Air pollution, foetal mortality, and long-term health: Evidence from the Great London Smog

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1 November 2014

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[Working Paper - First version: 2014/11/01. This version: 2015/03/25]

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Abstract

This paper provides new evidence on the consequences of foetal exposure to high levels of pollution for the risk of stillbirth, and for the long-term health and labour market outcomes of those that survive. Variation in *in utero* exposure comes from a persistent weather system that affected London for five days in December 1952, preventing the dispersion of atmospheric pollution. This increased levels of total suspended particulate matter by around 300%. Unaffected counties in England and Wales are used in a differences-in-differences design to identify the short and long-term effects.

Historical registrar data for the nine months following the smog show a 2% increase in reported stillbirths in London relative to national trends. As foetal deaths often go unreported, the exercise is then repeated for registered births. The data show around 400 fewer live births then expected in London, or a reduction of 3% against national trends. Survivors are then identified by district and quarter of birth, and their health and labour market outcomes observed at fifty and sixty years old. Differences-in-differences estimates show that survivors are in general less healthy, less likely to have a formal qualification, and less likely to be employed than those unaffected by the smog.

Keywords: Air Pollution, Health, Fetal Origins, The Great London Smog
JEL Classification Numbers: Q53, I12, I18

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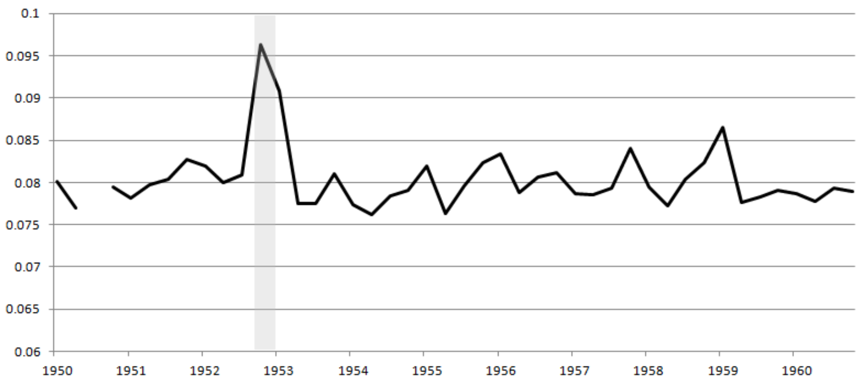
1. Foetal exposure to air pollution

The effects of exposure *in utero* are a largely hidden cost of pollution, but the impact on health and well-being can be profound. The goal of this paper is to study the short and long-term effects of foetal exposure to a strong pollution episode - the London Smog of 1952. This persistent smog was caused by a high-pressure weather system that hung over the city for five days, preventing the normal dispersion of pollution. During these days, visibility dropped to just a few metres, and ambient levels of pollution increased by up to 300%. There was no panic at the time as Londoners were accustomed to winter fogs, but the health effects were later found to be severe, with around 12,000 excess deaths eventually attributed to the smog. The contemporaneous impact of the smog on adult health can be seen in Figure 1 below, showing quarterly deaths in London as a proportion of those registered in England and Wales.

Figure 1: Ratio of deaths during the smog: London, and England & Wales



Notes: Shaded area represents the fourth quarter of 1952 - the period of the London Smog. Data on mortality from the English Registrar General. Q3 1950 is missing from the dataset.

There are a number of reasons why the London smog is a good environment in which to study the effects of foetal exposure to pollution. First, the unusually sharp exposure makes it possible to observe health effects by trimester, and to differentiate cleanly between foetal and neonatal effects. This is unusual as most plausibly exogenous variation in pollution, such as variation from recessions or policy changes, take one or two years to take full effect[1]. Second, as the smog occurred in 1952, it is possible to observe both the contemporaneous effect on foetal mortality, and the health and labour market outcomes of survivors over the subsequent fifty or sixty years. Lastly, levels of pollution were particularly high during the period. This is important because the majority of research on the health effects of pollution comes from high-income countries, where

[1]Two examples of research based on 'sharp' events are Currie and Walker (2011), who observe the effects of reduced traffic congestion near highways caused by the introduction of an automated tolling system; and Jayachandran (2009), who studies the health effects of wildfires that swept through Indonesia in 1997. Both papers are discussed in more detail below.

information on pollution and health are of good quality, but where pollution levels are generally low. While pollution levels[2] in developed countries are typically lower than $30\mu g/m^3$, those found in most low- and middle-income countries are generally much higher. In 2012, over a hundred cities had average levels of over $100\mu g/m^3$. Average levels in Delhi were $286\mu g/m^3$, while those in Peshwar, home to over three million people, were over $500\mu g/m^3$. As the shape of the dose-response of health to foetal exposure to pollution is still a subject of ongoing research, the London smog presents a unique opportunity to learn about the long-term health effects of the severe pollution levels currently found in much of the world[3].

Foetal deaths often go unreported in official statistics, and can even go unnoticed by the mother in some circumstances. As a result, the existing evidence on prenatal effects often exploit indirect measures of foetal survival. Jayachandran (2009) uses variation in atmospheric pollution from a large wildfire that swept through Indonesia in 1997. The wildfires caused severe atmospheric pollution, with levels of PM10 in some areas exceeding 1000 $\mu g/m^3$ for several days during the fires. The identification strategy exploits geographic variation in pollution and the sharp timing of the wildfire to test for reductions in the number of live births caused by prenatal mortality. Results show that the pollution led to 15,600 missing children, an effect driven predominantly by *in utero* exposure. Sanders and Stoecker (2011) take another indirect approach, exploiting the Trivers-Willard hypothesis that male foetuses are more vulnerable to external shocks than females. Using plausibly exogenous variation from the 1970 Clean Air Act and data from a 50% sample of U.S. birth certificates, the authors find that a one standard deviation drop in annual average particulates reduces the percentage of male live births by 3.1%. Results from both papers suggest that foetal survival is strongly linked to the education and income levels of the mother.

A possible issue in observing the health effects of foetal exposure to pollution among those surviving till birth is sample selection. If stillbirth caused by an *in utero* shock is more likely for less healthy foetuses, those observed after birth would be selected from the strongest in the cohort[4]. Bozzoli, Deaton and Qintana-Domeque (2009) encounter this effect when studying the cross-country link between child mortality and adult height. The authors find the expected relationship among most countries, but find that child mortality is associated with an *increase* in the height of the surviving population in the poorest countries, where mortality was particularly high. There is, nonetheless, strong evidence that foetal exposure to pollution affects infant health and mortality[5]. Chay and Greenstone (2003) use variation in pollution caused by the 1981-82 U.S. recession to

[2]All levels of pollution refer to annual average levels of particulate matter less than ten microns across(PM10). Source for data: the World Health Organization, available at *www.who.int/topics/airpollution/en*

[3]For an overview of the dose-response of health to atmospheric pollution, see Zivin & Neidell (2013). For a discussion of cross-country differences between dose-responses, see Arceo-Gomez et al (2014).

[4]See Almond and Currie (2011) for a fuller discussion of 'culling' in papers studying the effects of foetal shocks.

[5]See Zivin & Neidell (2013) for a survey of the health effects of pollution, including the effects of foetal exposure on infant mortality. Currie and Vogl (2013) provide an overview of the long-term effects of early shocks in developing countries, including those from atmospheric pollution.

study the effects of particulate pollution on infant mortality. They find that a 1% decrease in pollution in a county results in a 0.35% reduction in the infant mortality rate. The strongest effects were found for infants less than one month old, suggesting that foetal exposure was an important factor. Currie and Walker (2011) study the effects of air pollution caused by traffic using variation from the introduction of the EZ-Pass scheme in New Jersey and Pennsylvania. This scheme allowed drivers to pass through toll gates without stopping, and resulted in a sharp reduction in carbon monoxide pollution in residential areas close to the tolls. The paper uses a differences-in-differences strategy, comparing the change in infant health of those *in utero* close to highway tolls to those *in utero* close to other parts of the highway system. Their results show that the introduction of the EZ-Pass scheme resulted in around an 11% reduction in prematurity, and a 12% reduction in birth weight - a common proxy of infant health.

There is much less evidence from low and middle-income countries, due mostly to the difficulty in obtaining information on health and pollution. Arceo-Gomez, Hanna & Oliva (2014) gather ten years of weekly data on health for forty eight municipalities in Mexico City, where data for pollution is also available. The authors adopt an IV strategy using temperature inversions - which prevent the dispersion of atmospheric pollution - as an instrument for exposure. The IV estimates show that a $1000\mu g/m^3$ increase in particulates results in 0.24 infant deaths per 100,000 births - a health effect similar to those found in the literature on the United States. Greenstone and Hanna (2014) construct a database of infant health and pollution levels in India in order to study the effectiveness of environmental regulations. The authors also test the effects of the most successful of the reforms, which promoted the use of catalytic converters, on infant mortality. Their results were suggestive of a decline in infant mortality, but were not statistically significant.

Very few papers study the long-term effects of foetal exposure to pollution, mainly because of the difficulty in obtaining information on place of birth for individuals observed as adults. Sanders (2012) overcomes this issue with administrative education data from Texas that contains information on both students' test scores in high school and their counties of birth. Exposure to pollution is calculated using county-level data on total suspended particulate matter, and is instrumented using county-level changes in relative manufacturing employment. The author finds that a standard deviation decrease in particulates is associated with a 2% increase in grades using OLS, and in a 6% increase using IV. Isen, Rossin-Slater and Walker (2014) use linked administrative data from the U.S. census to investigate the effects of foetal exposure to particulates on incomes later in life. To identify the effect, the authors exploit a sharp drop in atmospheric pollution that followed the implementation of the 1970 Clean Air Act. Their results indicate that a 10 unit decrease in particulates resulted in a 1% increase in earnings for individuals aged 29-30, mostly driven by a drop in labour force participation.

This paper takes a differences-in-differences approach to measure the short and long-term health effects of foetal exposure to pollution, comparing outcomes in London over time to those in unaffected counties of England and Wales. In order to study the effects of foetal exposure to pollution on prenatal mortality, quarterly historical registrar data on stillbirths is gathered for the period from 1948 to 1964. Differences-in-differences estimates on stillbirths in the period from one to nine months after the smog show a 2% increase against national trends. As foetal deaths are often unreported, the exercise was repeated for numbers of live births. The data show around 400 fewer live births than expected, or a reduction of 3% against national trends. Overall, the results indicate that *in utero* exposure to air pollution had a strong effect on foetal mortality, much of which went unreported in official statistics.

Survivors are then identified in the ONS Longitudinal Study - a 1% sample of the population of England and Wales - using information on district and quarter of birth. Two related designs are used to observe the long-term effects of *in utero* exposure to pollution. The first is a differences-in-differences design comparing outcomes for those conceived in 1952 (and affected by the smog during the pregnancy) to those conceived in 1953, using unaffected counties of England and Wales to control for year-level effects. The second design splits London into 'low pollution' districts that experienced weaker (but still very high) pollution during the period, and 'high pollution' districts that experienced especially severe pollution. The estimates from this design compare outcomes for children conceived in 1952 in the high or low polluted areas with outcomes for children conceived in 1953 in the same areas, again using unaffected counties of England and Wales as a control.

As the short-term effects indicate that neonatal mortality was affected by the smog, the first outcome observed in the ONS-LS was the gender of survivors when they were first observed in the 1971 census. In contrast to other papers in the literature, there is little evidence that female foetuses were more likely to survive. Simple time series estimates of the proportion of males in the affected cohort in London are, in general, not significantly different from zero. There is weak evidence for the opposite effect - that males were more likely to survive than girls. Estimates on the proportions of males among those affected in the first and second trimesters, when children are especially vulnerable, are positive. An estimate of the effect for the areas of London most seriously affected are also positive, with a 95% confidence interval of [-0.01, 0.10]. These results are not supportive of the Trivers-Willard hypothesis that female foetuses are more likely to survive an adverse shock, but do not contradict previous studies finding this effect. The pollution levels observed during the smog are far higher than those in the United States, where most work on the Trivers-Willard hypothesis has been conducted. It is interesting to note that survivors affected as infants are more likely to be female, suggesting that there may be differences in the effects on survival of shocks experienced *in utero* and as a newborn.

The analysis of long-term effects focuses on individuals observed in 2001 and 2011 (at around fifty and sixty years old) in the ONS-LS. However, linked information on deaths makes it possible to observe mortality in youth and middle age. Results show that those affected by the smog are, on average, two percent less likely to die before sixty than their peers. The effect is statistically significant and appears strongest for those aged over forty five. Two hypotheses might explain this counter-intuitive result. The first is that 'what doesn't kill you makes you stronger', with a maternal or a foetal response to the shock protecting the child in later life. The second is that, as with Bozzoli et al (2009), those surviving the early health shock were drawn from the strongest in the cohort. Results from other outcomes are strongly supportive of the latter hypothesis: those observed in later life were 2% more likely to report themselves in poor health, 3% less likely to have an A-level qualification, and 1% less likely to be employed at fifty then their peers. The employment effects are driven almost entirely by males, who were 4% less likely to be employed at fifty than their peers.

Differences in gender balance among those first observed in the ONS-LS in 1971 suggest that the effects on foetal survival were much less severe in the 'low pollution' districts. As a result, estimates from these districts are likely to incorporate a smaller bias towards health caused by strong-survivor effects. Individuals born in these districts were 6% more likely to report themselves in poor heath, 10% less likely to have an A-Level qualification, and 4% less likely than their peers to be employed at fifty. In the 'high pollution' districts, where the gender balance among survivors shifted 4% towards males, the estimated differences between survivors and their peers were weaker, less likely to be statistically significant, and even positive in some circumstances. Individuals from these districts were 2% less likely to have an A-Level qualification, but were 3% *less* likely than the unaffected population to report themselves in poor health, a pattern observed in both male and female survivors. If the individual-level health effects in the 'high pollution' districts were as strong, or stronger than those in the 'low pollution' districts (where the impact was still over $800\mu g/m^3$) then foetal mortality must have had a profound impact on the characteristics of the surviving population. It should be noted that the estimated effects on the health and labour market outcomes of those in the 'low pollution' districts, although strong, are also likely to be lower-bounds of the true health effects for individuals.

This paper contributes to the literature in a number of ways. Most evidence on the effects of foetal exposure to pollution is based on relatively low levels of pollution - this paper provides new evidence on the effects of foetal exposure to severe pollution of a kind closer to those currently experienced in middle and low income countries. In the two areas of London studied, particulate pollution increased by an average of $800\mu g/m^3$ and $1800\mu g/m^3$ during the five days of the smog. Data from daily readings in Delhi[6], where the average level of pollution is currently around $280\mu g/m^3$, show how variable pollution levels can be. Between 2004 and 2010, there were fifty six occasions in which the Town Hall pollution meter recorded particulate levels over $800\mu g/m^3$, and

[6]Available from the Indian Central Pollution Control Board.

nine occasions when the levels were over $1000\mu g/m^3$. The Town Hall meter provides observations for only around one day in ten during the six years observed, but it is clear that the high annual levels of pollution recorded by the World Health Organisation are likely to hide a large number of severe pollution shocks of the kind observed in London 1952. Second, the unusually sharp variation in pollution caused by the smog makes it possible to separate effects by trimester and to differentiate cleanly between effects from prenatal and neonatal exposure. Third, the high quality data collected at the time makes it possible to gather evidence on foetal mortality, which is often under-reported, or impossible to observe at the levels of pollution studied. Fourth, the long period since the smog makes it possible to observe the long term effects of foetal exposure for up to sixty years, for a variety of outcomes.

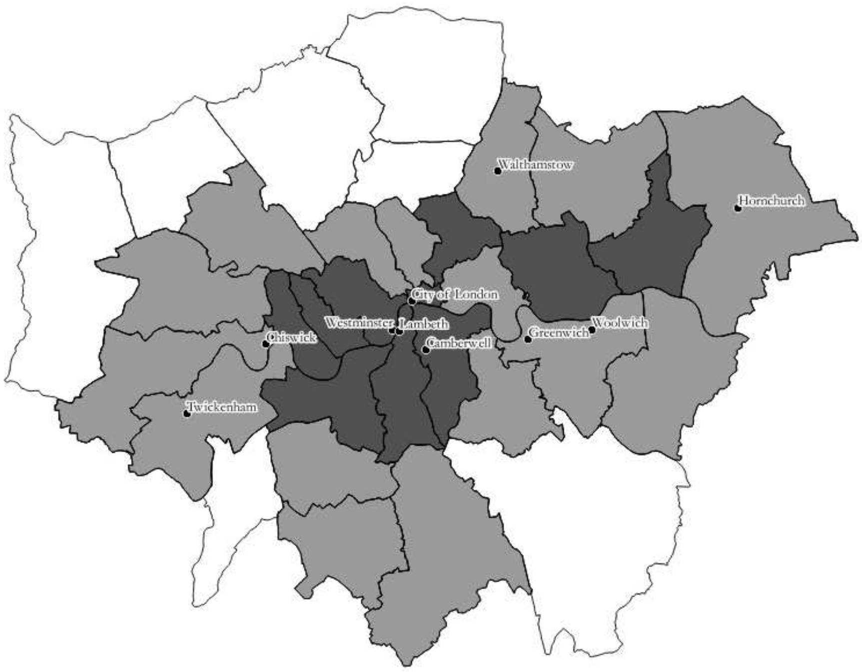
Taken as a whole, the results suggest that the London smog had a significant impact on foetal mortality, and limited the health, investment in education, and employment prospects of those that survived. Restricting attention to just mortality, the World Health Organisation estimates that pollution caused 3.7 million premature deaths worldwide in 2012, 88% of which occurred in low and middle income countries. The results of this study suggest that this figure is an underestimate, missing both the deaths, and the long-term scarring of those not yet born.

2. The London smog of 1952

On the fifth of December of 1952, winds dropped, and a high pressure weather system settled over London. Atmospheric pollution from traffic and the burning of coal that was normally dispersed by convection became trapped by the resulting temperature inversion, and a thick ground-level smog formed over the city. The weather conditions persisted for five more days, during which time visibility dropped to metres, and pollution levels increased threefold. London was accustomed to 'pea-soupers' - thick winter fogs - and there was little panic. The people of London stayed at home, which was the official advice at the time, and normal life continued on the eleventh. When official figures on deaths and hospitalisations arrived a week later, it became clear that something quite serious had happened. A report by the Ministry of Health (1954) attributed over four thousand deaths[7] to the smog, leading Parliament to pass the Clean Air Act of 1956, drafted with the goal of preventing any further smogs in London.

[7]Later studies have revised this number up to 12,000 Bell & Davis (2001)

Figure 2: Pollution in December 1952 - By district

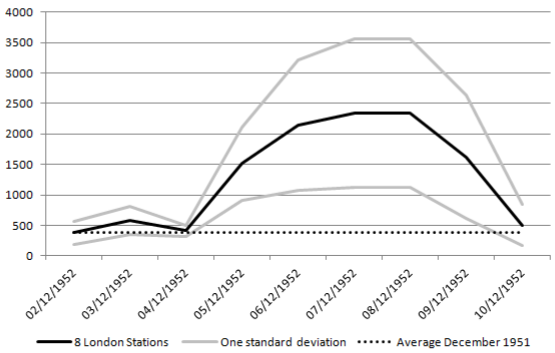


Notes: Points marked on the map indicate the locations of the twelve PM10 monitoring stations active during the smog. Light shaded areas indicate an average increase of around $800\mu g/m^3$, dark shaded areas indicate an average increase of $1800\mu g/m^3$. Pollution data from the Fuel Research Board and Wilson (1954), mapping data from the Ordinance Survey.

There is good information available on pollution levels during the smog. Figures 3, 4 and 5 show daily measurements taken during the first half of December for London, Great Britain, and for other large towns. The December smog appears not to have affected rest of Britain: there is a small increase in pollution levels in the other big towns on the seventh and eighth of December, but nothing close to the scale of the London smog. The smog affected rich and poor areas alike - with Kensington, Chelsea and South London among the worst hit areas. Figure 2 shows the effects of the smog by London borough. The Ministry of Health (1954) report divided London into two levels of impact using a combination of measurements of sulphur dioxide and particulates. The darkest areas in the map are the most seriously affected, experiencing an increase of around $1800\mu g/m^3$. The lighter gray areas indicate areas experiencing lower - but still very high - increases of around $800\mu g/m^3$. Average levels of pollution during the period from 1949/50 to 1954/5[8] can be seen in figure 6. For the period for which there is data available, there is an upward trend in average levels of Sulphur Dioxide, with a dip in the year prior to the smog.

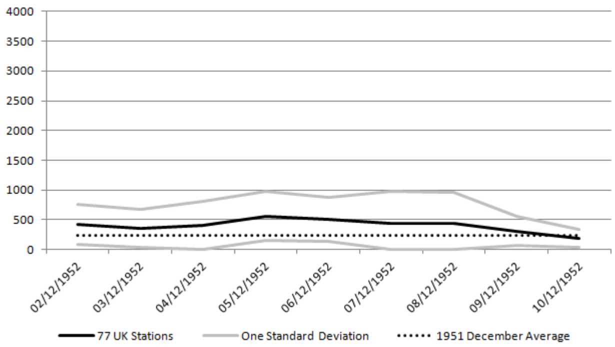
[8]Each yearly observation begins in October: the Fuel Research Board reported averages this way to avoid splitting the winter peak into two observations.

Figure 3: Pollution in December 1952 - London



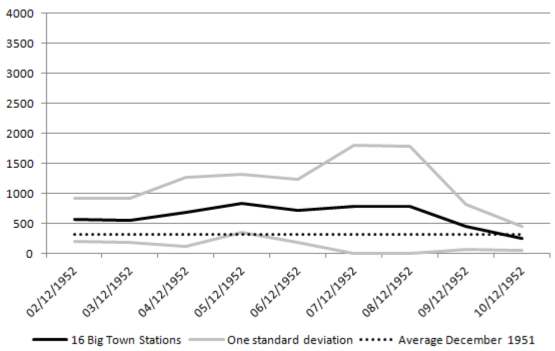
Notes: Pollution data is for PM10 particulates and is measured in microgrammes per cubic metre. Solid black line based on an average from 8 monitoring stations in London. Gray line shows the standard deviation of this average. Dotted line shows the December average from 1951. Data from the Fuel Research Board

Figure 4: Pollution in December 1952 - Great Britain (excluding London)



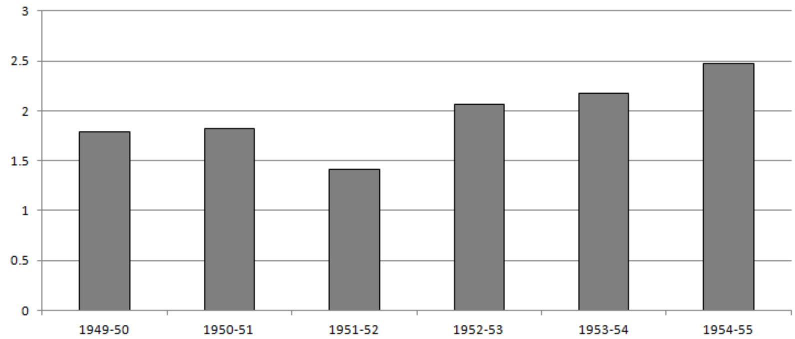
Notes: Pollution data is for PM10 particulates and is measured in microgrammes per cubic metre. Solid black line based on an average from 77 monitoring stations in Great Britain. The gray line shows the standard deviation of this average. Dotted line shows the December average from 1951.Data from the Fuel Research Board

Figure 5: Pollution in December 1952 - Other big towns (excluding London)



Notes: Pollution data is for PM10 particulates and is measured in microgrammes per cubic metre. Solid black line based on an average from 16 monitoring stations other large towns in the UK. These are: Bradford, Bristol, Cardiff, Glasgow, Leeds, Leicester, Liverpool, Manchester, Newcastle, Nottingham, and Sheffield. The gray line shows the standard deviation of this average. Dotted line shows the December average from 1951.Data from the Fuel Research Board

Figure 6: Annual levels of sulphur dioxide, parts per million



Notes: Reported years start in October (at the start of the winter peak.) Pollution data from the Fuel Research Board.

There is less information available[9] for England & Wales, but figures 17 and 18 in the appendix show information on emissions of smoke and sulphur dioxide and - as cold weather prevents the dispersion of atmospheric pollution - on monthly minimum temperatures. Figure 17 shows an increase in the emission of sulphur dioxide, similar to the trend for London shown in figure 6. Figure 18 shows monthly minimum temperatures for London and England for the period. Winter temperatures in London during 1952 were low relative to long-term trends, but almost identical to those in the five year period from 1951 to 1955. With the exception of the smog in December, average levels of pollution in 1952 appear broadly consistent with the general trends in London and the rest of the UK.

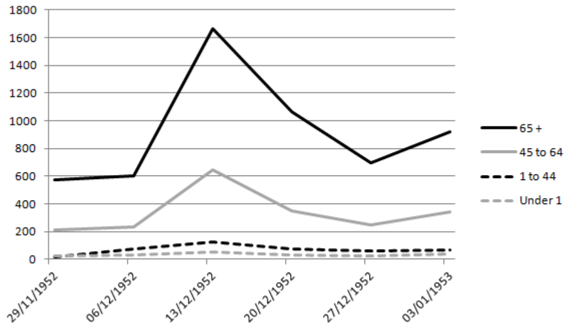
The four thousand excess deaths recorded in the next three months were initially attributed to influenza, but there was no evidence of influenza in the lungs of the diseased[10], and the Chief Medical Officer concluded that there was no major outbreak of influenza in 1952[11]. The majority of those that died during the smog were over forty five years old. Figure 7 shows the total number of deaths recorded during the weeks following the smog, broken down by age. Figure 1, shown earlier in the paper, shows the ratio of deaths in London to those in England and Wales. The impact of the smog is clearly visible, and there are no comparable incidents in the ten year period that the data covers.

[9]Pollution data from before 1960 is not stored centrally: the information presented comes from the records of the Fuel Research Board that were stored in the National Archives when the Board was disbanded. Only a given percentage of records were kept, making the construction of long series challenging. The gap in the quality of the information available for December 1952 and other times is due to the Fuel Research Board's particular interest in this episode.

[10]Ministry of Health (1954)

[11]Bell and Davis (2001)

Figure 7: Deaths in London during the smog of 1952, by age



Notes: Deaths reported at the end of each week to the London administrative county, recorded in Ministry of Health (1954)

3. The effect of the smog on foetal mortality

This section studies the effects of the London smog of 1952 on foetal mortality. Foetal mortality often goes unreported, and can even go unnoticed when it occurs early in the pregnancy. For this reason, an analysis of how stillbirths were affected by the smog will be supplemented with an analysis of the effects on live births. As discussed in Jayachandran (2009), evidence on 'missing children' can be a good proxy for foetal mortality, especially when official statistics are likely to provide an incomplete picture. Data on stillbirths and births comes from the Quarterly Report of the Registrar General, which form the basis for official statistics in the UK on births and deaths.

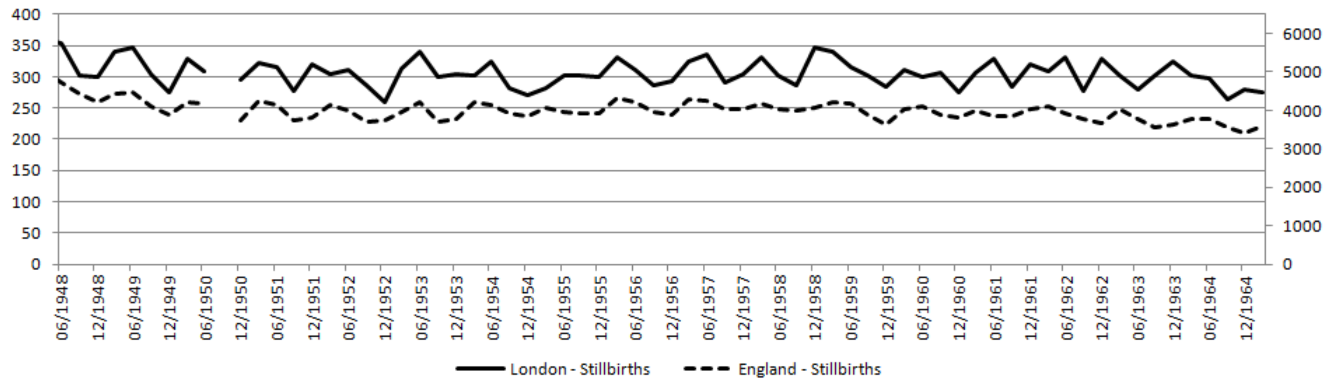
Stillbirths in London and in England & Wales can be seen in figure 8 below. The series for London is relatively volatile, but appears to share both quarterly fluctuations and the effects of nation-wide shocks with the English series. Figure 9 plots the ratio of these series. The first three quarters of 1953 are highlighted - this is the period in which stillbirths among children affected by the London smog would be observed. Although there appears to be an increase in relative reports of stillbirths, it is not clear whether this is a true effect or natural variation. In order to determine whether the effect is statistically significant, the series for London and England & Wales are normalised by population[12], and the effect of 1953 tested using the differences-in-differences model below.

$$\Delta S_t = \alpha + \beta 1953_t + \gamma \boldsymbol{\phi}(t) + \boldsymbol{\lambda} quarter_t + \epsilon_t \qquad (1)$$

The left hand side is the difference in stillbirths in London and England & Wales per one thousand people, $\boldsymbol{\phi}$ is a polynomial function of time used to capture any secular trends, *quarter* is a vector of dummies to control for seasonal effects, and 1953_t is a dummy taking the value of one for 1953, when stillbirths caused by the smog would be observed. Estimates for β, which should capture

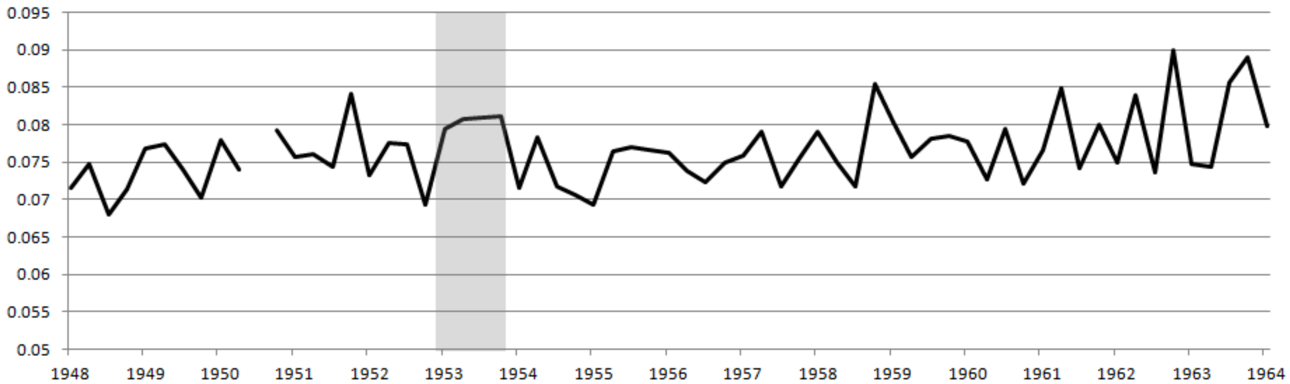
[12] A more common normalisation for stillbirth data is against total births - in this case this would be inappropriate as a foetal insult would be expected to affect both series.

Figure 8: Stillbirths in London (left axis), England & Wales (right axis)



Notes: Data from the Registrar General

Figure 9: Ratio of stillbirths in London, and England & Wales



Notes: Data from the Registrar General. Shaded area highlights where increased stillbirths due to London smog would be observed.

any effect on stillbirths, are shown in the table below, for polynomial trends of different orders. Estimated coefficients for all specifications are positive, with a central estimate of 0.006. This

$\hat{\beta}$	Standard Error	Polynomial Trend	Adjusted R^2
0.006*	0.002	2nd Order	0.68
0.006*	0.003	3rd Order	0.68
0.006*	0.003	4th Order	0.70
0.006*	0.003	5th Order	0.69
0.006*	0.003	6th Order	0.69

β measures the difference in stillbirths per 1000 people in London and in England & Wales. Estimated coefficient is equivalent to an increase of just over 2%. Stars indicate significance at the 5%, 1% and 0.1% levels

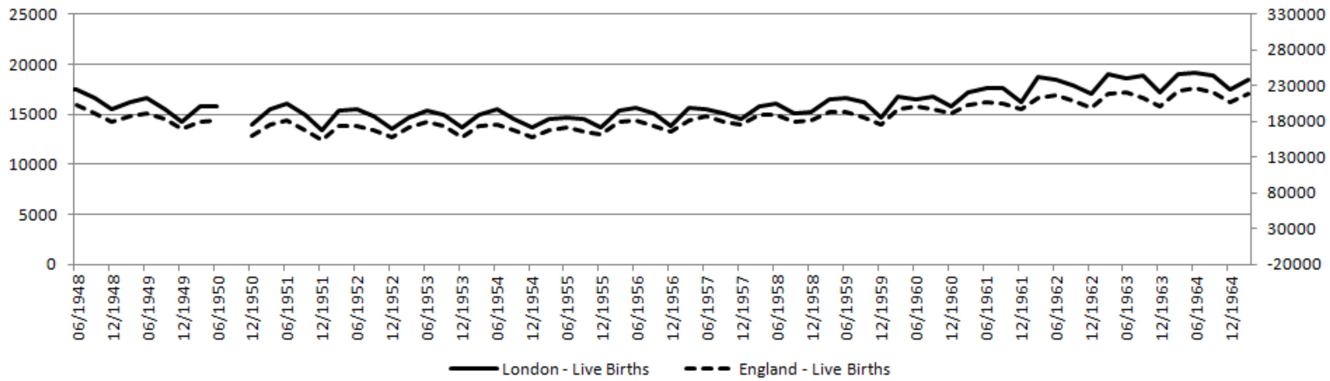
figure is equivalent to an extra 20.2 stillbirths in 1953, or an increase of just over 2%.

The effect on live births

A complementary approach for testing for foetal mortality is to observe births over time, and to check for 'missing' children. The strength of this approach is that, as stillbirths are often unreported, it can give a more accurate picture than official figures. Figure 10 shows births over time in London and in England & Wales. As with stillbirths, the two series share seasonal and broad long-term trends. Figure 11 shows the ratio of the two series. The plot is less volatile than that for stillbirths, and appears to show two well defined events. The first is the 1952 London smog - there appears to be a clear drop in the quarters in which foetuses affected by the smog could have been born. The second is the London smog of 1948, which was less severe than that of 1952, but still resulted in high levels of pollution. Those affected in the first and second trimester, when foetuses are most vulnerable, would have been born in the third and second quarters of 1949 respectively, where there appears to be a sharp drop in births in London. The secular trend in the series is more complex than that for stillbirths, with a increase, a decrease, and a levelling out of the relative numbers of births in London compared to England & Wales.

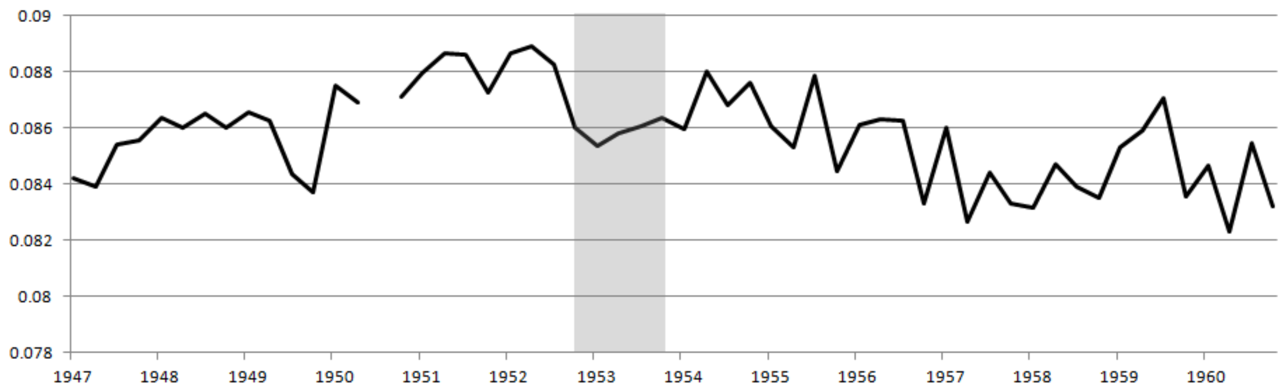
The statistical significance of this drop in births was tested in the same manner as with still-births. The results can be seen in the table below. The model with the fifth order polynomial is the most parsimonious model that fits the data well. As seen in figure 11, the secular trend has highly non-linear shape that lower order polynomials have trouble matching. Adding a sixth term does not improve the overall fit of the model or change the estimates substantively. The figure of -0.128 is equivalent to 404 fewer births than expected, or a drop of 3%. This estimate is

Figure 10: Births in London (left axis), England & Wales (right axis)



Notes: Data from the Registrar General

Figure 11: Ratio of births in London, and England & Wales



Notes: Data from the Registrar General

$\hat{\beta}$	Standard Error	Polynomial Trend	Adjusted R^2
−0.061	0.054	2nd Order	0.91
−0.078	0.055	3rd Order	0.92
−0.069	0.048	4th Order	0.93
−0.124*	0.043	5th Order	0.95
−0.128*	0.043	6th Order	0.95

β measures the difference in births per 1000 people in London and in England & Wales. Estimated coefficient is equivalent to an increase of just over 3%. Stars indicate significance at the 5%, 1% and 0.1% levels

higher than for stillbirths, implying that much of the prenatal mortality caused by the smog went unrecorded.

4. Long-term effects for survivors

The previous section showed that *in utero* exposure to severe pollution can have a significant impact on prenatal mortality: this section studies the impact on those that survive. Information on long-term outcomes comes from the U.K. Office of National Statistics Longitudinal Study. This is a survey based on a 1% sample of the decennial census for England and Wales, and has been linked to data on major events such as births, migrations, and deaths[13]. The survey holds information on around a million individuals, with around 423,000 linked to both the 2001 and 2011 censuses. Membership of the survey is determined by being born on one of four dates in a year.

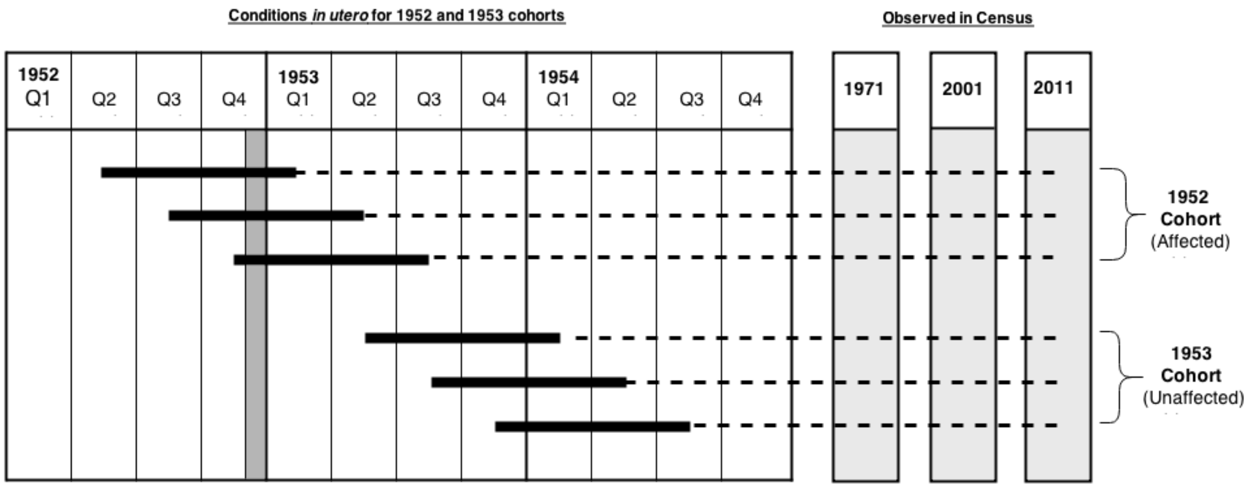
Individuals affected by the smog *in utero* are identified by their quarter and district of birth. The basic identification strategy is to compare the outcomes of the London '1952 Cohort' that were conceived in 1952 and exposed to the smog in December with outcomes for the '1953 Cohort' conceived in the subsequent year. The main comparison is illustrated in the figure below. An advantage of this design is that, aside from personal exposure to the smog, the two cohorts are exposed to most aggregate level shocks at very similar ages[14]. Looking forward, the two cohorts enter the labour market at almost the same time. Looking back, any non-health related effects from the smog, such as issues created by deaths in the family would be expected to affect the two cohorts in a similar way. Notice that individuals conceived in the first quarter are excluded

[13] The ONS-LS has also been linked to widow or widower status, and cancer registrations.

[14] Overall employment levels when the two cohorts entered the labour market can be seen in figure 19 in the appendix. The (affected) 1952 cohort entered the labour market between 1969 and 1971, when unemployment was 2.8% on average. The (unaffected) 1953 cohort entered between 1970 and 1972, when unemployment was 3.1% on average.

from both cohorts. This is because it is not possible to determine whether these individuals were exposed to the smog shortly before, or shortly after birth.

As was seen in figure 6, the average pollution levels during pregnancy are very similar for the 1952 and 1953 cohorts. As was seen in figure 18 in the appendix, weather in the two years was also similar. However, in order to control for any potential year-level effects, a differences-in-differences strategy is employed, using 1952 and 1953 cohorts from other counties of England & Wales, which were unaffected by the smog. The design does not study those *in utero* during 1951 (the year before the smog) because these children would have been exposed to the smog as one year olds, an age at which the children are still very vulnerable. Later years were also rejected - from the data available average levels of pollution appear appreciably higher[15].



Notes: Thick lines represent time spent *in utero*. Dotted line marks progression through the years after birth. The shaded area denotes the London smog of December 1952. Members of both cohorts are observed in the ONS-LS in 1971, 1981, 1991, 2001, and 2011. The analysis on the gender of survivors focuses on information from the 1971 census (when individuals were around 19.) The analysis on health and other outcomes focuses on information from individuals observed in 2001 and 2011, when they were around fifty and sixty years old.

The main equation to be estimated for an individual i born at time t in county c is:

$$Y_{ict} = \alpha + \boldsymbol{\beta}\mathbf{County}_c + \delta D_t^{1952} + \gamma D_c^L D_t^{1952} + \epsilon_{ict} \quad (2)$$

Where Y_{ict} is the outcome variable, $\mathbf{County}_c$ is a vector of county-level dummies, D^{1952} is a dummy for those conceived in 1952, and D^L is a dummy taking the value one for those born in London. The effect of the smog on outcome Y_{ict} should be summarised in γ. A second specification incorporating information on the severity of exposure to pollution is also estimated. Boroughs of London are divided into 'high' and 'low' levels of exposure using the Ministry of Health (1954) schema, illustrated in figure 2. In this design, the basic comparison is of outcomes for those *in utero* in high or low polluted areas with outcomes for those *in utero* in 1953 in the same area.

[15]An earlier version of this analysis did include this extra year, comparing outcomes for the 1952 cohort to those for both the 1953 and 1954 cohorts. Results are the same.

Unaffected counties outside of London are again used to control for year level effects.

$$Y_{ict} = \alpha + \boldsymbol{\beta}\mathbf{Area}_c + \delta D_t^{1952} + \gamma_L D_c^{Low} D_t^{1952} + \gamma_L D_c^{High} D_t^{1952} + \epsilon_{ict} \quad (3)$$

This specification is identical to equation 2, except that the **County** vector of dummies has been replaced with **Area**, as London's county has now been split into two parts. The dummy D^{Low} takes a value of one if individual i was *in utero* in a part of London less affected by the smog. The dummy D^{High} works in the same way for more severely affected parts of London. The parameters of interest are γ_L and γ_H, giving the effects of the smog on outcome Y in the areas experiencing low and high exposure during the smog.

Table 1 reports summary statistics for the four groups studied in the design. The first column shows information on individuals *in utero* in London during the smog. Compared to individuals in the subsequent year, they are slightly more likely to be male, are less likely to have either A-level or degree qualifications, are more likely to be in poor health, and are less likely to be employed. Differences are small for most measures. The third and fourth column show figures for the 1952 and 1953 cohorts born in unaffected parts of the country. In limiting illness and employment, they show the same small increase, meaning that England-wide trends might be driving some of the effects seen in London.

Table 1: Summary statistics for the 1952 and 1953 cohorts

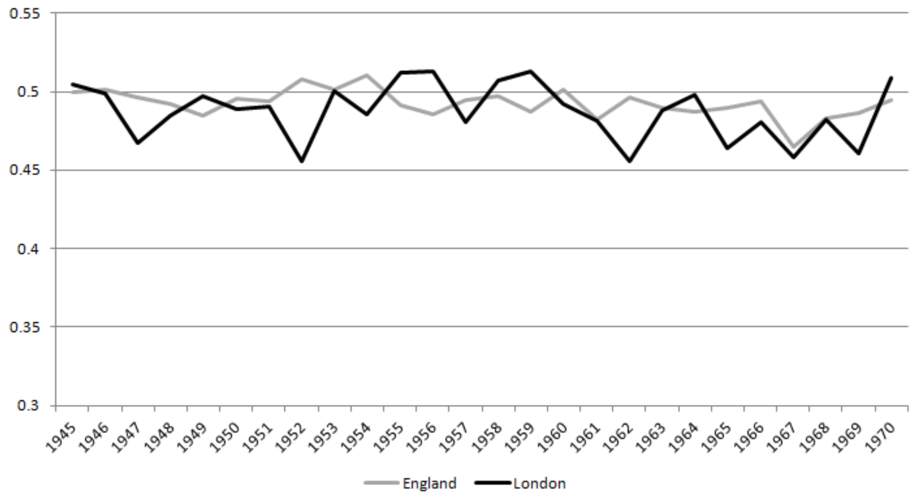
	London		**England & Wales**	
	1952 Cohort	1953 Cohort	1952 Cohort	1953 Cohort
Sample size	850	840	4040	4060
Male	0.50	0.49	0.50	0.51
A-levels	0.28	0.32	0.26	0.26
Degree	0.20	0.24	0.20	0.20
Poor health	0.07	0.06	0.09	0.09
Limiting illness	0.12	0.11	0.16	0.15
Employed	0.85	0.86	0.82	0.83

Notes: Percentages for poor health, limiting illness and employment recorded at age fifty. Sample sizes are rounded to the nearest ten. Source: ONS Longitudinal Survey.

Gender

As there is evidence that exposure to the smog resulted in foetal mortality, a natural first step is to gather evidence on who survived. The approach follows that of Sanders and Stoecker (2011), who use shifts in the gender of survivors as evidence of culling, motivated by the Trivers-Willard hypothesis that female foetuses may be more likely to survive adverse shocks. In this case, shifts in the gender composition will be taken as evidence of when exposure is most harmful, and how the effect on foetal mortality differed by intensity of exposure.

Figure 12: Percentage of males in ONS-LS sample



Notes: Source: Office of National Statistics Longitudinal Study

The analysis focuses on individuals aged around 19, when they were first observed in a representative sample of the 1971 census for England and Wales. Figure 11 shows the percentage of males in the ONS-LS sample, by year of birth. Both the series for London and England & Wales are relatively volatile, but there is a clear drop in the proportion of males for those born in 1952[16]. These individuals would have been under eleven months old when affected by the smog. There may also be signs of variation during those that experienced the 1962 and 1948 smogs as infants. There is no evidence, however, of variation among those that would have been *in utero* during the smog, and born in 1953.

In order to study the different effects of neonatal and prenatal exposure to the smog, the following equation was estimated separately for London and the rest of England & Wales using the full series of birth dates.

$$Prob(Male)_{it} = \alpha + \beta year_t + \boldsymbol{\delta}\mathbf{quarter}_t + \boldsymbol{\gamma}\mathbf{impact}_t + \epsilon_{it} \quad (4)$$

Where *year* is a simple linear trend, **quarter** is a vector of dummies to control for season, and **impact** is a vector of dummies for people born in the quarters before and after the smog. Results are summarised in the table below. For London, only one coefficient is significant at the 5% level - the analysis is based on some small sample sizes, particularly at the trimester level in London, and all other coefficients are imprecisely estimated. However, the central estimates for those affected during the smog are not supportive of the Trivers-Willard hypothesis that females are more likely

[16]Observing sample sizes by gender shows the same story, and suggests that this effect is driven entirely by a drop in males.

to survive a foetal shock. For foetuses affected in the first and second trimester, when they are expected to be most vulnerable, the estimates point in the opposite direction.

Table 2: Proportion of males, by age at exposure to smog

Quarter of Birth	Age affected	London	s.e.	England & Wales	s.e.
1952 Q1	11 months	-0.03	0.033	-0.01	0.014
1952 Q2	8 months	-0.09^{*}	0.034	-0.01	0.014
1952 Q3	5 months	0.02	0.031	0.02	0.014
1952 Q4	**2 months**	**-0.02**	**0.033**	**0.02**	**0.014**
1953 Q1	3rd Trimester	-0.03	0.033	0.01	0.014
1953 Q2	2nd Trimester	0.04	0.030	0.01	0.014
1953 Q3	1st Trimester	0.03	0.030	0.00	0.013

Notes: Sample size for London is 29830. The sample size for England & Wales is 153880. Age during the smog is correct to within one month. Source: Office of National Statistics Longitudinal Study

In order to observe prenatal effects by intensity of exposure to pollution, equation (4) is simplified by replacing the vector **impact** with a simple dummy for the 1952 cohort that was exposed to the smog *in utero*. Estimated coefficients for England & Wales, London, and the districts of London affected by 'high' and 'low' levels of pollution during the smog can be seen in the table below. In London and the districts that were less affected by the smog, there is no evidence of

Table 3: Proportion of males by strength of exposure

England & Wales	London Low exposure	London All districts	London High exposure
0.00	0.00	0.01	$0.04^{\dagger}$
(0.007)	(0.020)	0.016	0.026

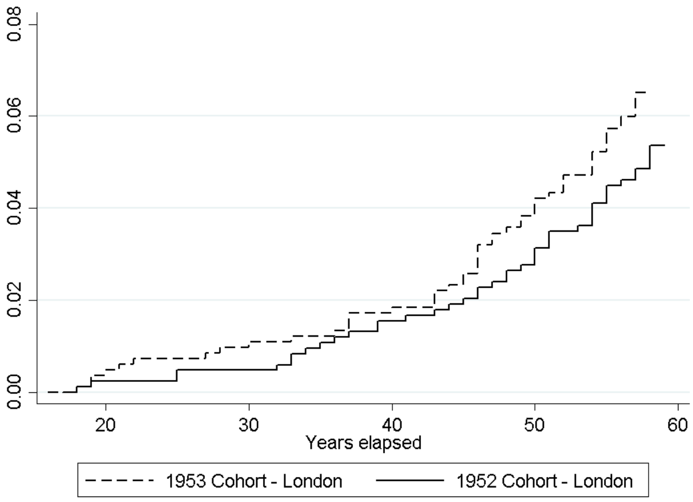
Notes: † indicates significance at the 10% level. 95% confidence interval is [-0.01, 0.10]. Sample size for London is 29830. The sample size for England & Wales is 153880. For high and low districts, 10770 and 13460. Age during the smog is correct to within one month. Source: Office of National Statistics Longitudinal Study

any effect. In areas of London that were most severely affected, the coefficient suggests a 4% upwards shift in the proportion of males. The estimate is not significant at standard levels, but the 95% confidence interval is [-0.01, 0.10]. Overall, there is no strong evidence of gender-biased survival for those affected *in utero*. In the context of this severe foetal shock, there is no support for the Trivers-Willard hypothesis. Most estimates, though imprecisely estimated, suggest that it was male, rather than female, foetuses that were more likely to survive the smog. Although not the focus of this paper, it is interesting to note that females affected by the smog after birth did appear more likely to survive, suggesting that the effects of pre- and neonatal exposures to atmospheric pollution may be quite different.

Mortality

There is little evidence to suggest what the effect of foetal exposure to pollution on the long-term mortality of survivors might be. On one hand, there is evidence that those surviving are less likely to perform well in school[17] and less likely to be in employment[18], suggesting a negative effect on health. On the other hand, evidence in the literature and from the earlier analysis show that foetal exposure has a significant effect on survival till birth. If survivors are drawn from the strongest in the cohort, they may be more likely to survive than cohorts in which less healthy individuals are still observed in the data. Figure 13 shows the cumulative hazard of death for people born in London, comparing outcomes for the affected 1952 cohort, and the unaffected 1953 cohort. The cumulative hazard of death for the unaffected cohort appears to accelerate at the age of around forty five, relative to that for the affected cohort. There may also be signs that the unaffected were more likely to die in their early twenties, but the effect is smaller.

Figure 13: Cumulative hazard of mortality - London



Notes: Nelson-Aalen cumulative hazard function. Source: Office of National Statistics Longitudinal Study

Differences in differences estimates are presented in table 4. An important factor in interpreting these estimates is the assumption of common trends: fitting a linear trend shows that older individuals born in London and the rest of England & Wales are more likely to die before 2011. The difference in the trends for London and England & Wales is 0.0005 which, although significantly different from zero at the 5% level, is too small to seriously affect the estimates. Two measures of mortality are reported. The first is the probability of dying before 2011, when the two cohorts were around sixty years old. Estimates come from a simple linear probability model (OLS), and

[17] Sanders (2012)
[18] Isen, Rossin-Slater and Walker (2014)

results can be interpreted as the percentage change in the probability of dying before 2011 caused by *in utero* exposure to the smog. The result for individuals born in all of London confirm that individuals affected were 2% less likely to die than their peers. The results for those born in areas of London affected by high and low levels of pollution from the smog are 2% and 3% respectively. All estimates are significant at the 0.1% level. The second measure is from a Cox proportional hazards model. This divides the hazard of dying in a particular year into a baseline hazard, determined by time alone, and a component that is affected by a given set of covariates. 'Ties' in the data are handed using the Breslow method. Estimates show a positive effect on the baseline hazard when they are greater than one, and a negative effect when they are less than one. The results from the two methods are essentially identical.

Table 4: Pollution and Mortality: all London, and two levels within London

	Died		Hazard of Death	
	London	Levels	London	Levels
1952 cohort	0.00	0.00	1.14	1.13
	(0.005)	(0.005)	(0.100)	(0.097)
London	0.00	-	1.00	-
	(0.003)		(0.059)	
Lond. High	-	0.00	-	1.00
		(0.003)		(0.061)
Lond. Low	-	0.00	-	1.06
		(0.003)		(0.061)
Smog impact	-0.02^{***}	-	0.72^{***}	-
	(0.005)		(0.003)	
High impact	-	-0.02^{***}	-	0.74^{***}
		(0.003)		(0.063)
Low impact	-	-0.03^{***}	-	0.63^{***}
		(0.003)		(0.063)
N	9720	9720	9720	9720
R^2	0.00	0.00	-	-

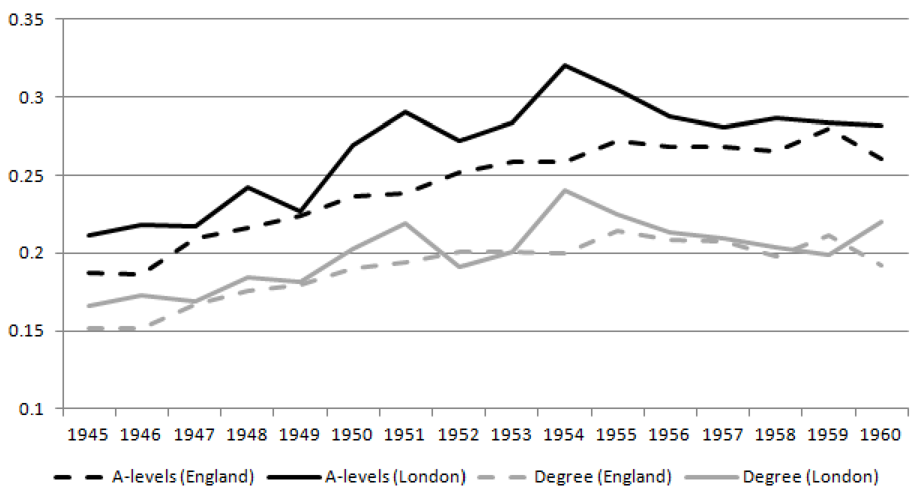
Notes: 1952 cohort refers to those *in utero* during the smog. Estimated smog impact from the interaction of treatment area and membership of 1952 cohort. Standard errors clustered at county level: stars indicate significance at 5 and 1, and 0.1%. Results from OLS linear probability model indicate percentage increase in probability of dying in sample. Estimates from the Cox proportional hazard model indicate a positive effect on the hazard of dying in a given year when above one, and a negative effect when below.

Education

Educational attainment can capture the effects of weaker health problems that might not appear in hospital records and mortality statistics. There is already evidence from Sanders (2012), who studies pupils in Texas, that foetal exposure to pollution can affect educational attainment later in life. The pollution levels studied in this paper are much stronger than those in Texas; it is possible that foetal mortality could bias estimates towards health (and better educational attainment) by the removal of weaker individuals. Nonetheless, results show that those affected by smog *in utero* are less likely than their peers to hold formal qualifications.

Figure 14 shows educational attainment by birth year for those born in London and the rest of England & Wales. Until 1954, the probability of holding a qualification in both England & Wales and London increase by around a percentage point every five years, and then level off. Two asymmetric shocks can be seen for London. The first is a dip in 1949 - this is the cohort that would have been *in utero* during the winter smog of 1948. This event was less severe than that in 1952, but was still a very serious pollution episode. The second is the Great London Smog of 1952. There is a noticeable dip for two cohorts - those born in 1952, who were affected by the smog as infants, and those born in 1953, who were *in utero* during the smog.

Figure 14: Percentage with formal qualifications, by year of birth



Notes: In the London series, those born in 1949 *in utero* during smog of 1948. Those born in 1952 affected as infants by the 1952 smog. Those born in 1953 affected *in utero* by the smog. Source: Office of National Statistics Longitudinal Study

Although the overall England & Wales and London trends are similar until 1954, the assumption of common trends is stronger in this case than with the other outcomes studied. A test of these trends over the sample supports this - with educational attainment in London growing around 0.2 of a percentage point faster in London than in England & Wales. The estimated effects of the smog are between fifteen and forty times larger, however, and are unlikely to be driven by this difference.

Differences-in-differences results can be seen in table 5 below. Two outcomes are studied. The first is the probability of holding an A-level qualification. This is a secondary level qualification taken at the age of seventeen or eighteen. The second is the probability of holding a degree. Both are binary variables, and are estimated using a linear probability model (OLS). Estimated effects can be interpreted as the change in the probability of holding a qualification with a change in the independent variable. Results from the main specification show that survivors of *in utero* exposure to the smog are 3% less likely to hold an A-level and 5% less likely to hold a degree than their peers. Separating London according to the severity of pollution exposure during the smog, survivors from the the 'low' treated area are far less likely to hold qualifications than those from the 'high' treated area. One explanation for this effect is the bias towards health (and educational attainment) caused by weaker individuals dying before being observed. Recall that those in the 'high' pollution area also seemed to have the largest in gender, implying that the effects on foetal mortality were strongest here.

Health

Individuals in the sample were asked to rate their health at the age of fifty (into three categories) and sixty (into five categories). Although self-reported health is a widely used measure in the health economics literature, it may not capture all health effects. Deaton (2008) discusses three key issues. The first is that people might not fully perceive the impacts of a health shock. Someone with small respiratory problems may not fully contemplate the career as a professional footballer they might have had in full health. The second is that people grow accustomed to their ailments, and no longer consider them to be day-to-day problems. The third is that there are cross-country differences in how this kind of question is answered due to both cultural differences, and differences in the average health of comparison groups. In the context of this study, the first two problems might result in an underestimate of any health effects. The issue of cross-country comparisons is unlikely to be important in this study as all people sampled are from the same, relatively homogeneous country. A second measure of heath will also be briefly discussed: the response to the question 'Do you have a condition that limits daily activities?'. Although this question is relatively concrete, it would also result in an underestimate of true health effects if unhealthy individuals had less strenuous 'daily activities.'

Figure 15 shows responses to questions about health in 2001 and 2011, by year of birth. As might be expected, those that are younger when asked the question are in better health. In general[19] the London and England & Wales series follow each other closely. In both England &

[19] The exception is the health in 2001 for people born in 1956. There does not appear to have been a large event

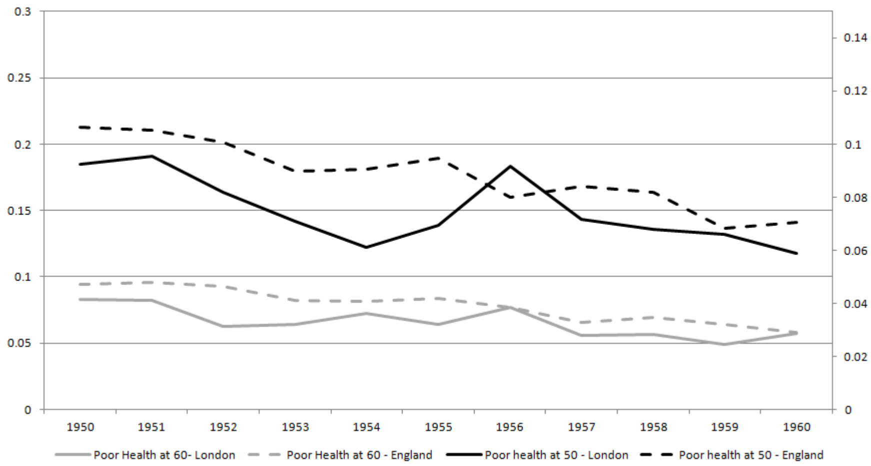
Table 5: Educational Attainment: all London, and two levels within London

	A-levels		Degree	
	London	Levels	All London	Levels
1952 cohort	0.00	0.00	0.00	0.00
	(0.013)	(0.013)	(0.012)	(0.011)
London	0.06^{***}	-	0.04^{***}	-
	(0.011)		(0.009)	
Lond. High	-	0.05^{***}	-	0.02^{*}
		(0.011)		(0.009)
Lond. Low	-	0.07^{***}	-	0.06^{***}
		(0.010)		(0.009)
Smog impact	-0.03^{*}	-	-0.05^{***}	-
	(0.013)		(0.012)	
High impact	-	$-0.02^{\dagger}$	-	-0.01
		(0.013)		(0.012)
Low impact	-	-0.09^{***}	-	-0.10^{***}
		(0.013)		(0.012)
N	6830	6830	6830	6830
R^2	0.00	0.00	0.00	0.00

Notes: 1952 cohort refers to those *in utero* during the smog. Estimated smog impact from the interaction of treatment area and membership of 1952 cohort. Standard errors clustered at county level: stars indicate significance at 5 and 1, and 0.1%. Results from OLS linear probability model indicate percentage increase in probability of holding the relevant qualification. † Significant at the 10% level - 95% confidence interval: [-0.05, 0.00]

Wales and London there is a slight dip, against trend, in the early fifties. Those affected as infants would have been born in 1952, while those affected *in utero* would have been born in 1953. There are no obvious effects of the smog in either series.

Figure 15: Poor health in 2001 (right axis) and 2011 (left axis), by year of birth



Notes: 'Poor health' at fifty defined by lowest response to a three category question on current health. 'Poor health' at sixty defined by lowest two responses to a five category question on current health. Source: Office of National Statistics Longitudinal Study

The difference in trends between England & Wales and London is statistically significant but small - at around 0.3 of a percent[20] at fifty and 0.2 of a percent for poor health at sixty. In principle, this difference (which would make those affected by the smog appear less healthy) could drive results. In practice, this is unlikely as results from the differences-in-differences model are precisely estimated, and an order of magnitude larger.

Table 6 shows differences-in-differences estimates from the linear probability model (OLS). The health measure used is a binary variable taking the value one if a person reports themself as being in poor health[21]. The categorical health variable answered in 2001, when the sample of interest are around fifty, has three categories. The question answered at sixty has five categories, with the 'poor health' dummy taking a value of one for the two bottom categories. Consequently, the direction, but not the magnitude of estimated effects are comparable between the 'aged fifty' and 'aged sixty' results.

Results for all districts of London show that those surviving the *in utero* exposure to pollution are 2% more likely to report themselves as being in poor health. By sixty, there is no health difference between those affected and their unaffected peers. These estimates are for the same

in London that might explain this data point. (The Asian flu epidemic was a year later and would also have affected England & Wales.)

[20] This is somewhat driven by the outlier in 1956 - without it, the difference is under 0.2.

[21] Results from the full categorical health variable are identical in terms of overall direction of effects and significance, and can be found in the appendix. Estimated coefficients from the ordered logit are in terms of percentage changes to log odds, which do not have a particularly intuitive interpretation.

individuals observed ten years apart: as those affected *in utero* are unlikely to have improved in health between fifty and sixty, this result can most easily be explained by the unaffected group 'catching up' in terms of poor heath by age sixty.

Dividing London into areas affected by high and low levels of pollution during the smog reveals significant heterogeneity in estimates. Those in the area affected by 'low' pollution show more serious health effects than the London average, at both fifty and sixty. Those that were in the area affected by 'high' pollution - where foetal mortality appears to have been most significant - are healthier than their unaffected peers. The effects are large and statistically significant, with individuals 3% less likely to be in poor health at fifty, and 4% less likely at sixty.

Table 6: Poor health: all London, and two levels within London

	Aged 50		Aged 60	
	London	Levels	All London	Levels
1952 cohort	0.00 (0.007)	0.00 (0.007)	0.00 (0.006)	0.00 (0.008)
London	-0.03^{***} (0.006)	-	-0.01 (0.036)	-
Lond. High	-	0.00 (0.006)	-	0.02^{*} (0.006)
Lond. Low	-	-0.03^{***} (0.006)	-	-0.02^{**} (0.006)
Smog impact	0.02^{**} (0.041)	-	-0.01 (0.006)	-
High impact	-	-0.03^{***} (0.007)	-	-0.04^{***} (0.033)
Low impact	-	0.06^{***} (0.007)	-	0.01^{*} (0.006)
N	6830	6830	6830	6830
R^2	0.00	0.00	0.00	0.00

Notes: 'Poor health' at fifty defined by lowest response to a three category question on current health. 'Poor health' at sixty defined by lowest two responses to a five category question on current health. 1952 cohort refers to those *in utero* during the smog. Estimated smog impact from the interaction of treatment area and membership of 1952 cohort. Standard errors clustered at county level: stars indicate significance at 5 and 1, and 0.1%.

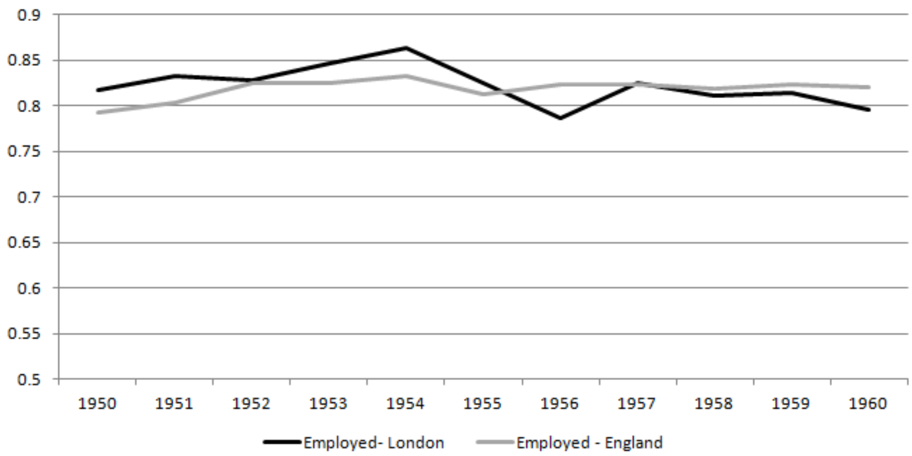
Effects on limiting illness

The exercise was repeated for a second measure of health - a binary measure for people declaring a health problem that limits their daily activities. Results are complementary to those for the measure of poor health discussed above. Those affected by the smog *in utero* were 1% more likely to have a limiting illness at both fifty and sixty, but the coefficient was not precisely estimated. Dividing London into areas affected by high and low levels of pollution reveals the same effect as with poor health: those observed at fifty in the low area were 3% more likely to report a limiting illness, while those observed in the high area were 3% less likely to report a limiting illness. Both estimates are significant at the 5% level.

Employment

Foetal exposure to pollution could affect employment directly, through its effects on health, or indirectly through its effects on educational attainment. As with education, changes in employment can be a good measure of the kind of health effects that would not appear in statistics on hospitalisations or mortality. The studied cohorts entered the labour market under very similar conditions. Figure 19 in the appendix shows that average levels of unemployment on entry were 2.8% while those for the 1953 cohort were 3.1%, and so any employment effects are unlikely to be driven by issues of timing. This section studies employment at the age of fifty[22]. Figure 16 shows the proportion of people employed by year of birth. As with the other series, London and England & Wales have similar trends, with the exception of those born in London in 1956. During the period from 1950 to 1954, the trends in the two series are essentially parallel, but a relative dip can be seen for those born in 1952 (and exposed to the smog as infants.) There is no clear effect for those born in 1953, who would have been affected *in utero*.

Figure 16: Employment in 2001, by year of birth



Notes: Source: Office of National Statistics Longitudinal Study

As with other outcomes, there is a statistically significant but small difference in the London and England & Wales trends of around 0.1 of a percent. This is unlikely to change the inter-

[22]Employment at sixty is not as good a measure of health effects: early retirement could either signal a successful career or poor health, and the distinction is not clear in the data.

pretation of results because - for London and the 'high' polluted districts within London - the estimates are negative but not significantly different from zero. Results from the area affected by 'low' pollution, where foetal mortality appears to have been less significant, are too strong and precisely estimated to have been driven by this difference.

Table 7 shows results for employment. The effect on employment for all of London is -1% but is not precisely estimated. For the areas of London less affected by the smog, those observed at fifty are 4% less likely to be in employment. For the more affected areas of London, the estimate positive, but is not significantly different from zero.

Table 7: Employment: all London, and two levels within London

	Aged 50	
	London	Levels
1952 cohort	-0.01 (0.011)	-0.01 (0.011)
London	0.04*** (0.009)	-
Lond. High	-	0.04*** (0.008)
Lond. Low	-	0.05*** (0.008)
Smog impact	-0.01 (0.011)	-
High impact	-	0.02 (0.010)
Low impact	-	-0.04*** (0.011)
N	6830	6830
R^2	0.00	0.00

Notes: 1952 cohort refers to those *in utero* during the smog. Estimated smog impact from the interaction of treatment area and membership of 1952 cohort. Standard errors clustered at county level: stars indicate significance at 5 and 1, and 0.1%.

Effects by gender

The surviving members of the cohort affected *in utero* by the smog were slightly (about 1%) more likely to be male than average. For those born in the areas most severely affected by the smog, the effect may have been quite strong - the 95% confidence interval for the estimate was [-1%, 10%]. To check whether results are being driven by a shift in the gender composition of the sample, the analysis was repeated for the two sub-samples. Overall, results were similar, but there were some differences in the effects on education and employment.

For education, the overall estimates were a 3% drop in the numbers with an A-level qualification. This result was driven entirely by changes in the academic achievement of girls, who were 7% less likely to have finished secondary school with this qualification. The effects for holding a degree were were the same for both genders, with those affected by the smog 5% less likely to hold a degree. For employment, the overall estimate was an imprecisely estimated drop of 1%. This was entirely driven by males in the sample, who were 4% less likely to be in employment than their peers, with the estimate significant at the 1% level.

5. Discussion

This paper aimed to study the short and long-term health impacts of foetal exposure the Great London Smog. The goal was to gather evidence about the health effects of high levels of pollution, such as those currently found in low- and middle-income countries.

Foetal Mortality

The first section used historical data on stillbirths to find whether exposure to the smog led to an increase in foetal mortality. Those *in utero* during the smog would have been born in 1953. In this year, the data showed a 2% increase in stillbirths in London, relative to national trends. As stillbirths often go unreported in official statistics, the exercise was repeated for live births. Results showed a 3% drop in live births against national trends, equivalent to 404 fewer births in London in the first nine months of 1953. Those surviving the smog were then observed in a 1% sample of the 1971 census (at around nineteen years old.) Expectations from Sanders and Stoecker (2011), and the papers cited within, were that foetal mortality would be more severe among boys - consistent with the Trivers-Willard Hypothesis that mothers might unknowingly favour female foetuses in hard times. For London as a whole, there was no evidence that foetal mortality was more common for girls. In the districts of London that were most seriously affected by the smog, there was evidence that boys may have been *more* likely to survive than girls. People born in these area were 4% more likely to be male, with a 95% confidence interval of [-1%, 10%][23].

Information on deaths among those affected *in utero* by the smog showed them to be less likely to die than their peers. The major difference in the hazard rates between affected and unaffected cohorts was from age 45 onwards, suggesting that those not surviving *in utero* exposure would have been disproportionately likely to die in middle age. This is not, however, the only possible

[23]Although the results of this study are not supportive of the Trivers-Willard Hypothesis, they do not contradict existing studies finding an effect - much of the evidence on the Trivers-Willard hypothesis uses information from the U.S., where pollution levels are far lower than in London during the smog.

explanation for this pattern in the mortality data. It is also consistent with an explanation in which foetal mortality was not selective, but some foetal or maternal response to the smog improved later health - 'what doesn't kill you makes you stronger.'

Outcomes for survivors

The first outcomes observed for survivors were educational attainment. Those affected were 3% less likely to hold an A-level, an effect driven almost entirely by a drop for females. Counter-intuitively, the estimated effect was weaker for the 'high polluted' districts of London. Both sexes from the affected cohorts were 5% less likely to hold a degree level qualification. Those affected by the smog were 2% more likely to report poor health at age 50. The figure for the 'low polluted' districts, in which foetal mortality appears to have been less severe, is 6%. Survivors exposed to the 'high polluted' areas were 3% *less* likely to report poor health than those in the control sample. Employment effects were similar, with those in 'low polluted' districts 4% less likely to be in employment, while there was some evidence that those *in utero* in 'high polluted' districts were more likely to be employed than peers.

What doesn't kill you

Taking information on the health, employment and educational prospects of survivors in to account, the hypothesis that a foetal or maternal response to the shock caused improved health seems less likely - those affected are, on average, in worse shape than their peers. The fact that negative health effects are 'stronger' in areas less affected by the smog also lends support to the strong-survivors hypothesis. It is plausible that stronger pollution produces a stronger effect on foetal mortality, and evidence on gender shifts in the 'high polluted' area lends support to this idea. If there was higher foetal mortality among those of poorer health, then survivors will be selected from particularly healthy individuals. Comparing these survivors to unaffected cohorts will result in a bias towards health.

Other episodes of severe pollution

Both of the areas of London labelled 'high polluted' and 'low polluted' in this paper experienced very high levels of atmospheric pollution. Levels were $800\mu g/m^3$ and $1800\mu g/m^3$ on average during the five days of the smog. Although pollution of this intensity essentially does not occur in high-income countries, there is evidence that it may occur quite frequently in low- and middle-income countries. Data from daily readings in Delhi[24], where the average level of pollution is currently around $280\mu g/m^3$, show how variable pollution levels can be. Between 2004 and 2010, there were fifty six occasions in which the Town Hall pollution meter recorded particulate levels

[24] Available from the Indian Central Pollution Control Board.

over $800\mu g/m^3$, and nine occasions when the levels were over $1000\mu g/m^3$. The Town Hall meter provides observations for only around one day in ten and the true numbers are likely to be far higher. Neither Delhi nor India are exceptional in this respect - in 2012 over one hundred cities surveyed by the World Health Organisation had annual average pollution levels of over $100\mu g/m^3$. The number of people exposed is very large. One of the most polluted cities, Peshwar, is home to over three million people and has annual average pollution levels almost twice those of Delhi.

6. Conclusion

Two hundred years since the beginning of the industrial revolution, the health and economic consequences of polluting economic activity are still not fully understood. There is growing evidence that *in utero* exposure to atmospheric pollution can cause foetal mortality, and low birth weight for those that survive. Much of the evidence on the foetal impact of atmospheric pollution comes from high-income countries where pollution levels are low, but where data on health and pollution are readily available. This paper studies the Great London Smog of 1952 in order to gain insights into the short and long-term consequences of foetal exposure to high levels of pollution. The essential approach of the paper is to compare the outcomes of people exposed to the smog *in utero* during 1952 (and born in 1953) to other cohorts in London, using unaffected counties of England & Wales to control for year-level effects. Evidence from historical registrar data showed that there were 2% more stillbirths in London in 1953, relative to national trends. As stillbirths are often unreported, this analysis was repeated with information on live births. Results showed a 3% reduction in the number of registered births in London, or around 400 fewer births in the first nine months of the year. Survivors were then identified by district and quarter of birth, and studied using the ONS-Longitudinal study, based on a 1% sample of individuals first observed in the 1971 census for England and Wales. In general, survivors observed fifty and sixty years after the smog were less likely to hold a formal qualification, less likely to be employed, and were generally in poorer health than their peers.

References

[1] Almond, D. (2006) "Is the 1918 Influenza Pandemic Over? Long-Term Effects of In-Utero Influenza Exposure in the Post-1940 U.S. Population" *Journal of Political Economy* 114(4), 672-712

[2] Almond, D. & J. Currie (2011) "Killing Me Softly: The Fetal Origins Hypothesis" *Journal of Economic Perspectives* 25(3), 153-172

[3] Arceo-Gomez, E. O., Hanna, R., & P. Oliva (2014) "Does the Effect of Pollution on Infant Mortality Differ Between Developing and Developed Countries? Evidence from Mexico City" *NBER Working Paper*, Number 18349

[4] Bell, M.L. & D.L. Davis (2001) "Reassessment of the Lethal London Fog of 1952: Novel Indicators of Acute and Chronic Indicators of Acute Exposure to Air Pollution" *Environmental Health Perspectives* 109(3)

[5] Bozzoli, C., Deaton, A., & C. Quintana-Domeque (2009) "Child Mortality, Income, and Adult Height" *Demography* 46(4), 647-669

[6] Chay, K. Y. & M. Greenstone (2003) "The Impact of Air Pollution on Infant Mortality: Variation in Pollution Shocks Induced by a Recession" *Quarterly Journal of Economics* 118(3), 1121-1167

[7] Currie, J. & M. Neidell (2005) "Air Pollution and Infant Health: What Can We Learn from California's Recent Experience? " *Quarterly Journal of Economics* 120(3), 1003-1030

[8] Currie, J. & R. Walker (2011) "Traffic Congestion and Infant Health: Evidence from EZ-Pass" *American Economic Journal: Applied Economics* 3(1), 65-90

[9] Currie, J. & T. Vogl (2013) "Early-Life Health and Adult Circumstance in Developing Countries" *Annual Review of Economics* 5(1), 1-36

[10] Deschenes, O. (2012) "Temprature, Human Health, and Adaptation: A Review of the Empirical Literature" *NBER Working Paper* Number 18345

[11] Deschenes, O. & M. Greenstone (2011) "Climate Change, Mortality and Adaptation: Evidence from Annual Fluctuations in Weather in the U.S." *American Economic Journal: Applied Economics* 3(4), 152-185

[12] Isen, A., Rossin-Slater, M. & W. R. Walker (2014) "Every Breath You Take - Every Dollar You'll Make: The Long-Term Consequences of the Clean Air Act of 1970" *NBER Working Paper*, Number 19858

[13] Jan, J., Johansson, & J.P. Nilsson (2014) "Economic Status, Air Quality, and Child Health: Evidence from Inversion Episodes" *IZA Discussion Paper* Number 7929

[14] S. Jayachandran (2009) "Air Quality and Early-Live Mortality Evidence from Indonesia's Wildfires " *The Journal of Human Resources* 44(4), 916-934

[15] Sanders, N. J. & C.F. Stoecker (2011) "Where Have All The Young Men Gone? Using Gender Ratios to Measure Fetal Death Rates" *NBER Working Paper* Number 17434

[16] Sanders, N. J. (2012) "What Doesn't Kill You Makes You Weaker: Prenatal Pollution Exposure and Educational Outcomes" *Journal of Human Resources* 47(3), 826-850

[17] Stein, Z., Susser, M., Saenger, G. & F. Marolla (1975) *Famine and Human Development: The Dutch Hunger Winter of 1944-1945* New York: Oxford University Press

[18] Wilson / Ministry of Health (1954) "Mortality and Morbidity During the London Smog of December 1952" *Reports on Public Health and Medical Subjects No.95* London: Ministry of Health

[19] Zivin, G. J., & M. Neidell (2013) "Environment, Health and Human Capital" *Journal of Economic Literature* 51(3), 689-730

Appendix

Health results using full categorical data

Table 8 shows differences-in-differences results from an an ordered logit model for self-reported categorical health. There are three categories for those aged fifty and five for those aged sixty, and so magnitudes are not directly comparable between ages. The ordered logit works on the odds of an individual choosing a particular category of health. The reported coefficients can be interpreted as the percentage change in the odds of being in a 'healther' category[25]. Results for London show that, compared to the general population, those affected *in utero* by the smog are 22% less likely, in expectation, to be in a 'healthier' category. The effect is in the same direction at sixty, but is not significantly different from zero. There are figures from the same individual viewed at different times - as the negative health effects presumably did not disappear after a decade, this might be explained by the comparison group 'catching up' in terms of poor health between fifty and sixty. Separating health effects for people affected by higher and lower levels of smog within London reveals large differences. In the area affected by weaker pollution, the effects are similar to those for the full sample - individuals are less healthy than their peers at both fifty and sixty. In the high pollution area that appears to have suffered the highest foetal mortality, survivors appear to be healthier than the general population at fifty, but are not significantly different at sixty.

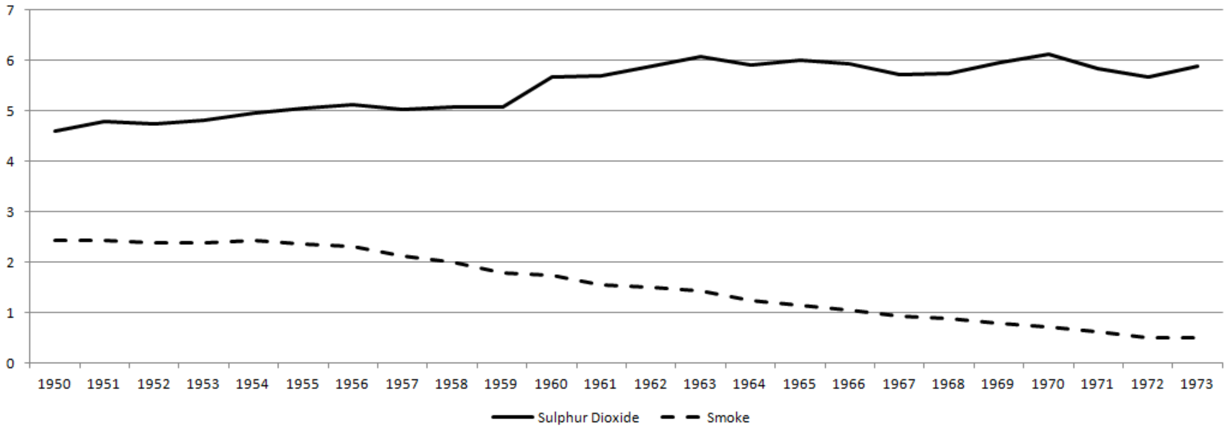
[25]For example, if an individual had 8:1 odds of being in the highest health category, an estimated coefficient of -0.50 would imply a 50% drop in this odds ratio, to 4:1.

Table 8: Self reported health: all London, and two levels within London

	Aged 50		Aged 60	
	London	Levels	All London	Levels
1952 cohort	0.06	0.04	−0.02	−0.02
	(0.041)	(0.045)	(0.030)	(0.011)
London	0.42***	-	0.29***	-
	(0.041)		(0.036)	
Lond. High	-	−0.01	-	0.24***
		(0.049)		(0.039)
Lond. Low	-	0.60***	-	0.23***
		(0.049)		(0.039)
Smog impact	−0.22***	-	−0.02	-
	(0.041)		(0.030)	
High impact	-	0.23***	-	−0.01
		(0.048)		(0.033)
Low impact	-	−0.46***	-	−0.08*
		(0.043)		(0.033)
N	6830	6830	6830	6830
R^2	0.00	0.00	0.00	0.00

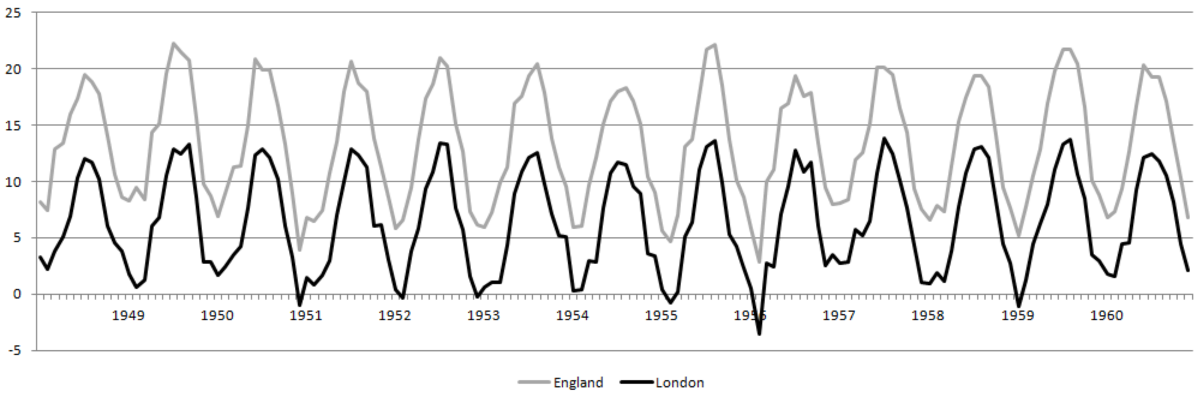
Notes: 1952 cohort refers to those *in utero* during the smog. Estimated smog impact from the interaction of treatment area and membership of 1952 cohort. Stars indicate significance at 5 and 1, and 0.1%. Self reported health in three categories for those observed in 2001 (at fifty) and in five categories for those observed in 2001 (at sixty.) Consequently, direction, but not magnitude of results are comparable between ages. Results from ordered logit can be interpreted as the percentage change in the expected odds of being in a 'healthier' health category.

Figure 17: UK wide emissions of smoke, millions of tonnes.



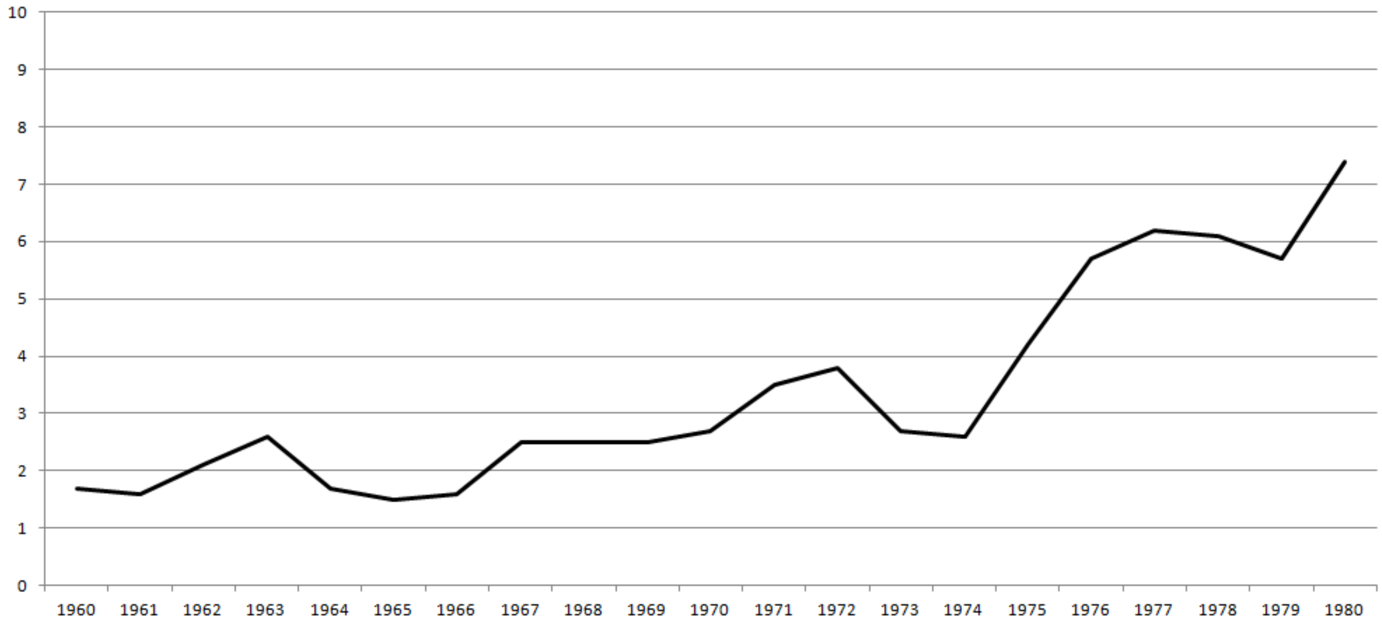
Notes: Data from the Fuel Research Board.

Figure 18: Daily minimum temperatures in London and England, degrees Celsius



Notes: Temperatures measured in degrees Celsius. Data from the Met Office.

Figure 19: Labour market conditions (unemployment) in the UK



Notes: The (affected) 1952 cohort would enter the labour market between 1969 and 1971 when average levels of unemployment were 2.8% on average. The (unaffected) 1953 cohort would enter the labour market between 1970 and 1972 when average levels of unemployment were 3.1% on average. Source: Office of National Statistics