Spatial Welfare Aspects of Limiting Air Pollution: The Danish Experience

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A city system is in balance when no benefit is obtained from moving from one city to another or from one place in the city to another. Air quality today has become important in evaluating quality of life. Air quality differs from city to city and from place to place.

The purpose of this paper is, based on collected data, to make a model of the development of air pollution from cars by lead and NO_x in Danish cities distributed in the city core and the periphery. The pollution is seen as a function of the number of cars, city size, and various initiatives to clean the air. The model shows that the relative gain of combating air pollution is at a maximum for the biggest towns and city cores and thereby shows that the competitive situation of big towns and city cores can be improved. The balance in the city system will thus be changed as a result of the anti-air pollution programs.

INTRODUCTION: HUMAN NEEDS AND CITY DEVELOPMENT

Demand for the spectrum of qualities of a town is decided by basic human needs sequentially revealed at increasing income. In economic theory, needs and choices are described by the income elasticity for different goods. In a more sociological context, the demand is described by a 'hierarchy of needs,' e.g., Maslow (1954). People's need for the qualities of a town can be listed as: jobs, housing, community (friendship, neighborhood), public services (schools, renovation, justice), amusement, and health (security, hospitals, clean air, no noise).

It can easily be illustrated that jobs in a town are more important than housing. In the developing countries, people from the country are moving into the cities to get jobs. With the lack of available housing, they can only afford to live in shanty towns. In the United States, workers formed newly raised mining towns. Later on, when the mines were empty and the jobs were gone, the towns were left. The houses stood as ghost towns, since no alternative job opportunities were created.

Today it is well known that towns can be built in a way that creates good or bad communities for people. There are communities built that discourage or en-

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courage crimes. The desire to live in good communities creates a necessity for good city planning. A need for justice can form a town. For example, harbor cities have been avoided by ship traffic because of crime.

As income rises, the demand for entertainment increases. Town areas have been developed to provide amusement (Sankt Pauli, Hamburg, Soho, London, Quartier Latin, Paris). Some towns have been built around amusement (Las Vegas) and other towns have been transformed into tourist towns (Florence, Venice). Some towns get their image because of their ability to amuse and entertain (Paris, Copenhagen, Vienna).

The desire for clean streets, clean air, and no noise, has encouraged rich people to move out of the city to form satellite towns. This makes the city center disintegrate, and are left to poor people. As wealth increases, less privileged people can afford to demand a clean town and less noise, so these goods have also started to be produced in the city core.

The growing concern about the quality of the city center made wealthy people want to go back to the city center. This reinforced the demand for environmental qualities. The progress made by improving the quality of the city core life and the availability of cars for medium incomes have reversed the social migration pattern in the big cities. In 1983–1988, Copenhagen City lost 17,889 inhabitants, but it gained 7,088 white collar workers, and lost 6,408 blue collar workers. The remaining net loss was mostly people outside the labor market. The awareness of unpolluted urban environments has, among other initiatives, created the WHO campaign for Healthy Town year 2000.

Urban economics discusses economic questions within a framework other than the classical (theory of) economics. In urban economics, equilibrium is reached when the relative sizes of cities and the distribution of citizens within these cities, is such that the welfare of the individual citizen is independent of city size or of where he lives in the city. If the general development results in giving some cities a larger welfare growth than others, disequilibrium will arise, and (in the long term) migration between cities and within cities will take place until the achieved welfare gain has been redistributed and the general level of welfare equalized. This paper argues that in recent years, a shift in the welfare level between the cities and within the cities has taken place due to the general efforts of environmental protection. This paper specifically deals with pollution problems arising from cars, but also from heating systems which are continuing to be developed (see Kristensen and Jensen, 1992).

Efforts to protect the environment are made at practically every level. If we control the individual sources, it will generally be possible to calculate the emission from each source (Andersen *et al.*, 1991) and to impose certain *maximum limits* of emission. Some laws are made as a direct regulation of the individual source of pollution. Another way of regulating is to introduce general *standards* of equipment and materials. This method is relatively simple and efficient for man-made goods. A third way is the use of *incentives* to persuade decisionmakers to choose non-polluting solutions. The efficiency of the regulations is measured by *air quality control.*

The most important effect, however, is the result of reducing pollution. Spatially the sources of pollution of a specific kind may be unevenly distributed. Because the diffusion of pollution is not normally frictionless, a topology of the impact on space has been developed. The purpose of this paper is to describe and analyze the spatial distribution patterns of air pollution in Denmark, as well as to outline the importance of this relationship to the balance of the Danish urban structure.

This investigation is based on data received from the National Agency of Environmental Protection. Since 1982, this institution has measured the air quality in Danish cities by collecting data on an annual, monthly, daily, and hourly basis. For each city, the air pollution is measured at a maximum of four points. This only allows intra urban pollution to be categorized in two areas: The city core and the rest of the city. Ideally, a spatial area should be treated as a continuum, allowing pollution to be illustrated by iso-pollution-curves in the landscape. The data that is used covers a period (between March 1982—February 1990) during which regulations were put in force. Thus, it is possible to evaluate the effects of the policy pursued in this area.

In the context of urban economics, air pollution is involved in the discussion of agglomeration economies and diseconomies, decline of city centers and, perhaps, also social segregation on account of environmental factors. In the theoretical literature analysis of agglomeration, urban economies and diseconomies are of central importance, (Fujita, 1989). City growth is constrained by urban diseconomies and the intra-urban structure of the city is affected by this phenomena. Several attempts have been made to measure urban economies quantitatively (see e.g., Carlino, 1982). Carlino made an overall assessment of urban economies in a cross-section analysis of cities by using wage statistics. Harvey (1973) deals with intra-urban sociological aspects of pollution. In his analysis, pollution only affects certain areas in the city in a specific way that aggravates inequalities among individuals and groups. Compared with these analyses and studies, the following analysis covers a more limited area, since only air pollution is investigated .

The central method of the model building is the expansion method (see appendix), which is a model building strategy that has turned out to be very useful in models of urban economics. Comprehensive literature is published using this method. This paper refers particularly to Casetti (1972), Casetti (1986); Krakover (1983), Krakover (1985); Kristensen (1991), Hansen and Kristensen (1991) and also Kristensen and Jensen (1992).

This paper first describes the air pollution of the individual city in a model (the initial model). Next, all cities are included on the basis of common features in an overall model by transforming the coefficients of the model into functions of population size. As seen below, the theme of the expansion method can be varied.

AIR POLLUTION FROM CARS

The different types of pollutants from cars are: nitric oxides (nitrogen oxides, NO_x), carbon monoxide (CO), carbon dioxide (CO_2), hydro carbon (HC) and lead (Pb). Lead often forms part of dust suspended in the air which is known technically, as 'Total Suspended Particulate' (TSP). This paper will focus on the development of NO_x, lead and TSP.

The developmental patterns of NO_x and lead differed during the investigation period between 1982 and 1989. The amount of NO_x in the air has increased while the amount of lead has decreased. This is mainly due to the fact that NO_x only derives partly from cars and has not yet been effectively removed from exhaust gases, whereas lead, which chiefly comes from gasoline, has been continuously removed from gasoline.

The health effects of air pollution from gasoline have been described in detail elsewhere (see e.g. WHO, 1987) and will only be briefly mentioned here.

Health risk from NO and NO_2

WHO has not, according to Nielsen and Grandjean (1988)), estimated NO with any regard to laying down a health limit, because the toxicity is relatively low. Nitrogen dioxide (NO_2) has a significantly negative influence on health. It can be bound in the lungs as nitrous acids (HNO_3) or (HNO_2) and is suspected of causing respiratory trouble especially for children, bronchitis and asthmatic patients, but for healthy adults, no significant health risk can be found.

Health risk from Pb

One of the health risks from lead is its effects on the central nervous system and on the blood pressure. Children up to 6 years are a special risk group, especially since the blood-brain barrier has not yet fully developed. Likewise, pregnant women are also a risk group because the placenta is not an effective biological barrier. Children get a relatively minor part of their lead intake directly from the air, which is why a low lead concentration in the air is not sufficient to guarantee children against air [lead] pollution. Previous studies of the harmful effects of (low) lead content in children's blood seem to have too much importance attached to the harmful effect on, for example, intelligence (WHO, 1987).

THE DEVELOPMENT OF THE EEC AND DANISH LEGISLATION ON AIR POLLUTION FROM EXHAUST GASES FROM CARS

The growing concern about the environment in the 1960s resulted in a progressive but also flexible anti-pollution policy which began in the 1970s. This was when the USA enacted The Clean Air Act and since has remained the leading nation internationally in clean air policy.

Regulation of exhaust gases

The EEC first provided rules for carbon monoxide (CO) and hydrocarbon (HC) by the order of the Council Directive of March 20, 1970 (7(0/22/EEC). It was stated by the Directive of November 30, 1976 (77/102/EEC) that nitric oxide was to be included among air pollutants and since then the permitted emission level has gradually been lowered (83/351/EEC, 88/76/EEC, 88/436/EEC). The Treaty of Rome from 1957 contains no specific articles concerning the environment. Environmental policy was first added to the treaty foundations of the EEC in 1986 by the articles 130R-130T in the European Single Act which specifies the general goals of the EEC environmental policy.

Danish legislation concerning exhaust gases was initiated in 1983 by the Ministry of Justice with a restriction on carbon monoxide. From 1984, it was extended to cover hydrocarbon and nitric oxides, and subsequently became stricter in 1987, 1989, and 1990. From October 1, 1990, all new cars built must be fitted with a three-way catalytic exhaust purifier. The catalyst removes 80-90 percent of the toxic content of exhaust gases.

Air pollution from NO_x

Iversen et al (1989) calculated the emission factor for different types of cars, as well as the emission from all Danish cars in 1980 and 1986 as shown in Table 1.

In Denmark as a whole, it has been calculated that approximately 31 percent of all emission of nitric oxides derives from cars. In the city centers, cars contribute about 70 percent.

Table 1: NO_x emission factors and calculated emission from Danish cars in 1980 and 1986.

		NO_x (1,000 tons)	
Car engine types	*Factor*	*1980*	*1986*
Cars with gasoline engines:			
Cars and light weight vans	2.1	43	50
Coomercial vehicles (over 2 t)	2.5	3	3
Cars with diesel engines:			
Cars and vans (under 3.5 t)	0.6	2	3
Trucks and buses	10.3	20	25
Total		68	81

Investigations in a number of cities show that the level of nitrogen monoxide (NO) changes significantly from year to year. The considerable annual changes in the actual amounts of NO_x make it difficult to measure the effect of regulation from year to year. Nielsen and Grandjean (1988) give the figures for NO and NO_2 as shown in Table 2.

Table 2: Annual average for a number of European towns.

	Annual average	
Location	*NO (ppb)*	*NO_2 (ppb)*
Town center	90–240	28–45
Town	10–60	14–40
Periphery (background pollution)	2–7	4–18

Nitrogen dioxide (NO_2) basically evolves by oxidation of nitric oxide (NO). The oxidation takes place under the influence of sunlight.

Not until 1990, did Denmark take efficient steps to limit the emission of NO from other sources than cars. In an EEC Directive from 1980 (80/779/EEC), the EEC established maximum values for the content level of sulphur dioxide and floating dust in the air. Nitrogen dioxide was included in a Council Directive (85/203/EEC) of March 7, 1985. Maximum levels were set by Danish legislation in March 1987. From 1980, the EEC member states were encouraged to establish measuring stations for air pollution. A European Council decision of June 1982 (82/459/EEC) requires that members of the Community exchange information and data from these stations.

DATA FOR MODELING AIR POLLUTION IN DANISH CITIES

The model below is based on *monthly* data received from the Danish Environmental Research. Compared to a model based on day to day data, a model based on monthly data has the advantage that it may include data from other sources that are only available on a monthly basis. Besides, a data base which includes eight years does not become overwhelmingly large, as would have been the case with a model based on daily observations. Data, other than the data received from the Danish Environmental Research (sale of gasoline, sun, wind force, temperature and rain), are obtained from *The Statistical Yearbook of Denmark.*

Measuring stations

The measuring stations cover eight towns with 25 different points. The measurements taken are shown in Table 3. All measuring stations in Table 3 took measurements of the pollutants lead and floating dust, but only 10 measuring stations covering 5 towns took measurements of the pollutant NO_x.

Volume of traffic

The general pattern shows that pollution rises with increasing traffic volume and city size. As shown below, pollution is highest on work days (weekly cycles).

This is a fact that makes the estimation procedure difficult because the sale of gasoline rises on holidays, but pollution from cars diminishes on holidays, which evidently proves that cars move away from city centers on holidays. Data gathered on the traffic volume are limited and inadequate. By applying this monthly data, the possibility of including the daily traffic volume is lost, even if this data were available.

For 1984, data collected on traffic volume from 15 different observation points were available, but not all are included here because of insufficient data collected on pollution. For 1989/90, 12 various observations on traffic were available. Of the 1989/90 observations, 4 observations were in the same points as the data collected from 1984.

Table:3: The measuring stations for air quality for individual towns with indication of town, station number, traffic volume and period of operation.

Town	*Number*	*Cars/day*	*Period*
Copenhagen	1103 x	60,000 c	82–86
	1255 x	50,000	87–
	1256 x	37,000	87–
	1257 x	22,000	87–
Århus	6151 x	13,000	88–
	6152	24,000	88–
Odense	9151 x	14,500	82–87
	9154	19,500	82–
	9155 x	19,500 c	88–
Ålborg	8151 x	28,500 c	82–
	8153	22,000	82–
Esbjerg	5651 x	7,700	82–86
	5652	6,000	82–86
	5655 x	6,500	88–
Randers	6351	35,000 c	82–86
	6352	2,000	82–86
	6353	200**	82–86
	6354	200**	82–86
Næstved	3351	16,000 c	82–86
	3352	200**	82–86
	3353	200**	82–86
	3354	8,000	82–86
Fredericia	5151	18,708*c	82–86
	5152/62	9,500*	82–
	5155	6,000	87–

* Estimated traffic volume.
** Arbitrary translation of 'insignificant' traffic volume.
x Measurements of NO and NO_2.
c Indicates that the observation is from city core.

The traffic volume in some cases is shown in approximate figures, whereas the estimated error lies in the interval 2–8 percent. Other figures are rounded off with a consequently even higher level of unreliability.

As the annual growth in traffic is approximately 1.7 percent, all observations are regarded as 1986 observations i.e. the middle of the period. The error made by this assumption is regarded as insignificant and will be modified below by including the development of gasoline consumption. With this procedure, traffic volume is ranked at 23 points.

Publications from The Air Quality Measuring Program also give a description of the locations of the measuring points for the following categories: city core, residential areas, mixed industry and residential areas, industrial areas, other areas (green or unspecified areas). It is assumed that the traffic depends on these five characteristics. For the points where the city characteristic is given, but where there are no data published on traffic volume, the traffic volume is calculated by a regression analysis. The calculated values are marked with (*) in Table 3. Pindyck and Rubinfeld (1991) show that this method of replacing missing observations increases the accuracy of the estimation. For four points, traffic volume was described as 'insignificant'. For these points traffic volume was arbitrarily set to 200 (marked by '**').

Working days

The measuring points are found in the cities. Pollution of the cities depends on whether the cars are in the city. From daily/hourly observations it appears that pollution from cars in the cities is lower during weekends. During holidays the pattern seems to be that traffic volume (measured in gasoline consumption) generally rises. This indicates, of course, that pollution during holidays is moved away from the cities but is not reduced on a total basis.

In this investigation, holidays are defined as Saturdays, Sundays, and public holidays The summer holiday is defined as the period from June 20–August 6.

Monthly traffic

As mentioned above, the value of traffic was estimated as an aggregate of the traffic level during the whole period, whereas the traffic in reality rose by 1.7 percent. In order to include the increase in traffic, the level value was multiplied by the monthly nationwide consumption of gasoline, whereby the variable TG = TRAFFIC*GASOLINE was found.

Transit roads

Highways are included as a special variable under the assumption that heavy traffic is diverted from the towns. As heavy trucks have a higher NO_2 factor, as shown in Table 1, the naked figures for traffic volume underestimate the NO_x pollution when the traffic mainly consists of heavy trucks. In this investigation, this type of traffic is found particularly at two points—point 8151, the Ålborg

Tunnel, and point 9154, the ring road at Odense which is used by the Danish east-westbound traffic. The points are included in the equation with a dummy TRANSIT—with the value 1 for transit roads and 0 for other roads–whereby the variable TRANSTG = TRANSIT*TRAFFIC*GASOLINE is created.

Weather conditions

The most relevant weather conditions turned out to be monthly data for sunshine, rain, temperature and wind force. Data for rain were distributed in different regions which meant that for eight cities, seven different time series were found. The remaining weather data were found nationwide.

A MODEL OF AIR CONTENT OF NO AND NO_2 IN WHICH CARS ARE CONSIDERED THE PRIMARY SOURCE OF POLLUTION

A model of air pollution from NO_x cannot be estimated for the individual city. For the individual city there is a maximum of only 4 different observations for the traffic level. For that reason, the models are estimated as nationwide.

The model structure

The basic elements of an NO_x-pollution model are pollution from gasoline combustion and fuel used for heating purposes which is expressed as

$$NO_x = f(\text{gasoline, fuel}) \tag{1}$$

This model expresses the fact that pollution coming from NO_x depends on combustion of gasoline and fuel. As fuel consumption varies conversely with temperature, and since temperature data are easily available, the temperature has been included instead of fuel consumption along with a time trend.

The basic model with a constant has the form:

$$NO_x = \alpha_0 + \alpha_1 TG + \alpha_2 TEMP + \alpha_3 TREND \tag{2}$$

where α_0 can be regarded as a combination of 'background' pollution which is mentioned in Table 2 and the effect of including a time trend. If this unexplained development in pollution, that is, the pollution which is explained with the trend, is increasing with increasing force, this will tend to give a negative constant element.

The *effect* on the environment from combustion of gasoline and fossil fuel was, however, dependent on dispersion as well as chemical reactions in the air. Thus, the *effect* will be dependent on the above mentioned variable TRANSIT, WORK, SUN, WIND and RAIN. The *effect* of a given emission on immission (air pollution) is included in the model by expanding α_1 (the general expression for the coefficients in (2)) according to the formula

$$\alpha_j = \beta_{j0} + \beta_{ji}\text{TRANSIT} + \beta_{j2}\text{WORK} + \beta_{j3}\text{SUN} + \beta_{j4}\text{WIND} + \beta_{j5}\text{RAIN} \qquad (3)$$

In principle, all four coefficients of (2) have to be expanded with (3) in the final model. For the sake of simplicity, and because pollution from cars is considered to be the dominating factor of the points in question, only α_1 will be expanded. Estimations, in which the other coefficients were also expanded, support this decision. This gives the model the following form:

$$\begin{aligned} NO_x = {} & \alpha_0 + (\beta_{10} + \beta_{11}\text{TRANSIT} + \beta_{12}\text{WORK} \\ & + \beta_{13}\text{SUN} + \beta_{14}\text{WIND} + \beta_{15}\text{RAIN})\text{TG} + \alpha_2\text{TEMP} + \alpha_3\text{TREND} \qquad (4) \end{aligned}$$

Equation (4) is the model for the individual town. The model which applies to all towns is obtained when each coefficient of (4) is expanded again with population size POP. To simplify the model, only α_0, α_2 and α_3 were expanded according to this formula:

$$\alpha_j + \beta_{j0} + \beta_{j1}\text{POP} \qquad (5)$$

A number of alternative estimations support this method. The model structure of the nationwide model (the terminal model) is thus:

$$\begin{aligned} NO_x = {} & \beta_{00} + \beta_{01}\text{POP} + (\beta_{10} + \beta_{11}\text{TRANSIT} + \beta_{12}\text{WORK} \\ & + \beta_{13}\text{SUN} + \beta_{14}\text{WIND} + \beta_{15}\text{RAIN})\text{TG} + (\beta_{20} + \beta_{21}\text{POP})\text{TEMP} \qquad (6) \\ & + (\beta_{30} + \beta_{31}\text{POP})\text{TREND} \end{aligned}$$

Because of the low number of towns and measurement points for NO_x (see Table 3) it is not possible to distinguish between the city core and the rest of the city.

Estimations

As mentioned above, only 10 stations in 5 towns measured pollution from NO_x The small amount of data on population density and traffic volume limits the value of the nationwide model. The total number of observations was 407 for NO and 408 for NO_x An unsophisticated model of NO pollution from cars was estimated as shown below.

The estimated model of NO pollution from cars in Denmark, including 5 towns:

$$\begin{aligned} NO = {} & \underset{(-9.20)}{-518.53} + \underset{(12.45)}{1.13\text{POP}} + \underset{(2.84)}{.008\text{TG}} + \underset{(17.21)}{.013\text{TRANSTG}} + \underset{(5.35)}{.0002\text{WORKTG}} \\ & \underset{(-3.58)}{-\ 1.80\text{E}{-}05\text{SUNTG}} \underset{(-6.17)}{-.0017\text{WINDTG}} \underset{(-2.88)}{-\ .75\text{TEMP}} + \underset{(2.18)}{.0009\text{POPTEMP}} \\ & + \underset{(9.81)}{6.43\text{TREND}} \underset{(-2.15)}{-.012\text{POPTREND}} \end{aligned}$$

$R^2 = .83$ DW* = 2.18 Obs = 379 rho = .61 (14.34)

The estimated model of NO_2 pollution from cars in Denmark, including 5 towns

$$NO_2 = \underset{(-9.34)}{-187.84} + \underset{(12.82)}{.41POP} + \underset{(.48)}{.00048TG} + \underset{(8.51)}{.0024TRANSTG} + \underset{(6.71)}{.0001WORKTG}$$

$$+ \underset{(3.02)}{5.35E-06SUNTG} - \underset{(-5.90)}{.00059WINDTG} - \underset{(-5.28)}{.49TEMP} + \underset{(3.17)}{.00044POPTEMP}$$

$$+ \underset{(11.10)}{2.59TREND} - \underset{(-12.38)}{.0045POPTREND}$$

$R^2 = .80$ DW* = 2.08 Obs = 381 rho = .48 (10.58)

The Durbin-Watson value (DW*) has been corrected for serial correlation.

The model above shows that pollution increases with city size, as the coefficient of POP in both equations is positive and strongly significant. As shown, a time trend was also included in the estimations. Both estimations indicate that pollution from NO_x is rising in Denmark, but less in Copenhagen than in the smaller cities. It is also seen that changes in temperature (fuel consumption) has less effect on pollution in the larger cities than in the smaller ones. The number of sunshine hours has the expected sign in both estimations. This confirms the theory of NO being transformed into NO_2 by the sun. The coefficients of rain were insignificant and therefore were later omitted. The significant and positive coefficient of POP shows that large cities have agglomeration diseconomies.

DEVELOPMENT OF EEC LEGISLATION AND DANISH LEGISLATION WITH REGARD TO LEAD AIR POLLUTION FROM CARS (1977–1991)

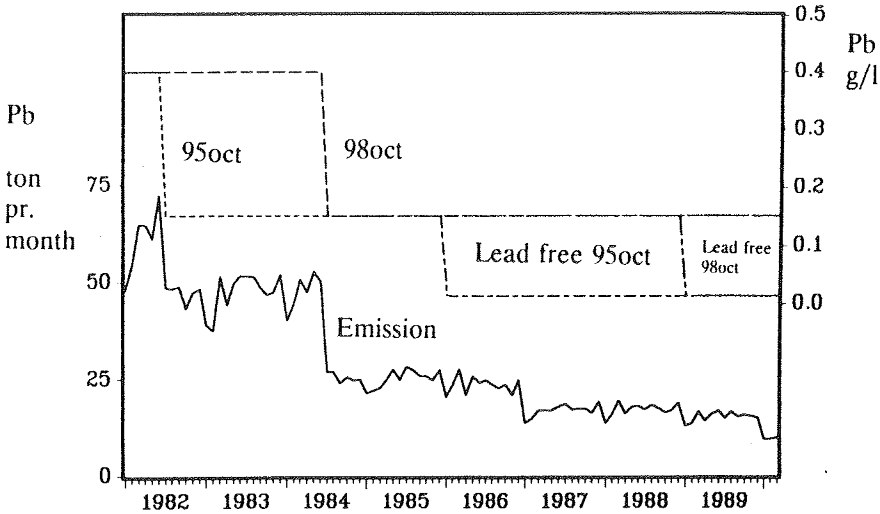
Gasoline is essentially a man-made product. This means that (in certain fields) it is easily regulated. Limitation of the lead content is an example. The legislative power has chosen two ways of reducing lead in gasoline, a mandatory way and a voluntary way based on incentives.

Regulation of lead content in gasoline by mandatory rules

As of January 1st 1981, a Council Directive of June 29th 1978, demanded that the member states should limit the content of lead in gasoline (from a level at around .55g Pb/l) to .40g Pb/l with the right to introduce further limits within the interval .40g Pb/l to .15 g Pb/l. Already in June 1977, the Danish Ministry of Environment had commenced its legislation regarding lead in gasoline. The decision that the maximum content of lead in petrol should be .40g Pb/l went into effect on January 1st 1978. The maximum content was further lowered to .15 g Pb/l on July 1st 1982. An exception was made, however, for gasoline that has an octane ranking above 97.5. For this category of gasoline, a maximum of .15 g Pb/l did not take effect before July 1st 1984.

The Council Directive of March 20th 1985, proposes that in due course, the member states should adopt an upper limit of .15 g Pb/l, introduce unleaded gasoline defined as gasoline containing less than .013 g Pb/l, secure its availability, and introduce incentives to encourage people to use unleaded gasoline.

Figure 1: Limits of lead in gasoline for various types of gasoline compared with the calculated emission of lead from different types of gasoline.



Source: N.A. Kilde, Risø.

The choice between leaded and unleaded gasoline

Unleaded gasoline with a low octane rating was introduced in Denmark on January 1986, and unleaded gasoline with a high octane rating (above 97) was introduced on January 1989. A mixture of unleaded and leaded gasoline was introduced in 1987 (with a content of .075 g Pb/l).

Unleaded gasoline introduced a change of political strategy. While the reduction of the lead content to .15 g Pb/l was mandatory, the following reductions were voluntary and supported by incentives. The anti-pollution policy became more visible. Taxes on unleaded gasoline (as shown in Figure 2) are lower than the tax on other types of gasoline, which encourages the population to use unleaded gasoline. The actual choice is shown in Figure 3.

The total effect of mandatory and voluntary limitation of Pb content in gasoline

The model, made to describe the removal of lead in gasoline, is a combination of a law model and a classical behavioral model in which the law model dominates. The element of the law model draws more attention to the consequence than to the prognosis.

Figure 2: Tax on unleaded gasoline in percent of tax on other types of gasoline.

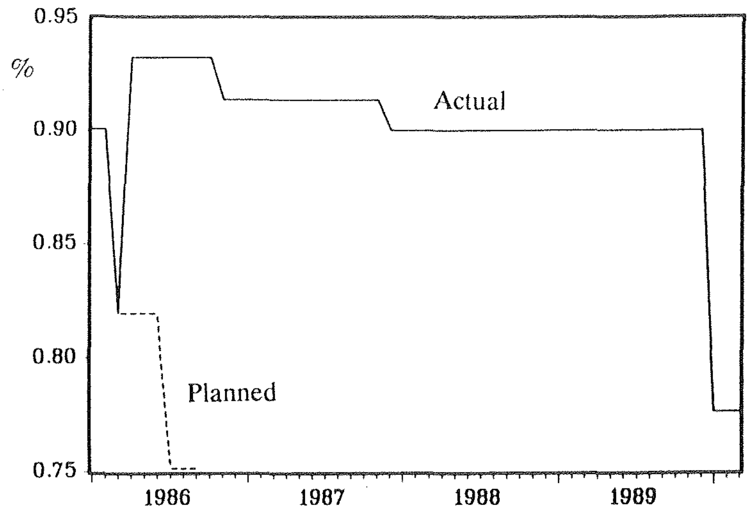
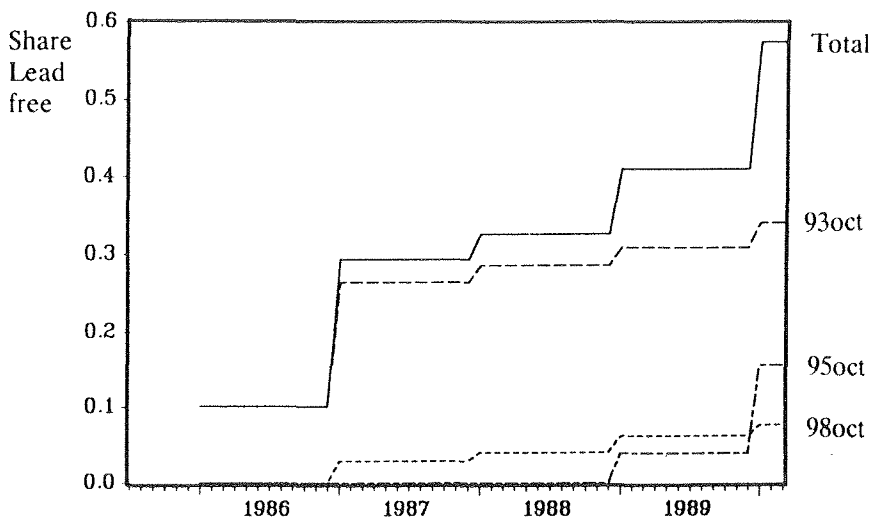


Figure 3: Share of unleaded gasoline distributed on octane ratings.



The development of rules on lead content in gasoline is shown in Figure 4, which gives a picture of the general development of the country as a whole. The rules are compared with the calculated emission of lead from gasoline. In Figure 5, the calculated emission of lead is compared with the measured lead content (immission) of the air in Copenhagen.

Figure 4: Calculated emission of lead from gasoline in Denmark as compared to the measured Pb-content (immission) of the air in Copenhagen (Pb 1103).

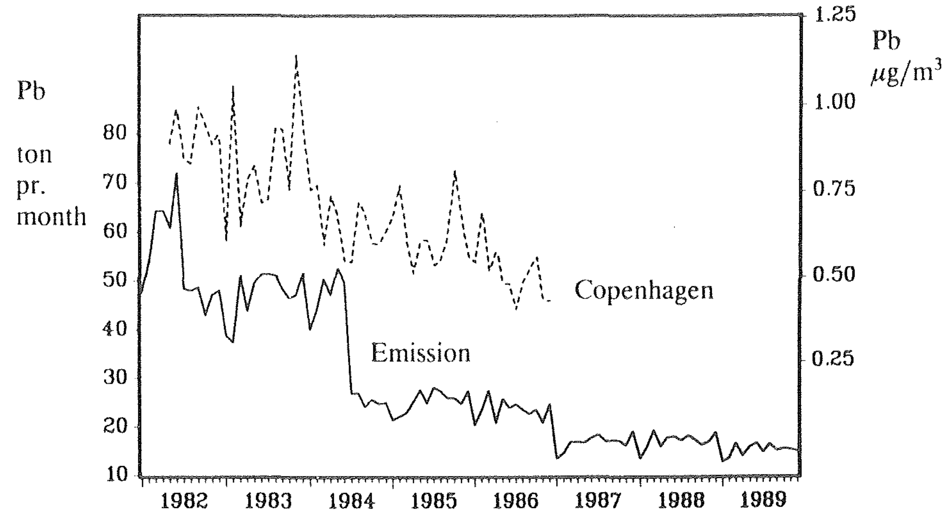
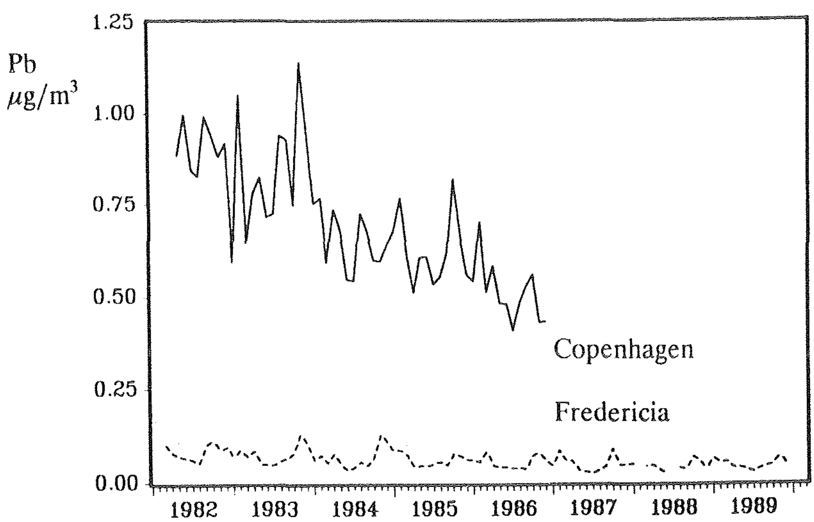


Figure 5: The measured lead content of the air in Copenhagen (Pb 1103) and Fredericia.



Lead in the air from other sources than cars

The Danish government has given high priority to the campaign against lead pollution. From 1985, the use of shot lead was limited. Likewise, higher standards were introduced in 1985 to protect workers from metallic lead poisoning. The air content as well as blood content of lead is now controlled.

Heating (combustion of fossil fuel) belongs to the category of 'other air pollution sources' coming from lead. The effect of the heating system may be related to the monthly temperature, as will will appear from the NO_x model.

Air quality control (immission control)

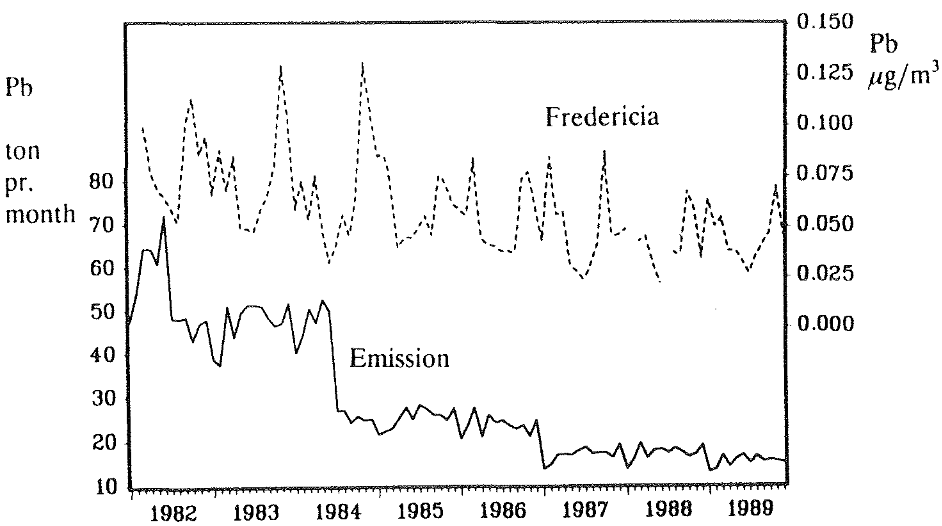
From 1982, new guidelines were set by the EEC regarding the maximum lead content in the air. No upper limit of lead pollution has been set in Denmark since the lead content of the air at its highest is considerably below the EEC-limit.

Eighty to ninety percent of the air pollution containing lead comes from the combustion of leaded gasoline. The remaining part is due to various sources, of which coal combustion is relevant to Denmark.

The effect on the air varies, however, between the individual cities. Figure 5 shows the measured lead content of the air for the largest town (Copenhagen) and the smallest (Fredericia) of the towns that were included in the investigation. In Figures 4 and 6, the nationwide calculated emission is compared with the actual pollution (immission) of Copenhagen and Fredericia.

By comparing Copenhagen and Fredericia it is seen that the general effect of reducing the permitted lead content in gasoline depends upon which town (or point characterized by traffic volume) is being considered.

Figure 6: Calculated emission of lead from gasoline in Denmark as compared to measured Pb-content (immission) of the air in Fredericia (Pb 5152).



A MODEL OF POLLUTION FROM LEAD IN DANISH CITIES

Data

Most of the data used in this part are the same as for NO_x above. As mentioned before, the lead content in gasoline is regulated by law. The law regarding the reductions (of the content of lead in gasoline) came into force in July 1982 and July 1984. In order to keep within the date limits of the law, in practice, it was necessary for the oil companies to reduce the lead content in gasoline prior to these date limits. By use of dummies, it was estimated that the new limits had already been obtained by the end of February 1982, and by the middle of February 1984. Because of the reliable data we have on lead content in gasoline we can go one step further by making the calculated lead emission an independent variable. Thus we have the variable TGL = TRAF*GASOLINE*LEAD where LEAD is the average g/l Pb content in gasoline. GASOLINE*LEAD, the calculated emission, is shown in Figures 4 and 6.

Initial estimates of a model of lead pollution in Denmark

The model structure is, apart from a few modifications, the same as the one found for NO_x. Sun is not included because there are no *a-priori* expectations that sunshine has any influence on the lead content of the air.

The initial, estimated model of pollution from cars in Denmark, includes 8 cities

$$\underset{}{\mathrm{Pb}} = \underset{(21.75)}{.109} + \underset{(16.35)}{9.56\mathrm{E{-}06POPGL}} + \underset{(13.44)}{.0033\mathrm{CORGL}}$$

$$+ \underset{(13.94)}{.00037\mathrm{TGL}} - \underset{(-9.97)}{3.71\mathrm{E{-}06TTGL}} + \underset{(42.93)}{.00043\mathrm{TRANSTGL}} + \underset{(8.53)}{5.26\mathrm{E{-}06WORKTGL}}$$

$$- \underset{(-8.06)}{2.78\mathrm{E{-}05WINDTGL}} - \underset{(-4.58)}{5.39\mathrm{E} - 07\mathrm{RAINTGL}} - \underset{(-11.11)}{.0046\mathrm{TEMP}}$$

$R^2 = .86$ DW* = 2.26 Obs = 1256 rho = .45 (17.86)

parentheses signify t-values and where:

POP	-	population
GL	-	GASOLINE*LEAD. Gasoline consumption in Denmark multiplied by calculated lead content per liter. Index for lead emission from gasoline in Denmark
POPGL	-	POP*GL
CORGL	-	COR*GL
TGL	-	TRAF*GL. Traffic level of the point considered multiplied by GL. Local index for lead emission
COR	-	dummy for city core
TTGL	-	TRAF*TGL

TRANSTGL – TRANSIT*TGL. Dummy for transit point multiplied with TGL

WORK – number of monthly working days

TEMP – monthly average temperature

The model shows that the declining emission of lead changes the air pollution pattern in the cities. The effect of POPGL is particularly significant. This gives the largest cities major advantages, as well as CORGL which also gives the city core of the individual city certain major advantages.

The reason for including TEMP is that fossil fuel used for heating purposes contains lead and, hence, TEMP represents a source of pollution. Combustion of coal has, however, another function that indirectly causes air pollution from lead to rise and that is the formation of floating dust, TSP—Total Suspended Particulate—in which lead from gasoline is absorbed and carried in the air. Rain or wind reduces the presence of floating dust whereby the amount of lead being carried in the air is also reduced. The effect of rain and wind on the lead content is thus indirect. For that reason, the model in principle should be changed to a two-equation model. The first equation expresses the presence of floating dust (see Kristensen and Jensen (1992)). The second equation includes floating dust as an explanatory variable of the function of lead pollution in the air.

The equation for floating dust was estimated at

$$
\begin{aligned}
TSP = {} & \underset{(21.92)}{72.02} + \underset{(7.46)}{.013POP} + \underset{(11.19)}{12.81COR} + \underset{(4.19)}{0.0076POPCOR} + \underset{(1.48)}{.00046TG} \\
& + \underset{(8.26)}{.0023TRANSTG} + \underset{(8.15)}{.58WORK} - \underset{(-10.20)}{4.12WIND} - \underset{(-3.13)}{.089RAIN} - \underset{(-9.54)}{.73TEMP} \\
& + \underset{(7.05)}{.54DIRS} + \underset{(7.83)}{.50DIRSE}
\end{aligned}
$$

$R^2 = .59$ DW= 1.03 Obs= 1260

where

TSP – monthly data on floating dust

DIRS – part of the month with a southerly wind

DIRSE – part of the month with a southeasterly wind

The amount of floating dust depends on TEMP and TRAF/WORK. The last effect is because cars stir up dust in the streets. The air is cleaned by rain and wind. Floating dust is 'imported' from northern Germany and Poland when the wind is blowing from the south/southeasterly direction.

The model that includes TSP is more satisfactory for two reasons. First, it has much higher explanatory power. Second, it emphasizes the two ways in which heating systems contribute to lead pollution. When lead is carried by dust, dust can be more important for lead pollution than the direct emission from coal. This model shows that the air quality on the one hand is poorest in large cities and city cores (POPGL and CORGL) but on the other hand is mostly improving due to regulations in large cities and city cores.

The role of dust is now included in the lead pollution equation

$$
\begin{aligned}
Pb = & -.12 + 6.19E-06POPGL + .0016CORGL \\
& (15.00) \quad (11.63) \qquad\qquad (7.35) \\
& + .00014TGL - 2.45E\text{-}06TTGL + .00039TRANSTGL + 2.25E-06WORKGL \\
& (8.84) \qquad (-7.35) \qquad (42.93) \qquad (4.78) \\
& + .0028TSP + 3.30E\text{-}05TSPGL \\
& (20.94) \qquad (10.98)
\end{aligned}
$$

$R^2 = .89$ $DW^* = 2.21$ Obs = 1219 rho = .40 (15.44)

TSPGL – lead emission (index) multiplied by the content of floating dust in the air.

Simulation with the estimated model

An important benefit of the model is that 'missing observations' can be calculated. For cities without air quality control it is possible to make a qualified guess at the historical development of the lead content at various points in an arbitrary city when some city characteristics are given. This data can be compared with other data for the city in question.

CONCLUSION

Denmark has been ahead of the legislative development of the European struggle for environmental protection. This struggle has seen both failures and successes. The efforts to reduce the emission of NO_x have not yet had any significantly positive effect on the air quality. But, the statutory use of catalysts in new cars from 1990 will probably yield good results in the future. Nielsen *et al.* (1988) have estimated a number of scenarios. The main features are that NO_x will decrease from the beginning of the 1990s towards the year 2005, when it will begin to rise again. The endeavors to diminish the lead content of the air have, however, been successful. A significant and general decrease of the lead content of the air has taken place. The considerable effect of statutory measures (intervention) against lead pollution appears to have passed unnoticed by the public before 1986, as compared with the public debate which took place in connection with the voluntary and much more visible policy on unleaded gasoline. A similarly positive development, as shown by Kristensen and Jensen (1992), has taken place for SO_2, whereas the air content of TSP is largely unchanged.

The goal of the world-wide legislative process is to have total elimination of lead from gasoline. This process is irreversible, because unleaded gasoline depends on engines that are able to run on unleaded gasoline, and these engines are gradually becoming dominant in the automobile industry, as well as on the development of improved types of gasoline. The welfare consequences of these results cannot, of course, be measured exactly. Nonetheless, they constitute a change in the environment that is highly demanded.

There are important spatial dimensions in combating pollution. Pollution in the air from lead, NO_x and SO_2 is mainly a problem in the cities, particularly the large cities. This is why a reduction of pollution improves the living conditions of the cities as compared with the living conditions of the rural districts. Because air pollution is worst in the city core, a reduction of pollution will improve living conditions within the city, benefiting the city core. It is well known in the literature, that externalities with different spatial impacts influence spatial allocations (see e.g., Thrall, 1982). In the case where the environment improves in cities, especially in city cores, the option of living in cities and city cores becomes much more desired. This may put a stop to a possible deterioration process of the city core. Together with these changes in living conditions, land values will increase relatively more in the cities and particularly in the city core. Under theoretical economic assumptions, with perfect mobility, people in cities capitalize the whole benefit of the improved environment, and thus, existing landowners take full advantage of the efforts in this area. However, in practice, the mobility of people is not perfect and, in this case, the advantages of the improved environment will be divided between existing landowners and the residents of the city. In both cases, the costs, in connection with the purification of the air, are borne mainly by the whole population and the environmental protection then redistributes wealth in favor of residents and the existing landowners of the city.

APPENDIX: THE EXPANSION METHOD

By (using) the expansion method, two data sets X and Z of exogenous variables are, in principle, available as explanations of the endogenous variable.

The expansion methods consists of two stages. In the first stage, a basic model is set up on the basis of one of the two data sets. The choice of data set decides which will be regarded as the primary model and which will be regarded as the dual model. In the next stage, all coefficients of the basic model are made functions of the second set of variables, whereby the final model arises.

The initial model (X_j is the primary data set for a given level of Z) can be written as

$$D_z = \alpha_0 + \alpha_1 X_1 + \alpha_2 X_2 + \alpha_3 X_3 \tag{A1}$$

where X is the independent variable. If the expansion method is used, the coefficients in equation (A1) may be seen as functions of Z; this can be expressed as

$$\alpha_j = \alpha_{0j} + \alpha_{1j}Z_1 + \alpha_{2j}Z_2 + \alpha_{3j}Z_3 \tag{A2}$$

The terminal model is now formulated as the primary model (Casetti (1986))

$$\begin{aligned} D \;=\; & a_{00} + a_{10}Z_1 + a_{20}Z_2 + a_{30}Z_3 \\ & + (a_{01} + a_{11}Z_1 + a_{21}Z_2 + a_{31}Z_3)X_1 \\ & + (a_{02} + a_{12}Z_1 + a_{22}Z_2 + a_{32}Z_3)X_2 \\ & + (a_{03} + a_{13}Z_1 + a_{23}Z_2 + a_{33}Z_3)X_3 \end{aligned} \tag{A3}$$

Formulated as the dual model (for given level of X) the initial model is

$$D_x = \beta_0 + \beta_1 Z_1 + \beta_2 Z_2 + \beta_3 Z_3 \tag{A4}$$

$$\beta_1 = a_{0i} + a_{1i}X_1 + a_{2i}X_2 + a_{3i}X_3 \tag{A5}$$

$$\begin{aligned} D = \; & a_{00} + a_{01}X_1 + a_{02}X_2 + a_{03}X_3 \\ & + (a_{10} + a_{11}X_1 + a_{12}X_2 + a_{13}X_3)Z_1 \\ & + (a_{20} + a_{21}X_1 + a_{22}X_2 + a_{23}X_3)Z_2 \\ & + (a_{30} + a_{31}X_1 + a_{32}X_2 + a_{33}X_3)Z_3 \end{aligned} \tag{A6}$$

It is seen that the final model is identical in both cases.

Casetti (1986) maintains that the choice of model to be considered the primary one is arbitrary. It seems, however, appropriate that the model that begins with policy variables should be considered as the primary one, because, frequently, in order to make the model fairly simple and to avoid multicollinearity, some variables are omitted for practical purposes.

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