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Reassessing Past European Gasoline Lead Policies

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Introduction

For the foreseeable future, the atmosphere and the environment will remain a dumping ground for various anthropogenic substances. Some substances will have negative properties, and society will sooner or later begin regulating their emissions. To that end, science must provide society with the tools for the retrospective evaluation of the physical and economical impacts of past regulations, and for evaluating scenarios in which alternative future regulations are implemented.

A tool for reconstructing lead air concentrations and depositions across Europe from 1958 through 1995 has been developed that incorporates detailed emissions, a regionalized history of weather events, and an atmospheric transport model. This tool was used in conjunction with lead measurements in both biota and human blood and with economic analysis to assess past European gasoline-lead regulations. Some of the specific questions asked in this assessment were: How did lead emissions, atmospheric concentrations, and depositions develop since the 1950s? Was the decline in air concentrations matched by corresponding declines in plants, animals, and humans? Did the regulations result in considerable economic burdens in Germany, for example?

There were several reasons for choosing gasoline lead additives as the basis for a case study of European emission regulations. First, lead emissions underwent significant changes; there was an unabated increase in lead concentrations followed by a post-1970s series of sometimes drastic reductions. Thus, there is a strong and well-defined signal to be detected. Second, once released into the atmosphere, lead accumulates and persists indefinitely in some environmental compartments such as aquatic sediments. What might the ecological and human health impacts of this neurotoxin's environmental distribution be? Finally, airborne lead behaves to a first order approximation as inert, so simulating its transport and deposition is relatively simple. In principle, our tool can be used for any other particle-bound substance of limited reactivity.

This approach is successful for describing the temporal evolution of the spatial distribution of lead deposition in Europe. Demonstrating the effectiveness of gasoline-lead policies, the reconstructed concentrations in the atmosphere, in plant leaves, and in human blood show a steady decline since the early 1980s, while concentrations in marine organisms along the North

Sea coast, however, seem unaffected to date. Contrary to initial expectations, the German mineral oil industry was not negatively affected. While competition conditions changed in the German gasoline and automobile markets, no impacts of the regulations could be identified in the macro-economic indicators.

European Regulation of Gasoline Lead Additives

Air pollution problems introduced by automobile traffic in the 1960s, of which the most visible was urban smog, were addressed in the United States by the 1963 Clean Air Act. In Europe, serious concern about the effects of air pollution on human health first surfaced in the 1970s. Lead, in particular, added to gasoline for its anti-knock properties, was perceived as a health threat at this time, given new evidence of its neurotoxicological effects, which are especially severe in children. After lead-based paint and lead solder in water pipes and food cans was prohibited, gasoline lead--tetraethyl and tetramethyl lead additives--became the next target.

In the 1970s, the German government was the first in Europe to regulate lead additives in gasoline. A maximum content of 0.4 g Pb/l was imposed in Germany in 1972--down from the usual 0.6 g Pb/l--and it was lowered further to 0.15 g Pb/l in 1976. A preliminary analysis of newspaper coverage shows that gasoline lead-induced health risks were first reported in the German press in the 1960s. Instead of focusing on lead, British articles focused on urban smog. And in 1972, a group of French government experts did not acknowledge that any automobile emissions were dangerous (see *von Storch et al.* [2002]). The European Union (EU) fixed its limit modestly at 0.4 g Pb/l, beginning only in 1981, and prohibited all countries from stipulating national limits lower than 0.15 g Pb/l (Council Directive 78/611/EEC of 1978) [*Hagner*, 2000].

In the 1980s, discussion of automobile air pollution in Europe moved to concerns about forest protection due to the effects of massive NO_x, CO, and C_xH_y emissions. This discussion was also initiated by Germany, where citizens were concerned with the death of their beloved forests due to acid rain and photo-oxidation. In 1985, Germany passed a law to reduce total automobile emissions. This law led to the introduction of unleaded gasoline, because the largest reductions of NO_x, CO, C_xH_y, and other pollutants could be achieved with catalytic converters that were incompatible with lead. Catalytic converters were already in use in the United States. Opposing views expressed in some European countries are briefly reviewed in *von Storch et al.* [2002]. Press coverage in the 1980s emphasized the expected economic problems of the automobile industry and the European difficulty in finding a compromise solution.

Despite this opposition, in 1985 the EU mandated all member states to offer unleaded gasoline starting October 1989 and recommended a maximum of 0.15 g Pb/l. While some countries promptly adhered, others lagged behind (see *Hagner* [2000]). The Århus Treaty, signed in 1998 by nearly all European countries, stipulates the exclusive usage of unleaded gasoline by the year 2005.

Reconstructing Atmospheric Pathways

To run a model of atmospheric lead transport, regional weather information is required, including wind speed and direction, precipitation rate, and boundary layer depth. Global weather analyses, available from the National Centers for Environmental Protection (Camp Springs, Maryland) since 1958 at 2° spatial resolution, were considered too coarse; hence, the regional atmospheric model REMO was used to "downscale" them to a 0.5° grid covering all of western Europe and parts of the north Atlantic [*Feser et al.*, 2001].

The regional climate model is a grid-point model and uses a terrain-following hybrid coordinates system in the vertical direction. The physics scheme of the global model ECHAM4 was adapted to the higher resolution of 0.5° and was then incorporated into the regional model. The prognostic variables are surface air pressure, horizontal wind components, temperature, specific humidity, and cloud water.

Emission estimates disaggregated to the 0.5° grid were provided by *Pacyna and Pacyna* [2000] for 1955, 1965, 1975, 1985, 1990, and 1995. Figure 1 shows the yearly totals, peaking at nearly 160,000 tons in 1975, and shows the predominance of automobile emissions. The sharp decrease

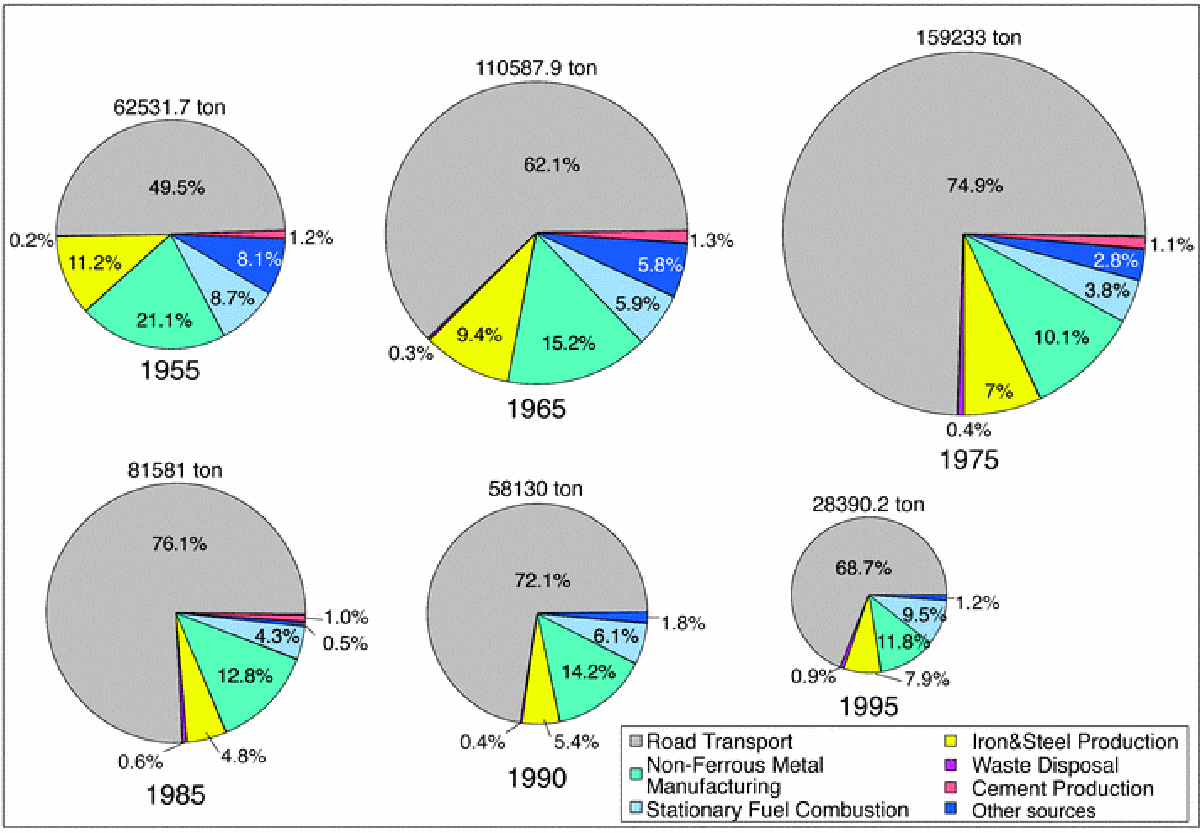

Fig.1. European lead emissions estimates are listed by source category (from *Pacyna and Pacyna* [2000]).

since the 1970s resulted from the gasoline lead additives regulations, as well as from abatement of fixed-source lead emissions (industrial and others).

Using these emission estimates and the regionalized atmospheric forcing, lead concentrations and depositions over Europe were computed by the two-dimensional Lagrangian model TUBES [*Costa-Cabral*, 1999] using a 6-hourly time step and 0.5° spatial resolution. A feature of this model is that flow tubes of variable width are used instead of the commonly used linear trajectories. It was assumed that lead remains within the well-mixed planetary boundary layer, where it is horizontally advected by wind and deposited to the surface by turbulent transport and precipitation scavenging. The dry settling velocity used was 0.2 cm s^{-1}, and the precipitation scavenging constant used was 5 x 10^5.

For validation, the model results were compared with local measurements of lead concentrations and depositions by the European Monitoring and Evaluation Programme [*von Storch et al.*, 2002]. Accumulations of lead in peat bogs are also a good candidate with which to compare the model output (Figure 2). The general pattern of deposition since 1960 is very well reproduced by the model.

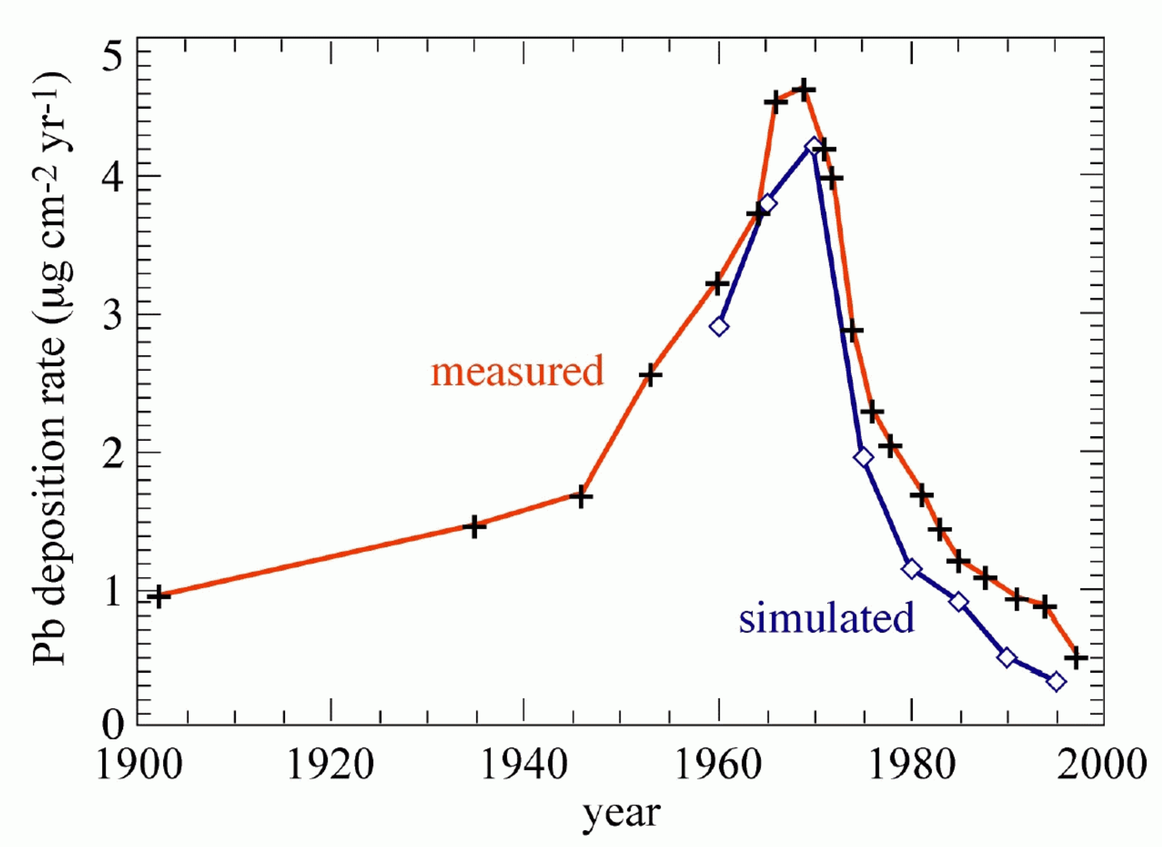

Fig. 2. The lead deposition rate at a peat bog in Denmark is plotted with crosses [*Goodsite et al.*, 2001]; simulated depositions are also shown.

Simulation results indicate that most of the lead deposited in a country originates from its own emissions. Only smaller countries like Switzerland and the Netherlands have suffered substantial depositions from neighboring states [*von Storch et al.*, 2002]. For the Baltic Sea, 23% of total depositions originate from Poland, 20% from Germany, and 16% from Finland. The total input peaked in the mid-1970s, surpassing 3,500 tons annually, and declined to under 500 tons in 1995 (Figure 3). Simulations compare favorably with comprehensive analyses based on observational evidence in the second half of the 1980s (Figure 3).

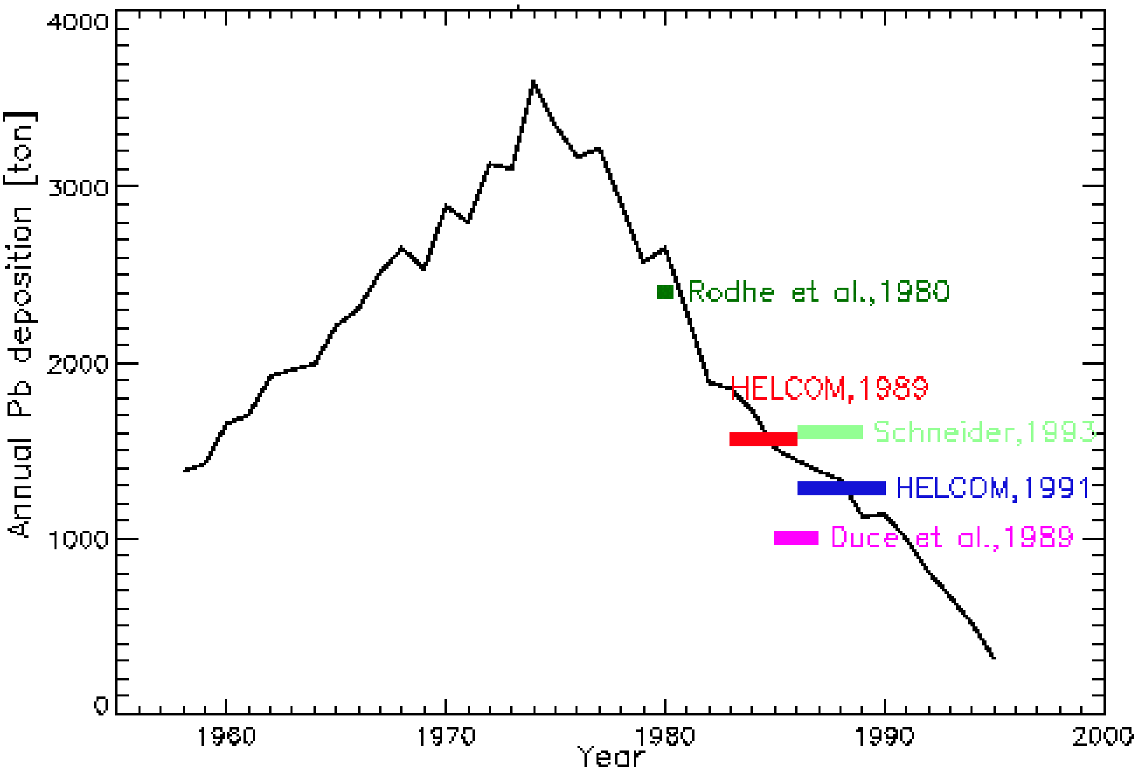

Fig. 3. The input of lead into the Baltic Sea is simulated (line), and estimates based on comprehensive analyses of observational data (colored bars) are also shown.

Environmental and Economic Impacts

Measurements in Germany in the 1980s and 1990s showed that atmospheric lead concentrations were halved about every 4.5 years [*Hagner*, 2000]. The same trend could be observed in plants; from 1985 to 1996, lead levels in annual spruce needles and poplar leaves declined in Germany. But lead levels in marine organisms, such as mussels and fish in the German Wadden Sea, for example, have not diminished since the 1980s [*Hagner*, 2001].

Fom 1979 to 1997, several studies in Germany measured lead levels in human blood. Levels always remained below those indicated by medical experts as hazardous for adults. In Figure 4, the blood lead levels are crudely estimated back to 195, using the recorded lead concentrations in adults blood (in red) and the simulated aerial lead concentrations in one grid box. In the early 1970s, the estimated blood levels (in green) reached a peak level of about 150 µg Pb/l. This estimate is an average value, so some adults may have had concentrations well above 150 µg Pb/l. The mean value of 150 µg Pb/l is below the German Human Biomonitoring Commission threshold of 250 µg Pb/l, above which health risks for adults are expected [*Hagner*, 2000]. However, a critical value of µg Pb/l was adopted for pregnant women and for children. It appears likely that the lead concentrations in ambient air in the mid-1970s may have been high enough to raise serious medical concerns. Interestingly, American researchers believe that the intellectual development of children is already disturbed at a blood lead level of 100 µg Pb/l.

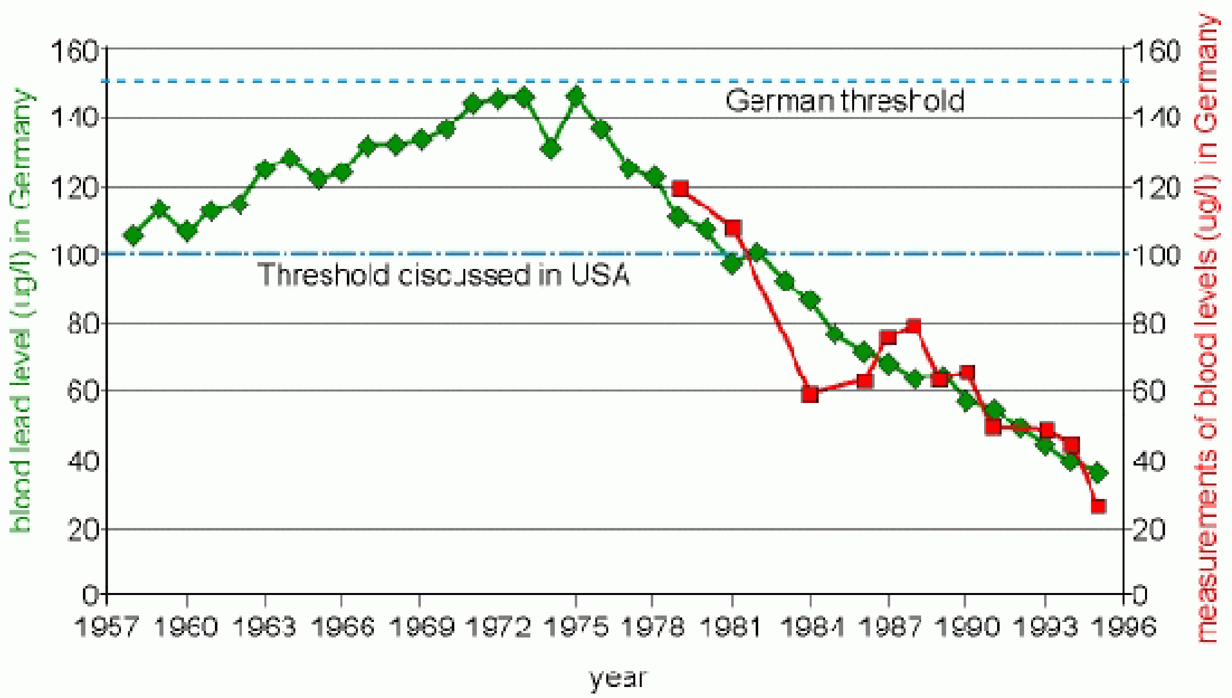

Fig. 4. Lead concentrations in the blood of adults in Germany are plotted; red indicates recorded values and green indicates estimated values.

What about the most immediate economic impacts of the regulations? Despite concerns of the German mineral oil industry that gasoline production costs might increase following the first regulation in 1972, it turned out that its costs actually dropped, thanks to savings in lead additives. Only after the second regulation in 1976 did production costs indeed rise because new additives with high octane numbers were now required to maintain gasoline performance [*Hagner*, 2000].

The impacts of the introduction of unleaded gasoline in 1985 were more complex. Tax incentives for unleaded gasoline and low-emission cars increased sales of both. Most independent gasoline traders went bankrupt, as gas station reconstruction represented a higher financial strain for them than for the large international companies. Automobile manufacturers Daimler-Benz, whose motors were easily compatible with catalysts, and whose customer demand was inelastic, and Volkswagen, which offered a wide selection of catalyst-equipped cars, benefited greatly. Car manufacturers with the highest technical standards, who had already gathered experience with catalyst systems in the U.S. market, were better able to compete [*Hagner*, 2000].

Aside from these shifts in market competition conditions, no significant impact could be seen in German macro-economic indicators, including gross national product, economic growth, price stability, the rate of unemployment, or foreign trade balance.

Summary and Outlook

A tool for reconstructing past lead air concentrations and depositions across Europe has been developed. With the help of regionalized atmospheric data, spatially disaggregated lead emissions from road traffic and point sources, and various local data, an attempt was made to reconstruct the airborne pathways and deposition of gasoline lead in Europe since 1958. Trends in concentrations in biota and human blood were also analyzed, and the most direct economic impacts of gasoline-lead regulations in Germany were evaluated.

For the case of lead, the tool is functioning well. Modeled data show that European reduction regulations for lead additives in gasoline may be considered a successful example of environmental policy. However, the success of lead policies was limited to atmospheric pathways, which had little effect on some marine biota, underscoring the fact that a low residence time is a necessary condition for substance abatement through emission regulations in a given environmental compartment, once considerable substance amounts have already been released. For those anthropogenic substances that persist for a long time in the environment, that are subject to bioaccumulation, and whose main route of human exposure is the food chain, late emission regulations may be ineffective for protecting human health. In such cases, the principle of prevention, by which any significant releases are precluded from the start, may be appropriate.

One should, however, not forget that the large amounts of lead emitted in the past 50 years have not simply vanished but now reside for good—and are ubiquitous--- in the global environment. The use of lead in gasoline was indeed a large-scale geophysical pollution exercise, and it remains to be seen if long-term effects may later emerge.

In the future, the modeling system needs to be extended by modules; by describing the transport in river catchments and channels; and through substance transformations, depositions and resuspension, and the interactions with the ecosystems. Furthermore, the methodology should be applied to other substances; a few candidates are persistent organic pollutants, radioactive substances, and pollens. Because of the increased complexity with respect to such substances, in particular concerning chemical transformations, cooperation partners are sought.

For additional information, refer to: http://w3g.gkss.de/staff/blei. The annual emissions and modeled concentrations and depositions data are available for download from a link on this page.

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[*]**Correction:** After publication of this article, we realized that the correct reference for the measurement-based estimates shown in Figure 2 was not the listed Goodsite et al. (2001) reference, but was the following instead:

Shotyk, W., M.E. Goodsite, F. Roos, J. Heinemeier, W. Rom, P.G. Appleby, R. Frei, G. Asmind, and H.F. Biester, Atmospheric Hg, Pb, and As in peat cores from Greenland and Denmark dated using the 14C ams bomb pulse technique and 210Pb: concentrations, natural and anthropogenic enrichments, and fluxes. Earth and Planetary Science Letters (revision in preparation).