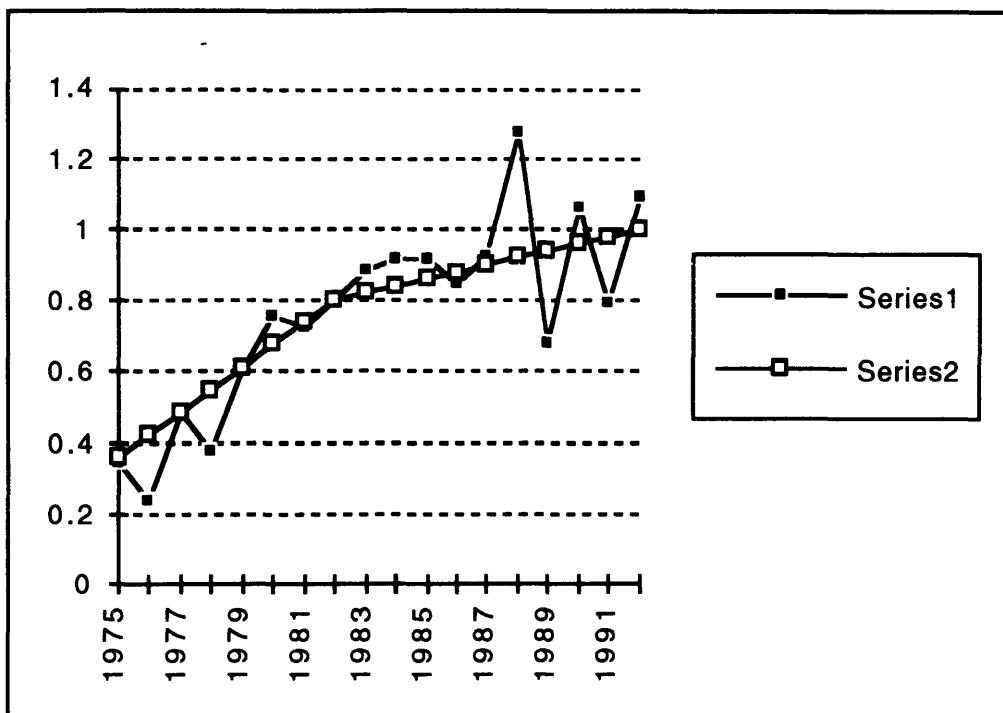


Fig. 8.6 Raw survival rate (dark, series 1) and adjusted survival rate (light, series 2)

The available statistics present only a total number of cars built before 1975. The model extrapolates the linear survivability function for these early model years. However, the slope of the function was slightly adjusted to make the model predict the correct total number of cars.

As a result, the survivability function is made up of three linear segments (figure 8.7). The arrow points at the model year 1975, where the first and second segments meet.

In order to check the assumptions, the adjusted survival rate was applied to the actual number of newly registered vehicles. The sum of all vehicles of model years 1975 through 1992²² as well as the sum of all cars of model years before 1975²³ are practically identical to the statistical data.

²² model: 3,559,154, real: 3,560,452 [BIL:5]

²³ model: 234,588, real: 234,771[BIL:5]

This survival rate is assumed to be constant over the time frame of the forecast. In reality, the different design of modern cars, changes in the national economy, and other factors could influence the time owners keep their cars before replacing them. However, one can expect this effect to be outweighed by new (and probably stricter) inspection and maintenance schemes or buy back programs. In the later case, the car survival rate calculated here would be an upper limit, giving a worst case forecast in terms of emissions.

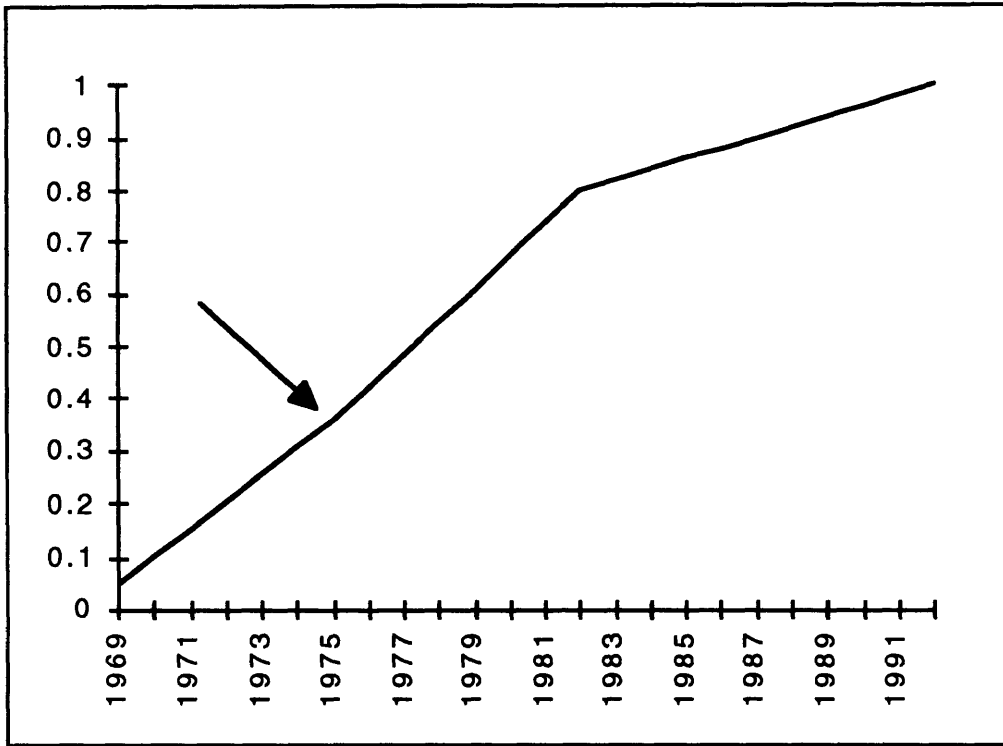


Fig. 8.7 Adjusted survival rate, extended to incorporate cars of up to 23 years of age

Based on the survival rates calculated in PRESENT FLEET, the spreadsheet FLEET FORECAST attempts a forecast of the Swedish car fleet and its emissions. The computation derives from the 1992 statistical data provided by the Association of Swedish Automobile Manufacturers [BIL]. The forecast spans a time horizon until the year 2002. All inputs can be changed to accommodate different sets of assumptions or to evaluate the sensitivity to the final result. The structure of the spreadsheet is shown in figure 8.8.

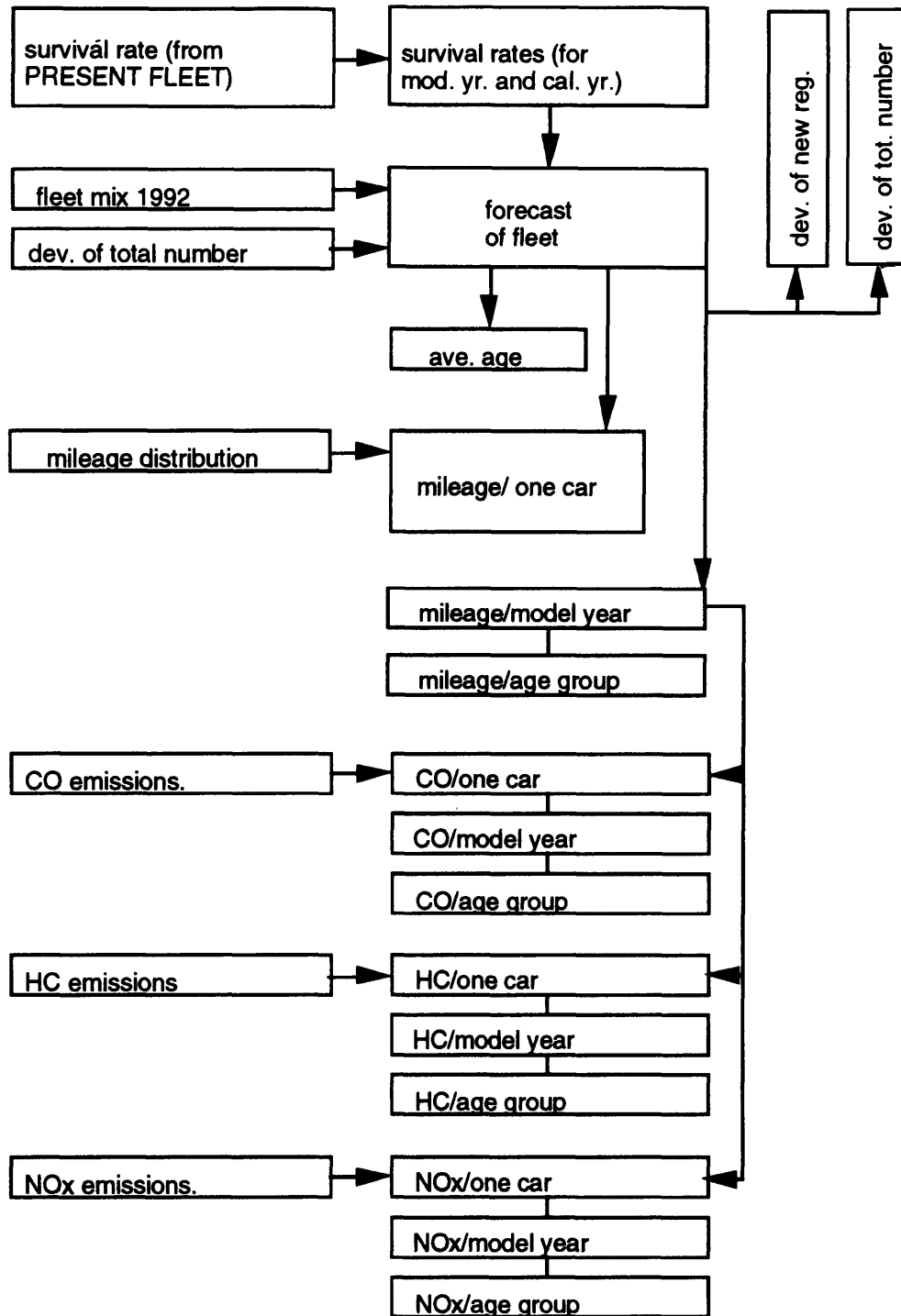


Fig. 8.8 Basic Structure of Spreadsheet FLEET FORECAST

From the survivability rate of vehicles developed in the spreadsheet PRESENT FLEET, a matrix extracts the percentage of the different models years that are still operational in the respective calendar year.

This matrix, in conjunction with the knowledge of the make-up of the car fleet in the year 1992 and an assumption on the total number of cars, leads to a forecast of the composition of the car fleet. In 1992, 26255 cars of the subsequent model year were sold. This number is assumed to be constant in the following years.

Figure 8.9 shows the growth of the Swedish car fleet since 1945. In the 50's and 60's, the number of cars increased almost linearly by 100,000 per year. In the years 1976 to 1981, there was hardly any change in the total number of cars. As similar plateau was experienced between 1989 to 1992, the last year for which data was available. In 1992, the total number of cars was 3.6 million, which translates to one car per 2.4 inhabitants [BIL: 2].

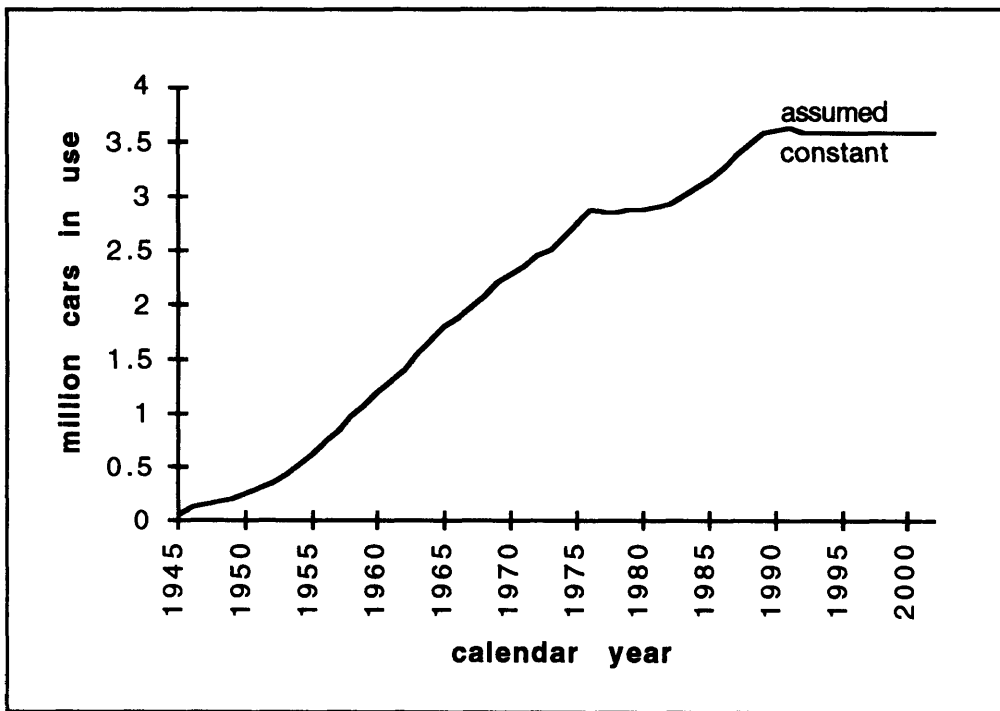


Fig. 8.9 Number of cars in the Swedish car fleet (1945-1992: data, 1993-2002: assumed constant)

The ratio of 2.4 inhabitants per car is already lower than that of Western Europe taken together (2.8 cars per inhabitant in 1986 [Brown et al.]). Thus the market can be assumed to be sufficiently saturated to make a continued growth of 100,000 cars virtually impossible. On the other hand, no evidence suggests that the number of cars will decrease significantly. A constant number of cars therefore seems to be a sensible approximation.

Figure 8.10 represents the number of car sales that are needed to achieve the changes in the car fleet. If cars from previous “boom periods” will need to be replaced, sales of new cars will go up in the late 1990s. The predicted sale figures illustrate the 11 year cycle described by the Association of Swedish Automobile Manufacturers.

With the expected sales boom in the last half of the 90’s the average age of the car fleet will drop from nine to five years (figure 8.11). However, the Swedish car fleet would remain comparatively old.²⁴

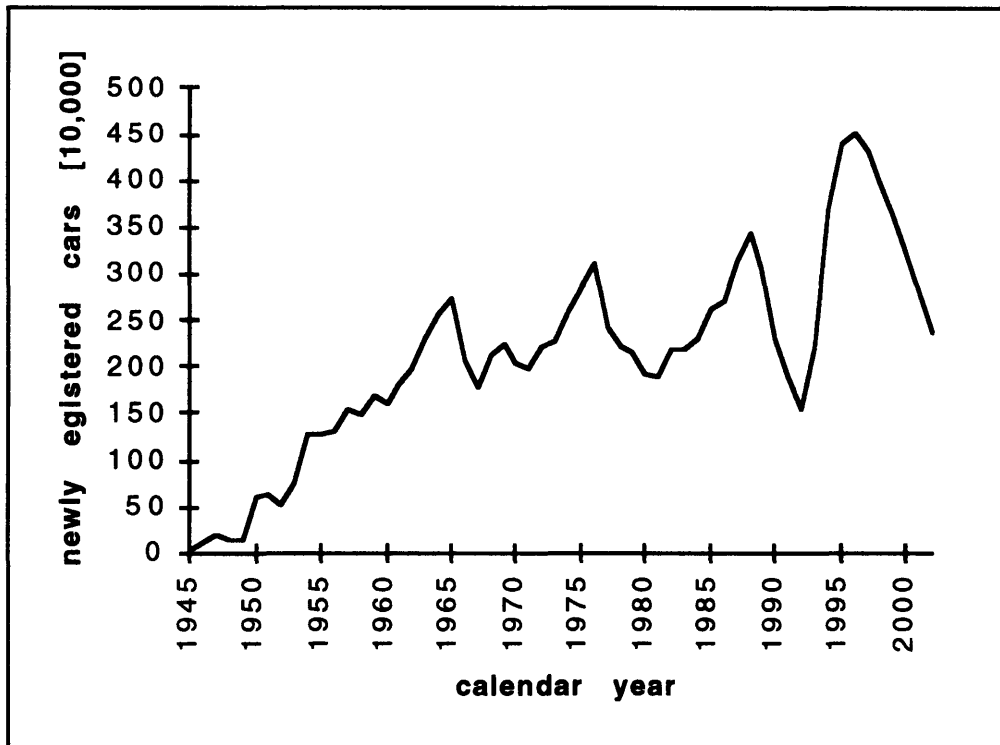


Fig. 8.10 Number of newly registered cars in the Swedish car fleet (1945-1992: data, 1993-2002: forecast)

²⁴ In the United States, the average vehicle age is presently 4 years [Christian Science Monitor].

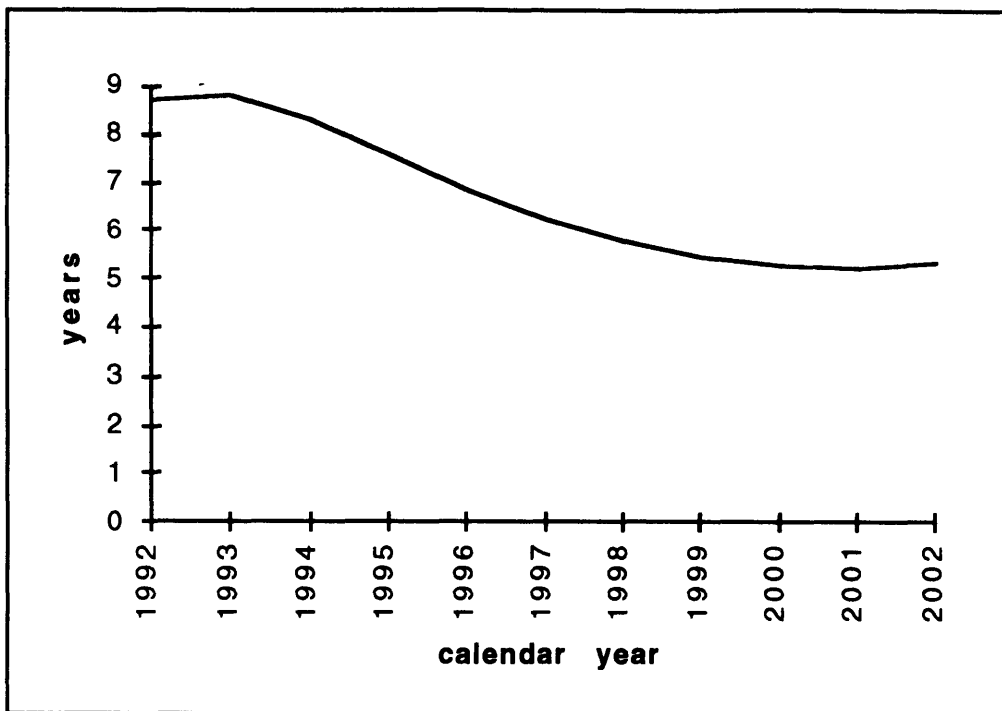


Fig. 8.11 Average age of the Swedish car fleet over time
(1992: data, 1993-2002: forecast)

Based on the attrition rate of old cars and the sales of new cars, it is possible to calculate the composition of the Swedish car fleet over time. Fig. 8.12 shows different groups of model years that were chosen to mark significant changes in the emissions regulation. For instance, in 1987 the first catalytic converters were introduced on a voluntary basis. In 1989, the three way catalytic converter became mandatory. Adding up all cars of model years from 1988 to present gives a good approximation for the number of cars equipped with catalytic converters ²⁵ [BIL: 1].

²⁵ spreadsheet: 1.24 million, real: 1.174 million (1992 data),
spreadsheet: 1.43 million, real: 1,328 million (1993 data)

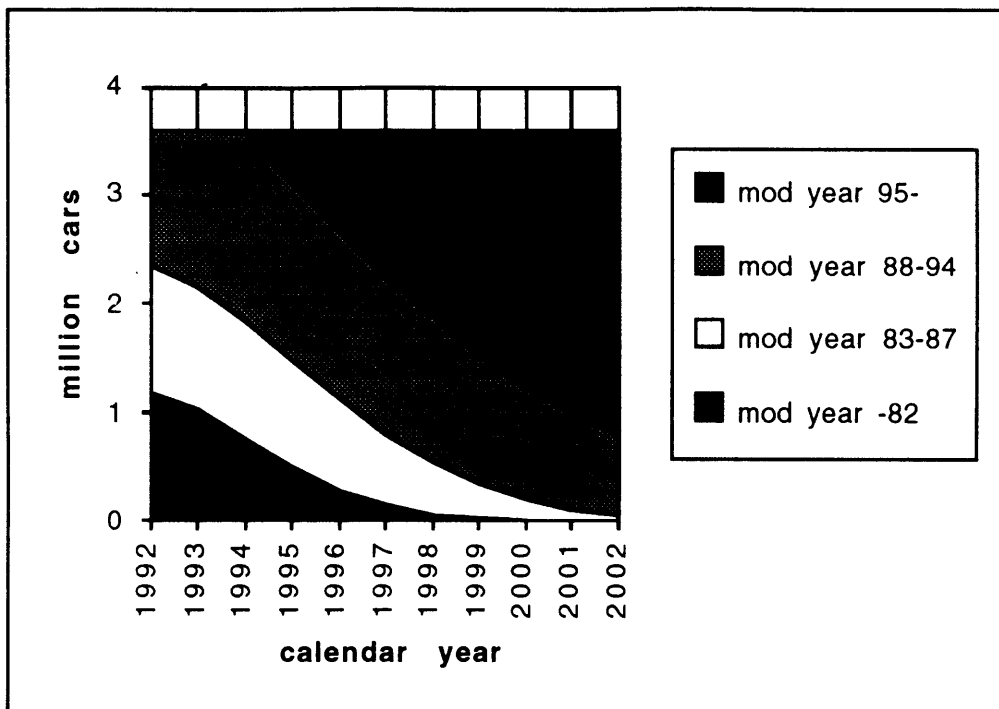


Fig. 8.12 Forecast of the composition of the Swedish car fleet

Statistical data on the average mileage of cars of different ages was provided by Svensk Bilprovning, the Swedish car test center. The data indicate the annual distance driven to be 20,000 km for cars up to three years old. Cars of four years of age are driven 13,000 km on average. This figure declines further with the age of the car and eventually reaches 7,000 km for cars 17 years old [all data by Ljungdahl].²⁶

From this, the annual mileage of individual cars can be calculated as a function of the model year and the calendar year. Multiplying this matrix with the number of cars in each model year gives the cumulative annual distance driven by all cars of one model year, or in one particular age group (figure 8.13).

²⁶ The average distance driven is around 6km [Norén 1993: 13]

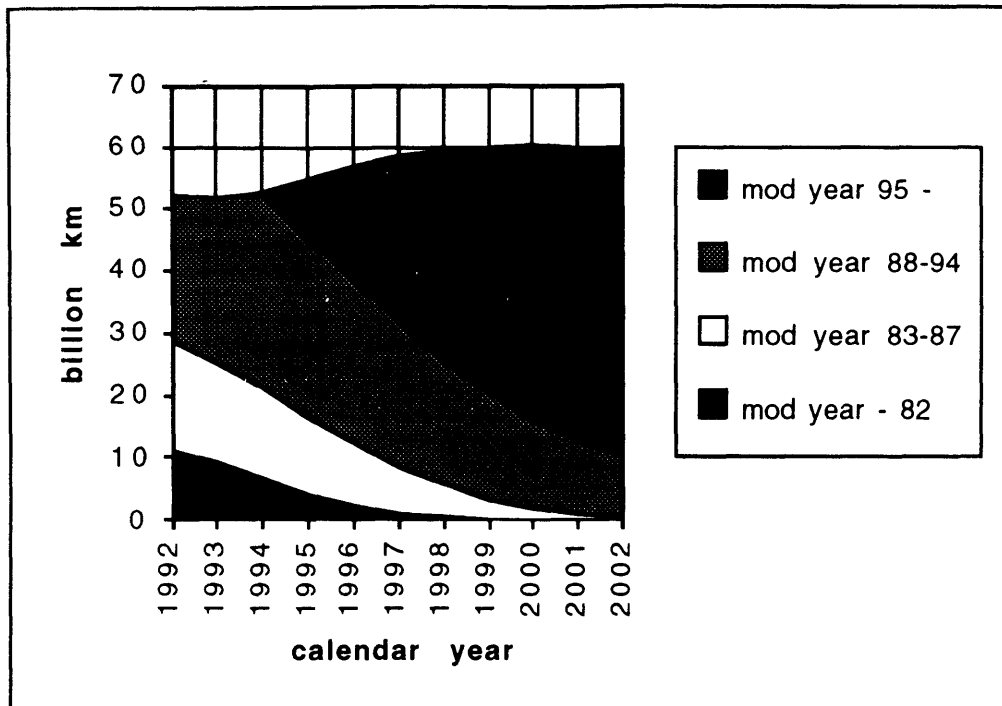


Fig. 8.13 "Raw" mileage of different groups of model years

As the average age of the car fleet decreases and as newer model years tend to register a higher mileage than older vehicles, the model forecasts an increasing total mileage for the Swedish car fleet. In reality, however, total distance driven has only increased very slightly.²⁷ As a first approximation, the model therefore assumes the total fleet mileage to remain at its 1992 level.

To achieve a constant fleet mileage with the model, the annual mileage of each car is adjusted by a correction factor (identical to all cars). This correction factor is computed as the ratio of the desired total fleet mileage (1992 fleet mileage) and the "raw" mileage. The result of this calculation is shown in figure 8.14.

²⁷ During the period between 1980 and 1992, the mean increase in traffic was 2% annually. In 1992, traffic increased only 1% [National Road Administration, quoted in BIL].

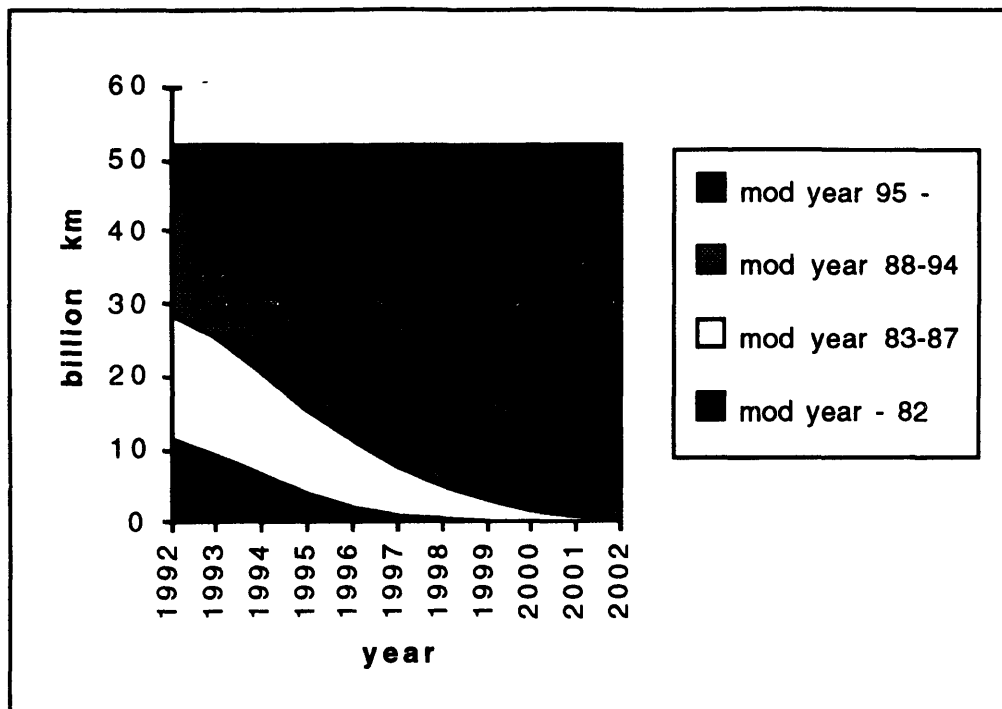


Fig. 8.14 Adjusted mileage of different groups of model years

The demarcation of age groups is defined by the introduction of state mandates for technologies and performance. In the years 1971 to 1982, exhaust gas recycling systems became commonplace. In the years 1983 to 1988, much stricter standards were enacted and the first voluntary catalytic converters came on the market, some of which were of the simple, unregulated type. Finally in 1989, regulated "three-way" catalytic converters became compulsory. As this analysis is being carried out in 1994/95, only cars of model years later than 1994 can be influenced technologically. The years 1969 to 1971 are added to the age groups 1972 to 1982.

The results of this spreadsheet are in agreement with statistical data showing that in 1993, about half of the total mileage can be attributed to cars with catalytic converters, which show in the diagram as the model years 1988 up to the present [BIL: 1]. The distribution is also consistent with the forecast of the Association of Swedish Automobile Manufacturers and Wholesalers, which predicts that in the year 2000, catalyst cars will account for 95% of the total mileage [BIL: 1].

8.3 Forecast of Emissions of Swedish Car Fleet

8.3.1 Present Emissions

Fig. 8.15 shows representative emissions of cars with and without catalytic converters. The numbers were compiled by the United Nations Environment Program, based on the Swedish Ministry of the Environment, the Swedish Road and Traffic Research Institute and Saab-SCANIA [Tolba: 409]. For completeness' sake, the energy use per km is indicated as well.

The emission standards for cars without catalytic converters (-1982) and with catalytic converters (1983-) are shown in brackets in figure 8.15. The emissions of carbon monoxide and hydrocarbons are significantly lower than the legal limits. However, the emissions of NO_x for cars without converters slightly exceed the standard. This is further evidence that reductions of this pollutant are of prime importance.

without special fuel	CO [g/km]	HC [g/km]	NO _x [g/km]	energy use [kWh/km]
car without converter	9.2 (24.2)	1.2 (2.1)	2.2 (1.9)	0.8
car with converter	0.6 (2.1)	0.08 (0.25)	0.1 (0.62)	0.8

Fig. 8.15 Representative emissions and energy use of cars with and without catalytic converters [Tolba: 409] in brackets: Swedish emission standards for cars with and without converters [MTC: 3]

8.3.2 Emissions with New Gasoline Blends

In the preceding section, the percentage reductions of different emissions were calculated for oxygenated gasoline and gasoline with a detergent additive. In the later case, there was a distinction made between clean and dirty valves. As valves can collect significant amounts of deposits after distances as short as 2000 miles (3200km) [Center], the emission reduction figures for dirty valves are assumed. This might overestimate the potential savings. Figure 8.16 and 8.17 show figures for the emissions per km driven that were later used in the spreadsheet FLEET FORECAST.

with 2.7 wt% oxygenates	CO [g/km]	HC [g/km]	NO _x [g/km]
car without converter	7.54	1.15	2.3
car with converter	0.51	0.08	0.11

Fig. 8.16 Expected emissions with the use of 15 vol% MTBE only (2.7 wt% oxygen)

with detergent only (dirty valves)	CO [g/km]	HC [g/km]	NO _x [g/km]
car without converter	8.63	0.96	1.75
car with converter	0.55	0.06	0.08

Fig. 8.17 Expected emissions with the use of inlet valve detergent only

8.3.3 No Action Scenario

Figures 8.18 to 8.20 were achieved with the help of the spreadsheet FLEET FORECAST. They show the expected temporal evolution of emissions if nothing is done, assuming that the total mileage remains constant. One sees that by the attrition of old cars alone, very substantial pollution savings are achieved over time. The emissions from modern cars with catalytic converters (model years 88 and younger) are relatively modest in comparison.

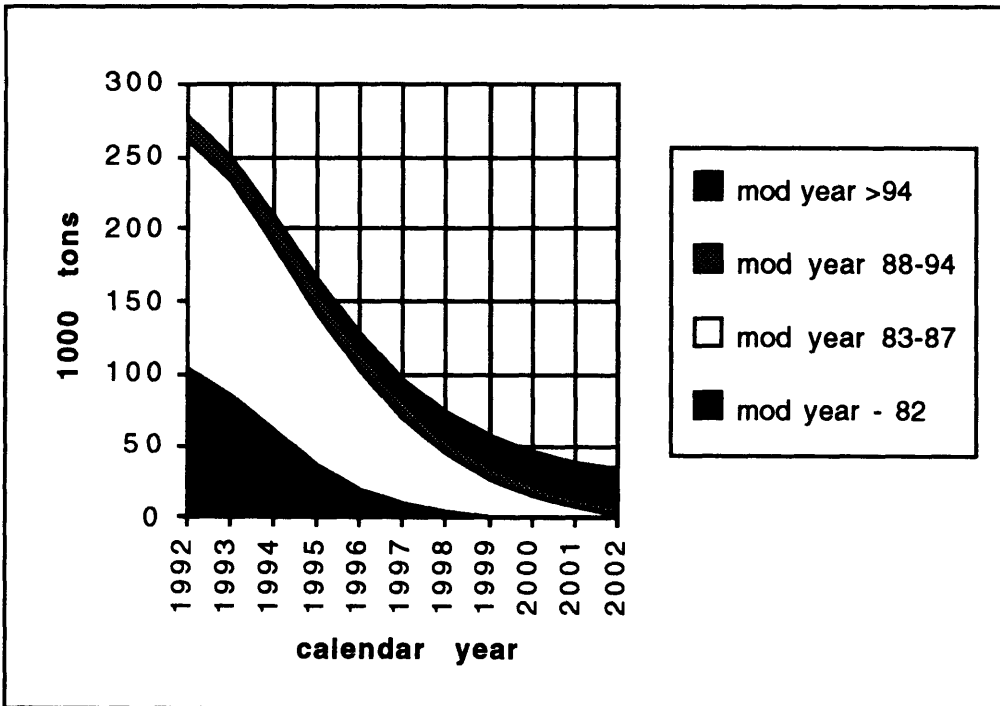


Fig. 8.18 No Action Scenario: emissions of CO over time

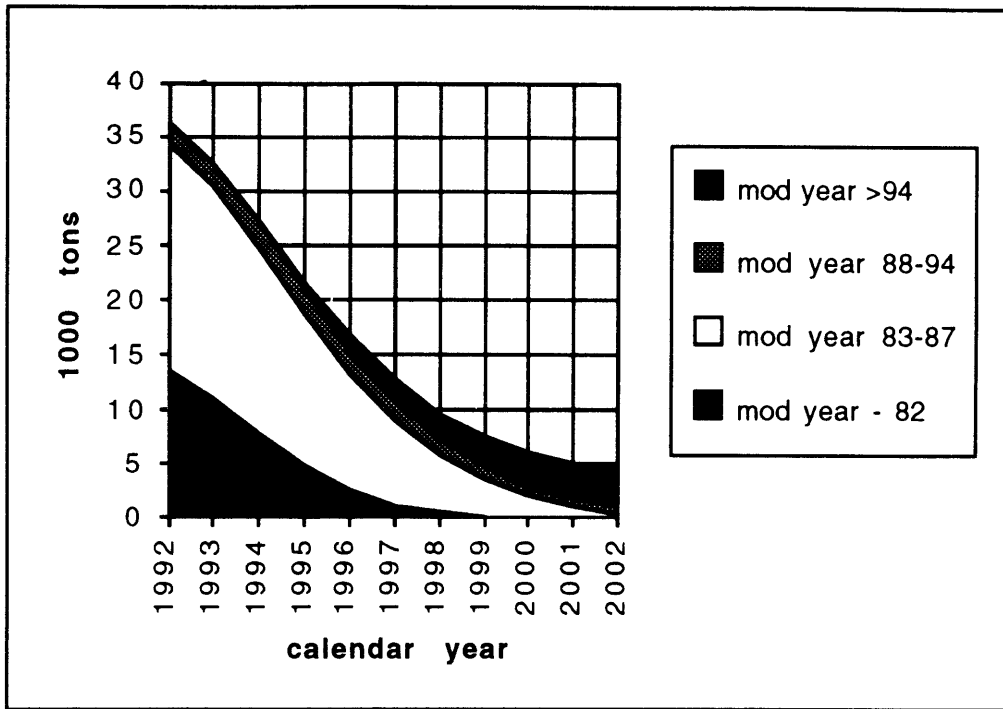


Fig. 8.19 No Action Scenario: emissions of HC over time

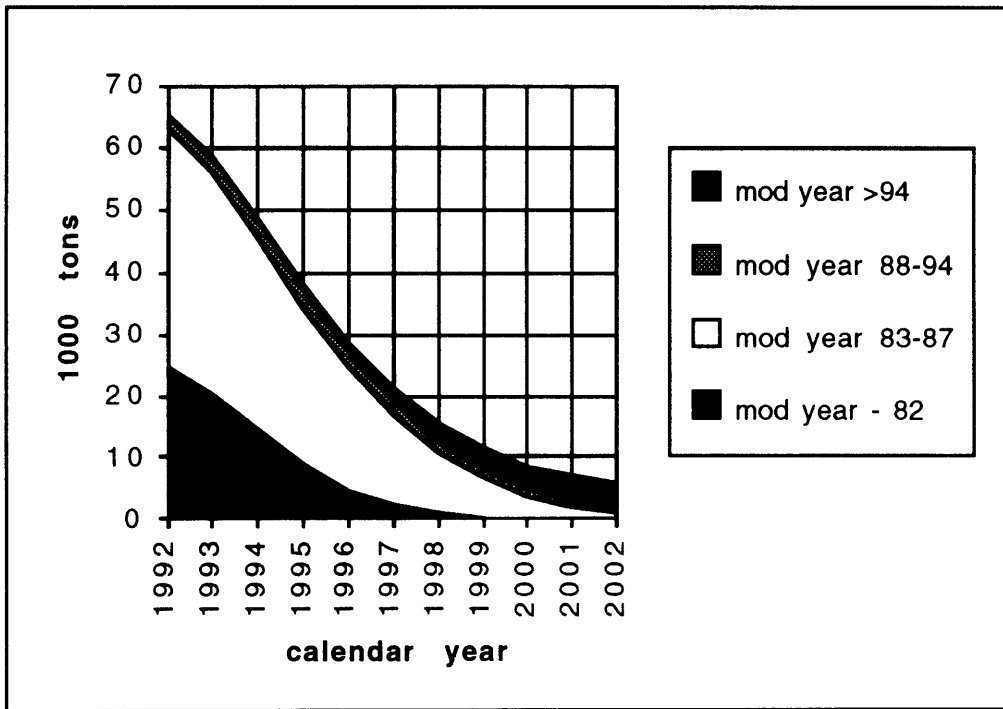


Fig. 8.20 No Action Scenario: emissions of NO_x over time

8.3.4 Oxygenated Gasoline Scenario

Figures 8.21 to 8.23 are based on the spreadsheet FLEET FORECAST. They depict the expected emission reduction over time if oxygenated gasoline is used (15 vol% MTBE). As the emissions of cars with catalytic converters are so low to begin with, pollution savings of CO and HC in this segment are almost negligible. Substantial savings can however be realized with older cars. This implies that the total emission reduction declines over time, when the old cars are phased out. There is a slight increase in NO_x emissions that also fades off with time.

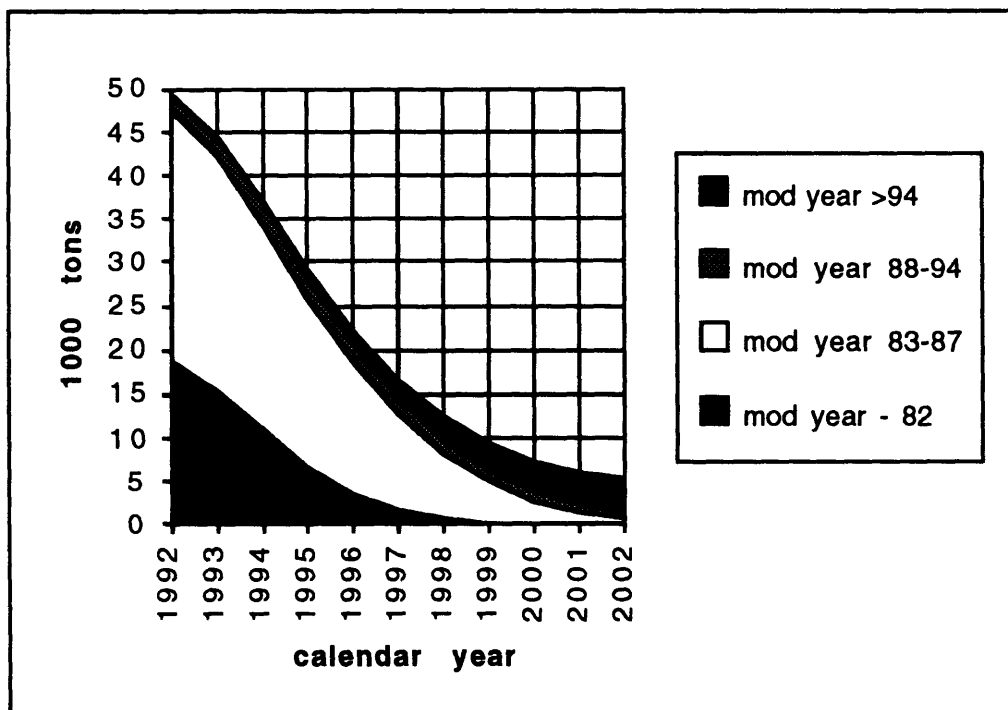


Fig. 8.21 Oxygenated Gasoline Scenario: expected reduction of CO emissions over time

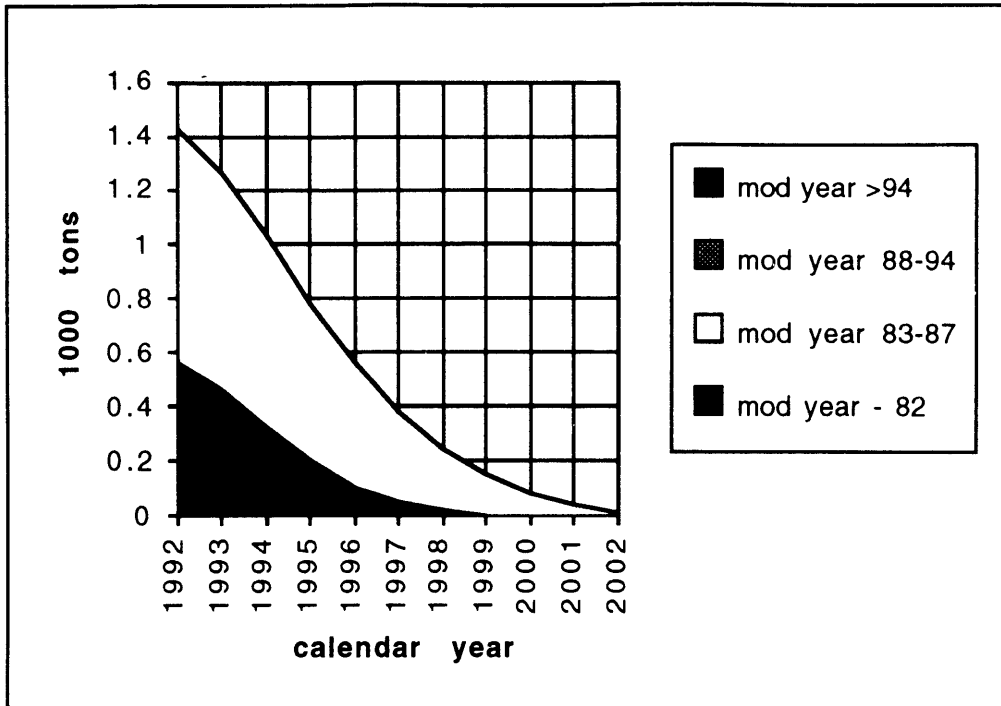


Fig. 8.22 Oxygenated Gasoline Scenario:
expected reduction of HC emissions over time

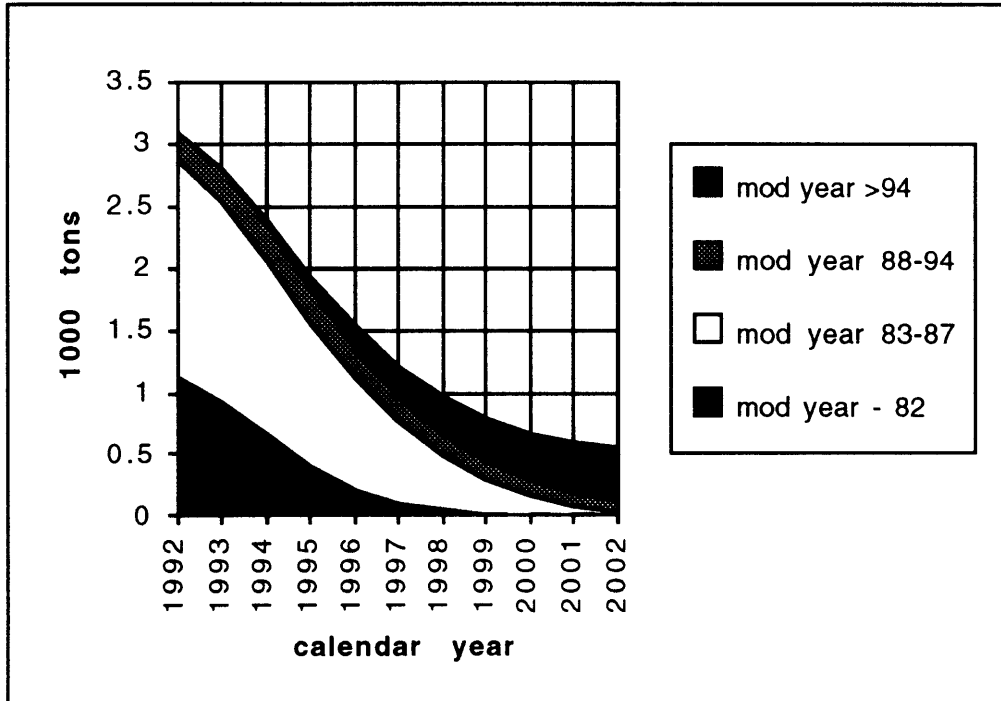


Fig. 8.23 Oxygenated Gasoline Scenario:
expected INCREASE of NO_x emissions over time

8.3.5 Detergent Gasoline Scenario

Figures 8.24 to 8.26 are derived from the spreadsheet FLEET FORECAST. They exhibit the expected emission reduction over time if an inlet valve detergent is used. There are reductions in all three categories of pollution. The temporal evolution resembles that for oxygenated fuels. The savings are relatively high in the beginning and then decline as more modern cars are introduced in the market.

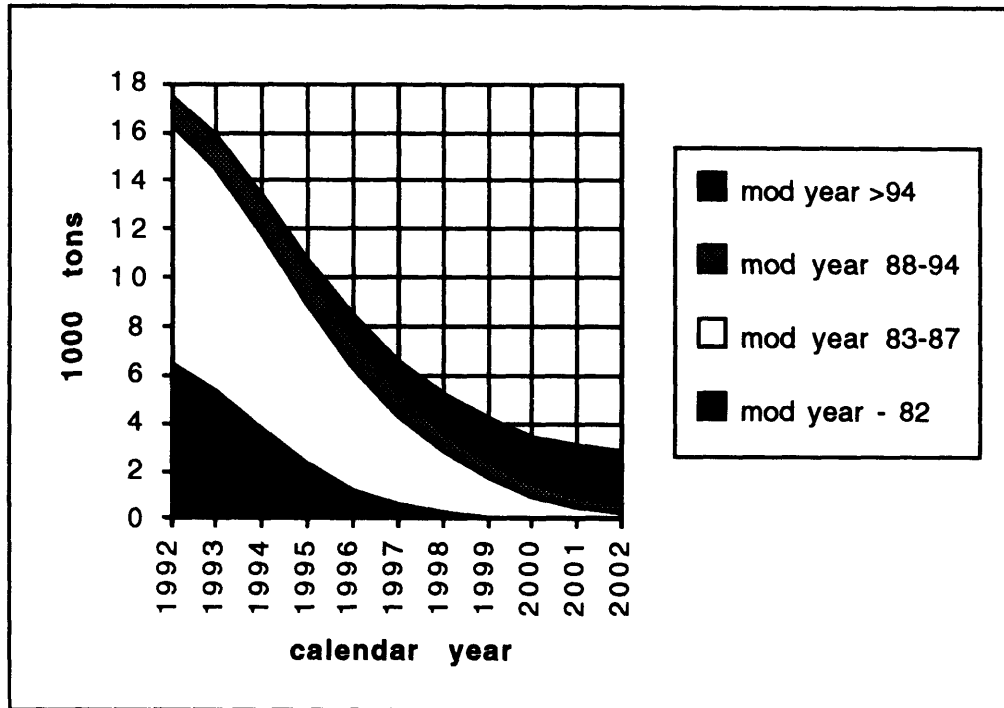


Fig. 8.24 Detergent Gasoline Scenario: expected reduction of CO emissions over time

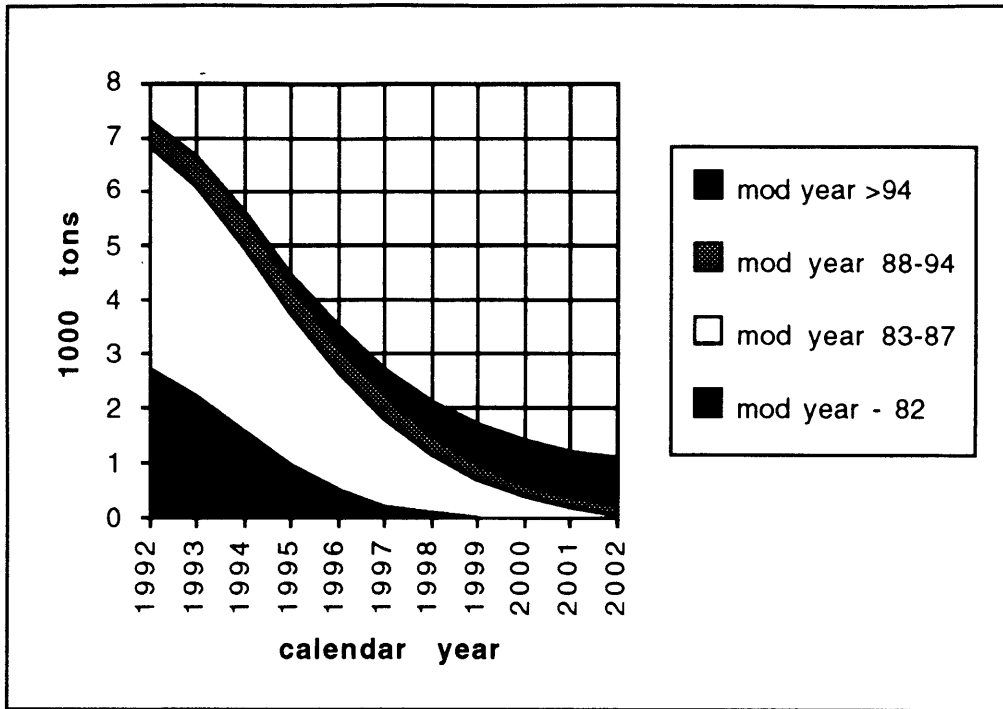


Fig. 8.25 Detergent Gasoline Scenario: expected reduction of HC emissions over time

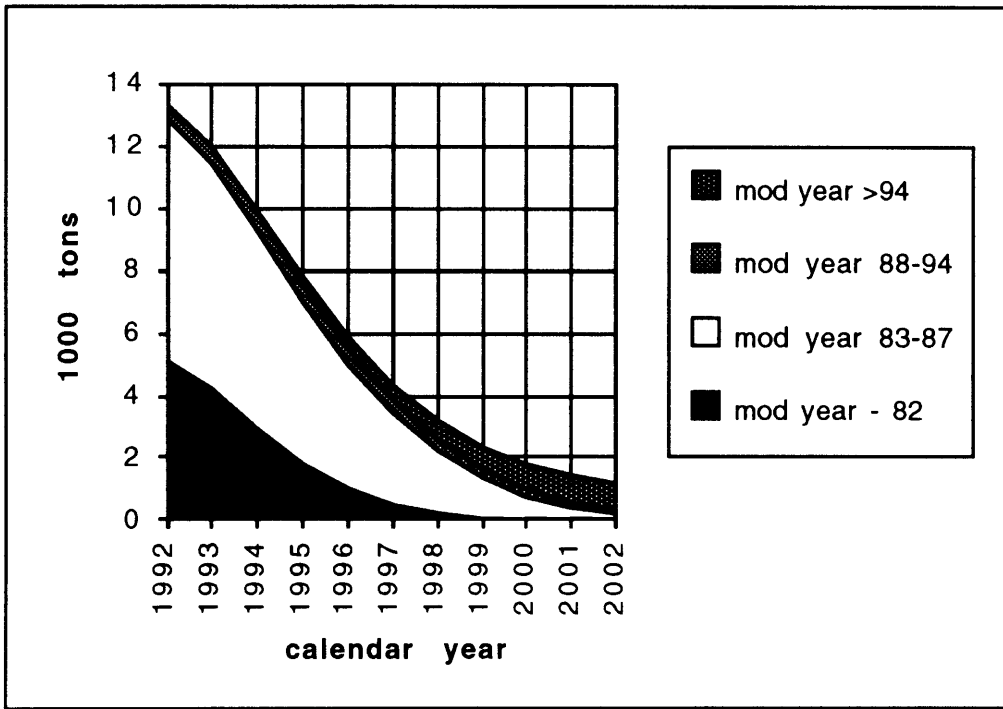


Fig. 8.26 Detergent Gasoline Scenario: expected reduction of NO_x emissions over time

8.4 Methodology of Policy Comparison

Most policies for pollution abatement result in emissions reductions that are a function of time with the type of pollutant being an additional parameter. Knowledge of the particular environmental problems of Sweden makes it possible to assign a relative importance to the different pollutants. However, it is not clear how pollution reductions that take place at different times can be compared.

A similar problem is known from economics, where payments made or received at different points in time have to be compared. This can be done by discounting future transactions. The government of Sweden uses a social discount rate of 7.25% annually to evaluate infrastructure investments [Odoni]. In this study, the same discount rate is used to determine the cost of the different pollution abatement measures.

Emissions harm the environment. The damage from pollution could be expressed in monetary terms. Once the monetary value has been established, it would be discounted to the present to compare the savings from different abatement measures. However, as environmental accounting is only emerging as a field, it is difficult to come up with a dollar figure for the value of cleaner air. Another approach is to discount the emissions figures themselves. The only assumption needed is that the damages of pollution are linearly proportional to the amount of pollution.²⁸

Not discounting pollution reductions means that reductions are valued identically, no matter when they take place. However, as the costs for abatement measures are still discounted, the logical consequence of such a scheme is to procrastinate all efforts.

In order to allow an unbiased comparison between costs and benefits, the social discount rate of 7.25% is therefore applied to the costs of emissions reduction programs as well as to the reductions themselves.

²⁸ This is not self evident, especially in the case of the ozone precursors HC and NO_x

8.5 Introduction of Catalytic Converter as a Reference Policy

In order to determine a reference point for the cost efficiency of emission reductions, it is helpful to analyze policies that have already been implemented. So far, the most drastic step to curb automotive emissions has been the introduction of the catalytic converter, which in the case of Sweden occurred in 1989. The emission rates with and without catalytic converter are compared in figure 8.27.

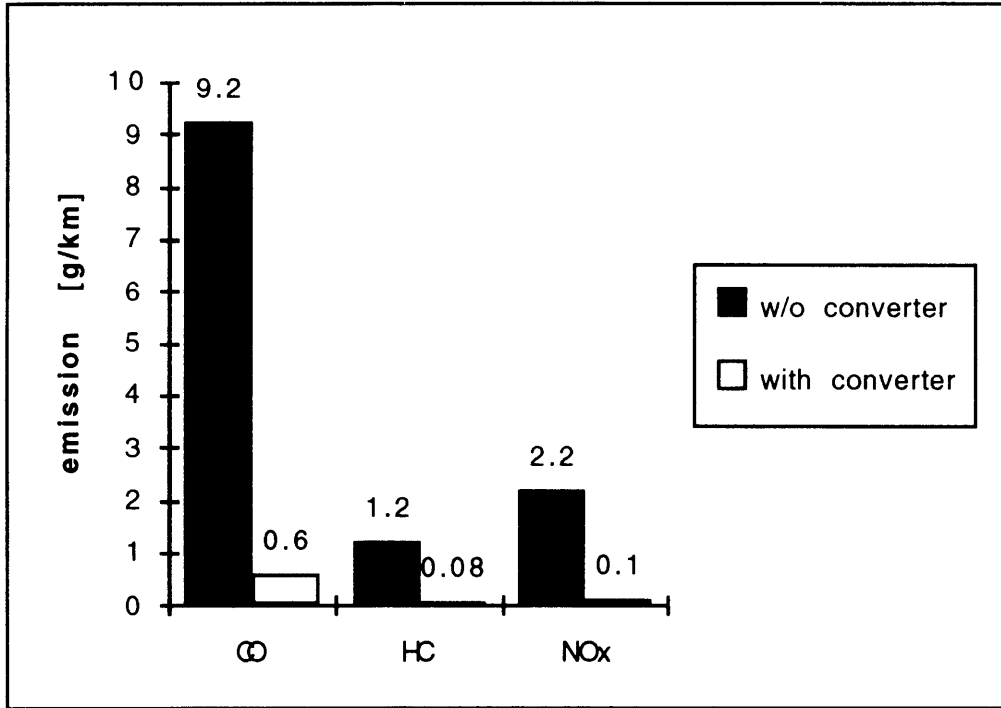


Fig. 8.27 Emissions of cars without and with catalytic converter [Mansson]

Based on the data on distance driven and average age²⁹, one can derive the temporal evolution of the emission savings. In figure 8.28, these savings are added up (discount rate 0%). However, as pollution reductions in the present are more valuable than the prospect of future reductions, the savings can also be added up, using a discount rate. This procedure corresponds to the calculation of the net present value of financial transactions expected in the future. Three discount rates (5, 7.25 and 10%) are included in figure 8.28.

²⁹ in [BIL], respectively derived in the spreadsheet "present car fleet"

discount rate	pollution reductions by catalytic converter [kg]		
	CO	HC	NO _x
0% (simple sum)	1353	176	330
5%	1140	148	278
7.25 %	1063	139	260
10%	982	128	240

Fig. 8.28 Pollution reductions by catalytic converters as a function of discount rate

Figure 8.29 shows the reductions per invested dollar if \$500 is assumed to be the cost of a catalytic converter. This is probably a high estimate.

discount rate	pollution reductions by catalytic converter [kg/\$]		
	CO	HC	NO _x
0% (simple sum)	2.71	0.35	0.66
5%	2.28	0.30	0.56
7.25 %	2.13	0.28	0.52
10%	1.96	0.26	0.48

Fig. 8.29 Pollution reduction with catalytic converter per dollar invested

8.6 Comparison of Oxygenated Gasoline and Detergent Gasoline

8.6.1 Comparison in Terms of Emission Reductions

The following sets of diagrams show the emissions reductions of oxygenated gasoline (15 vol% MTBE, i.e. 2.7 wt% oxygen - figures 8.30 to 8.32) and gasoline with additives (figures 8.33 to 8.35, discounted to the year 1995). The figures are cumulative, meaning that all reductions to the respective calendar year have been added up.

Two effects explain the flattening out of the curves. First, the absolute amount of emissions reductions declines as more modern cars are introduced to the fleet. Second, the long term emissions reductions are not valued as highly as short term emissions reductions.

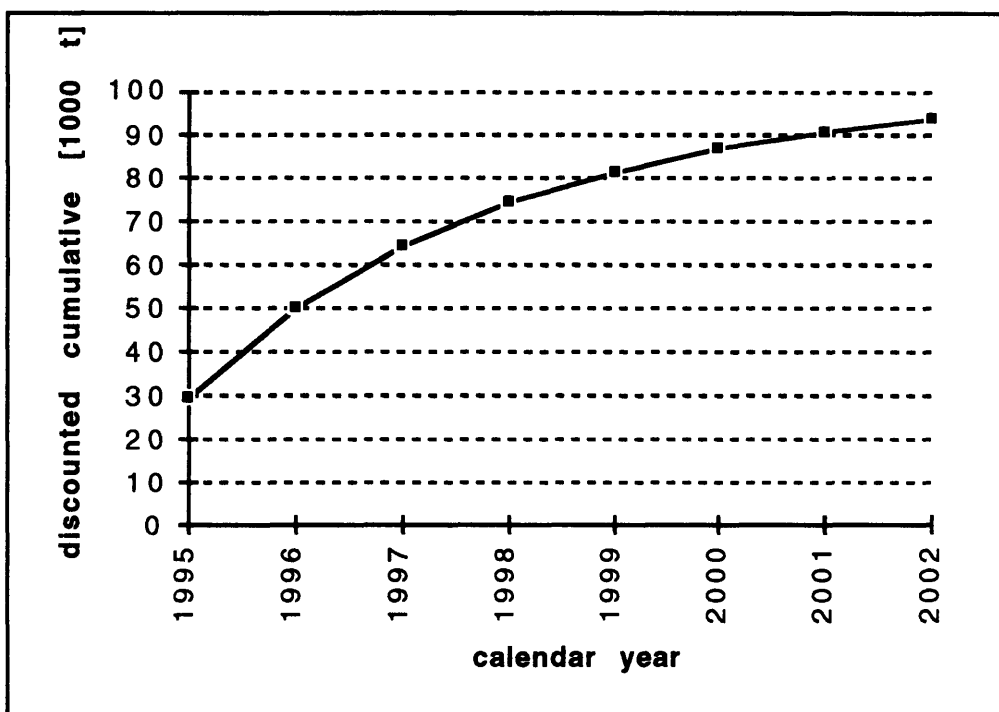


Fig. 8.30 Oxygenated Fuel Scenario:
Cumulative reductions of CO, discounted to 1995

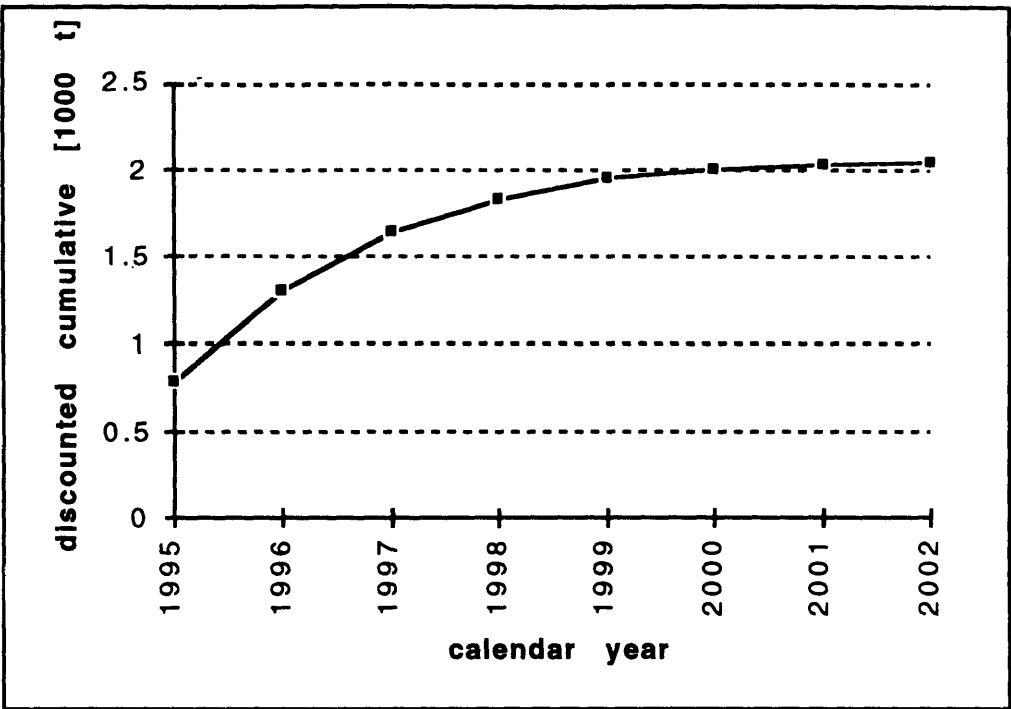


Fig. 8.31 Oxygenated Fuel Scenario:
Cumulative reductions of HC, discounted to 1995

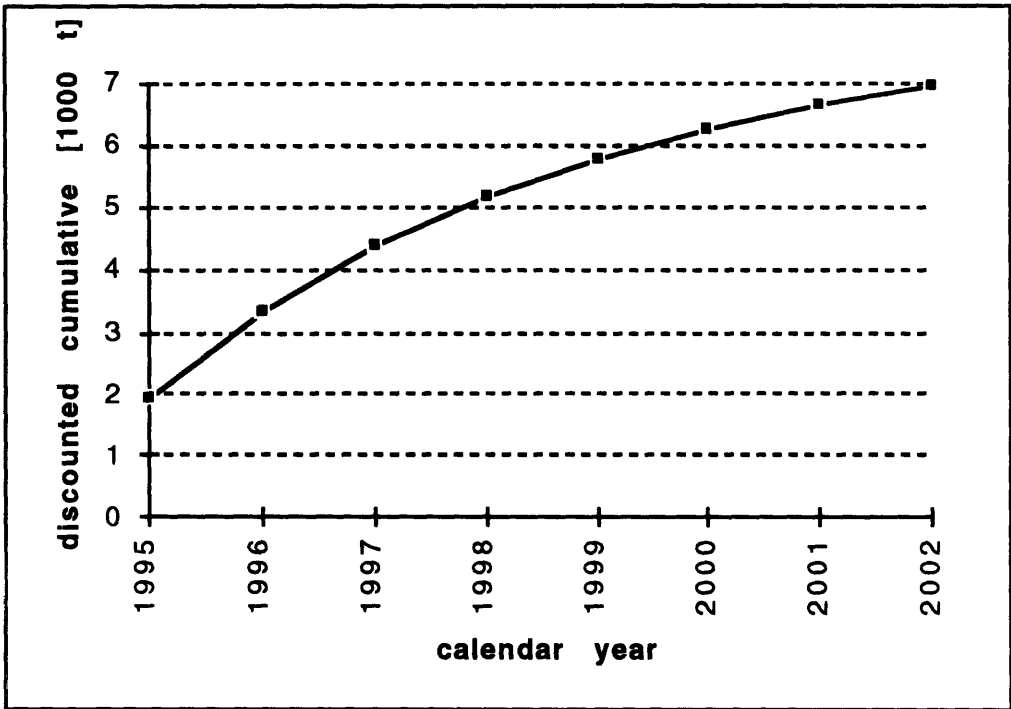


Fig. 8.32 Oxygenated Gasoline Scenario:
cumulative INCREASES of NO_x, discounted to 1995

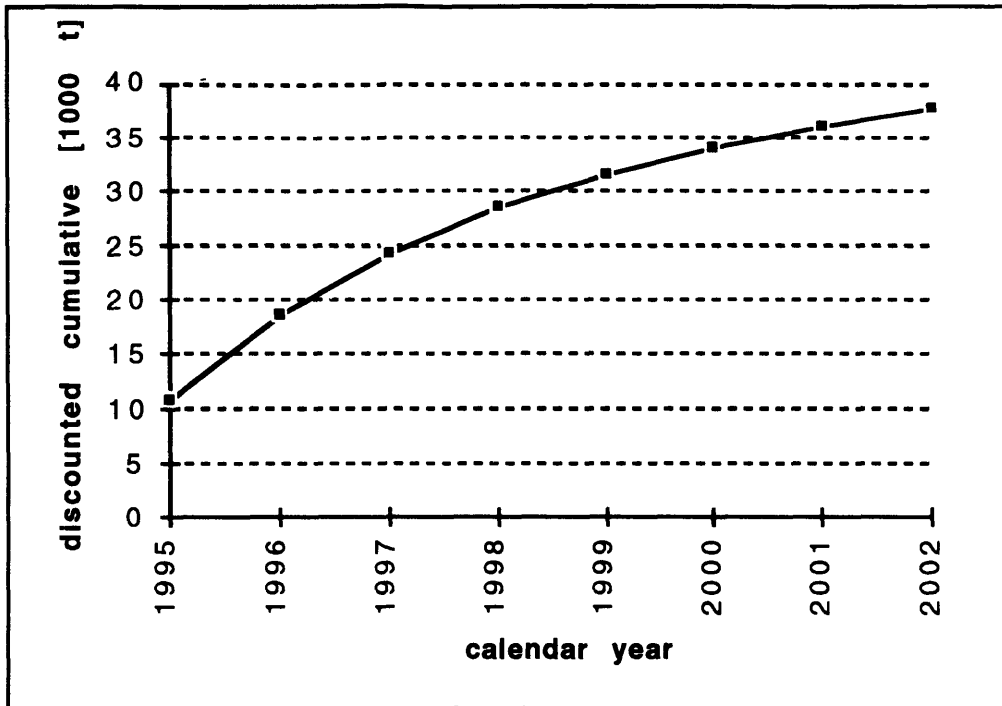


Fig. 8.33 Detergent Gasoline Scenario:
Cumulative reductions of CO, discounted to 1995

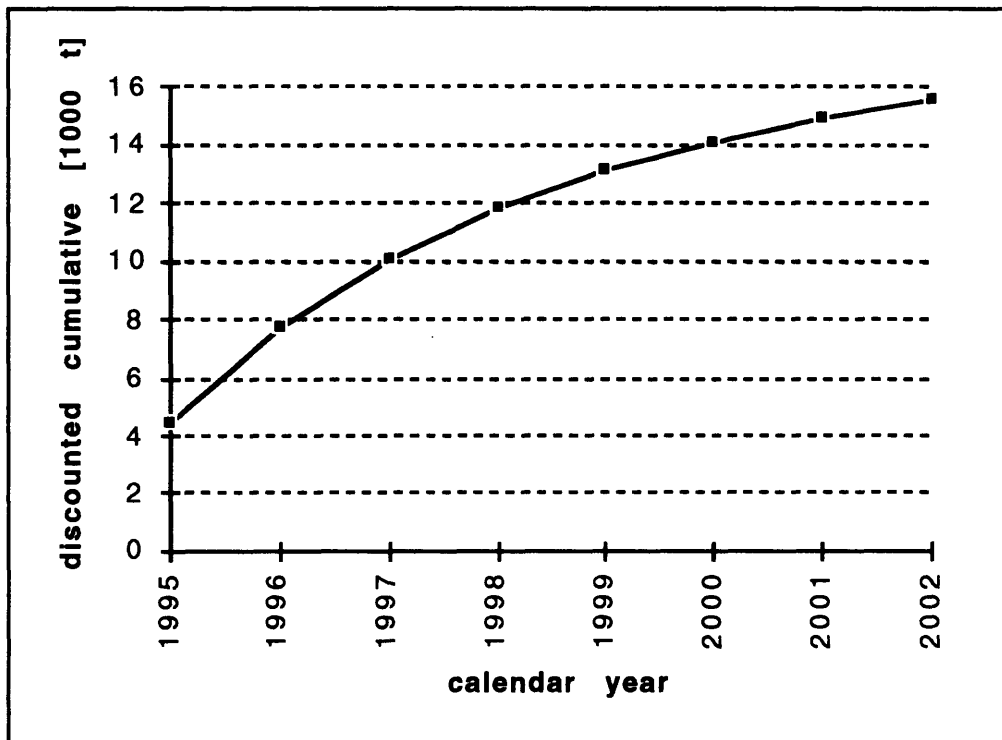


Fig. 8.34 Detergent Gasoline Scenario:
Cumulative reductions of HC, discounted to 1995

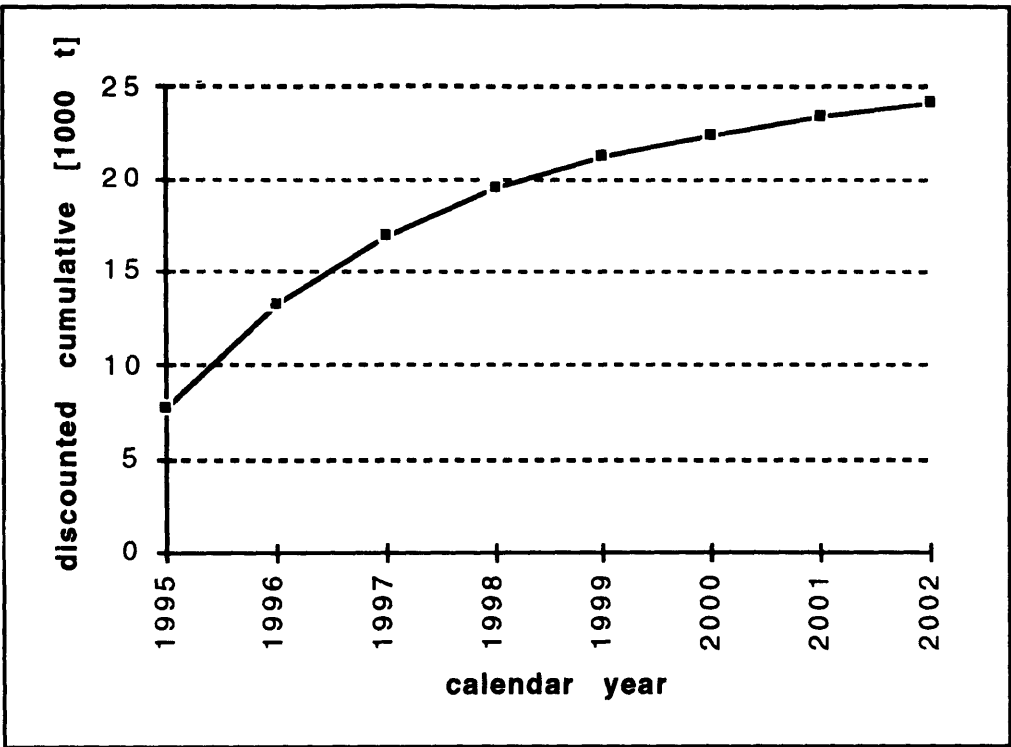


Fig. 8.35 Detergent Gasoline Scenario:
Cumulative reductions of HC, discounted to 1995

8.6.2 Comparison in Terms of Costs

Obviously the costs of the two fuel programs are related to the total fuel consumption. The fuel consumption of the Swedish car fleet ranges between 8 and 9 l/100 km, which translates to 28 mi/gal [BIL: 35]. This is lower than the average fuel consumption for Western Europe (9.5 l/100 km), but higher than the fuel consumption of other Nordic countries, such as Denmark (7.5 l/100 km) [Tolba: 413].

Past data indicate a slight increase in fuel efficiency [Tolba: 413]. The cost calculations are therefore based on the fuel consumption figures listed in figure 8.36. The values lead to an average fuel consumption of the Swedish car fleet of 8.8 l/100 km for the year 1992.

model years	fuel consumption [l/100 km]
1982 and older	10
1983 to 1987	9
1988 to 1994	8
1995 and younger	7

Fig. 8.36 Fuel consumption figures, based on [BIL: 35]

In the Colorado oxygenated fuel program, the price of gasoline increased by 0.67 ¢/gal [Gallagher: 306], which translates into 0.18 ¢/l. However, the oil companies assumed 40% of the total cost themselves [Gallagher: 306] so that a more realistic estimate of the true cost to society ranges around 0.3 ¢/l. The additional cost of a liter of gasoline with a detergent has been estimated at about 0.05 ¢ [Center].

All prices are assumed to be constant in terms of 1995 dollars. Inflation is therefore not explicitly considered.

Figure 8.37 shows the estimated discounted cost of the two fuel programs. As in the case of the diagrams on the pollution reduction, the figures are cumulative. This means that the yearly costs have been discounted and summed up to the respective calendar year.

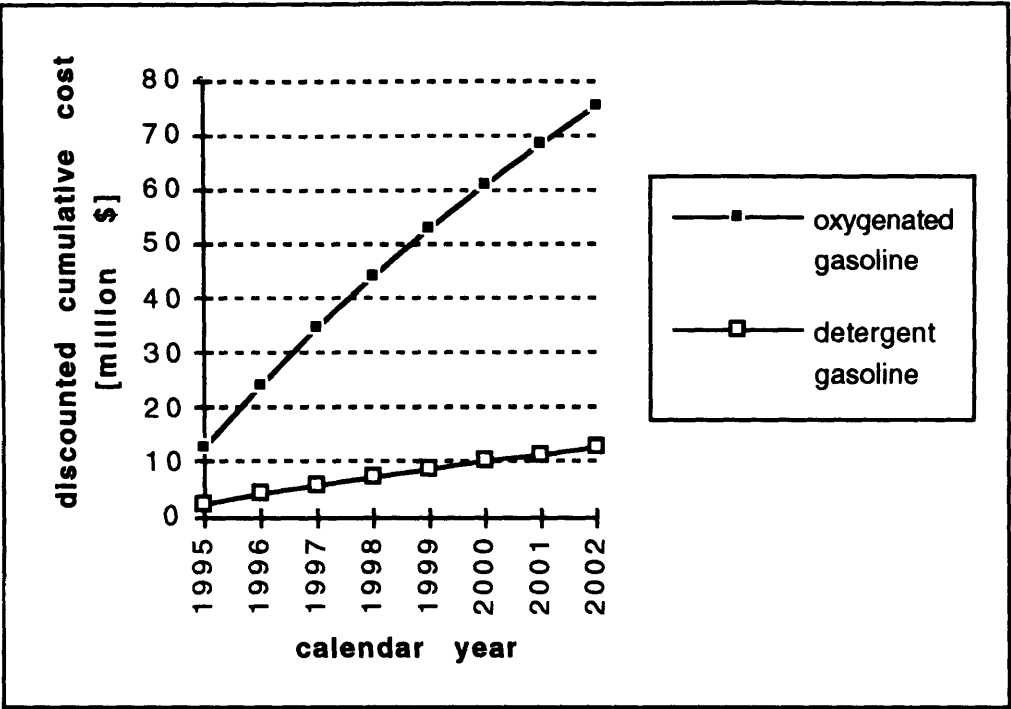


Fig. 8.37 Cumulative costs of oxygenated gasoline scenario and detergent gasoline scenario, discounted to 1995

8.6.3 Comparison in Terms of Cost Effectiveness

As the additional cost of a liter of fuel enters linearly in both cost estimates, the cost of the oxygenated fuel program is always approximately six times as high as the cost of the fuel program based on a detergent. The curves differ from the emission reduction curves in that they do not flatten out. It is therefore probable that a point in time exists for either fuel program when the costs outweigh the benefits.

In order to estimate the useful life span of a fuel program, one divides the (discounted) pollution savings by the (discounted) costs. The ratio then determines the *cost effectiveness* of a measure. This has been done in figure 8.38 and 8.39. As expected, the cost effectiveness of both fuel programs declines with time.

Both sets of curves can be compared with the cost effectiveness of a catalytic converter. For a discount rate of 7.25%, this is 2.13 kg of CO, 0.28 kg of HC, and 0.52 kg of NO_x per dollar invested. As all costs are incurred at the beginning, but the benefits are spread out over the life time of the converter, a lower discount rate tends to increase its cost effectiveness (see figure 8.29, in prior section).

In the case of gasoline programs, costs and benefits accrue continuously. For this reason, the cost effectiveness figures depend only very little on the discount rate chosen. Applying a discount rate of 10% instead of 7.25% results in a slightly higher cost effectiveness (+2.5%). Conversely, reducing the discount rate to 5% produces a marginally lower cost effectiveness (-2.5%). This holds true for both programs and all three pollutants.

For every pollutant, the gasoline with a detergent is more cost effective than oxygenated gasoline. In the Swedish car fleet there already is a substantial share of vehicles equipped with catalytic converters. As shown, this tends to reduce the cost effectiveness of fuel programs. Still, the introduction of a detergent in 1995 or 1996 would be more cost effective than the introduction of catalytic converters was in 1988.

On the other hand, the introduction of a detergent offers only very small pollution savings in absolute terms, compared to catalytic converters or oxygenated fuel (in the case of carbon monoxide).

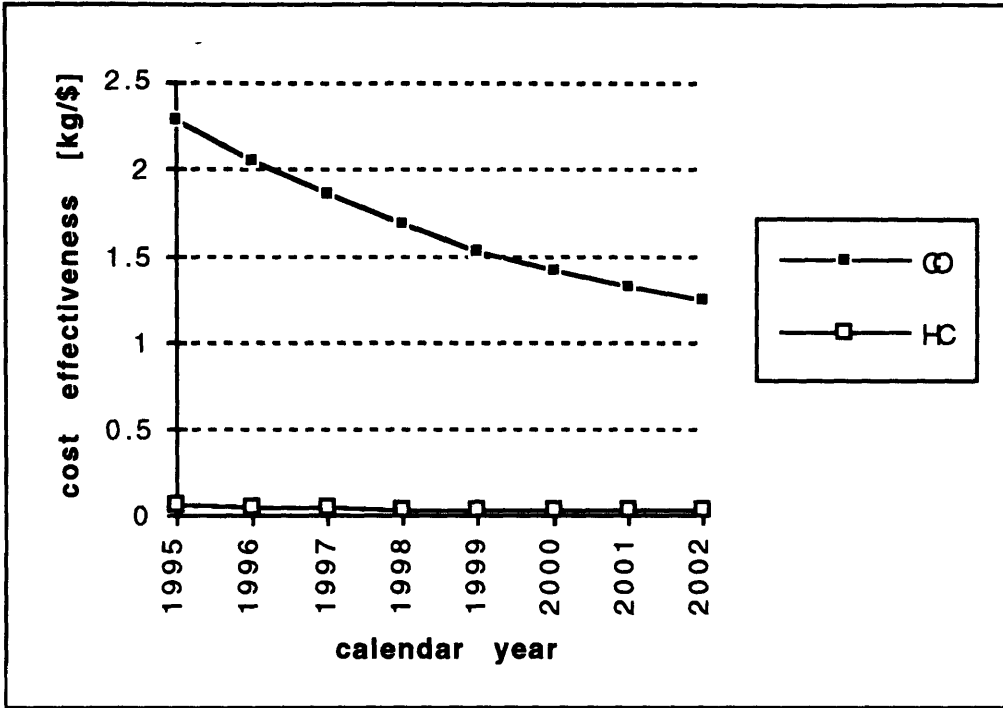


Fig. 8.38 Cost effectiveness of oxygenated gasoline (NO_x is not included as it slightly increases)

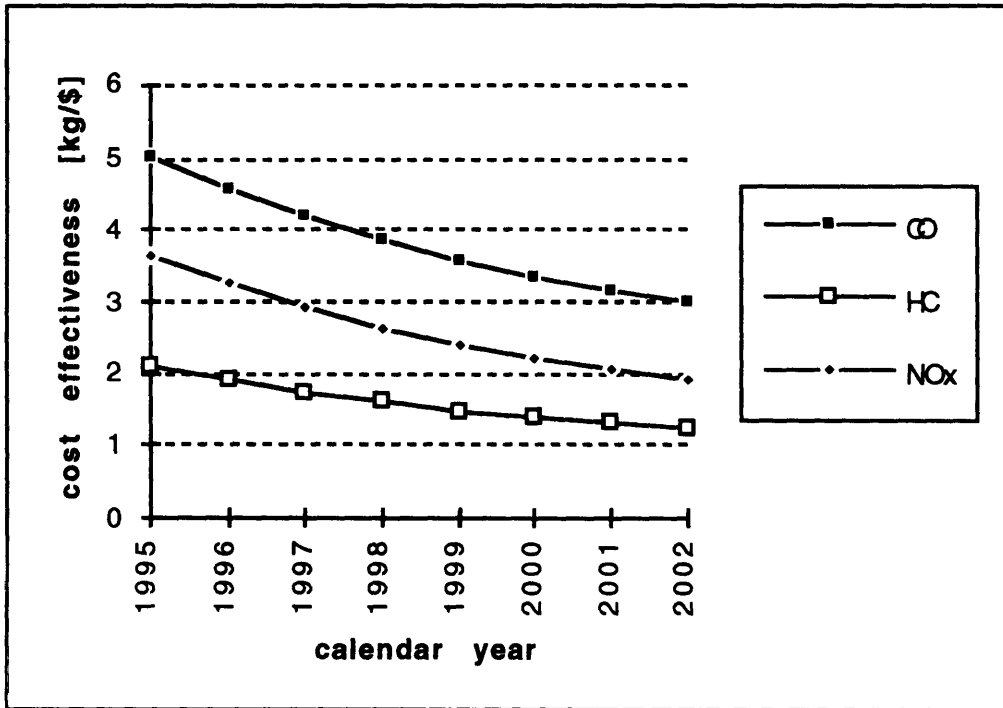


Fig. 8.39 Cost effectiveness of detergent gasoline

8.7 Alternatives

The spreadsheet FLEET FORECAST permits the manipulation of other variables that influence total emissions. It has been suggested to buy up old cars for scrapping them ('buy back program'). They would then be replaced with modern, cleaner cars. It is also possible to promote car pooling and public transportation. Such policy measures could lead to changes of the driving pattern and thus to diminished pollution.

8.7.1 Buy Back Program

It was assumed that in 1995, the buy back program removes all cars of a certain age. Obviously, this instant and thorough effect is a very optimistic assumption. Figure 8.42 compares the total discounted emission reductions of two buy back programs with the reductions by changing the gasoline blend. The figures were achieved using the spreadsheet FLEET FORECAST with a discount rate of 7.25%.

A buy back of model year 1977 and older would involve 142,000 cars. If all model year up to and including 1980 were bought up, this would affect 321,000 cars. With a conservative estimate of \$500 as the cost per car, the programs would cost \$71 million and \$161 million respectively. The fuel programs, on the other hand would cost \$76 million (oxygenated gasoline) and \$12 million (detergent gasoline). However, the costs of a buy back program would accrue to the state, as opposed to the cost of a fuel program which would be borne by the consumer.

Compared to the introduction of a detergent additive, a buy back program that includes all model year 1980 and older would save only half the amount of the most critical emissions HC and NO_x, and about the same amount of CO. On the other hand, the buy back program would cost more than ten times as much.

The presented emissions reductions of a buy back program are somewhat understated as the degenerative inefficiencies of old cars are not taken into account. Nevertheless, it is quite clear that buy back programs have a very limited impact. They affect only a small fraction of the car fleet (in the above examples, 4% and 9% respectively). Furthermore, old cars naturally leave the car fleet through attrition. Replacing them therefore produces only a short term benefit. The short term nature of buy back programs becomes clearer when looking at emission savings over time (figure 8.40).

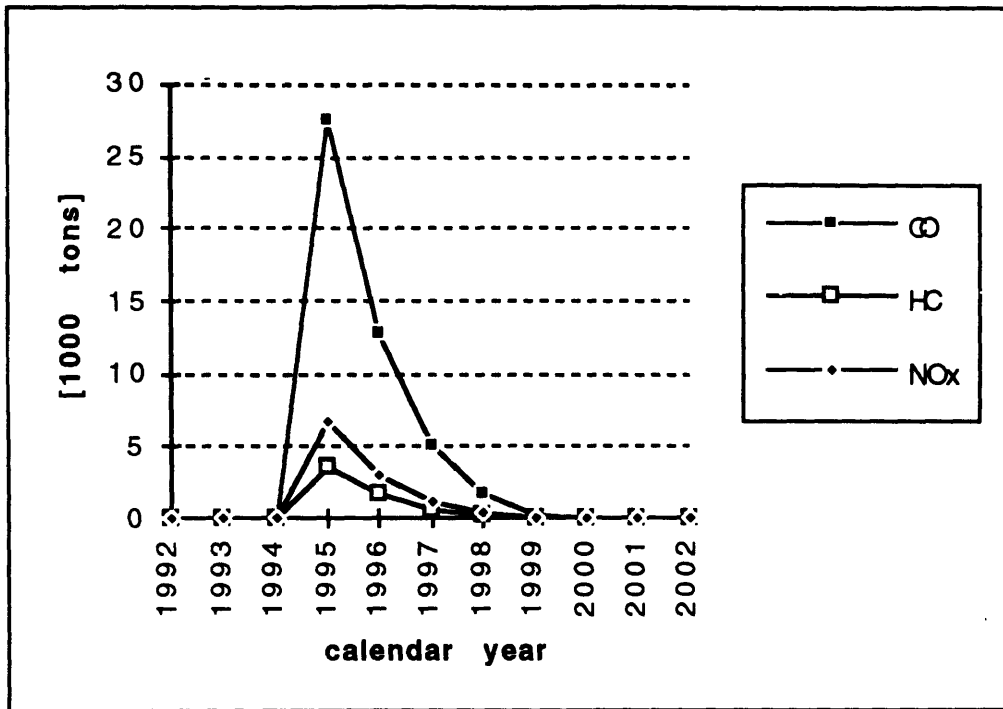


Fig. 8.40 Buy back of model years 1980 and older: pollution savings over time

8.7.2 Changes of Driving Pattern

It was assumed that starting in 1995, the total distance driven by the Swedish car fleet would decrease by certain percentage annually. Implicit in the assumption is that this policy affects all cars evenly. Figure 8.41 shows the cumulative savings over the period 1995 to 2002, discounted at 7.25% to the year 1995. The figures were determined using the spreadsheet "car fleet, future."

In the initial two or three years, the annual savings increase as the mileage continues to drop. In subsequent years, new and cleaner cars are introduced into the fleet that already have reduced the emissions per mile, so that any reduction of the mileage can produce less savings. The annual savings therefore remain approximately constant over time (figure 8.41). If the time horizon was increased beyond 2002, continued reductions of the total mileage would therefore be even more attractive.

The temporal evolution of the additional emissions caused by an increase in fleet mileage is very similar to the one shown for a mileage reduction in figure 8.41. As a result, the absolute amount of additional pollution caused by a 2% increase in the annual mileage, is approximately equal to the savings of a 2% reduction of annual mileage (figure 8.42).

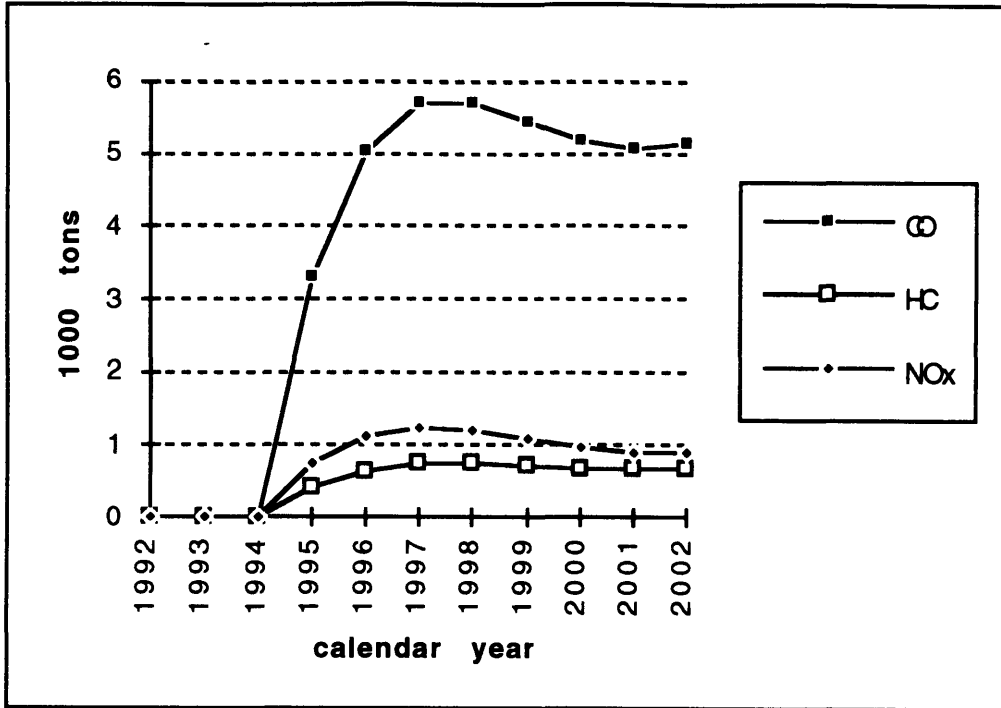


Fig. 8.41 Annual mileage reduction of 2%: pollution savings over time

	CO	HC	NO _x	cost
unit	[1000 t]			[\$ million]
oxygenated gasoline	94	2	-7 ³⁰	76
detergent gasoline	38	16	24	12
buy back of mod. years 1977 and older	18	2	4	71
buy back of mod. years 1980 and older	45	6	11	161
annual mileage reduction of 2%	32	4	6	?
annual mileage reduction of 5%	76	10	16	?
annual mileage INCREASE of 2%	-34	-5	-7	?

Fig. 8.42 Cumulative emission reductions of different policies, discounted to 1995

³⁰ NO_x increases

8.8 Comparison with Swedish Emission Targets

The Swedish government set objectives of the reduction of various pollutants in the road transportation sector. Hydrocarbon emissions are supposed to be reduced by 70% between 1988 and 2000, emissions of NO_x should be cut by 50% between 1980 and 1995 [Norén 1993: 7].

In order to establish the emissions of hydrocarbons in the reference year, the 1992 and 1993 data in the spreadsheet FLEET FORECAST was linearly extrapolated. The emission of hydrocarbons by cars in the year 1988 was thus estimated as 15 000 t. This figure is probably somewhat too high as the pollution savings prior to 1993 are smaller than those in later years.

Assuming that all modes of transportation will have to equally contribute to emissions reductions, cars in the year 2000 would be allowed to emit no more than 4,500 t of hydrocarbons. This is 1,500 t less than what the spreadsheet FLEET FORECAST predicts for the no action scenario.

A detergent additive would save 1,400 t of HC, almost fulfilling the requirement. If started in 1995, reducing the mileage by 2% annually would save 720 t, implementing an oxygenated fuel program would save 80 t. The impact of either buy back program is negligible.

According to figures provided by Naturvårdsverket, emissions of NO_x were 13% higher in 1980 than in 1992 ³¹[Andersson]. This translates into 73,600 t in the year 1980 so that emissions in 1995 would have to be limited to 36,800 t.

The spreadsheet FLEET FORECAST predicts slightly higher emissions for 1995, but by 1996, NO_x emissions will pass the threshold, even if no measures are taken. Introduction of detergent additives or a buy back scheme could speed up the compliance. Mileage reductions would produce no measurable effect in the short run, and oxygenated fuel would even lead to a slight increase of NO_x emissions.

³¹ This refers to passenger cars only.

9. Conclusions

The Swedish EPA has reached a point in time where strategy and priorities rather than absolute emissions reductions guide policy formulation for air quality. In 1989, the introduction of the three-way catalytic converter began chiseling all pollutants from the air - CO, HC, NO_x - in substantial volumes. The cost/benefit ratio stood out as incontestably effective. Pollution declined by more than a factor of ten at a cost of approximately \$500 per car or less than \$50 per year amortized over a ten year car life. Between 1995 and 2002, such uniform, inexpensive, and one time results in air pollution remain elusive. Policy makers must now confront choices among pollutants to be restricted and the amount the Swedish population is willing to pay for these reductions.

Two alternatives hold themselves out as unworthy candidates for immediate consideration as a single measure of improving air quality: buy back programs, and alterations in driving habits. These alternatives, measured in absolute reduction of pollutants and cost/benefit hardly compare with the short-term salubrious outcomes from changes in fuel technologies with oxygenated or detergent gasolines.

The choice between the two fuel alternatives - oxygenate or detergent - invokes the need for devising policy strategies that mirror the priorities and preferences of the Swedish people. While policy makers struggle to gauge the choices for public welfare with lingering doubts about costs, health, environmental decay, and long-term outcomes, the analysis does provide definitive choices for policy makers.

Oxygenated gasoline can substantially decrease the emissions of carbon monoxide. In doing so, it leads to increases in NO_x emissions, which in turn aggravate one of foremost concerns in Sweden, acid rain. Other detractions accompany reformulated gasoline. The fuel poses logistical problems with storage. Overall, oxygenated gasoline seems a costly way to achieve reductions in CO emissions, while flouting other expressed anxieties of Swedish policy makers.

While gasoline with a detergent stems carbon monoxide emissions by a lesser amount than oxygenated fuel, it can significantly curtail emissions of carbon monoxide, hydrocarbons and nitrous oxides. Other attributes recommend detergent gasoline. Additives, blended at the refinery, require no changes in the infrastructure. Emission reductions through a detergent additive cost substantially less than oxygenated fuel. For a given investment, detergent gasoline registers at least twice the pollution savings of oxygenated fuel.

With emissions of nitrous oxides a prime concern for the Swedish government, oxygenated gasoline falters as a conclusive choice. Instead, as catalytic converters spread throughout the Swedish automobile fleet, the usage of detergent gasoline can serve as an effective, economical transitory fuel to contain pollution from aging cars without converters.

In the long run, improvements in the internal combustion engine or innovations in engine technologies with non-gasoline fuels will accomplish clean air standards of the future. Perhaps, automobiles with natural gas will flourish or fuel cells powered by hydrogen will substitute for hydrocarbons. Biologically produced alcohol has received relatively little attention, despite some signs of a paradigm shift in Western Europe and especially Sweden. By avoiding carbon dioxide emissions, alcohols avert contributing to the greenhouse effect.

Other technologies and policies may foster air quality in indirect ways. Telecommuting or improved mass transit may promote modifications in driving habits.

Until the coming of these halcyon days, improvements in air quality standards seemingly depend on cooperation and collaboration among automobile manufacturers, oil companies, and regulators to achieve the optimum mixture of fuel and engine technologies for compliance with public welfare.

10 Critical Issues for Further Research

The analytical tool proposed in this study relies on data that come either from recent journal publications or contacts with industry and regulatory agencies. As the knowledge of automotive emission evolves, it will be possible to further refine the model.

While there already exists a comprehensive body of literature on the effect of oxygenates, less is known on the function of detergent additives. The figures used in the spreadsheet FUTURE CAR FLEET were provided by an additive company and could not be verified independently. Potential biases in the choice of the test vehicles and of the reference fuel need to be addressed in further studies.

The evolution of emissions over the life time of the car is a complex function of age, distance driven, model year and maintenance. Some generalizations have been made by EPA. However, the underlying assumptions relate to the conditions found in the U.S. Even for this more limited use, serious questions are being raised on their [Fox].

For this reason, the study assumes that all vehicle emissions stay within their legal limits. While the thorough I/M programs in Sweden seem to offer a good compliance rate, a statistical confirmation is still lacking. The modular structure of the spreadsheet FUTURE CAR FLEET allows for the easy incorporation of variability of emission rates.

Diesel driven trucks are the single biggest emitters of nitrous oxides in Sweden, which are critical in combating acid rain. For this reason, a project similar to this should be initiated that focuses on emissions of diesel vehicles. The analytic tools for both fuels could then be used in conjunction in order to investigate the effect of changes in the ratio of gasoline to diesel vehicles in the Swedish car fleet.

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