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# The UK Clean Air Act, Black Smoke, and Infant Mortality[*]

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## Abstract

This paper estimates the effects of the 1956 UK Clean Air Act on infant mortality. Using novel data, I exploit the seasonality in demand for coal to analyze the effects of a staggered expansion of a ban on local smoke emission. The findings show that the policy eliminated the seasonal difference in air quality as well as infant mortality. According to my instrumental variables estimates, the reduction in air pollution between 1957 and 1973 can account for 70 % of the observed decline in infant mortality during the same period. The results are relevant to explain the fast decline in post-war infant mortality in developed countries and understand the effect of pollution on infant mortality in many developing countries.

*Keywords*: Health economics, Child mortality, Air pollution, Air pollution control

JEL *Classification*: *I12, J13, N540, Q51, Q53, Q58*

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# 1 Introduction

Many high-income countries experienced an extraordinarily rapid decline in infant mortality in the 20th century. The most common explanations for the sharp fall in infant mortality are medical interventions, increased health-care provision, and poverty reduction. Less attention is paid to the impact of improvement in air quality to explain the reduction. For example, in London, ambient smoke particle concentration (black smoke) declined from thirty times the level of exposure considered safe by WHO, to just above the recommended level between 1956 and 1990. One reason for the lack of association between infant mortality and air quality is the scarcity of historical data. Another reason is that most studies on air quality and infant health are from high-income countries with levels and sources of pollution vastly different from those that prevailed well into the second half of the 20th century, particularly in coal-dependent countries such as the UK.

The lack of evidence on the health impact from high-level pollution is also of concern, since air pollution exposure for the vast majority of people living in low- and middle-income countries far exceeds any limits considered safe. Three similarities between pollution in low- and middle-income countries today and the UK in the 1950s–1970s make the analysis particularly relevant. First, the historical levels of pollution in the UK and pollution levels in developing countries today are comparable. Second, coal emissions account for a large share of ambient air pollution. Third, a large fraction of air pollution comes from smoke emitted by households.

In this paper, I use novel historical data from the 1956 UK Clean Air Act to investigate its largely unknown effects on smoke particles (black smoke) and infant mortality, and explore the role of high-level air pollution on infant mortality.[1] In particular, I analyze the effect of a subsection of the act

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[1] The Clean Air Act was enacted as a direct response to the London smog episode in December 1952 that is estimated to have killed up to 12,000 people in the weeks following the incident.

that gave local authorities in the UK the mandate to ban smoke emission in designated smoke control areas (SCAs). The work builds on an extensive data collection effort. I have digitized information for more than 1,100 smoke control areas and compiled quarterly sub-national data on infant mortality. Other data work includes digitizing archived local industry employment, and pollution data, and industry input data from input-output tables for the UK. The panel data consists of 58 urban locations (County Boroughs), excluding London, in England between 1957–1973, representing 20 % of England's total population in 1961.

The staggered expansion of SCAs across County Boroughs and the seasonality in demand for heating allows me to exclude possible confounders from the policy effect using a triple-difference identification strategy. The results show that the policy accounted for 18% of the total reduction in black smoke concentration between 1957–1973, and effectively eliminated the seasonal variation in smoke pollution caused by a surge in coal demand for heating in the winter season. The results also show that the policy successfully erased the difference in summer- and winter-infant mortality and reduced baseline mortality by over 15%.

A central challenge in the literature seeking to estimate the effects of air pollution is that pollution exposure typically correlates with other factors that may affect the outcomes of interest. The policy-induced sharp drop in smoke pollution allows me to treat SCAs as an instrument for black smoke concentration, to analyze the effect of coal burning on infant mortality. The instrumental variable regression (IV) estimates suggest that a microgram per cubic meter reduction in black smoke concentration reduced infant mortality by 0.04 deaths per 1,000 live births. With smoke particles falling by $200\mu g/m^3$ on average over the whole period, the effect corresponds to a 30% reduction in baseline mortality, and can possibly explain as much as 70% of the sample's reduction in infant mortality.

The considerable variation in smoke pollution allows me to compare my results with estimates in the existing literature and investigate plausible heterogeneity in the marginal effect at levels of pollution not previously studied. The analysis reveals that fears of increasing marginal effects of air pollution on infant mortality are likely unfounded. Additionally, the results suggest that the impact is larger on male infants and the youngest infants in particular. I also find suggestive evidence that infants in socioeconomically vulnerable groups are affected the most. Finally, the results reveal that smoke pollution from coal reduces fertility, suggesting that the effect on infant mortality is an underestimation of the true impact of pollution on infant health.

This paper contributes to the body of literature that explains the reduction in infant mortality in the previous century and presents new evidence on the broader impacts of the UK Clean Air Act. So far, the existing literature on the historical reduction in infant mortality has mainly relied on time series data to analyze the effects of, for example, medical interventions and nutrition (CDC, 1999 and Wegman, 2001), poverty reduction (Dorling, 2008; Turner et al., 2020), and maternal care (Fryer and Ashford, 1972). This paper adds to the literature by using multiple sources of variation to identify the role of pollution in reducing infant mortality. Following the pioneering work by Chay et al. (2003) and Chay and Greenstone (2003a), who estimate the effects of the US Clean Air Act on health, several studies have studied the impact of air pollution regulation on local air quality and health.[2] However, the UK Clean Air Act differs from previous studies in various aspects by targeting emissions from industries and households alike, and by providing financial support to private dwellings to enable changes in heating technology, making it a compelling complement to the analysis of the US Clean Air Act.

This paper also makes several contributions to the literature on the effect

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[2] For papers on the effect of environmental regulations in the US context, see, for example, Sanders and Stoecker (2015) and Auffhammer and Kellogg (2011). For analysis of environmental policy impact in developing countries, see Tanaka (2015) and Greenstone and Hanna (2014).

of air pollution on health. Notably, it studies the impact of air pollution at much higher levels than in previous studies. It also investigates the health impact of coal, which we have little knowledge of despite its widespread and dominant role as an air pollutant.[3] Finally, the paper departs from previous literature by extending the investigation of the effect of air pollution on live birth outcomes to its impact on fertility (see Currie et al., 2014 for an extensive review of that literature).

The rest of the paper is organized as follows. Section 2 provides the historical background and descriptive statistics on infant mortality, air pollution, and environmental regulations in the UK. Section 3 describes the data. Section 4 discusses identification strategies. Section 5 presents the results of the analysis, along with the results from the robustness analysis. A discussion of the results is presented in section 6, while section 7 concludes the analysis.

# 2 Background

## 2.1 Clean Air Act and Smoke Control Orders

Attempts to curb the problem with smoke pollution started in the late 19th century and the early 20th century. However, none proved effective due to the vague formulation of the laws and the fact that residential houses were exempt (Ashby, 1977). Even though lawmakers were aware that any attempt to control smoke emission was doomed to fail without addressing the households, the immense popularity of open fires across all social classes was a tremendous obstacle to overcome. It was not until the Great Smog of London in December 1952 that brought premature death to thousands of citizens that the public became aware of the hazards of smoke and was

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[3] Some exceptions that study the effect of coal on health are Beach and Hanlon (2017) and Barreca et al. (2014), who use historical data to construct indirect measures of industrial coal usage and household coal consumption to analyze its effect on infant mortality. However, none of these studies have pollution data to measure the direct link between air pollution and health.

sufficiently prepared to welcome the swift passing of the Clean Air Act in 1956.

The law was enacted at the very height of UK coal dependency and prohibited the emission of dark smoke from chimneys, but, more importantly, gave the local authorities the mandate to create Smoke Control Areas (SCAs).[4] Instead of focusing on the shade of smoke from industries, SCAs prohibited the emission of *any smoke* of *any color* from *any premises* within the designated area.[5] The banning of all visible smoke emissions within a specified area meant that monitoring regulation compliance required no special equipment or training, and was therefore less likely to discriminate against houses closer to gauge stations. Violating a smoke control order carried a maximum fine of 10 pounds per offense, until the late 1960s when the fine doubled to 20 pounds.[6] The local authorities were free to decide the start dates of the orders but required to provide a minimum of six months' notice to the public by taking suitable steps to bring the effect of the order to the notice of persons affected. The announcement of the first orders appeared in 1957. Although few in numbers at the start, they quickly escalated to over 2,500 orders of varying sizes by 1973, in about half of the 329 local authorities then in existence in England.

To meet the new restrictions, the owner of a private dwelling could ei-

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[4] Data on coal consumption from 1853 indicate that the domestic coal consumption peaked in 1956 with 221 million tons. (Department for Business, Energy & Industrial Strategy, 2019)

[5] The Clean Air Act of 1956 and its supplementary Smoke Control Orders only targeted emission of smoke and no other air pollutants including gaseous pollutants. For example, although the high concentration of sulfur dioxide was known to the government, they could not amass enough support to regulate the pollutant, mainly based on the belief that abatement of sulfur dioxide was unattainable for the industry at the time.

[6] 10 GBP in 1956 and 1968 is approximately 200 GBP and 140 GBP in 2017, respectively. The amounts correspond to the gross weekly earnings for a full-time adult male manual worker in each period. In a separate paper, Fukushima (2021) studies the impact the increase in fines had on air pollution. She finds that the regulation effect on pollution increased after doubling the monetary penalty. Nevertheless, the effect is secondary to the main effect, which is why its effects are studied separately.

ther replace bituminous coal with a smokeless fuel such as anthracite, or other manufactured smokeless fuel, or make adjustments to the dwelling and expect a minimum 70% reimbursement from the local authority.[7] The reimbursement scheme, however, did not apply to new dwellings or commercial or industrial plants.[8] The local authority would receive a contribution from the exchequer as large as "four-sevenths" of the cost, to meet the rise in public spending due to the generous reimbursement scheme.

It is commonly held that coal fires were the predominant form of heating in most dwellings at the end of the 1950s, and remained so well into the 1960s. For example, random sample data collected for the Schoolchild Chest Health Survey (1980) in 1966 in urban and rural areas in England and Wales suggests that central heating, the preferred method of heating today, was only adopted in approximately 17% of urban households by 1966, and highly correlated with socioeconomic status (see Appendix D for further details).[9] By 1970, the first nationwide data on home heating shows that central heating was installed in a quarter of all homes, although half of these systems still relied on coal burners to produce heat. Only with the discovery of natural gas in the North Sea in the early 60s with subsequent production beginning in 1967, did the energy market for industries and private homes start to transform drastically (Palmer and Cooper, 2013). The slow adoption of the central heating system and correlation with socioeconomic status suggest

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[7] Although the supply of smokeless fuel remained stable initially, concerns over a supply shortage started to appear in the political discussion from 1964. To keep the price of authorized coal from rising, the Government began denying approval of smoke control areas in urban local authorities where air quality was not considered alarming (Scarrow, 1972).

[8] Furnaces with less than 55,000 British thermal units per hour per house were considered to be for domestic purposes. In addition, an occupier of a private dwelling who is not the owner could only expect a maximum of 35 percent reimbursement (see Fukushima (2021) for more details).

[9] In comparison, Barreca et al. (2014) report that central heating systems were installed in 42 percent of US households in 1940 and only 55 percent of the households depended on the use of coal for heating. The use of bituminous coal for home heating in the US was as low as 9 percent by 1960.

that liquidity-constrained households facing smoke control orders were more likely choose to comply with the regulation by replacing smoke-producing bituminous coal with smokeless fuel.

Black smoke was the first and the most common type of ambient air pollutant measured until the late 1990s. At the start, black smoke concentration was compiled by the Investigation of Atmospheric Pollution run by the Warren Spring Laboratory. The organization was first set up in 1912 with less than 30 participating bodies, but had more than 500 participants and approximately 1,200 monitoring sites by 1961 when it changed its name to the National Survey of Smoke and Sulfur Dioxide and become the world's first coordinated national air pollution monitoring network. The organization evolved from being an interest group consisting of the leading figures in atmospheric research and the smoke abatement movement, to a collaboration between clean air groups, the central government, local authorities, industry, and other institutions by the mid-1960s. Despite their difference in interests and agendas, the collaboration is by many considered a great success (Mosley, 2009).

Black smoke was measured using smoke samplers that drew 50 cubic meters of air through a white filter paper over 24 hours.[10] The density of the deposit was then assessed using a reflectometer, or in the earlier days, by the naked eye. Since an early investigation by McFarland et al. (1982) showing that a standard black smoke sampler was capable of capturing fine particulate matter less than 4.4 micrometers in diameter, i.e. PM4.4, additional studies have suggested that black smoke sampled in the UK before the early 1970s can reasonably be compared to particulate matter less than 2.5 micrometers in diameter, i.e. PM2.5.[11] Particulate matter this small is particularly dam-

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[10] Black smoke sampling was replaced by sampling particulate matter, starting in the 1990s.

[11] The comparison between black smoke and PM2.5 is possible since most particles emitted from the combustion of coal are of size smaller than 2.5 micrometers in diameter, and given the absence of air-pollution from other sources in the UK at the time. For further discussion on comparability, see appendix A.

aging to health as it can penetrate into the respiratory system and reach a wide range of internal organs. Besides black carbon, coal combustion releases particles containing a complex mixture of organic carbons and toxic elements such as arsenic, silicon dioxide, cadmium and calcium oxide, in addition to toxins such as fluorine, selenium, and lead.

## 2.2 Infant mortality

Infant mortality is often preferred to adult mortality when measuring the health impact of pollution exposure because it circumvents the issue of "harvesting" and is less sensitive to variation in hard-to-measure lifetime exposure to pollution. Figure 1a shows the rapid decline in infant mortality in England and Wales following WWII. Starting at over 40 deaths per 1,000 live births in 1946, it quickly plummeted to less than ten deaths per 1,000 births by 1980. In 2017, it had dropped to four deaths per 1,000 live births. The fall is explained mainly by the decline in neonatal deaths, i.e. deaths before 28 days. In comparison, stillbirth rates in the postwar period initially remained stable at around 23 deaths per 1,000 live births but experienced a rapid decline starting in 1957, converging to the neonatal death rate by 1973. The high rate of infant mortality in urban areas compared to rural areas in Britain is well documented, for example, by Lee (1991), and also observed in the current analysis. Comparing the sample mean to the national mean reveals that mean infant mortality rate in the sample starts at a much higher rate in 1957 (28 deaths per 1,000 live births compared to 23 deaths per 1,000 live births) but converges to the national mean by 1973.[12]

Perinatal complications, i.e. in the period between 28 weeks of gestation and one week of birth, accounted for about half of all infant deaths in the UK at the time. The two most common causes of death in newborns (0 - 28 days) related to perinatal complications between 1950–1978 are short

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[12] Common explanations for the higher mortality are housing density, sanitation, mining industry, and various illnesses.

gestation/low birth weight and respiratory conditions. These are shown in Figure 1b.[13] While both graphs show each cause of death falling, we observe the fastest decline in short gestation and low birth weight, led by a reduction in deaths of male infants. Of particular interest for this paper are the kinks observed in 1957, coinciding with the start of the Clean Air Act. While the graphs cannot point us to the cause, they seem to suggest the existence of an exogenous event that changed the course of infant health dramatically.

# 3 Data

## 3.1 Smoke Control Areas

The study is confined to densely populated urban areas in England that remained intact between 1957–1973 without missing data on infant mortality, pollution, or other key covariates. The subjects of the analysis are English county boroughs (CBs) and exclude London.[14] Combined, these areas represented 20% of the total population in England in 1961.[15] Fifty-eight of a total of eighty-three CBs in England kept their status and boundaries unchanged between 1955–1973. Of these, 45 CBs introduced at least one smoke control order before 1973 and are henceforward referred to as adopters, while the remaining thirteen CBs never introduced a smoke control order and are referred to as non-adopters.[16]

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[13] The remaining categories are *other causes* at just under 40 percent, *influenza and pneumonia* at approximately 10 percent, and *tuberculosis* for the remaining share.

[14] Appendix H includes a comprehensive list of accessible data for all county boroughs.

[15] The first CBs were created in 1889 and referred to cities or boroughs that, owing to their population size and density, were granted administrative independence from County Councils, which was the administrative body in the absence of such title. Bath, Dudley, and Oxford, however, were granted the status even before reaching the population size due to their historical significance. New CBs appeared as the population surged, but the practice of changing status to a CB was more or less suspended after the second world war and abolished altogether in the 1972 Local Government Act.

[16] Ten additional CBs were dropped from the sample. In particular, six CBs did not monitor air pollution during the period, while birth data was of questionable quality in

The location and information on more than 1,100 Smoke Control Orders were collected via communication with local authorities or via local historical archives but, in most instances, from public notices in historical editions of the London Gazette. Although a standard template for an announcement of a smoke control order did not exist, most orders state i ) the name of the order, ii) the area of the subject, iii) the size of the fine, iv) the operation date, and v) the date of the agreement/announcement.[17] Data made available from different sources have been cross-validated.

The geographic boundary of each SCA was digitized according to the description in the order and the fraction of SCAs derived as the share of total hectares of land dedicated to SCAs within a CB in any given month.[18] The 'operation date' defines the start date of the ordinance and was considered preferable to 'announcement date' in the analysis. However, given that the operation date also captures households that complied with the reform in advance of the date of enactment, the result of the analysis is downward biased.

A local authority would typically announce and publicize a smoke control order 12–18 months in advance (Mean: 16.3, SD:11.6), with 75 percent setting a start date in the second half of the calendar year. If the start date was lost beyond recovery, as was the case of a limited number of orders (96), the average number of months from announcement to start date of the remaining orders within the CB was used to replace the missing data.

Figure 2 shows the geographic location of the CBs and the fraction of land covered by SCAs in 1957, 1965, and 1973. The graphs illustrate the spatial and temporal variation in the timing and the rate of SCA adoption and reveal the location of adopters and non-adopters. For instance, we see that adopters are predominantly located in the midlands and the northern

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four.

[17] For an example of a smoke control order from the London Gazette, see appendix C.

[18] Archived maps of the local area used when the current topography has changed beyond recognition.

regions, while the coastal cities in the south-east are, to a greater extent, home to non-adopting CBs. Figure 3, complements the previous figure by showing the variation in SCA coverage, i.e. treatment intensity, by year. It shows that just under 50 percent of the total land area was covered by SCAs in 1973 by adopters on average. Including non-adopters, the number drops to 35 percent.

## 3.2 Infant mortality

The data on infant mortality was compiled using a transcribed civil registration index of births, marriages, and deaths for England and Wales published by the genealogy website Freebmd.org.uk. The civil registration index is organized chronologically by event, year, and quarter of registration. The birth registry includes information on the individual's surname, given name, mother's maiden name, and the administrative area of registration, while the deaths registry includes information on the surname, given name, place name, and the age of the deceased in years. Throughout the period, all deaths were legally required to be reported within five days of the event, while births had to be registered within 42 days of delivery.[19]

Data were obtained for the period 1957–1973, and a search of the deceased, restricted to age under 1. No information on gestation period or birth weight exists. However, since the death registry is restricted to death after live birth and life-supporting technology for preterm birth was not yet invented at the time, we may with some confidence bound the age of the children in the death registry to 28 weeks from conception to one year after birth.[20] Data were cleaned from human errors and differences in the regis-

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[19] While there are few reasons to expect low compliance in the reporting of births and deaths in the UK at the time, the free health care service provided by the national health service (NHS) to all residents since 1948 additionally reduces any risk in differences in the incentive to report a pregnancy across regions or over time.

[20] A separate national register for stillbirths exists but is not available to the public.

tration procedures related to the parents' marital status were considered.[21] In addition, county boroughs for which the civil registration uptake area substantially contrasted that of the administrative boundary, or where the area suddenly changed, affecting the number of reported births, were omitted from the analysis.[22] A further caveat is the absence of the 4th quarter mortality data from 1964 due to only half of the December births records from 1964 having yet been transcribed at the time of this project.[23]

Infant mortality is defined as the probability that an infant born in a specific quarter will die before reaching 1 year of age and is derived by dividing the quarterly number of deaths by the quarterly number of live births*1,000 for each CB. The total number of births and deaths in the sample is 3,572,147 and 87,670, respectively and the pooled sample mean is 24.5 deaths per 1,000 live births.

To study if the effect of pollution varies with the age of the infants, I used the surname(s), given name(s), and information on the deceased's location at death (CB) and match it with the birth record in the corresponding quarter or any of the preceding four quarters prior to death to obtain an approximate age interval in quarters. The matching exercise successfully links death and birth for more than three-quarters of the individuals in the death registry, while the age at death for the remaining infants remains unidentified. Although one may worry that the age at death in quarters is a somewhat crude estimate, over 80 percent of all identified deaths are registered in the same quarter as births, suggesting that most deaths occurred in the first three months after birth.[24] Finally, the sex of the identified group of infants was

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[21] For example, misplaced and unspecified individuals were removed before names were cleaned and standardized. All duplicate birth entries were also dropped from the sample since a significant share of children were registered twice, which was the custom if a child had been born to an unmarried couple.

[22] For example, Bootle, Rochdale, Wigan, and York were entirely omitted in the analysis. For other changes, see Appendix H.

[23] In comparison, Freebmd reports that >99% of records have been digitized for the remaining years.

[24] In comparison, the official data from the Office of National Statistics report that

identified using the first name of the deceased.[25] The results reveal that 56.4 percent and 39.9 percent of the deceased are males and females, respectively. The gender of the remaining individuals, however, could not be verified.[26]

## 3.3 Black smoke

The pollution data between 1957–1961 comes from the annual reports published by the Investigation of Atmospheric Pollution, while the data for 1961–1973 is freely accessible via the website of the Department for Environment, Food & Rural Affairs (DEFRA).[27] The transcript records for black smoke are reported in monthly units and consist of mean daily concentration and mean highest daily concentration recorded at each active gauge site.[28] The number of active gauge sites per county borough during the observation period is approximately four, with one site per 1,250 ha on average. The pollution data is weighted by the inverse distance from the city center, to allow for spatial variation in population density within CBs.[29] However, none of the results in the study change substantially if the unweighted pollution records are used.

Figure 4 illustrates the sample average black smoke concentration by sea-

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around 50 percent of all infant deaths in England and Wales occur within the first week after birth at the time.

[25] Python gender-guesser 0.4.0 using UK name dictionary. The high matching score is likely the result of the high prevalence of traditional British names at the time.

[26] See Appendix E for further details regarding the deaths of unidentified infants.

[27] While the information for the first and the last quarter of 1961 exists, the 1961 summer quarters, i.e., quarters two and three, are not accounted for in any source.

[28] Despite increasing interest in pollution surveillance, some county boroughs never established the practice to measure or only started measuring late in the period. For example, pollution gauging was less common among non-adopters, with Great Yarmouth, Grimsby, Hastings, and Worcester having no data on pollution during the entire period and Canterbury, Carlisle, Chester, Rotherham, and Sunderland having less than ten consecutive years of pollution data. Among adopters, Dewsbury and Southport never measured pollution, while Burton-upon-Trent only has consecutive data for less than ten years. See appendix H for further details.

[29] The eight-digit grid reference system allows us to locate the gauge site to 10-meter precision.

son and year between 1957 and 1973. Two patterns immediately stand out. First, black smoke concentration is significantly higher in the colder winter months.[30] Second, while both seasons display declining smoke particle concentration, the fastest reduction is observed in the winter. The graph also reveals that PM2.5 exposure is much higher than 25 micrograms per cubic meter – the maximum level of exposure over 24 hours recommended by WHO – throughout the analysis, both in regards to level and duration. It also reveals that pollution in the UK was comparable to the most polluted place in the world on record today (horizontal line).[31]

## 3.4 Additional data

Information on CB industry employment, unemployment, and population come from the 1951, 1961, 1966 and 1971 Census of England and Wales: Occupation, Industry, Socioeconomic Groups. A per-capita industry fuel-dependency variable has been constructed using the input-output matrices from 1954, 1963, 1968 and 1974, matched against the nearest industry data from the 1951, 1961, 1966 and 1971 censuses.[32] Annual fiscal data for the county boroughs was compiled in the mid-1970s as part of a project to map local government expenditure and is available via UK Data Archive (Le Grand

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[30] While industries were by no means innocent, the low height of chimneys, ineffective combustion methods, and population density explain why private dwellings were the more significant polluters in many urban areas. Similarly, Almond et al. (2009) find that total suspended particles (TSP) were 300 mg/m3 higher in cities north of Huai River in China with access to a free supply of coal for winter heating in home and offices.

[31] The highest annual mean level of PM2.5 concentration as per the Ambient Air Quality Database by WHO (2018) was measured in Kanpur, India, in 2016. Appendix B displays the top 10 most polluted places on record from the same database.

[32] Industry fuel-dependency ratio (IFDPC);

$$IFDPC_{c,t} = \frac{\sum_{i=i}^{I} Emp_{i,c,t} * \frac{Fuel_{i,t}}{\sum_{i=1}^{I} Fuel_{i,t}}}{Pop_{c,t}}, \tag{1}$$

where $Fuel = \{Coal, Coke, Oil, Electricity, Gas\&Water\}$ and $Emp$ is employment in industry $i$ in county borough $c$ in year $t$.

and Winter, 1980).[33] With the exception of rateable property value and tax collection, for which information is available from 1951, fiscal data exits for the years 1957(59)–1973.[34]

# 4 Empirical strategy

To identify policy impact, I exploit the spatial and temporal variation in SCA roll-out and its variation in intensity using a staggered difference-in-difference identification strategy. A difference-in-difference strategy, however, must satisfy the assumptions of treatment exogeneity and parallel trends. In this paper's context, this means that we must be sure that the timing of SCA expansion is orthogonal to unobserved factors explaining the reduction in infant mortality, and that there are no underlying trends that explain the difference in the outcome. Ideally, one would have a long period of pre-intervention data to verify the parallel trends assumption. However, with no data before 1957, I resort to comparing baseline observables across different subgroups. The idea behind the comparison exercise is that if we can show that the observables are the same, it increases the likelihood of the unobservables being the same and, therefore, the probability that the parallel trends assumption holds.

However, a comparison of baseline observables between non-adopters and adopters, on the one hand, and between aggressive and moderate SCA adopters (or early and late adopters), reveals considerable differences in several characteristics. Table 1 displays the results for the difference in the speed of adoption, while the results for early and late adopters are shown in Appendix F. For example, compared to non-adopters, adopters have less energy-intensive

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[33] Although extensive in composition, the parsimonious description of the variables greatly limits its potentiality. Hence, I restrict the use of the data to include the most intelligible variables of interest and limit other plausibly relevant variables in the robustness analysis.

[34] Rateable value is an official value given to a building in the UK, based partly on its size and type, which decided how much local tax the owner had to pay.

industries but are still significantly more polluted.[35] SCA adopting county boroughs also tend to be more populous, slightly younger, and more impoverished than non-adopting county boroughs. While differences between more aggressive and moderate adopters of SCAs are not as pronounced, a random roll-out of SCAs seems unlikely, and although a comparison of the baseline characteristics by the timing of adoption shows no difference in observables between early and late adopters with the exception of pollution, the tables reveal that the identification assumptions are less likely to hold.[36]

To overcome the threats in the proposed identification strategy, I exploit the seasonal variation in the demand for coal in a triple-difference identification strategy (DDD). The third source of variation arises from the theory that even if SCAs are adopted, the SCA impact will vary with the season due to the seasonal variation in the demand for heating. Thus, if the winter season is treated while summer is not, we can use the summer season as a natural control group within each county borough-year-cell to compare the effect of SCAs against. The suggested identification strategy will take care of any unobserved factors that are correlated with both the outcome variable and SCA but that do not vary by season, and holds under the assumption that the summer season shares all relevant characteristics with the winter season, except for the treatment assignment.

Before proceeding to the formal DDD strategy, however, we must test that the assumption of seasonality in reform impact is justified. For the purpose, I exploit the variation in the adoption of SCAs with respect to space, time, and coverage intensity to analyze its effect on black smoke concentration. To capture any variation in demand for coal, I allow for heterogeneity in impact by calendar month according to the following specification:

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[35] While this may seem at odds with the modern perception of the source of pollution in the developed countries, the accumulated emissions from private dwellings from heating with solid fuel was in many places more severe than emissions from industries.

[36] 36 CBs implemented their first SCA between 1958 -1963, while only 7 implemented after 1965.

$$BS_{cym} = \sum_{m \in M} \theta_m SCA_{cym} + \varphi X_{c,1957} \times t + \alpha_m + \sigma_y + \omega_c + \epsilon_{cym} \qquad (2)$$

where BS is the black smoke concentration in county borough $c$ in year $y$ and month $m$ and $SCA \in [0, 1]$ is the corresponding smoke control designated fraction of land that varies by month $M = \{1, 2, ..., 12\}$. The year and month fixed effects, $\sigma_y$ and $\alpha_m$, absorb common time-shocks across county boroughs while the county borough fixed effects control for all unobserved determinants of black smoke concentration that are constant over time. A vector of baseline covariates, $X$, including tax raised per capita, average property value per capita, and the log of the 1957 population, is interacted with linear time trend, $t$.[37] The parameter of interest is captured by $\theta_m$.[38]

Figure 5 displays the average effect of SCAs in reducing black smoke concentration across calendar months, along with the average level of concentration. The results show that SCAs significantly reduced black smoke concentration from January to March and again from October to December but had no effect in the summer (April–September). The analysis verifies the assumption that and SCA was most effective in reducing black smoke concentration in the cold season but had no effect in the summer season when the need for heating was substantially lower. Also, the lack of effect in the summer and the proportional impact of SCAs on black smoke concentration relative to its mean levels is particularly noteworthy as it reveals the effectiveness of SCAs in targeting the use of bituminous coal and reduces the possibility that factors unrelated to SCAs are driving the results.

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[37] I use the baseline 1957 value instead of the covariates' annual value since the latter may be endogenous with treatment. The linear time-trend, on the other hand, is included to consider variable evolution over time.

[38] The analysis includes non-adopting county boroughs to deal with the issue of negative weights from heterogeneous treatment effects caused by unit and time fixed effects.(de Chaisemartin and D'Haultfœuille, 2020).

The heterogeneity in impact provides us with a credible assurance that we may separate treatment status by season. By constructing a dummy variable for the winter season, where the quarters covering October–December and January–March are treated (1) and April–June and July–September are untreated (0), I implement the following triple-difference specification:

$$Y_{cyq} = \beta_0 + \beta_1 SCA_{cyq} + \beta_2 (SCA_{cyq} \times Winter_q) + \omega_{qy} + \sigma_{yc} + \tau_{cq} + \epsilon_{cyq} \quad (3)$$

where the outcome variable, $Y$, is black smoke concentration or infant mortality rate, and $SCA \in [0, 1]$ is, as before, the smoke control designated fraction of land in county borough $c$ in quarter $q$ and year $y$. By interacting SCA coverage with winter, we allow for heterogeneity in effect to depend on the season. $\beta_1$ will then capture the average impact of changes in SCA adoption across the summer quarters while $\beta_2$ captures any deviation in impact from the summer season related to the expansion of SCA. The sets of two-way fixed effects are county borough-by-year, quarter-by-year, and county borough-by-quarter fixed effects. County borough-by-year fixed effects control unit and year-specific fluctuations, such as local economic activity or migration flow. In contrast, quarter-by-year fixed effects control factors common to a year and quarter, such as severe seasonal influenza outbreaks or weather phenomena, and county borough-by-quarter fixed effects control for seasonal differences across county boroughs, such as geography induced variation in the impact of weather.[39]

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[39] For example, location and topography may have different effects on the pollution depending on the season.

## 4.1 Instrumental variable approach

In the next part of the analysis, I estimate the effect of black smoke on infant mortality. Figure 6 shows the relationship between the log-transformed average quarterly black smoke concentration and IMR by season. Despite the strong association between the variables, we cannot presume causality. In particular, the relationship might be explained by poverty or by secular trends in infant mortality and black smoke concentration that could generate similar variable alignments, independent of the effect of pollution on health.[40] Although unit and time fixed effects are a natural starting point to alleviate biases, the strategy fails to remedy unobservables that vary with county borough and year. For example, an extreme local drop in temperature may cause a temporal surge in deaths while also increasing coal demand. Failure to consider correlation with the unobservables will then lead us to overestimate black smoke's impact on infant mortality. Bias in estimates may also arise from a sudden economic shock in a county borough that may increase infant mortality and decrease the household resources spent on heating, leading us to underestimate the impact of black smoke on health. Moreover, the strategy fails to correct measurement error in the pollution data, leading to attenuation bias in the estimates.

To cut the ties to possible confounders and correct the measurement errors in pollution data, I use the shift in black smoke concentration caused by SCA in an instrumental variable (IV) regression analysis. The IV strategy, however, must satisfy the assumptions of instrument relevance and exclusion restriction. In other words, the IV assumptions require SCA to be relevant enough to explain the variation in black smoke concentration but not affect the outcome in any other way than through its effect on black smoke. With the knowledge that SCA is a good predictor of black smoke concentration and the CAA formulated to target smoke emission explicitly, I claim these

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[40] For instance, we can imagine the relationship is explained by improvements in maternity care and fuel technology.

conditions are likely satisfied.[41]

The two stage least square equations identifying the relationship between IMR and black smoke are;

Second stage:

$$IMR_{cyq} = \mu + \rho BS_{cyq} + \gamma X_{c,1957} \times t + \tau_{2,q} + \sigma_{2,y} + \omega_{2,c} + \epsilon_{2,cyq} \tag{4}$$

First stage:

$$\begin{split} BS_{cyq} = \lambda_0 + \lambda_1 SCA_{cyq} + \lambda_2(SCA_{cyq} \times Winter_q) + \\ \varphi X_{c,1957} \times t + \tau_{1,q} + \sigma_{1,y} + \omega_{1,c} + \epsilon_{1,cyq} \end{split} \tag{5}$$

where $BS_{cyq}$ and $IMR_{cyq}$ are the levels of black smoke concentration and IMR in county borough $c$ in year $y$ and quarter $q$. Year, quarter, and county borough fixed effects are denoted $\sigma_y$, $\tau_q$ and $\xi_c$, respectively. $X$ includes the same economic and population covariates from 1957 interacted with linear time trend $t$ to control for unobserved trends correlated with the expansion of SCAs and infant mortality. SCA coverage is again interacted with a dummy for the winter-season to capture the seasonal difference in SCA impact. As such, the first stage equation is a triple-difference equation with causal properties on its own. Finally, the coefficient of interest, $\rho$, in equation 4, measures the impact of a one microgram increase in black smoke concentration on infant mortality per 1,000 live births.

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[41] Although a limitation when studying the effect of pollution on health is that a specific pollutant seldom exists in confinement from other air pollutants, an advantage in the current setting is that smoke particles have a single point of source in coal combustion. In effect, one may consider the strategy to identify a reduced form effect of coal combustion on infant mortality.

# 5 Results

## 5.1 The impact of Clean Air Act

The effect of SCAs is displayed in Table 2. Panel A displays the impact on black smoke concentration while Panel B shows the effect of the SCA on IMR. Column (1) contains the results from a difference-in-difference (DD) analysis, while columns (2) and (3) display the results of the triple-difference analysis (DDD) as defined in equation (3).

The large negative coefficient in Panel A column (1) suggests that SCAs had a sizable effect in reducing black smoke concentration. However, in column (2), we see that once we interact SCAs with a winter dummy, the effect is exclusive to the winter season, as also shown in Figure 5. The absence of effect in the summer season and the magnitude of the impact, which is comparable to the average seasonal difference in black smoke concentration, suggest a high compliance rate and that the regulation was effective in targeting the source of pollution. Column (3) shows that the effect remains robust to including two-way FEs.

Panel B, column (1), shows that SCAs had a seemingly negative effect on infant mortality, albeit insignificant. However, once we interact SCAs with a winter dummy, the results in column (2) reveal that the effect was large and significant in the winter season and increases further when controlling for two-way FE, as shown in column (3). The coefficients suggest a change in SCA coverage from 0 to 100% reduced winter mortality by 4.3 - 5.3 deaths per 1,000 births. Notably, the effect size is similar to the difference in the seasonal infant mortality among adopters.[42]

The evidence showing that regulation impact is isolated to the winter season is compelling for several reasons. First, although the reduced form analysis studies the total effect of the regulation on black smoke concentration

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[42] The effects remain more or less similar if non-adopters are excluded and do not alter the essence of the findings.

and infant mortality separately, the winter season restricted impact of SCA strengthens the probability of a causal relationship between infant health and air quality. Second, the impact on winter mortality suggests an instantaneous effect of air pollution on infant health that is less likely to be the result of, for example, improvements in the general health status of the mother, since such an effect should show across both seasons. Finally, given the winter impact and the lower bound of the age of the deceased infants in the death registry (i.e. 28 weeks into pregnancy), it is tempting to conclude that the pollution has the largest effect on children in the last trimester and beyond. Such a conclusion will, however, disregard any effect pollution may have on fertility, which would bias the estimates. To establish the direction of bias and better understand the pathophysiological mechanism of air pollution on the unborn, 5.3.1 explores the effects of smoke pollution on fertility.

Despite the results in Table 2, we may worry that county borough and season varying unobservable trends can bias the results. For instance, we would violate the parallel trends assumption if we fail to recognize local variations in improvement in treatments that reduce winter mortality but not summer mortality, such as progress in the treatment of respiratory conditions in children. Therefore, to test the validity of the assumption, I run an event study analysis to look for signs of pre-trends according to the following specification;

$$\Delta Y_{ct} = \alpha + \tau_t + \varsigma_c + \sum_{k=-3}^{8} \beta_k D_{ct}^k + \upsilon_{ct} \tag{6}$$

where $\Delta Y_{ct}$ is the difference between summer and winter black smoke concentration or IMR in county borough $c$ in year $t$. The indicator variable, $D_{ct}^k$, is defined as $D_{ct}^k = 1[t = e_c + k]$ where $e_c = [min\{t\}|SCA > 0]$ is the first year SCA was implemented. However, we should note that with over 70 % of all orders set to begin in the second half of the year, the event year will not pick up the full effect.

Figure 7, Panel (a), shows the results for the seasonal difference in black smoke concentration, while Panel (b) shows the corresponding graph using the seasonal difference in infant mortality as an outcome. With no visible signs of pre-trends, the results from the event study analysis suggest that the assumption of parallel trends is likely satisfied.

The event analysis also plots the evolution of the effects of SCA on black smoke concentration and infant mortality, with the triangular line illustrating the staggered SCA adoption. For instance, it is clear from Figure 7a that the impact of SCA on black smoke concentration increased with SCA expansion, which is the result of declining bias owing to measurement errors in the pollution data. Note that although scarcity of monitoring stations produces measurement errors in the data, all errors constant across seasons are canceled out when using the seasonal difference in black smoke concentration as the outcome variable. However, when monitoring stations are few and the SCA coverage small relative to the total land area, measurement bias in the regulation-induced winter pollution only wanes with the expansion of SCAs, which explains the steady increase in effect size over time.[43] In contrast, since infant mortality does not suffer from errors in measurement-induced attenuation bias, we see that the effect is immediate and remains stable over time, as shown in Figure 7b.

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[43] Weighting black smoke concentration using the inverse distance to the town center is an attempt to alleviate some of the measurement errors in the pollution data. An alternative technique uses the inverse of the squared distance and gives even more weight to centrally located gauge stations. Indeed, an event study exercise using such re-weighted pollution data reveals that the impact on black smoke concentration was decisively more similar to that of infant mortality. However, although quadratic weighting may be preferable initially, the weighting will lead to new biases by assigning too little weight to the gauge stations in the periphery with the expansion of SCAs.

## 5.2 IV results

The effects of black smoke concentration on infant mortality are presented in Table 3. Columns (1)–(3) show the OLS estimates with gradually expanding sets of fixed effects. Notably, we can see that the association between black smoke and infant mortality observed in Figure 6 disappears once we control for year fixed-effects, suggesting that secular trends in the variables are more likely to explain the variable relationship in Figure 6. Columns (2) and (3) show that the inclusion of county borough fixed-effects and baseline controls eradicate any remaining association between variables. However, the lack of association is also amplified by fixed-effect induced attenuation bias in the presence of measurement error in the pollution data.[44]

In stark contrast to the OLS estimates, the IV estimates suggest a sizable effect of black smoke on infant mortality. The IV estimates in Table 3 columns (4) and (5) imply that a one microgram decrease in the average black smoke concentration reduces infant mortality by 0.042-0.045 deaths per 1,000 live births. The results are robust to including county borough specific trends.[45] With the black smoke concentration declining by almost $200\mu g$ between 1957 and 1973 ($\overline{BS_{1957}} - \overline{BS_{1973}} \approx 196.5$ µg/$m^3$), the numbers translate into a total reduction in mortality of around 8 deaths per 1,000 live

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[44] For recent papers on the discussion on measurement error in pollution data, see for example Arceo et al. (2016), Schlenker and Walker (2016) and Zivin and Neidall (2013).

[45] The effects remain similar when pollution concentration is expressed in levels, but suffer from less precise first stage regression due to the skewness in the pollution distribution. Separately, I also test for the robustness of the model specification by replacing the trends and the fixed effects with a more demanding combination of two-way fixed effects. The results of the first stage regression are identical to the triple-difference model in equation (3). However, while the IV estimate is higher in magnitude and remains significant ($\beta$ =0.643, SE=0.034), the low first stage F-statistics (5.3) suggest plausible bias in the estimate. In particular, studies have shown that even small violation of the exclusion restriction can cause large bias in the IV estimate if the instrument is weak.(Young, 2020) Since we cannot reject that SCAs had an effect on reducing other pollutants, and the preferred interpretation of the IV estimate is the reduced from impact of the ban of bituminous coal, the weak instrument is a cause of concern. All results are available upon request.

births, or a close to 30 percent reduction in baseline mortality. Furthermore, with the infant death rate falling by an average of 11 deaths per 1,000 births between 1957–1973, the IV estimates suggest that air quality improvement stands for over 70% of the total decline in the sample.

### 5.2.1 Linearity

Figure 8 depicts the population-weighted distribution of PM2.5 exposure from 801 locations in 53 WHO member countries by income status in bins of 25 micrograms, and the coefficient estimates for different ranges of black smoke concentration on infant mortality from the current study.[46] The estimates are obtained by interacting black smoke concentration and the instruments in equations (4) and (5) with a categorical variable indicating different levels of black smoke concentration to allow flexibility in the treatment effects.

First, the graph reveals that most levels of air pollution in low- and middle-income countries are within the range of pollution in the current analysis. Second, the pollution effect on infant mortality is statistically indistinguishable across all concentration levels ($\beta : 0.05$–$0.11$ deaths per 1,000 live births), suggesting that the impact of fine particulate matter on infant mortality is likely linear. Moreover, the impact magnitudes are similar to many earlier studies, despite differences in the particle sizes and concentration levels analyzed.[47] For instance, Chay and Greenstone (2003a,b), one of the first papers in economics to use natural experiments to identify the

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[46] See Appendix G for the list of countries and locations.

[47] To enable comparison, I transform each study's reported mean level of particulate concentration according to the ratios PM10 = 0.55 TSP (Knittel et al. (2016)), and PM2.5 = 0.5 PM10 and PM2.5 = 0.57 PM10 for high-income and low- and middle-income countries, respectively. The PM2.5:PM10 conversion ratio is derived using the Ambient Air Quality Database (WHO, 2018) by regressing PM10 on PM2.5, a dummy variable that indicates the economic status of the country, and an interaction term of the two variables, which yields the following estimates: $PM10 = \underset{(1.093)}{-4.69} + \underset{(0.067)}{2} * PM2.5 + \underset{(2.287)}{6.83} * LMIC - \underset{(0.078)}{0.26} * LMIC \times PM2.5 + error$.

impact of changes in particulate matter on IMR, finds that a one microgram reduction in TSP leads to 0.082 and between 0.04–0.07 fewer infant deaths per 1,000 live births in an environment where mean TSP is 86 and 64 $\mu g/m^3$, respectively.[48] Arceo et al. (2016), who study the impact of air-pollution on infant mortality in Mexico City with a mean PM10 level of 67$\mu g/m^3$, found that a one microgram reduction in PM10 led to 0.09-0.12 fewer infant deaths per 1,000 births, well in line with the results of this study.[49] The graph also shows the results from studies investigating vehicle exhaust, a major source of air pollution in high-income countries, on infant mortality. These findings are inconclusive, however. For example, while Knittel et al. (2016) show that a one microgram increase in PM10 reduces infant mortality by 0.10 deaths by 1,000 live births, Currie and Neidell (2005) finds no statistically significant effect (the average level of pollution is 29 and 39 $\mu g/m^3$, respectively). The similar effect size with the estimates from studies that analyzes low-level pollution effects on infant mortality further reinforces the linearity proposition and suggests that a reduction in smoke particle concentration will contribute to the same marginal improvement in infant health, independent of the initial level and source of pollution.[50]

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[48] TSP is defined as all particulate matter with less than 30 micrometers in diameter, i.e. PM30.

[49] Note that the size of the particulate matter used in the original analysis is often irrelevant to the result. This is because we usually only care for changes in pollution concentration caused by the treatment. Specifically, the vast majority of particulate matter emitted in fuel combustion belongs to PM2.5. This means that most studies that analyze the effects of particles emitted from fuel combustion, including car exhausts, will capture the effect of changes in PM2.5 concentration, independent of the size of particles used in the analysis.

[50] In investigating the effects of a policy that restricted the emissions from coal-fired power plants in China, Tanaka (2015) finds the policy reduced IMR with 3.29 deaths per 1,000 live births. Although his study focuses on the reduced form effects of the regulation due to limited pollution data, a back of the envelope calculation using policy impact on pollution suggests that the effect corresponds to roughly 0.06 deaths per microgram reduction in TSP in an environment where average TSP is 314. Similarly, Cesur et al. (2017) look at the expansion of gas infrastructure in Turkey on infant health. Again, despite limited pollution data, their results suggest 0.04 fewer infant deaths per 1,000 births for every percentage reduction in PM10. With an average pre-treatment PM10

Although the marginal effects are statistically indistinguishable for the different ranges of pollution concentration, they show a tendency to decline with the level of exposure. A plausible explanation for the decline is the raised awareness of the harmful effects of pollution on health prompted by the London smog incident in 1952.[51] In particular, heavy pollution episodes are likely to have triggered a behavioral response since heightened black smoke concentration is easily perceptible to the senses. For example, concerned parents may decide to keep young children indoors or protect them from high-level air pollution with the unintended consequence of exposing them to even lower pollution levels than usual. Such a behavioral response to higher air pollution would dampen the adverse effect of pollution on infant health.

Understanding the effect of avoidance behavior is particularly important in the context of this analysis, as the effect of improved air quality may be even greater in developing countries where the cost of avoidance is particularly high (Zivin and Neidell, 2013).[52] While the current analysis cannot provide a complete account for behavioral response to smoke pollution, if high-level air pollution triggered behavioral response, we may interpret these coefficients as more likely to capture the total effect of pollution rather than the biological effect of pollution. On the flip side of the same argument, if lower pollution levels did not trigger a behavioral response to pollution, we may interpret the lower end of the pollution spectrum to capture the health effect absent of any behavioral response to pollution.

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concentration at 66 $\mu g/m^3$, auxiliary results suggest a reduction in infant mortality of 0.06 deaths per 1,000 live births for every microgram reduction in PM10.

[51] For household perception and reaction to episodes of local air pollution in the 1960s-70s, see Schusky (1966), Stalker and Robison (1967) and Wall (1973).

[52] The failure to account for the social cost of avoidance behavior from the total effect of pollution is discussed by Zivin and Neidell (2013).

## 5.3 Heterogeneous treatment effects

Heterogeneity in treatment effects can shed light on the causal mechanism to help shape better policies. This section will extend the previous analysis to look at the effect of black smoke on the age at death, gender composition, and live birth outcome.

The disproportional age effect of pollution is apparent in Figure 9. The estimates are the results of replacing the dependent variable in equations 4 by age-separated infant mortality and reveal that nearly all deaths occurred in the first three months after births, with no effect observed in older cohorts. A plausible explanation for the difference in effect is young children's heightened sensitivity to external stimuli, highly correlated with the stage of organ maturation. Yet, another explanation is that pollution has a forward-shifting effect on mortality, causing the weakest infants to die earlier than they would have without pollution, i.e. harvesting effect.

Despite the strong effect on the youngest, the magnitude is now only half of that in the main analysis. To study if the age-unknown category of children explains the reduced effect, I run a separate regression excluding all age-identified infants from the nominator of infant mortality rate. Indeed, the exercise shows that the missing effect is picked up by the unidentified group of infants in its entirety. Comparing the results to the baseline death ratio in each category reveals that unidentified infants are more than twice as likely to die from pollution before one year of age. A plausible explanation for the difference in effect is the higher prevalence of socioeconomically vulnerable individuals among the unidentified, which many studies have proved to be at greater risk of death.[53] Appendix E discusses the evidence for socioeconomic vulnerability in the group of age-unknown children.

Separately, gender-separated analysis reveals that black smoke is likely

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[53] For studies on heterogeneity in the effects of pollution related to SEC, see for example Jayachandran (2009), Sanders and Stoecker (2015), Currie and Walker (2011), Bharadwaj et al. (2017).

one factor explaining the differences in infant mortality across gender. While infant mortality is typically higher among male infants than among female infants (male mortality in England and Wales was 56 % in 1957), the last two coefficients in Figure 9 show how smoke pollution caused greater harm on male infants, with female infants approximately 35 % less likely to die from pollution. The difference is only slightly higher than the pooled mortality difference between the genders ((56-40)/56=29%).[54]

### 5.3.1 Birth effects

A common assumption when analyzing infant mortality is that treatment only affects the nominator, i.e. the number of deaths, while the denominator, the number of births, remains unaffected. That is, the underlying assumption is that pollution-induced deaths only occur after birth, which disregards the possibility that smoke particles may cause lethal harm to fetuses, with miscarriage or stillbirth as outcomes. Such an assumption, however, stands in considerable contrast to the extensive evidence of air pollution's adverse effects on fetal health.

The knowledge of when the most harm is inflicted on children is essential from a policy perspective, and in order to determine the direction of possible bias in the main estimates. For example, studies have found evidence of fetal deaths after 26 weeks of gestation (Currie and Neidell, 2005) and an increased risk of prematurity and low birth weight due to air pollution exposure (Currie and Walker, 2011), while Chay and Greenstone (2003a) discusses the in-utero exposure to air pollution as the plausible reason why the largest adverse health impact of pollution is found among neonatal infants. If fetus exposure to air pollution determines the survival rate, we ought to expect a greater number of births of children of weak constitution, and thereby also a greater number of infant deaths. Indeed, such a relationship is supported by Knittel et al. (2016) who finds traffic congestion-induced infant mortality to be 2.0 to

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[54] The difference is confirmed by testing for equality of the coefficients.

2.6 times larger for premature infants and 1.7 to 1.8 times larger for infants of low birth weight. Therefore, failure to account for fetal deaths caused by pollution would lead to underestimating the true effect on infant mortality.[55]

Here I suggest that changes in birth counts can substitute for the lack of data on prenatal deaths. An advantage of focusing on birth numbers instead of registered fetal deaths is that the former does not discriminate between stillbirth and miscarriage, and captures all fetal deaths.[56] To estimate the effects of black smoke on fetal deaths, I replace the outcome variable in the second stage equation (4) with the log of birth counts and re-run the SCA instrumented black smoke concentration analysis.

The main challenge to the proposed identification strategy comes from plausible threats to the exclusion restriction assumption. That is, we must consider the possibility that SCAs can have affected births in other ways than through its effect on black smoke concentration. For example, this would be the case if parents time conception with the introduction of an SCA.[57] Although such a reaction to SCAs seems unlikely, we can test for a behavioral response to SCAs by studying the seasonal difference in the effect of SCAs on birth counts, since any behavioral responses to SCAs are unlikely to differ with the season.

The reduced form results for all births are shown in Table 4 column

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[55] Although the physiological mechanism of pollution on fetal development is not yet fully understood, inhaling particulate matter smaller than $10\mu g$ can cause an inflammatory response in the lungs of the mother that can induce adverse reactions harmful to the fetus. A long-standing belief in the medical field was the impenetrability of xenobiotics' through the placental barrier. However, several recent studies have found evidence of nanoparticles, including black carbon particles, on the inside of the placental barrier, and no longer discard the possibility that even larger particles are able to reach the fetus and cause direct harm to the child (Wick et al., 2010, Bové et al., 2019 ).

[56] Miscarriages are incredibly challenging to detect since most take place in the first four weeks of pregnancy. Also, fetal deaths often remain unreported, adding to the concern over the reliability official prenatal death records. The free health care system in the UK may, however, dampen such concern somewhat.

[57] Contraceptive pills were introduced in 1961 but were only prescribed to married women until the law changed in 1967.

(1). The clear evidence showing an effect of SCAs on winter fertility but nothing in the summer suggests that the regulation did not trigger behavioral responses that would threaten our exclusion restriction assumption. Column (2) shows the IV result on the log-transformed total number of births. It tells us that a 10 microgram increase in black smoke concentration reduced births counts by 0.5 percent or, provided physiological symmetry in the outcome, increased fetal mortality by 0.5 percent. The number translates into just over 10 percent increase in the total number of births when evaluated at the average reduction in black smoke concentration over the period.

Separately, I also analyze the effect of black smoke on gender composition at birth.[58] Evidence from previous studies has shown unfavorable in-utero shock to skew fetus' survival ratio in favor of female infants (Almond and Edlund (2007), Almond et al. (2009)).[59] Given these results, we expect greater effect of pollution on male births than on female births.[60] Indeed, the results in columns (3) and (4) suggest that the pollution effect was larger on male fetuses with a 10 microgram increase in black smoke concentration reducing male and female births by 0.55% and 0.40%, respectively. Notably, the results provide a plausible explanation for the trends in perinatal mortality seen in Figure 1. However, the difference in the coefficients in columns (3) and (4) is not significant at 95% (p-value: 0.13), suggesting we should be cautious not to over-interpret the results.

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[58] The method follows the idea first adopted by Sanders and Stoecker (2015) who, similarly to the current study, find that the probability of live male birth increases with reduced pollution.

[59] According to the evolutionary theory developed by Trivers & Willard Trivers and Willard (1973), to optimize the number of offspring, we should expect heightened sensitivity to external shocks among male fetuses compared to their female counterparts due to natural selection.

[60] Besides having more children, one may also consider that the unborn child would receive a different degree of care due to its gender. For instance, if expecting mothers avoid pollution exposure depending on gender preference in society, this could affect survival. However, the sex of the unborn child could only be determined following the introduction of ultrasound in the 1970s. The possibility of tampering with the chance of survival by gender is, therefore, limited.

## 5.4 Sensitivity Analysis

The results from a number of alternative IV specifications are presented in Figure 10. As a first measure, I test the model by excluding non-adopters from the analysis. While this generates smaller standard errors, the results remain within the margin of error.

Second, a violation of the exclusion restriction assumption occurs if resources are redirected from sources relevant for infant health to finance the installation of SCAs. To test the model sensitivity to such a possibility, I control for annual health and child services expenditure per capita for the years between 1959–1973. The results indicate that this does not seem to be the case.

Next, to test for the possibility that historically healthier economies have a different trajectory in outcome than poorer districts, I exclude the quintile with the lowest unemployment in 1951 from the analysis. Again, the limited change in impact suggests that the identification assumption remains robust to the particular threat.

The first stage and the reduced form analysis in Figure (5) shows heterogeneity in impact across winter quarters. For example, the impact of SCAs on black smoke concentration is, on average, much higher in the fourth quarter. To test for heterogeneity in impact across winter-quarters, I omit the first quarter of the year from the analysis. However, the coefficient remains similar in size, suggesting that the specification does not suffer from bias related to unobserved differences across the winter-quarters.

I also test the model specification for birth weighted death counts. With all regression variables aggregated to quarterly county borough means, the weighted and the unweighted main analysis should yield similar results.[61] Indeed, while somewhat lower, the results indicate that the estimate is again

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[61] Note that the outcome variable is now the county borough and quarter-specific mean survival rate of infants in the first year of life.

within the margin of error.[62]

The possibility to delay birth registration by up to 42 days means that recorded births from the third month in the previous quarter could plausibly inflate the total number of births in the subsequent quarter. For example, it would seem reasonable to assume that if Christmas and New Year's Eve holidays fall on particular weekdays, a large fraction of parents may decide to postpone the registration of their newborn until the end of the holiday season. The unintended consequence of such delay is that the birth is registered in an index catalog belonging to the subsequent year and quarter. To test the outcome sensitivity to potential issues caused by a systematic discrepancy in the registration of births, I replace the outcome with the 3-quarters moving-average. The result shows no sign of such a concern.[63]

Lastly, I investigate whether the results are robust to excluding county boroughs for which the time series data on infant mortality is intermittent. Again, the results remain robust to the omission.

## 6 Discussion

The problem of pollution from the burning of solid fuel is as old as civilization, yet rapid changes in technology and energy consumption in the second half of the 20th century caused the focus on ambient air pollution to shift from coal to fumes from industrial plants and vehicular emissions. However, due to China and India's economic progress, smoke pollution has recently regained a spot in the limelight. While the remarkable economic development has lifted many out of poverty, it has often come at the expense of ambient air quality because of heavy reliance on coal for energy production. Moreover,

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[62] The death counts are weighted by the square root of the quarterly number of births.

[63] The 3 quarters moving average is defined as;

$$BirthMA_{c,q} = (births_{c,q-1} + births_{c,q} + births_{c,q+1})/3$$

the ever-so-significant role of small-scale coal furnaces for heating and cooking combined with population density has further added to the deterioration of air quality and placed many cities in India and China among the most polluted in the world.

Current investigation shows that improved air quality likely played a significant role in reducing postwar infant mortality in the UK. For instance, a simple counterfactual exercise for infant mortality in the UK between 1957–2000 using the estimate from the IV analysis shows the role of air pollution in its reduction. In particular, Figure 11 shows the rate of infant mortality had the level of black smoke concentration remained the same as in 1957, assuming no bias in air pollution measurement over time.[64] The graph suggests that infant mortality would have changed little between 1957–1975, absent an improvement in air quality. It is particularly noteworthy that counterfactual analysis becomes a straightforward exercise when the marginal effect of pollution concentration on infant mortality is known to be linear.

Also, the findings are important for improved understanding of the effect of air pollution in countries with high pollution levels, or estimating the number of infant lives affected by a sudden change in air quality. For example, one can apply the study results to evaluate the impact of reduced air pollution on infant mortality due to reduced economic activities or to estimate the effects caused by a sudden increase in smoke pollution from wildfires expected to become more frequent in the future.[65] To provide a topical example, in the attempt to control the outbreak of SARS-COV-2 in the spring of 2020, the lockdown in India reduced PM2.5 in New Delhi and Bombay, almost 40 $\mu g/m^3$ compared to the preceding four-year average.[66] Applying the results

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[64] I am grateful to Professor Heal for kindly sharing the data on black smoke concentration for the UK.

[65] Pollution from wildfires can easily reach a similar level to the pollution in the mid-20th century UK. For example, the 1997 wildfire in Indonesia reported PM10 (PM2.5) of over $1000\mu g/m^3$ ($500\mu g/m^3$) in the worst-hit areas (Jayachandran, 2009) while PM2.5 of over $250\mu g/m^3$ was measured in the wildfire in California in November 2018.

[66] https://www2.iqair.com/sites/default/files/documents/REPORT-COVID-19-

from the current study suggests that the improved air quality resulting from the lockdown would reduce infant mortality by approximately 1.6 deaths per 1,000 births, corresponding to a 6-7 % reduction in average local infant mortality.

Infant mortality is not only a measure of the loss of life, but also a proxy for public health in general. For example, the adverse health impact of exposure to pollution may translate into increased medical expenditure and impaired cognitive ability for the surviving children.[67] Since human capital is central to economic development, any adverse health effect of air pollution is particularly damaging in highly polluted struggling economies. The current study reveals that SCAs successfully reduced black smoke concentration and improved the health of the youngest and that monitoring transparency, financial aid, and simple alternatives to help conform to the regulation can contribute to the desired effects.

The study also raises concerns about air pollution's effect on infant mortality when exposure reduces fertility. For instance, if air quality improvement causes more children to survive pregnancy, we should see increased postnatal deaths. Such a shift in the timing of death would imply that the results in the study are an underestimation of the actual impact of air pollution. Furthermore, another limitation of the study is that it cannot address avoidance behavior. Suppose people take shelter in response to increased pollution. In that case, the behavioral response will add downward bias to the impact of pollution on health. Since avoidance behavior is likely to be greater with visible pollution (or with regular air quality alarms), the bias in the estimates may be especially large in the current setting.

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Impact-on-Air-Quality-in-10-Major-Cities_V6.pdf [Retrieved: 2020-05-29]

[67] See Duque and Gilraine (2020) on the effect of coal combustion on student performance and Almond et al. (2018) for a comprehensive review of recent studies that investigate the effect of early childhood shock on adult outcome.

# 7 Conclusion

While the number of studies on the effect of ambient air pollution on health, and infant mortality in particular, have rocketed across many fields, only a fraction have so far attempted to go beyond establishing a correlational linkage to identify a causal relationship.[68] Even with a persuasive identification strategy, most studies rely on data from developed countries with low air pollution, which casts doubt on the generalizability of their findings to developing countries. Here, I suggest that the similarities between the UK in the 1950s and developing countries today can better predict the expected benefits of an effective environmental policy when adopted in a developing country.

In this paper, I analyze the effects of an early environmental regulation on coal-induced smoke particles and infant mortality in addition to the causal effects of smoke pollution on infant mortality. I find that the regulation roughly eliminated the intra-annual difference in smoke pollution and that improved air quality led to reduced infant mortality. The effect size suggests improved air quality can explain 70 % of the observed reduction in infant mortality. I also find evidence that the health impact was most significant on children under three months of age and male infants in particular. The results also suggest that the marginal effect of pollution on mortality is linear, but tends to decline with air pollution. Evidence suggests that children to more vulnerable populations were affected the most, but that changes in mortality are also affected by the impact of pollution on fetal mortality.

Although the results are robust to various sensitivity checks, some limitations remain. In particular, the paper cannot distinguish the biological effects of pollution from behavioral responses to pollution. Neither does the study speak to the pathophysiological mechanism behind the impact nor can it separate postnatal mortality due to preterm births from deaths following

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[68] For a good overview of causal studies, see Currie (2013).

full-term births. In light of these circumstances, the results of the study are likely to underestimate the true effects.

Finally, although medical progress, health care, and improvement in the socio-economic environment are commonly recognized contributors to the decline in infant mortality in the previous century, the role of pollution has gained less attention. The current investigation reveals that improved air quality deserves more attention for its role in improving infant health.

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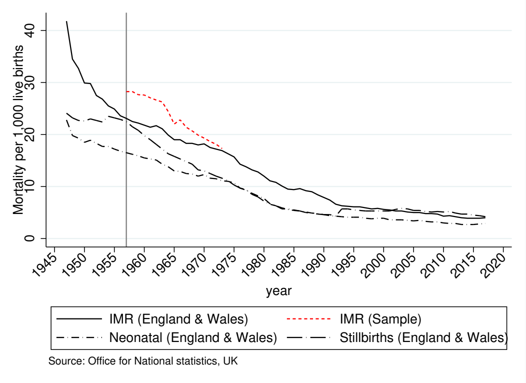
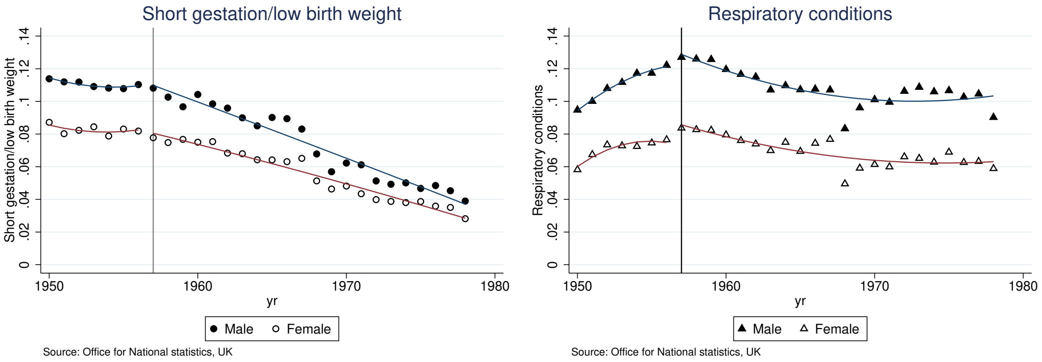
Figure 1: Infant Mortality in England and Wales by Type and Cause

(a) Mortality rate in England and Wales 1946-2017



Source: Office for National statistics, UK

(b) Causes of neonate death by gender 1950-1978

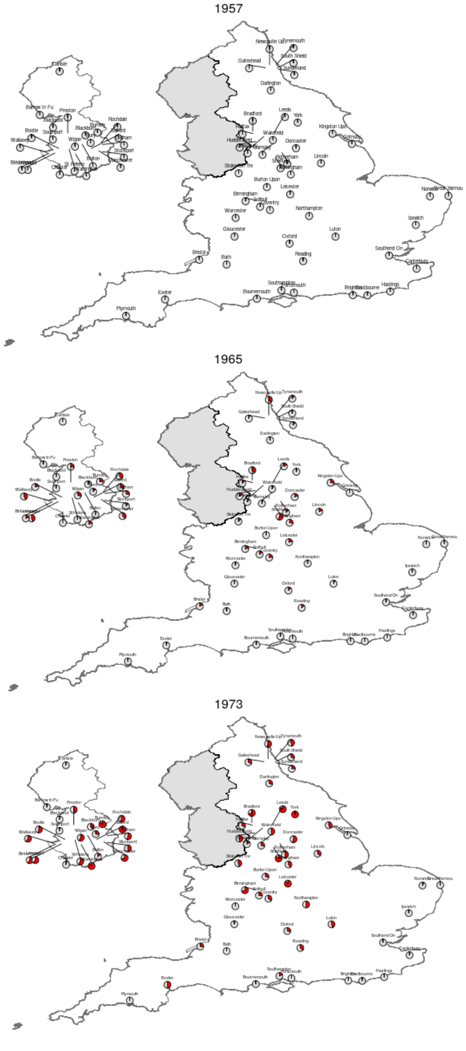


Source: Office for National statistics, UK

Source: Office for National statistics, UK

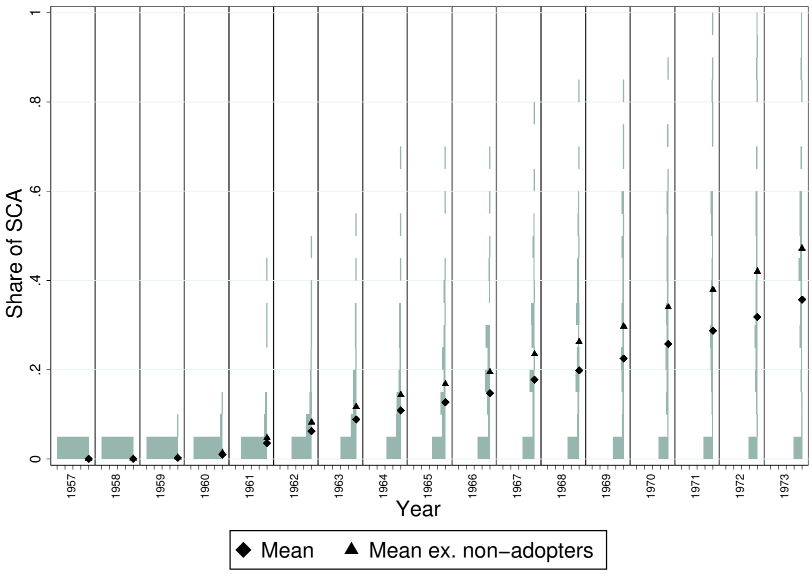
Notes: Figure (a) depicts all infant deaths under one year of age (IMR) and neonatal deaths, i.e., infants' deaths in the first 28 days of life. Stillbirths are defined as deaths before birth after 28 weeks of pregnancy. The vertical lines in 1957 represent the first year a smoke control area was enacted. Figures in (b) show the two most common causes of newborn death due to perinatal complications, the period between 28 weeks gestation and one week of birth, in England and Wales by gender as the share of total infant mortality. The vertical line shows the first year of SCA rollout.

Figure 2: An illustration on the expansion of Smoke Control Areas in County Boroughs 1957-1973



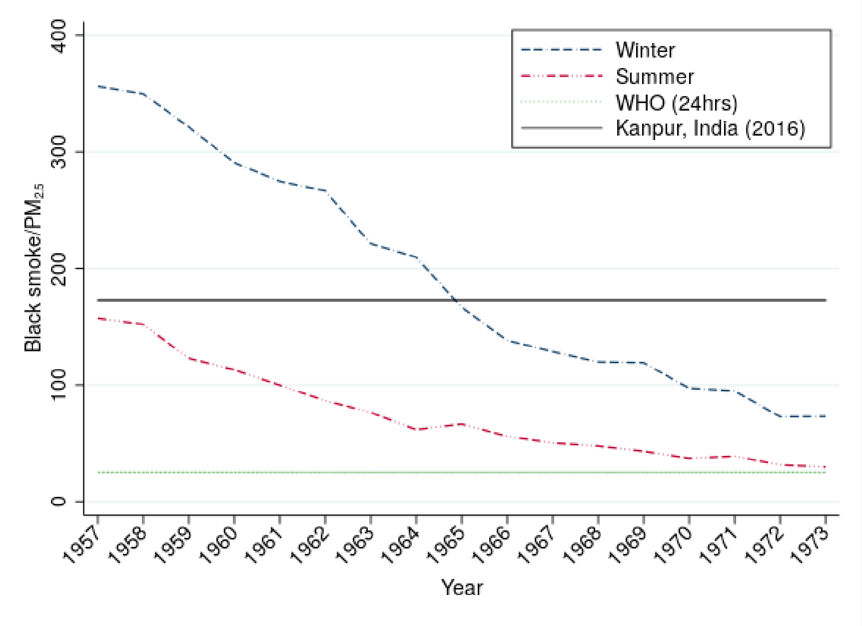
Notes: The figures show the location of all county boroughs in England and the share of SCA coverage in 1957, 1965, and 1973.

Figure 3: The Expansion Rate of Smoke Control Areas



Notes: Each column in the graph corresponds to the frequency distribution of SCA coverage in any given year. The dots are the mean rate of coverage, including and excluding non-adopters.

Figure 4: Trends in Black Smoke Concentration



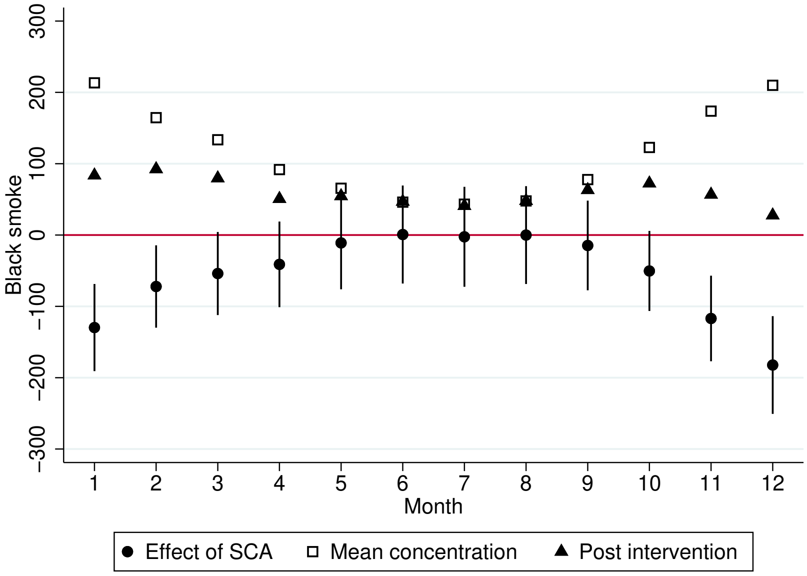
Notes: The lines are the average quarterly black smoke concentrations. The green area indicates the level of exposure to PM2.5 one should not exceed over 24 hours period, according to the WHO. The horizontal black line (173ug/m3) from Kanpur (India) in 2016 represents the highest concentration of mean annual concentration of PM2.5 recorded in the latest sweep by WHO. Source: Ambient Air Quality Database, WHO, April 2018.

# Table 1: Sample Statistics

| | ***Non-adopters*** | | ***Adopters*** | | | | | | ***Mean difference:*** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | (1) All | | (2) All | | (3) $\text{SCA}_{'73}<0.5$ | | (4) $\text{SCA}_{'73}\geq0.5$ | | (1)-(2) | | (3)-(4) | |
| | Mean | Std. | Mean | Std. | Mean | Std. | Mean | Std. | Diff. | t-stat | Diff. | t-stat |
| ***Baselines in 1951:*** | | | | | | | | | | | | |
| Industry coal dependency p.c. | 0.06 | 0.01 | 0.05 | 0.01 | 0.05 | 0.01 | 0.05 | 0.01 | 0.01 | (3.13) | -0.00 | (-0.25) |
| Industry coke dependency p.c. | 0.05 | 0.01 | 0.05 | 0.01 | 0.05 | 0.01 | 0.05 | 0.02 | 0.01 | (1.50) | -0.00 | (-0.82) |
| Industry oil dependency p.c. | 0.16 | 0.04 | 0.12 | 0.03 | 0.12 | 0.03 | 0.12 | 0.03 | 0.04 | (3.84) | -0.00 | (-0.08) |
| Industry electricity dependency p.c. | 0.09 | 0.02 | 0.08 | 0.02 | 0.08 | 0.01 | 0.08 | 0.02 | 0.02 | (3.11) | -0.00 | (-0.19) |
| Industry gas and water dependency p.c. | 0.13 | 0.03 | 0.10 | 0.02 | 0.10 | 0.02 | 0.10 | 0.02 | 0.03 | (3.66) | -0.00 | (-0.19) |
| Ln(Population) | 11.39 | 0.58 | 11.95 | 0.75 | 11.73 | 0.57 | 12.31 | 0.88 | -0.56 | (-2.48) | -0.58 | (-2.69) |
| Population density | 24.57 | 8.36 | 36.98 | 14.64 | 32.22 | 10.44 | 44.81 | 17.34 | -12.40 | (-2.91) | -12.59 | (-3.05) |
| CB Area (ha) | 4226.53 | 1998.54 | 5644.18 | 4319.71 | 4628.10 | 2538.05 | 7317.73 | 5971.76 | -1417.65 | (-1.14) | -2689.63 | (-2.10) |
| Age>15/pop | 0.79 | 0.02 | 0.77 | 0.02 | 0.77 | 0.02 | 0.77 | 0.01 | 0.02 | (3.50) | 0.00 | (0.31) |
| Share of self-employment | 0.03 | 0.01 | 0.02 | 0.00 | 0.02 | 0.00 | 0.02 | 0.00 | 0.01 | (2.16) | -0.00 | (-1.20) |
| Labor force/pop | 0.44 | 0.02 | 0.48 | 0.04 | 0.47 | 0.03 | 0.49 | 0.03 | -0.03 | (-3.18) | -0.02 | (-2.13) |
| Rate of unemployment | 0.03 | 0.01 | 0.02 | 0.01 | 0.02 | 0.01 | 0.02 | 0.01 | 0.01 | (1.31) | 0.00 | (0.16) |
| All-age mortality rate (%) | 1.34 | 0.24 | 1.23 | 0.14 | 1.22 | 0.16 | 1.25 | 0.12 | 0.11 | (2.14) | -0.03 | (-0.70) |
| Raised tax p.c. | 8.66 | 1.57 | 7.20 | 1.22 | 7.09 | 1.19 | 7.39 | 1.28 | 1.46 | (3.56) | -0.30 | (-0.79) |
| Est. expenditure p.c. | 10.06 | 1.30 | 9.02 | 0.84 | 8.93 | 0.84 | 9.18 | 0.84 | 1.04 | (3.45) | -0.25 | (-0.96) |
| Rateable value p.c. (£000) | 9.79 | 3.20 | 7.11 | 1.28 | 6.99 | 1.26 | 7.30 | 1.33 | 2.68 | (4.56) | -0.31 | (-0.78) |
| ***Baselines in 1959:*** | | | | | | | | | | | | |
| Health services p.c. | 0.07 | 0.02 | 0.10 | 0.03 | 0.10 | 0.03 | 0.11 | 0.03 | -0.04 | (-6.03) | -0.00 | (-0.03) |
| Child services p.c. | 0.03 | 0.01 | 0.04 | 0.01 | 0.04 | 0.01 | 0.04 | 0.01 | -0.01 | (-5.24) | -0.00 | (-1.14) |
| Welfare services p.c. | 0.04 | 0.01 | 0.05 | 0.02 | 0.05 | 0.02 | 0.05 | 0.02 | -0.01 | (-4.20) | 0.00 | (1.31) |
| Housing services p.c. | 0.09 | 0.05 | 0.14 | 0.05 | 0.14 | 0.06 | 0.14 | 0.03 | -0.05 | (-4.62) | 0.01 | (0.60) |
| ***Infant mortality rate:*** | | | | | | | | | | | | |
| 1957: | 25.18 | 6.56 | 30.35 | 7.53 | 30.50 | 8.22 | 30.10 | 6.35 | -5.17 | (-3.17) | 0.40 | (0.24) |
| — Jan-Mar | 27.97 | 5.61 | 31.31 | 9.06 | 32.38 | 9.60 | 29.57 | 7.92 | -3.35 | (-1.78) | 2.81 | (1.43) |
| — Apr-Jun | 21.69 | 9.40 | 29.23 | 9.45 | 29.05 | 10.67 | 29.53 | 7.15 | -7.54 | (-3.58) | -0.49 | (-0.24) |
| — Jul-Sep | 23.95 | 9.52 | 27.24 | 8.47 | 27.63 | 8.50 | 26.60 | 8.53 | -3.29 | (-1.70) | 1.03 | (0.56) |
| — Oct-Dec | 27.40 | 12.69 | 33.65 | 10.18 | 32.74 | 11.70 | 35.14 | 6.89 | -6.24 | (-2.60) | -2.39 | (-1.08) |
| ***Black smoke:*** | | | | | | | | | | | | |
| 1957-1973: | 67.65 | 33.98 | 133.36 | 58.97 | 121.93 | 56.73 | 152.20 | 59.39 | -65.71 | (-3.82) | -30.27 | (-1.71) |
| — Jan-Mar | 99.82 | 45.39 | 179.47 | 72.71 | 161.29 | 66.38 | 209.41 | 73.68 | -79.65 | (-5.29) | -48.12 | (-3.20) |
| — Apr-Jun | 34.59 | 17.82 | 73.77 | 33.14 | 65.32 | 29.88 | 87.68 | 33.96 | -39.18 | (-5.78) | -22.36 | (-3.27) |
| — Jul-Sep | 25.87 | 13.81 | 61.88 | 29.61 | 55.32 | 27.26 | 72.68 | 30.53 | -36.01 | (-6.00) | -17.36 | (-2.80) |
| — Oct-Dec | 95.02 | 49.10 | 179.43 | 78.70 | 163.10 | 73.14 | 206.32 | 81.18 | -84.41 | (-5.18) | -43.22 | (-2.61) |

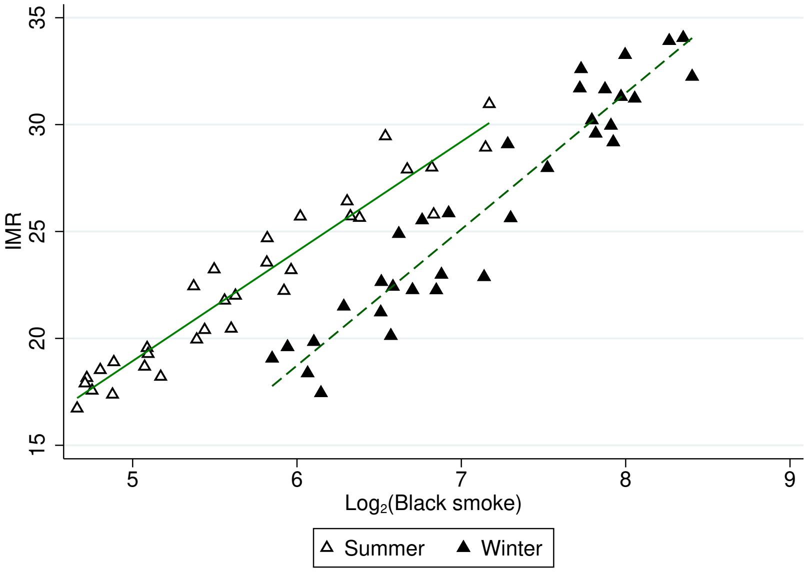
Notes: Non-Adopters (13 in total) are the county boroughs that never introduce any SCA before 1974. Adopters (45 in total) are then further divided into groups depending on the rate of SCA expansion defined by the share of CB coverage exceeding half of the total land area by 1973 or not.

Figure 5: The Effect of Smoke Control Areas on Black Smoke Concentration Across Months



Notes: The graph depicts the coefficients and the 95 percent CI for SCA's monthly effect, mean black smoke concentration, and the post-intervention effect of black smoke concentration. The regression analysis controls for CB, year and month FE, the annual per capita CB tax revenue and the annual CB per-capita rateable property value in 1957 interacted with a linear time trends.

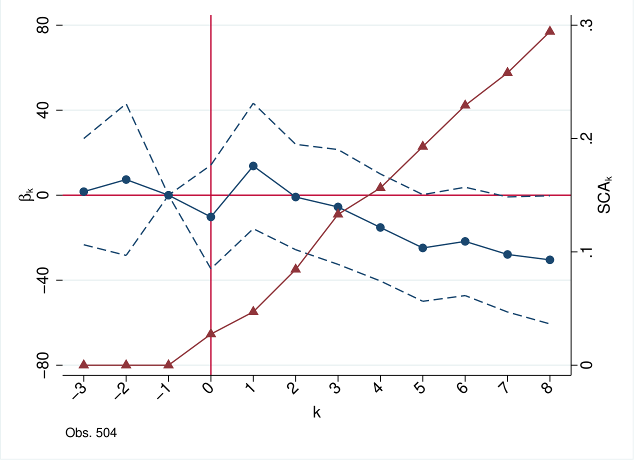
Figure 6: Infant Mortality and Black Smoke Concentration



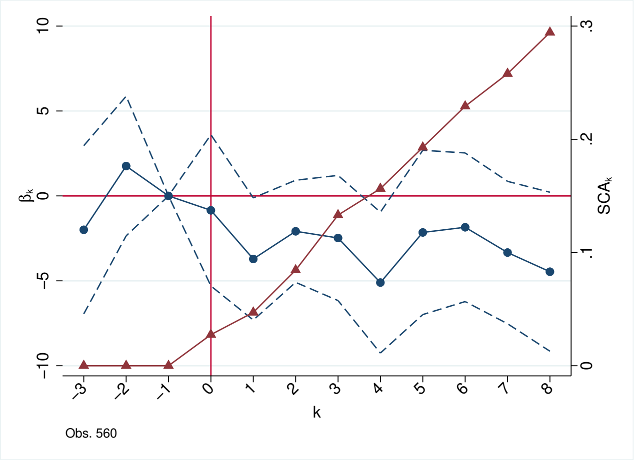
Notes: The figure depicts the relationship between IMR and the quarterly average 24-hours concentration of smoke particles (black smoke) in logs by season for 1957-1973.

Figure 7: Event Study

(a) Smoke control areas and the seasonal difference in black smoke



(b) Smoke control areas and the seasonal difference in IMR



Notes: The event studies analysis show pre-trends in the analysis and the dynamic effect of SCA once implemented. The outcome variable is the seasonal difference in black smoke concentration by county borough and year. The event year is defined as the first SCA was adopted. The x-axis displays the number of years before and after the event year while the y-axis depicts the point estimate for the corresponding year along with 95 percent CI. The red line is the mean rate of SCA coverage by year among adopters.

Table 2: The Effect of Smoke Control Areas

| | DD<br>(1) | DDD<br>(2) | DDD<br>(3) |
|---|---|---|---|
| **A. Dependent variable: *Black smoke*** | | | |
| SCA | -75.07** | -23.74 | 35.23 |
| | (31.15) | (35.41) | (31.86) |
| SCA × Winter | | -95.58*** | -97.39*** |
| | | (19.71) | (25.85) |
| No. Obs. | 2962 | 2962 | 2944 |
| No. CBs | 58 | 58 | 58 |
| Dep. mean | 99.82 | | |
| **B. Dependent variable: *IMR*** | | | |
| SCA | -3.477 | -1.167 | 7.851 |
| | (3.12) | (3.05) | (9.38) |
| SCA × Winter | | -4.300*** | -5.256** |
| | | (1.16) | (2.28) |
| No. Obs. | 2962 | 2962 | 2944 |
| No. CBs | 58 | 58 | 58 |
| Dep. mean | 23.36 | | |
| CB FE | X | X | |
| Year FE | X | X | |
| Quarter FE | X | X | |
| Baseline controls | X | X | |
| CB × Year FE | | | X |
| Quarter × Year FE | | | X |
| CB × Quarter FE | | | X |

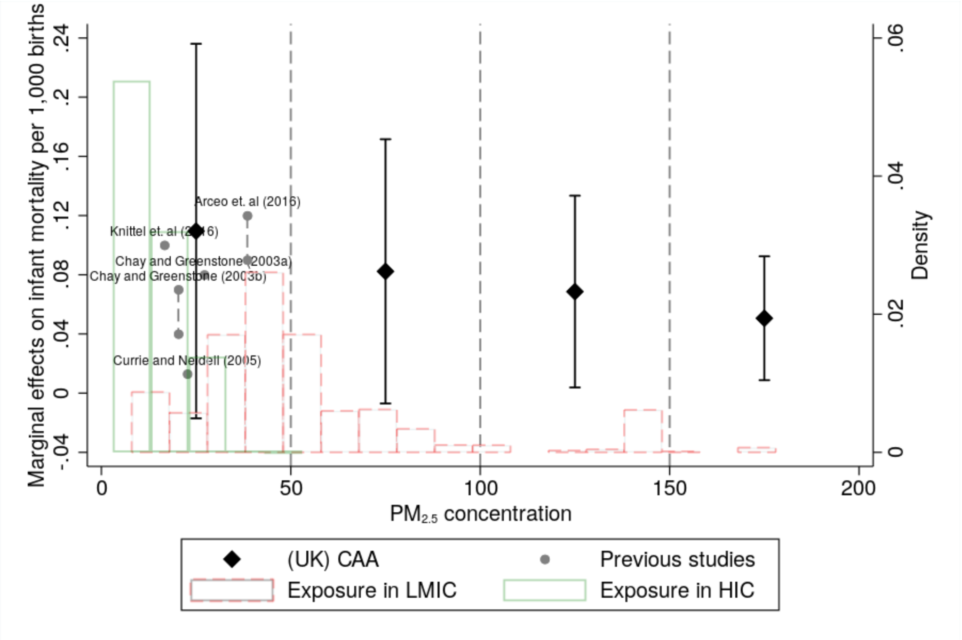
Notes: Standard errors in parentheses and clustered at the CB level. *p<0.10, **p<0.05, p<*** 0.01. Column 1-3 shows the DD and DDD results, while columns 4 and 5 are the first-stage and the reduced form results from the IV analysis that controls for linear-year trend interacted baseline CB tax revenue and rateable property value per capita and log population.

Table 3: The 2SLS Effects of Black Smoke on Infant Mortality

| | IMR | | | | |
|---|---|---|---|---|---|
| | OLS<br>(1) | OLS<br>(2) | OLS<br>(3) | IV<br>(4) | IV<br>(5) |
| Black smoke | 0.0113<br>(0.007) | 0.00178<br>(0.004) | 0.00453<br>(0.004) | 0.0454$^{***}$<br>(0.017) | 0.0417$^{***}$<br>(0.013) |
| Obs. | 2962 | 2962 | 2962 | 2962 | 2962 |
| CBs | 58 | 58 | 58 | 58 | 58 |
| First-stage F-stat | | | | 18.46 | 15.81 |
| $R^2(adj)$ | 0.227 | 0.510 | 0.519 | 0.475 | 0.525 |
| Quarter FE | X | X | X | X | X |
| Year FE | X | X | X | X | X |
| CB FE | | X | X | X | X |
| Baseline controls | | | X | X | X |
| CB × Year trend | | | | | X |

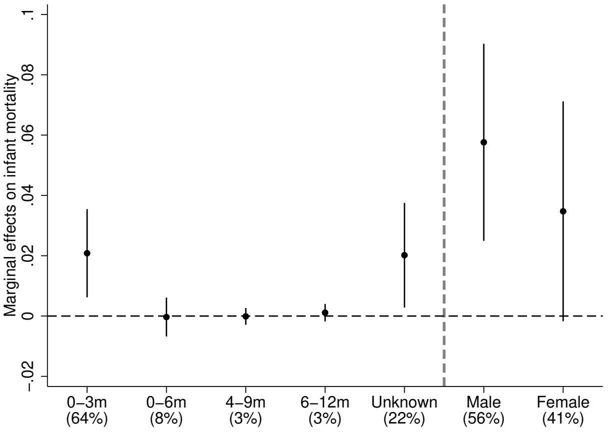
Notes: Standard errors in parentheses and clustered at the CB level. *$p<0.10$, **$p<0.05$, $p<^{***}$ 0.01. The baseline controls in Column (4)-(6) include linear-trend interacted CB tax revenue and rateable property value per capita, and log population. The F statistics reported in columns 5 and 6 are the Montiel Olea-Pflueger (2013) effective first-stage F statistic.

Figure 8: The Dose-response Function in the Effect of Black Smoke Concentration on Infant Mortality



Notes: The Clean Air Act (UK CAA) effects (95CI) is the IV results obtained from interacting black smoke concentration with an ordinal categorical variable that separates the black smoke concentration into bins 0-49, 50-99, 100-149, 150+ micrograms per square meter. The coefficient estimates from previous studies are marked in circles. The reported mean levels of particulate concentration from previous analysis are transformed according to the following PM ratios: PM10 = 0.55TSP (Knittel et al., 2016) and PM2.5 = 0.5PM10 in high-income countries (HIC) and PM2.5 = 0.57 in low- and middle-income countries (LMIC), respectively. (Regression results using AAQD database (WHO): PM10 = -4.69(1.093) + 2*PM2.5(0.067) + 6.83*LMIC(2.287) - 0.26*LMICxPM2.5(0.078)+error. Standard errors in parenthesis.) The LMIC and HIC distributions are the population-weighted exposure to PM2.5 in towns and cities by the country's economic status as defined by WHO and includes 331 locations in LMIC and 478 locations in HIC. Source: Ambient Air Quality Database, WHO (2018) and GHS Urban Centre Database 2015, European Commission (2019).

Figure 9: Heterogeneous Effects of Black Smoke on Infant Mortality



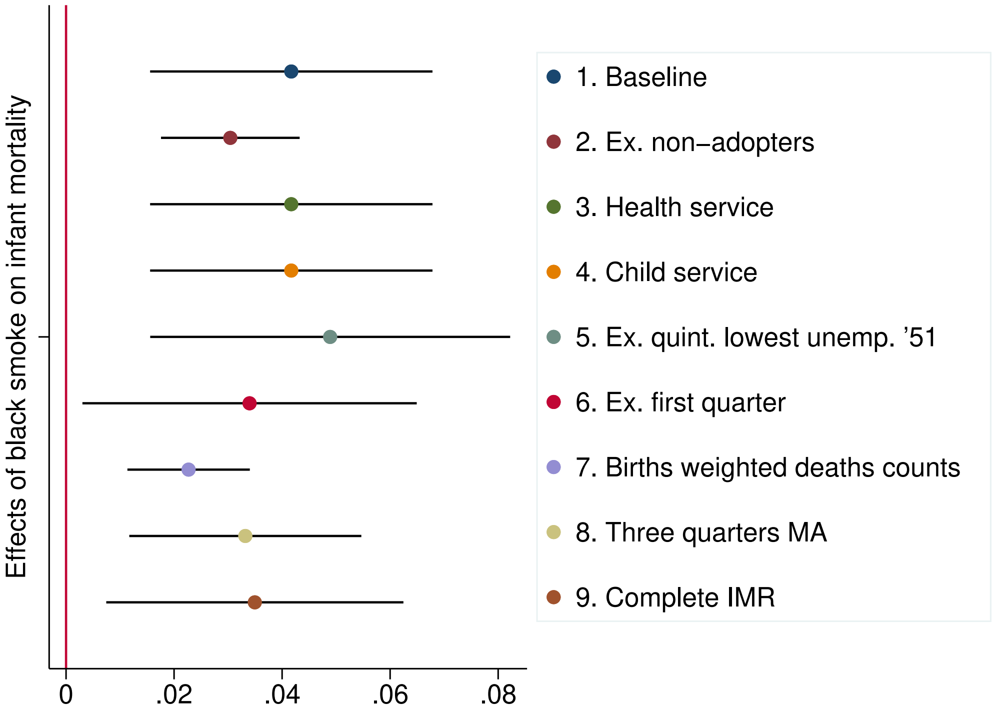
Notes: The nominator in the dependent variables are deaths of infants by age in months at the time of death (0-3m, 0-6m, 4-9m, 6-12), death of infants with unidentified birth records (Unknown), male deaths (Male), and female deaths (Female). The age-span in each age category is the likely age of infant at the time of death determined by if match in birth occurs in the same quarter as death (0-3 months), one quarter before death (0-6 month), two quarters before death (4-9 month), and between 3-4 quarters before death (6-12m). The dependent variables by sex are male (female) mortality under one year of age divided by the number of male (female) births. The parantheses show the category share of baseline mortality. The regression controls for baseline capita CB tax revenue, per capita rateable property value, and log population, interacted with linear time-trends.

Table 4: The Effects of Black Smoke on Births

| | Reduced form | IV | | |
|---|---|---|---|---|
| | Total | Total | Male | Female |
| Black Smoke (10mg) | | -0.00495*** | -0.00545*** | -0.00399** |
| | | (0.002) | (0.002) | (0.002) |
| SCA | 0.0280 | | | |
| | (0.105) | | | |
| SCA × Winter | 0.0452*** | | | |
| | (0.012) | | | |
| Obs. | 2962 | 2962 | 2962 | 2962 |
| CBs | 58 | 58 | 58 | 58 |
| First-stage Fstat | | 15.81 | 15.81 | 15.81 |
| Quarter FE | X | X | X | X |
| Year FE | X | X | X | X |
| CB FE | X | X | X | X |
| Baseline controls | X | X | X | X |
| CB × Year trend | X | X | X | X |
| Dep. mean | | 7.907 | 7.227 | 7.143 |

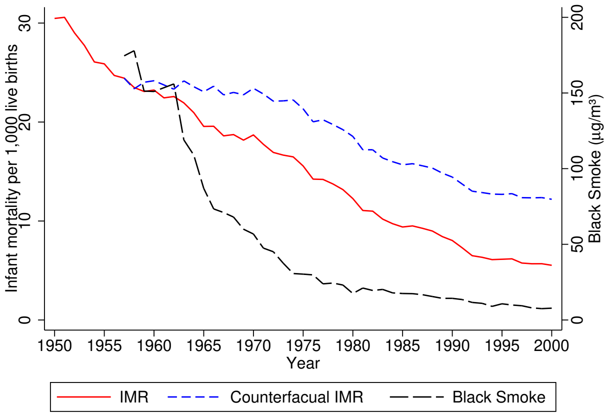
Notes: Column (1) shows the triple difference reduced form results of the effect of SCA on the total number of births. Column (2)-(4) shows the 2SLS estimates of the effect of black Smoke on total number of births, births of male infants, and female infants. All regressions control for CB specific linear trends and trends interacted with baseline values, including annual per capita tax revenue, rateable property value, and log population in addition to CB, year, and quarter FE. The F statistic reported in columns (2)-(4) are the Montiel Olea-Pflueger (2013) effective first-stage F statistic. Standard errors in parentheses and clustered at the CB level. *p<0.10, **p<0.05, p<*** 0.01.

Figure 10: Sensitivity Analysis



Notes: The name of the analysis refers to the following test. 1: The baseline IV estimate. 2: Excluding non-adopting CBs. 3: Controls for CB health service expenditure per capita between 1959-1973. 4: Controls for CB child service expenditure per capita between 1959-1973. 5: Excluding quintile with the lowest unemployment in 1951. 6: Excluding the first quarter from the analysis. 7: Births weighted deaths counts. 8: Replaces quarterly mortality rate with three-quarters moving-average mortality. 9: Excludes CBs with missing infant mortality for more than one quarter. (Gloucester Norwich, Chester, Preston, St Helens, Wakefield, and Birkenhead)

Figure 11: Counterfactual and Actual Infant Mortality in the UK



Source: UNICEF & Heal and Beverland (2017)

Notes: The graph plots the counterfactual infant mortality rate in the UK using the IV estimate from Table 3, column 5. It is defined as the mortality rate that would have been if the UK black smoke concentration had remained at the 1957 level. Note of caution: the representativeness of the pollution data declines beginning in the 1980s, when the number of sites in the monitoring network started dropping rapidly. For example, a decrease in monitoring sites in less polluted areas implies that the counterfactual mortality rate is below the true value.

# A Comparing black smoke to PM2.5

To compare more recent studies that analyze the health impact of exposure to airborne particulate matter, one must convert black smoke (BS) to its equivalent size in particulate matter. Although McFarland et al. (1982) find that a standard black smoke filter can capture particulate matter with a diameter as large as 4.4 micrometers, comparing BS to PM4.4 is too liberal a comparison.[69] Heal and Beverland (2017) estimate a unit BS:PM2.5 ratio in the UK in 1970 (95CI:0.9-1.1). According to their estimates, the BS:PM2.5 ratio only started to decline after 1970, reaching a BS:PM2.5 ratio of approximately 0.8 (95CI:0.7-0.9) by 1974 and a ratio of 0.7 (95CI:0.6-0.8) by 1980 due to increasing demand for petroleum products. This is because while coal remained the predominant energy source in the UK throughout the 1960s, it coincides with increased demand for petroleum products by large-scale industries and electricity generation. Particulate matter emission from motor vehicles, however, was still considered insignificant despite an increase in car ownership (DUKES, 2009).[70]

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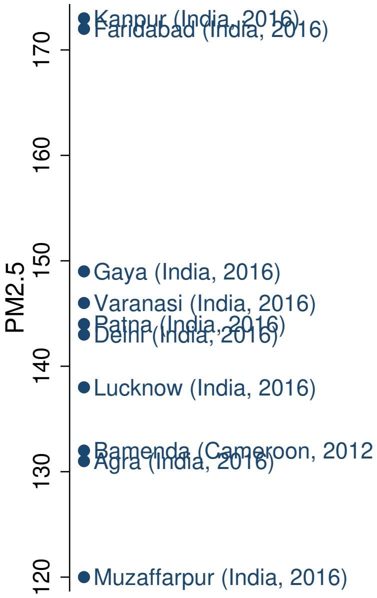
[69] For example, Mitchell et al. (2016) shows that 98 percent of PM emitted from combustion of bituminous coal in a standard domestic furnace is smaller than PM2.5.

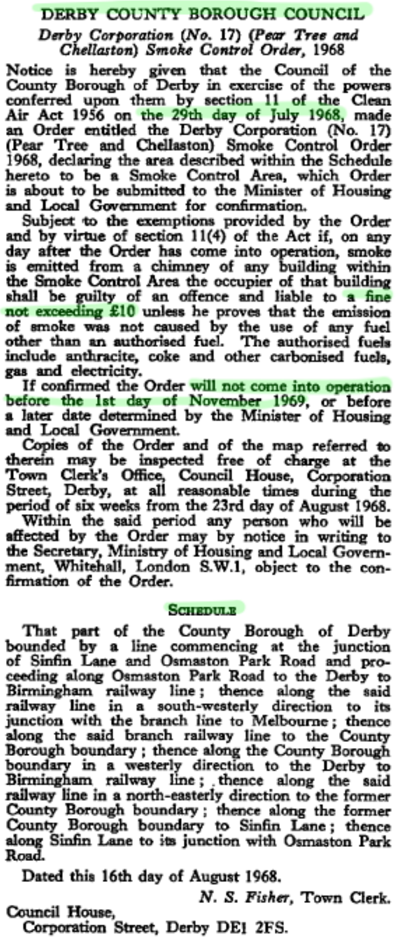
[70] To compare, Barreca et al. (2014) report that the share of particulate matter from on-road vehicles with a diameter less than 10, i.e. PM10, only accounted for 2 percent of all PM10 in the US in 1960.

# B Top 10 highest PM2.5 concentrations



Notes: The figure lists the ten most polluted localities and cities in the world measured by the annual mean concentration of particulate matter less than 2.5 micrometer (PM2.5) [ug/m3]. Source: Ambient Air Quality Database, WHO, April 2018.

# C Smoke control order



**DERBY COUNTY BOROUGH COUNCIL**

*Derby Corporation (No. 17) (Pear Tree and Chellaston) Smoke Control Order*, 1968

Notice is hereby given that the Council of the County Borough of Derby in exercise of the powers conferred upon them by section 11 of the Clean Air Act 1956 on the 29th day of July 1968, made an Order entitled the Derby Corporation (No. 17) (Pear Tree and Chellaston) Smoke Control Order 1968, declaring the area described within the Schedule hereto to be a Smoke Control Area, which Order is about to be submitted to the Minister of Housing and Local Government for confirmation.

Subject to the exemptions provided by the Order and by virtue of section 11(4) of the Act if, on any day after the Order has come into operation, smoke is emitted from a chimney of any building within the Smoke Control Area the occupier of that building shall be guilty of an offence and liable to a fine not exceeding £10 unless he proves that the emission of smoke was not caused by the use of any fuel other than an authorised fuel. The authorised fuels include anthracite, coke and other carbonised fuels, gas and electricity.

If confirmed the Order will not come into operation before the 1st day of November 1969, or before a later date determined by the Minister of Housing and Local Government.

Copies of the Order and of the map referred to therein may be inspected free of charge at the Town Clerk's Office, Council House, Corporation Street, Derby, at all reasonable times during the period of six weeks from the 23rd day of August 1968.

Within the said period any person who will be affected by the Order may by notice in writing to the Secretary, Ministry of Housing and Local Government, Whitehall, London S.W.1, object to the confirmation of the Order.

SCHEDULE

That part of the County Borough of Derby bounded by a line commencing at the junction of Sinfin Lane and Osmaston Park Road and proceeding along Osmaston Park Road to the Derby to Birmingham railway line; thence along the said railway line in a south-westerly direction to its junction with the branch line to Melbourne; thence along the said branch railway line to the County Borough boundary; thence along the County Borough boundary in a westerly direction to the Derby to Birmingham railway line; thence along the said railway line in a north-easterly direction to the former County Borough boundary; thence along the former County Borough boundary to Sinfin Lane; thence along Sinfin Lane to its junction with Osmaston Park Road.

Dated this 16th day of August 1968.

*N. S. Fisher*, Town Clerk.

Council House,
Corporation Street, Derby DE1 2FS.

# D The Schoolchild Chest Health Survey

The Schoolchild Chest Health Survey (SCHS) includes responses from 11,000 children from 11 geographical areas of various backgrounds in the UK in 1966. It reveals that only 16% of the households had central heating. In comparison, 66.7% of the homes reported using coal-fired furnaces. A comparison between urban and rural households shows that the prevalence of central heating systems did not differ between urban and rural households (15.5% versus 17.3%). Still, there was a big difference in the use of coal, with 73.2% of rural households using coal for heating and only 55.6% of urban households. Other heating methods used in urban homes were gas-heated fires (10.7%) and electric stoves and converters (10.9%). The survey also reveals that the prevalence of central heating increases with socio-economic groups (SEG), underscoring the notion that central heating systems were an expensive investment.[71] Finally, central heating was more common among the respondents who reported moving homes between 1961-1966, with 28.5% of the movers having a central heating system installed. The corresponding number for non-movers is 11.9 %. The relationship supports anecdotal evidence that new buildings came with central heating pre-installed following the recommendations from the national housing design guidance of council estates for local governments (Kuijer and Watson, 2017).

# E Unidentified deaths

The failure to match an infant death to a birth record is due to one of the following alternatives: 1) No first name was registered at the time of death. 2) The child was born outside the district of death. 3) The names do not match (for instance, due to misspelling). However, a closer examination reveals that the number of infants with no given name is scarce (1.7%). In

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[71] The prevalence of central heating system by socioeconomic group in ascending order was 1. 54%, 2. 30.6%, 3. 14.2%, 4. 6.4%, 5. 4.92%.

addition, a limited random sample of deaths of unidentified children shows that a substantial share of the children were born outside the district of death, indicating migration between the time of birth and death. Furthermore, by running a gender recognition algorithm, we can identify the gender of the deceased in each category. The exercise reveals a similar gender ratio across the group categories (both showing a higher share of male deaths). However, although it is possible to determine the gender of the deceased for the vast majority of infants in the unidentified group (93.8 %), ambiguous gender names are twice as common among age-unidentified infants, which is partially explained by the higher prevalence of ethnic minority names and other non-traditional UK names. The data also reveals higher prevalence of birth outside wedlock among deceased infants in the age unidentified category.[72]

To conclude, while the entries in the death registry cannot provide further clues as to the socio-economic status of the deceased, if migration, minority background, birth outside wedlock, and failure to register a given name at the time of death are characteristics associated with lower SEC, it may suggest that the unidentified group of infants represents a more disadvantaged group of children on average.

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[72] While neither the birth registry nor the death registry asks for the marital status, a child received its mother's surname at birth if born outside wedlock. Therefore, minding such cases when the mother and the father coincidentally shared the same surname before marriage, the same surname as the mother suggests birth outside wedlock. However, if a father was present and recognized the child's birth despite not being married to the mother, the child automatically received the father's surname. In such cases, the birth record was registered twice, once with the mother's maiden name as the child's surname and once with the father's name as the surname (the mother's maiden name does not change). The ratio of birth to unmarried mothers in the analysis is more or less identical to the national mean estimated by Kiernan (1971) and displays a similar increasing trend over time, suggesting that the identification strategy using marriage status provides reasonable estimates.

# F Sample statistics by year of SCA adoption

| | ***Non-adopters*** | | ***Adopters*** | | | | | | ***Mean difference:*** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | (1) All | | (2) All | | (3) First SCA $< 1964$ | | (4) First SCA $\geq 1964$ | | (1)-(2) | | (3)-(4) | |
| | Mean | Std. | Mean | Std. | Mean | Std. | Mean | Std. | Diff. | t-stat | Diff. | t-stat |
| ***Baselines in 1951:*** | | | | | | | | | | | | |
| Industry coal dependency p.c. | 0.06 | 0.01 | 0.05 | 0.01 | 0.05 | 0.01 | 0.05 | 0.01 | 0.01 | (3.13) | 0.00 | (0.57) |
| Industry coke dependency p.c. | 0.05 | 0.01 | 0.05 | 0.01 | 0.05 | 0.02 | 0.04 | 0.01 | 0.01 | (1.50) | 0.00 | (0.81) |
| Industry oil dependency p.c. | 0.16 | 0.04 | 0.12 | 0.03 | 0.12 | 0.03 | 0.12 | 0.03 | 0.04 | (3.84) | 0.00 | (0.32) |
| Industry electricity dependency p.c. | 0.09 | 0.02 | 0.08 | 0.02 | 0.08 | 0.02 | 0.07 | 0.01 | 0.02 | (3.11) | 0.01 | (0.85) |
| Industry gas and water dependency p.c. | 0.13 | 0.03 | 0.10 | 0.02 | 0.10 | 0.02 | 0.10 | 0.02 | 0.03 | (3.66) | 0.00 | (0.44) |
| Ln(Population) | 11.39 | 0.58 | 11.95 | 0.75 | 12.02 | 0.77 | 11.57 | 0.46 | -0.56 | (-2.48) | 0.46 | (1.50) |
| Population density | 24.57 | 8.36 | 36.98 | 14.64 | 37.30 | 15.30 | 35.22 | 11.10 | -12.40 | (-2.91) | 2.09 | (0.34) |
| CB Area (ha) | 4226.53 | 1998.54 | 5644.18 | 4319.71 | 6072.83 | 4554.98 | 3317.22 | 1188.96 | -1417.65 | (-1.14) | 2755.61 | (1.58) |
| Age>15/pop | 0.79 | 0.02 | 0.77 | 0.02 | 0.77 | 0.02 | 0.77 | 0.01 | 0.02 | (3.50) | 0.00 | (0.23) |
| Share of self-employment | 0.03 | 0.01 | 0.02 | 0.00 | 0.02 | 0.00 | 0.02 | 0.00 | 0.01 | (2.16) | 0.00 | (1.45) |
| Labor force/pop | 0.44 | 0.02 | 0.48 | 0.04 | 0.48 | 0.04 | 0.46 | 0.03 | -0.03 | (-3.18) | 0.03 | (1.79) |
| Rate of unemployment | 0.03 | 0.01 | 0.02 | 0.01 | 0.02 | 0.01 | 0.02 | 0.02 | 0.01 | (1.31) | -0.00 | (-0.37) |
| All-age mortality rate (%) | 1.34 | 0.24 | 1.23 | 0.14 | 1.23 | 0.15 | 1.22 | 0.07 | 0.11 | (2.14) | 0.01 | (0.19) |
| Raised tax p.c. | 8.66 | 1.57 | 7.20 | 1.22 | 7.30 | 1.12 | 6.67 | 1.68 | 1.46 | (3.56) | 0.63 | (1.26) |
| Est. expenditure p.c. | 10.06 | 1.30 | 9.02 | 0.84 | 9.11 | 0.79 | 8.56 | 1.02 | 1.04 | (3.45) | 0.54 | (1.60) |
| Rateable value p.c. (£000) | 9.79 | 3.20 | 7.11 | 1.28 | 7.17 | 1.30 | 6.74 | 1.20 | 2.68 | (4.56) | 0.44 | (0.83) |
| ***Baselines in 1959:*** | | | | | | | | | | | | |
| Health services p.c. | 0.07 | 0.02 | 0.10 | 0.03 | 0.11 | 0.03 | 0.09 | 0.03 | -0.04 | (-6.03) | 0.02 | (2.31) |
| Child services p.c. | 0.03 | 0.01 | 0.04 | 0.01 | 0.04 | 0.01 | 0.03 | 0.01 | -0.01 | (-5.24) | 0.01 | (1.58) |
| Welfare services p.c. | 0.04 | 0.01 | 0.05 | 0.02 | 0.05 | 0.02 | 0.05 | 0.01 | -0.01 | (-4.20) | 0.00 | (0.73) |
| Housing services p.c. | 0.09 | 0.05 | 0.14 | 0.05 | 0.14 | 0.05 | 0.14 | 0.06 | -0.05 | (-4.62) | 0.00 | (0.24) |
| ***Infant mortality rate:*** | | | | | | | | | | | | |
| 1957: | 25.18 | 6.56 | 30.35 | 7.53 | 30.45 | 7.87 | 29.80 | 5.51 | -5.17 | (-3.17) | 0.65 | (0.29) |
| — Jan-Mar | 27.97 | 5.61 | 31.31 | 9.06 | 31.01 | 9.32 | 32.96 | 7.56 | -3.35 | (-1.78) | -1.95 | (-0.74) |
| — Apr-Jun | 21.69 | 9.40 | 29.23 | 9.45 | 29.62 | 9.31 | 27.13 | 10.29 | -7.54 | (-3.58) | 2.48 | (0.90) |
| — Jul-Sep | 23.95 | 9.52 | 27.24 | 8.47 | 27.52 | 8.98 | 25.72 | 4.83 | -3.29 | (-1.70) | 1.80 | (0.73) |
| — Oct-Dec | 27.40 | 12.69 | 33.65 | 10.18 | 33.75 | 10.54 | 33.09 | 8.26 | -6.24 | (-2.60) | 0.66 | (0.22) |
| ***Black smoke:*** | | | | | | | | | | | | |
| 1957-1973: | 67.65 | 33.98 | 133.36 | 58.97 | 138.91 | 55.17 | 103.26 | 74.05 | -65.71 | (-3.82) | 35.65 | (1.49) |
| — Jan-Mar | 99.82 | 45.39 | 179.47 | 72.71 | 186.45 | 68.78 | 141.55 | 84.04 | -79.65 | (-5.29) | 44.90 | (2.17) |
| — Apr-Jun | 34.59 | 17.82 | 73.77 | 33.14 | 77.28 | 32.18 | 54.68 | 32.87 | -39.18 | (-5.78) | 22.60 | (2.41) |
| — Jul-Sep | 25.87 | 13.81 | 61.88 | 29.61 | 65.29 | 29.18 | 43.39 | 25.55 | -36.01 | (-6.00) | 21.90 | (2.63) |
| — Oct-Dec | 95.02 | 49.10 | 179.43 | 78.70 | 187.70 | 75.82 | 134.54 | 81.65 | -84.41 | (-5.18) | 53.15 | (2.38) |

Notes: Non-Adopters (13 in total) are the county boroughs that never introduced an SCA before 1974. Adopters (45 in total) are further divided into groups by SCA adoption year: 38 CBs before 1964 and 7 CBs after 1965.

# G List of countries (Fig 8)

Australia (8), Austria (4), Bangladesh (6), Belgium (7) Brazil (6) Bulgaria (5) Canada (28) Chile (20) China (227) Colombia (4) Croatia (4) Cyprus (1) Czechia (8) Ecuador (1) El Salvador (1) Estonia (2) Finland (4) France (46) Germany (48) Ghana (1) Hungary (3) Iceland (1) India (18) Indonesia (2) Iran (25) Israel (1) Italy (54) Japan (1) Latvia (2) Lithuania (3) Luxembourg (1) Mongolia (1) Netherlands (9) Norway (4) Peru (1) Philippines (1) Poland (24) Portugal (2) Republic of Korea (3) Romania (9) Singapore (1) Slovakia (1) Slovenia (2) South Africa (3) Spain (19) Sweden (3) Switzerland (3) Macedonia (1) Turkey (14) UK (27) US (137) Uruguay (1) Viet Nam (1)

# H Data availability

| **County borough:** | **Irregularity:** | | **SCA** | **Pollution** | **Econ.** |
|---|---|---|---|---|---|
| | **Borders** | **IMR** | | | |
| Barnsley | | | 1959 | 1958 | |
| Barrow-in-Furness | | | . | 1978 | |
| Bath | | | . | 1962 | |
| Birkenhead | | X[73] | 1961 | 1961 | |
| Birmingham | | | 1958 | 1949 | |
| Blackburn | | | 1960 | 1959 | |
| Blackpool | | | . | 1961 | |
| Bolton | | | 1957 | 1951 | |
| Bootle | | X | 1959 | 1959 | |
| Bournemouth | | | . | 1962 | |
| Bradford | | | 1959 | 1951 | |
| Brighton | | | . | 1962 | |
| Bristol | | | 1958 | 1949 | |
| Burnley | | | 1960 | 1945 | |
| Burton upon Trent | | | 1964 | 1976 | |
| Bury | | | 1959 | 1960 | |
| Canterbury | | | (1971)[74] | 1965 | |
| Carlisle | | | . | 1964 | |
| Chester[75] | | X[76] | . | 1960 | |
| Coventry | | | 1959 | 1959 | |
| Croydon | X | | . | . | |
| Darlington | | | 1965 | 1963 | |
| Derby | X | | 1961 | 1958 | |
| Dewsbury | | | 1958 | 1976 | |
| Doncaster | | | 1960 | 1954 | |
| Dudley | X | | 1958 | 1951 | |
| Eastbourne | | | . | 1961 | |

| **County borough:** | **Irregularity:** | | **SCA** | **Pollution** | **Econ.** |
|---|---|---|---|---|---|
| | **Borders** | **IMR** | | | |
| East Ham | X | | . | . | |
| Exeter | | | 1957 | 1955 | |
| Gateshead | | | 1959 | 1960 | |
| Gloucester | | X[77] | (1963)[78] | 1968 | |
| Great Yarmouth | | | . | . | |
| Grimsby | | | . | . | |
| Halifax | | | 1958 | 1959 | |
| Hartlepool | X | | 1963 | 1961 | |
| Hastings | | | . | . | |
| Huddersfield | | | 1958 | 1957 | |
| Ipswich | | | . | 1961 | |
| Kingston upon Hull | | | 1958 | 1962 | |
| Leeds | | | 1958 | 1950 | |
| Leicester | | | 1958 | 1955 | |
| Lincoln | | | 1960 | 1960 | |
| Liverpool | | | 1957 | 1956 | |
| Luton[79] | | | 1956 | 1950 | No data |
| Manchester | | | 1958 | 1949 | |
| Middlesbrough | X | | 1959 | . | |
| Newcastle upon Tyne | | | 1958 | 1954 | |
| Northampton | | | 1969 | 1967 | |
| Norwich | | X[80] | 1968 | 1959 | |
| Nottingham | | | 1959 | 1954 | |
| Oldham | | | 1960 | 1958 | |
| Oxford | | | 1958 | 1956 | |
| Plymouth | | | . | 1961 | |
| Portsmouth | | | 1973 | 1956 | |
| Preston | | X[81] | 1958 | 1954 | |
| Reading | | | 1958 | 1958 | |
| Rochdale | | X | 1958 | 1969 | |

| County borough: | Irregularity: Borders | IMR | SCA | Pollution | Econ. |
|---|---|---|---|---|---|
| Rotherham | | | 1958 | 1980 | |
| Salford | | | 1959 | 1949 | |
| Sheffield | | | 1958 | 1949 | |
| Smethwick | X | | 1958 | . | |
| Solihull[82] | | | 1959 | 1960 | No data |
| South Shields | | | 1966 | 1962 | |
| Southampton | | | 1961 | 1955 | |
| Southend-on-Sea | | | . | 1961 | |
| Southport | | | 1960 | 1974 | |
| St Helens | | X[83] | 1965 | 1957 | |
| Stockport | | | 1958 | 1961 | |
| Stoke on Trent | | | 1960 | 1960 | |
| Sunderland | | | 1959 | 1961 | |
| Teesside | X | | 1969 | 1961 | |
| Torbay | X | | . | 1961 | |
| Tynemouth | | | 1962 | 1958 | |
| Wakefield | | X[84] | 1959 | 1957 | |
| Wallasey | | | 1958 | 1961 | |
| Walsall | X | | 1960 | 1955 | |
| Warley | X | | 1968 | 1958 | |
| Warrington | | | 1959 | 1950 | |
| West Bromwich | X | | 1957 | 1958 | |
| West Ham | X | | . | . | |
| West Hartlepool | X | | 1962 | . | |
| Wigan | | X | 1962 | 1959 | |
| Wolverhampton | X | | 1960 | 1944 | |
| Worcester | | | . | 1974 | |
| York | | X | 1968 | 1959 | |

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[73] Omitted between 1973q1-1973q4.

[74] Non-adopter: SCO only applied to greenfield area.

[75] Hoole UD was incorporated into Chester CB in 1954.

[76] Omitted between 1971q4-1973q4.

[77] Omitted between 1958q3-1958q4.

[78] Non-adopter: SCO only applied to greenfield area after 1967.

[79] Changed status from Municipal Borough to CB in 1964.

[80] Omitted between 1965q1-1973q4.

[81] 1973q4 omitted.

[82] Changed status from UD to MB in 1954 and to CB in 1964.

[83] Omitted between 1973q2-1973q4.

[84] 1973q4 omitted.