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The Effect of Leaded Aviation Gasoline on Blood Lead in Children

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Abstract

Lead is a neurotoxin with developmentally harmful effects in children. In the United States, over half of the current flow of lead into the atmosphere is attributable to lead-formulated aviation gasoline (avgas), used in a large fraction of piston-engine aircraft. Deposition of lead from avgas may pose a health risk to children proximate to airport facilities that service lead-emitting aircraft. Extrapolating from epidemiological evidence on the health and human capital costs of lead poisoning, various public interest firms have petitioned the EPA to find endangerment from and regulate lead emitted by piston-engine aircraft. In the absence of sufficient empirical evidence linking avgas to blood lead levels (BLLs) in children, the EPA has ruled against petitions to find endangerment. To address an EPA request for more evidence, we constructed a novel dataset that links time and spatially referenced blood lead data from 1,043,391 children to 448 nearby airports in Michigan, as well as a subset of airports with detailed data on the volume of piston-engine aircraft traffic. Across a series of tests, and adjusting for other known sources of lead exposure, we find that child BLLs: 1) increase dose-responsively in proximity to airports, 2) decline measurably in children residing in neighborhoods proximate to airports in the months after 9-11, and 3) increase dose-responsively in the flow of piston-engine aircraft traffic. To quantify the policy relevance of our results, we provide a conservative estimate of the social damages attributable to avgas consumption.

Key Words: Child Health; Lead Exposure; Blood Lead Levels; Aviation Gasoline

JEL Codes: I120, I180, J130, Q510, Q530

1 Introduction

In 2010, the US Environmental Protection Agency's Office of Transportation and Air Quality issued a regulatory announcement requesting information on lead exposure risk "from the use of leaded aviation gasoline (avgas) in piston-engine powered aircraft." The EPA issued this announcement in response to a petition submitted by Friends of the Earth (FoE) in 2006 requesting that the EPA "find endangerment from and regulate lead emitted by piston-engine aircraft." While both the EPA and the US Centers for Disease Control and Prevention maintain that *there is no known safe level of lead exposure* (DHHS 2012; CDC 2012a, 2012b), the EPA ruled against the FoE request for an endangerment finding, holding that additional studies were necessary "to differentiate aircraft lead emissions from other sources of ambient air lead." In April of 2014, FoE, Physicians for Social Responsibility, and Oregon Aviation Watch filed petition seeking reconsideration from the EPA, maintaining that "[t]he only showing required for a finding of endangerment is that lead emissions from aircraft engines fueled by leaded aviation gasoline cause, or contribute to, air pollution which may reasonably be anticipated to endanger public health or welfare."

While there is little epidemiological doubt on the dangers of lead exposure, the primary rationale for the continued use of lead in avgas is safety of air travel. Piston-engine aircraft (PEA) constitute 71% of the U.S. air fleet (EIA, 2012), and a sizable fraction of these aircraft require high-octane gasoline to avoid dangerous knocking. Lead is one of the best known ingredients for raising gasoline octane. Eliminating its use from this class of aircraft would require expensive modifications to a significant fraction of the existing fleet (FAA, 2012);

nevertheless, according to Kessler (2013), about two-thirds of the existing fleet could transition safely to lead (and ethanol) free automotive gasoline (*mogas*) at negligible additional costs.

Under current regulations, lead emissions associated with avgas account for somewhere between half and two-thirds of the current flow of lead into the atmosphere (EPA, 2008). An estimated 225 million gallons of avgas were sold in the United States in 2011 (EIA, 2012). This implies a flow into the environment of about a million pounds per year. Approximately half of this is deposited near airports (EPA, 2008). Meanwhile, about 16 million people - and 3 million children - live within a kilometer of approximately 20,000 airport facilities that service lead-emitting aircraft.

Prior studies link lead usage in avgas to elevated atmospheric lead levels in the vicinity of airports (Carr et al., 2011; Callahan 2010; EPA, 2010b; Tetra Tech, Inc, 2007; Piazza 1999). Nevertheless, only one study has linked airport proximity to BLLs in children. Miranda et al. (2011) found a significant correlation between child BLLs and proximity to airport facilities in six counties in North Carolina, suggesting that avgas may endanger the health of children residing near airports. However, many details remain unresolved with respect to establishing a convincing link between lead in avgas and blood lead outcomes in children. At least three unresolved methodological issues support the EPAs position on the need for more studies before the agency can reasonably rule that avgas directly and meaningfully endangers public health.

First, the atmospheric deposition of lead from avgas is coincidental with the resuspension of contaminated soils/road dust. Both sources are driven in sync by local weather conditions. Atmospheric soil levels peak in the summer and retreat in the winter (Laidlaw et al. 2012; Zahran et al. 2013). Similarly, in Michigan and across airports with sufficiently detailed data, PEA departures and arrivals are significantly higher ($t = -6.43, p < .01$) in the summer (428 per month) than in the winter (286 per month) (FAAOP, 2012). Failure to account for this seasonal coincidence could upwardly bias evaluations of the health risks from avgas. Second, in determining the risk of elevated blood lead from avgas deposition, both distance to an airport and volume of PEA traffic are important. In our sample, the average monthly number of PEA operations varies from 7 (at MTC Selfridge) to 1,099 (at PTK Pontiac). Neglecting the volume of PEA traffic amounts to assuming that all airports traffic equally in PEA, which at least for Michigan would be inaccurate. Finally, due to typical zoning rules, other point sources of lead like metal industries that use lead and lead compounds in production are more common in the vicinity of airports. In our data, of the 400+ census tracts within 2 kilometers of an airport in Michigan, 41% also have a lead emitting facility within 2 kilometers. Failure to account for the spatial coincidence of airports and point-source polluters could also inflate the estimated health risks from avgas consumption.

The current study builds on the seminal work of Miranda et al (2011) to address these limitations and to address the EPAs call for additional information to evaluate the public health risks from avgas. First we expand the spatial and temporal scope of Miranda et al (2011), analyzing blood lead data on over 1 million children proximate to 448 airports across Michigan. Importantly, our econometric models adjust for residential proximity of sampled children to point-source polluters (among other relevant controls) to test whether child BLLs are dose-responsive in distance to airports. Second, using a difference-in-differences approach, we exploit an exogenous lead-deposition shock that resulted from the grounding and restriction of PEA traffic following the tragic events of September 11th, 2001. This test allows us to disentangle the avgas-associated flow of lead from the atmospheric re-suspension of legacy sources that co-vary seasonally.[2] Third, using data on PEA arrivals and departures at 27 airports across Michigan, we test whether child BLLs are dose-responsive in the volume of PEA traffic. This exercise exploits variation in PEA traffic driven by (exogenous) local meteorological conditions that vary meaningfully across Michigan.

Across all tests, we find consistent evidence that avgas use is significantly linked to elevated BLLs in children residing near airports. The odds of eclipsing various CDC thresholds for concern 1) increase in proximity to airports, 2) decline measurably in neighborhoods proximate to airports in the months following 9-11, and 3) increase significantly in the flow of PEA traffic. We also show that mean BLLs in children and total PEA traffic oscillate together at the monthly time-step.

To quantify the policy relevance of our results, we estimate the social benefits from a reduction in PEA traffic from the 50th percentile (407 monthly operations) to the 10th percentile (133 operations) across airports in Michigan. This reduction happens to correspond with the claim that about two-thirds of the existing PEA fleet could transition readily to *mogas*. To quantify social benefits, we deploy a standard syllogism in environmental health economics linking BLLs to IQ point loss, and IQ point loss to future earnings (Gould 2009; Grosse et al., 2002; Schwartz 1994). We estimate that a two-thirds decrease in PEA traffic at the representative airport in Michigan would yield a reduction in social damages attributable to avgas of about $102 million in net present value of future earnings. This translates into $8.60 in external social costs per gallon of avgas sold and can be compared to a price of about $6.30 per gallon.[3] Thus,

[2] The most common lead exposure pathways for children in the United States today are dust sources, including deteriorating or haphazardly removed lead-based paint (Farfel et al., 2005; Rabito et al., 2007) and ingestion or inhalation of lead-concentrated soils re-suspended during summer months (Filippelli et al., 2005, Laidlaw et al., 2005, Laidlaw et al., 2012, Zahran et al., 2010, and Zahran et al., 2013).

[3] Self-service price retrieved for Coleman Young Airport in Detroit, September 1st, 2014. We also show that the estimate of marginal damages is robust to the choice of percentiles.

an emission fee equal in magnitude to our estimate of the external social cost would more than double the user cost of avgas. Our social benefit exercise is not meant to be a full accounting of the external costs of lead exposure. Our social benefits estimate is conservative because the study considers only a subset of the population (children under five) and only one of the many known benefit channels associated with reduction of lead exposure in society (mainly, the impact of IQ loss on future earnings).[4]

2 Materials and Methods

2.1 Data

Blood lead data was obtained from the Michigan Department of Community Health (MDCH). The dataset contains blood samples on over 1 million children collected from January 2001 through December 2009. Measurements are reported in units of micrograms per deciliter of blood (μg/dL). The MDCH data also contain information on the census tract residential location of each child, the month and year of sample collection, child age in years (0 - 5), and child sex (male = 1, female = 0). As with previous research (Zahran et al. 2011), we analyze child BLL as a binary variable corresponding to the CDCs present (≥ 5 μg/dL = 1, < 5 μg/dL = 0) and past (≥ 10 μg/dL = 1, < 10 μg/dL = 0) reference values.

Point location data on airports in Michigan were gathered from the Geographic Names Information System (GNIS). A total of 448 airports satisfied our inclusion criterion of having at least 1 child (with a BLL reading) residing within 10 km. Additionally, we collected data from the Federal Aviation Administration's Operations and Performance (FAAOP) system on the

[4] Lead exposure can cause irreversible health problems, including learning disabilities, growth stunting, seizures, and lasting damage to various body systems. Kemper et al (1998) provide comprehensive health care cost estimates from medical interventions necessary to treat both low and high level exposure to lead. Others have estimated the total direct costs of lead-linked crime, including victim costs, criminal justice processing and incarceration, as well as lost earnings to victims and perpetrators of crime (Gould 2009).

monthly sum of piston-engine aircraft departures, arrivals, and aircraft seat count. A total of 27 airports were inventoried in the FAAOP system. In analyses that follow, we estimate whether child BLLs are dose-responsive in distance to GNIS airports *and* dose-responsive in the volume of piston-engine aircraft traffic.

Our econometric models control for a variety of other sources of lead exposure risk. Data from the Toxic Release Inventory (TRI) system identify 578 facilities that emitted lead in Michigan between 2001 and 2009 (EPA 2013). We measure the distance from the population-weighted centroid of each census tract to these lead-emitting facilities. This allows us to estimate whether the presence of a point source polluter within 2 km of a child's residential neighborhood increases their likelihood of exceeding various CDC thresholds for concern.[5]

To proxy for the risk of lead-based paint exposure, we use census tract population and housing data from the U.S. Census Bureau to measure the percentage of housing stock built prior to 1950. Following Miranda et al. (2011), we also measure the percentage of households receiving public assistance income to estimate levels of social disadvantage in a child's neighborhood. We also track population density since this correlates strongly with road density, and road density is a reasonably good proxy for prior period use of leaded gasoline, thus of prior lead accumulation in neighborhood roads and soils (Quinn 2013).

2.2 Econometric Models

We begin by analyzing whether child BLLs levels are dose-responsive in distance to GNIS airports in Michigan. We estimate a random intercept logistic regression with a tract-

[5] We calculated various distance buffers (0.5km, 1km, 1.5km, etc.) and determined through both statistical analysis (in terms of predictive efficacy) and prior research (in terms of emissions dispersion) that a 2 km buffer was optimal.

specific random intercept (ζ_j) to account for unobserved characteristics or conditions at the tract scale (for example, the accumulation of lead in neighborhood roads and soils). Y indicates BLL surpassing a given threshold for concern; Y = 1 if blood lead is ≥ 5 μg/dL (or ≥ 10 μg/dL), and Y = 0 if blood lead is < 5 μg/dL (or < 10 μg/dL). Y is modeled, for child i in census tract j in month t, by the following reduced form logistic equation:

$$\text{Prob}\big(Y_{ijt} = 1 | D_j, M_i, A_i, Z_t, S_t, F_j, H_j, P_j, W_j\big)$$
$$= \Lambda\left[\alpha_j + \beta_1 D_j + \Gamma_1 M_i + \Gamma_2 A_i + \Gamma_3 Z_t + \Gamma_4 S_t + \lambda_1 \mathrm{F}_j + \lambda_2 H_j + \lambda_3 P_j + \lambda_4 \mathrm{W}_j + \zeta_j\right]. \qquad (1)$$

Here, $\Lambda[\cdot]$ is the CDF of the logistic distribution, D_j is the distance (in km) of the population-weighted centroid of census tract j to the nearest GNIS airport, M_i = 1 if the child is male, A_i denotes a series of dummy variables corresponding to child age in years, Z_t is the year blood was drawn ("2001"=1), S_t is the season blood was drawn, F_j is an indicator variable that equals 1 if a lead facility operates within 2 km, H_j is the percentage of housing stock in a child's neighborhood built before 1950, P_j is the population density in the child's neighborhood, and W_j is the percentage of households in a child's neighborhood receiving public assistance income. In addition to measuring distance continuously, we examine categories of distance (< 1km; 1-2km; 2-3km, and >3km, with >3km constituting our reference category) to check for non-linearities in the relationship between child BLL and airport distance. *Insofar as deposition of lead from piston-engine aircraft traffic is a source of blood lead in children, we expect the odds of a child eclipsing CDC reference values to decrease in distance from GNIS airports.*

Our next test is designed to separate the flow of avgas from the stock of lead in the lived environment that circulates seasonally (see Laidlaw et al 2012; Zahran et al., 2013) and coincidentally with the flow of PEA traffic (and consequent deposition of Pb from avgas use). Following the tragic events of 9-11, aircraft traffic in the U.S. was substantially restricted. The effect of this aircraft traffic restriction is reflected in monthly aviation gasoline sales and deliveries, which were significantly lower than expected in September, October, and November of 2001. Insofar as avgas sales proxy for the monthly level of lead deposition across GNIS airports, we analytically leverage the exogenous restriction of PEA traffic as a quasi-experiment in lead deposition. In the air traffic restriction period following 9-11, the flow of avgas is shocked downward but the dynamic involving atmospheric resuspension of lead-contaminated soils and road dust is unperturbed. We estimate the following model:

$$\text{Prob}\left(Y_{ijt} = 1 | D_j, E_{t,} M_i, A_i, Z_t, S_t, F_j, H_j, P_j, W_j\right)$$
$$= \Lambda\left[\alpha_j + \beta_1 D_j + \beta_2 E_t + \delta\left(D_j \times E_t\right) + \Gamma_1 M_i + \Gamma_2 A_i + \Gamma_3 Z_t + \Gamma_4 S_t + \lambda_1 \mathrm{F}_j + \lambda_2 H_j + \lambda_3 P_j + \lambda_4 \mathrm{W}_j + \zeta_j\right] \quad (2)$$

The definition of terms carries over from Eq.(1) with the exception of D_j, which here assumes a value of 1 if a child resides within 1 kilometer of an airport, and E_t= 1 if blood was drawn during the episode of depressed avgas sales from 09/2001 to 11/2001. The impact of the deposition shock is captured by a coefficient of interaction (δ) which measures the combined effect of airport proximity (D_j) and the episode indicator (E_t). *To the extent child BLL is dose-responsive is airport proximity and lead deposition from PEA traffic, the coefficient of interaction should be negative.*

The above tests follow Miranda et al (2011) in assuming that PEA traffic is the same across airports. For the 27 airports in our sample inventoried in the FAAOP system, we obtained data on the monthly flow of PEA traffic. We use this to analyze the relationship between child

BLLs and the volume of PEA traffic. We exploit the fact that a portion of the observed variation in PEA traffic is determined by exogenous fluctuations in local weather conditions. These conditions vary meaningfully across airport facilities examined.[6] The augmented regression model is

$$\text{Prob}\left(Y_{ijt} = 1 | D_j, T_{jt,} M_i, A_i, Z_t, S_t, F_j, H_j, P_j, W_j\right)$$
$$= \Lambda\left[\alpha_j + \beta_1 D_j \ + \beta_2 T_{jt} \ + \Gamma_1 M_i + \Gamma_2 A_i + \Gamma_3 Z_t + \Gamma_4 S_t + \lambda_1 \mathrm{F}_j + \lambda_2 H_j + \lambda_3 P_j + \lambda_4 \mathrm{W}_j + \zeta_j\right].$$
(3)

All terms carry over from Eq.(1), while T_{jt} represents the monthly (t) sum of PEA arrivals and departures at the nearest airport.

As a robustness check on the above test, we also analyze the extent to which the above PEA traffic effect (*T*) varies by distance (*D*). The logic is that the PEA traffic effect, to the extent it is important, ought to amplify in airport proximity. We estimate the following:

$$\text{Prob}\left(Y_{ijt} = 1 | D_j, T_{jt,} M_i, A_i, Z_t, S_t, F_j, H_j, P_j, W_j\right)$$
$$= \Lambda\left[\alpha_j + \beta_1 D_j \ + \beta_2 T_{jt} \ + \delta\left(D_j \times T_{jt}\right) + \Gamma_1 M_i + \Gamma_2 A_i + \Gamma_3 Z_t + \Gamma_4 S_t + \lambda_1 \mathrm{F}_j + \lambda_2 H_j + \lambda_3 P_j + \lambda_4 \mathrm{W}_j + \zeta_j\right]. \quad (4)$$

All terms carry over from Eq. (3). The lead deposition effect of PEA traffic by tract distance is captured by the coefficient δ, denoting the interaction between *D* and *T*. *D* in this case is an

[6] The average annual number of snow days and precipitation inches varies considerably across airports. For instance, CIU (in the northeast end of Michigan's Upper Peninsula) has more than twice the number of average annual snow days as DET (that is 9km northeast of Detroit's central business district). Not only does total precipitation vary across examined airports, but so does the peak month of precipitation and the percentage difference between peak and trough months over the calendar year. Variation in precipitation across airports, and within airports in time, importantly determine the level of PEA traffic and consequent deposition of lead on neighborhoods nearby.

indicator variable that equals 1 if the child resides within 2 kilometers of an airport.[7] In terms of expectations: *If deposition of Pb from PEA traffic is a significant source of BLL in children, the odds a child eclipses the CDC reference values should increase in PEA traffic; moreover, the PEA traffic effect should rise in airport proximity.*

3 Results

Table 1 reports descriptive statistics on the proportion of observed children exceeding present and past CDC reference values of 5 and 10 μg/dL by model predictors. All covariates behave as expected. The proportion of children with BLL above threshold increases in proximity to the nearest GNIS airport, in the monthly flow of PEA traffic, in the percentage of housing built before 1950, in summer and fall relative to spring and winter, in proximity to Pb-emitting TRI facilities, and in neighborhood population density, among other things.

[Insert Table 1]

Table 2 reports odds ratios predicting likelihoods of child BLL exceeding present and past CDC reference values. In Model 1, all else equal, a 1 km increase in distance from the nearest GNIS airport decreases the risk of a child eclipsing the CDC reference value of 5 μg/dL by 2.5% (95% CI: 1.5, 3.4). Similarly, in Model 2, a 1 km increase in neighborhood distance from a GNIS airport reduces the odds of a child's BLL exceeding 10 μg/dL by a multiplicative factor of 0.970 (95% CI: 0.954, 0.986). Models 3 and 4 divide airport distance (D) into discrete categories ($D \leq 1$ km; 1 km > D < 2 km; 2 km > D < 3 km; and D >3 km) to estimate the distance

[7] The cut point of <2km corresponds to the empirically derived distance where the deposition effect retreats to chance indistinguishable, as reported in Table 3 below. This test also addresses a modest sampling gradient in distance to airports. Children residing near airports are slightly more likely to have their blood sampled for lead content. The sampling ratio increases less than 1% ($b = -0.86$, 95% CI: $-1.13, -0.58$) for every kilometer in distance from the nearest airport, equal to about 9 fewer children sampled per kilometer of distance.

at which the risk of elevated BLL dissipates to chance occurrence. At <1km from the nearest airport, children are 23.6% more likely to record a BLL level >5 μg/dL. Children residing between 1 and 2km from the nearest airport are 14.4% more likely have a BLL reading >5 μg/dL. Across Models 2 and 4, the risk of elevated BLL (under present and past CDC reference levels) fades to zero ($p < .05$) beyond 2 km from the nearest GNIS airport.

Before moving on, it is worth noting the intuitive behavior of other variables known to influence BLL outcomes. In Model 1, for instance, a 1% increase in percent of housing stock built prior to 1950—a common proxy for the risk of Pb-based paint exposure—increases the child's odds of superseding the CDC threshold of 5 μg/dL by a factor of 1.022 (95% CI: 1.020, 1.023). The model also detects the known seasonality in child BLL (Zahran et al. 2012), showing that, as compared to the reference seasons of winter/spring, children having their blood drawn in summer (OR = 1.37) and fall (OR = 1.25) months have significantly higher odds of having BLL ≥ 5 μg/dL.

[Insert Table 2]

Table 3 reports results from our quasi-experiment leveraging the decrease of air traffic following the events of 9-11. We rendered a series of models, analyzing likelihoods of a child's BLL eclipsing various thresholds (including 3, 5, 7 and 10 μg/dL). The coefficient of interest in all models is our difference-in-differences term constituting the interaction of airport proximity and period of blood draw. In Model 1 we find that the odds of eclipsing 3 μg/dL declined by 19.2% (95% CI: 1.6, 32.0) in our experimental group, representing children residing within 1km of an airport that had their blood drawn during the deposition shock period. Similarly, in Model 2, the risk of exceeding the CDC reference value of 5 μg/dL was 19.5% (95% CI: 2.0, 32.3) lower in our experimental group. While lower bound estimates for the shock effect are modest across models rendered, ~ 2%, they are distinguishable from chance, suggesting that avgas deposition may pose a health risk to children residing near GNIS airports.

[Insert Table 3]

While results in Tables 2 and 3 corroborate and extend Miranda et al (2011), and are suggestive of a Pb deposition effect, airports are assumed to be equal with respect to the volume of PEA traffic. A more telling test would evaluate BLL levels in response to PEA traffic. We begin with an ecological view of the data. Figure 1 (Panel A) shows joint movement of monthly average BLL over all measured children in Michigan (residing < 10 km from 27 airports with valid PEA traffic), as well as the average monthly sum of PEA departures and arrivals (at the same 27 airports). Both series are standardized ($\mu = 0, \sigma = 1$). The series share strikingly similar seasonality, and drift downward together in time. The temporal correlation is strong ($r = 0.823$). While Figure 1 Panel A is strongly suggestive, recall that soil re-suspension is a known source of seasonal variation in child BLLs (Zahran et al. 2013). Panel B addresses this potential confounding. Again, time is on the x-axis, but now monthly average BLL is divided into two categories of child exposure to relatively high (above average) or low (below average) PEA traffic. The two series diverge intuitively with respect to a hypothesized Pb deposition effect – the high traffic series sits above the low traffic series.

[Insert Figure 1]

Returning then to the micro level, Table 4 reports odds ratios predicting likelihoods of child BLL exceedance of present and past CDC reference thresholds as a function of PEA traffic. The population analyzed is restricted to children residing less than 10 km from a FAAOP airport (with valid monthly PEA traffic). To estimate the effect of PEA traffic, children are matched spatially to the nearest FAAOP airport, and temporally by matching the month of blood draw and corresponding total PEA traffic at the nearest FAAOP airport. This test is particularly strong because it exploits variation in Pb deposition from PEA traffic that is partially governed by local meteorological conditions that vary meaningfully across FAAOP airport locations. As reported in Models 1 & 2, and adjusting for child residential proximity to a FAAOP airport and known correlates of child BLL, we find that a one standard deviation increase (~267 operations) in PEA traffic increases the odds that a child's BLL ≥ 5 μg/dL by a factor of 1.067 (95% CI: 1.041, 1.094), and by a factor of 1.075 (95% CI: 1.025, 1.128) with respect to the odds of a child's BLL ≥ 10 μg/dL.

Models 3 & 4 in Table 4 report ORs on the risk of elevated BLLs in children from PEA traffic by distance to the nearest FAAOP airport. Intuitively, we find that an increase in the volume of PEA traffic imposes a substantially higher burden on children within 2 km of a FAAOP airport, as compared to children living beyond 2 km of an airport. More precisely, the likelihood of a child's BLL exceeding 5 μg/dL for a standard deviation in PEA traffic is ~18.6% higher (1.057×1.122) for children residing <2km relative to children residing >2km from an airport. In Model 4, we see that children proximate to airports are ~15.8% (1.064×1.088) more likely than children distant from airports to exceed 10 μg/dL with a standard deviation increase in PEA traffic.

[Insert Table 4]

Figure 2 graphs results from Model 3. Predicted probabilities of a child's BLL level ≥ 5 μg/dL is on the y-axis, and PEA traffic in on the x-axis (moving in standard deviation units).

Two connected lines intersect the space, with one corresponding to predicted probabilities for children < 2km and the other for children > 2km from the nearest FAAOP airport. Control variables in Model 3 are fixed at their sample means. Interestingly, at lower than average levels of PEA traffic, children have roughly equal risk of clearing the CDC's threshold of concern (≥ 5 μg/dL) regardless of if they reside less or more than 2km from an airport. However, at greater than average PEA traffic, probabilities of exceedance in the two groups of children diverge. At 2 standard deviations above the mean in PEA traffic, for instance, children at < 2km of an airport have a predicted probability of threshold exceedance of 0.285 (95% CI: 0.254, 0.315) as compared to children at > 2km of an airport at 0.212 (95% CI: 0.202, 0.223).

[Insert Figure 2]

We briefly note the behavior of other covariates in Table 4. As with previous research (and implied in Figure 1), we find that BLL levels have a distinct seasonality, rising significantly in the summer and fall as compared to reference seasons of spring in winter (see Laidlaw et al 2012; Zahran et al 2013). For instance, in Model 1, and other things held equal, we find that the odds of child's BLL being ≥ 5 μg/dL increases by a multiplicative factor of 1.356 (95% CI: 1.324, 1.389) in the summer and by 1.231 (95% CI: 1.205, 1.259) in fall over reference seasons. Staying with Model 1, we also find that a point increase in the percentage of housing stock built prior to 1950 increases the odds of threshold exceedance by a factor of 1.022 (95% CI: 1.020, 1.024). A standard deviation increase in PEA traffic has roughly the same effect on the risk of an elevated BLL reading as increasing the percentage of the housing stock built < 1950 by ~3 points over average. Finally, we find that residing within 2km of lead-emitting facility increases the odds of a registering a BLL of ≥ 5 μg/dL by 3.4%.

3.1 Social benefits

To infer the significance of our results for policy, we conservatively estimate the social benefits of a reduction in monthly PEA traffic from the 50th (407) to the 10th (133) percentile in total departures and arrivals, equivalent to a two-thirds reduction in avgas deposition at the representative airport. Our choice to emphasize a movement from the 50th to 10th percentile corresponds to a reduction in PEA traffic at the representative airport to near zero, while staying within the support of the estimated distribution. This two-thirds reduction scenario also happens to coincide with the fraction of the existing fleet that could transition to mogas with minimal adjustments (Kessler 2013). Despite these considerations, the marginal damage estimate behaves consistently across reduction scenarios.[8]

To estimate the social benefit of reduced avgas consumption, we leverage the regression coefficients from Eq. (3), and we use a standard syllogism in environmental health economics linking BLL to IQ point loss and IQ point loss to future earnings (Gould 2009; Grosse et al., 2002; Schwartz 1994). Table 5 summarizes the steps. First, according to Census Bureau data and tract distance calculations to the nearest airport, a total of 164,782 children reside within 2km of an airport facility in Michigan. Columns A & B estimate the number of children falling into various BLL categories, ranging from < 5 μg/dL to >20 μg/dL under 10th and 50th percentile levels of monthly PEA traffic respectively. These BLL categories correspond to observed breaks in the nonlinear association of IQ and BLL (Gould 2009; Lanphear et al., 2005). The count of

[8] As discussed below, moving from the 50th to the 10th percentile implies a marginal damage estimate of $8.60 per gallon. In contrast, moving from the 95th to the 5th percentile implies $8.91 per gallon, 90th to 10th implies $8.80 per gallon, 75th to 25th implies $8.74 per gallon, and 25th to 10th implies $8.53 per gallon.

children per BLL category is estimated by Eq. (3) under 10th and 50th percentile traffic scenarios.[9]

[Insert Table 5]

The number of children above the CDC's reference value of 5μg/dL is higher in Column B (reflecting more PEA traffic) than Column A (reflecting less PEA traffic). Columns C and D indicate the average BLL level within each BLL category and the average IQ point loss per μg/dL, respectively. The marginal effects in Column D are from Gould (2009) and Lanphear et al. (2005). Columns E and F estimate IQ point loss under 10th and 50th percentile PEA traffic by multiplying the estimated number of affected children (in Columns A or B), the average BLL level per at-risk category, and the average IQ point loss per μg/dL by BLL category. The sum of IQ points gained in going from the 50th to the 10th percentile in PEA traffic (5,710 IQ points) is reported in Column G. This reflects the difference between Columns F and E.

Following others (Salkever 1995; Schwartz 1994; Nevin et al. 2008; Grosse et al; 2002), each IQ point gained corresponds to a gain in the present discounted value of lifetime earnings of $17,815 (2006 USD). Multiplying this by the sum of IQ points gained (5,710) gives a total social benefit of $102 million. This benefit would be realized annually. Assuming population density near airports and other conditions in Michigan generalize, this suggests a national benefit of about $4.0 billion annually.[10] It also implies an external social cost of $8.60 per gallon for currently formulated avgas in Michigan. This estimate is not comprehensive since it reflects gains to only a subset of the population (children ≤ 5 years of age), and it considers only one

[9] Fixing other covariates at their means, we estimate the proportion of children exceeding specified thresholds under 10th and 50th percentile PEA traffic scenarios. The derived proportions are then multiplied by the count of children in census tracts within 2km of an airport (specifically, 164,782) to get the count of children per BLL category.
[10] In Michigan, there are 76,875 children within 1 km of airports, while the corresponding national number is 3 million. Scaling the Michigan benefit estimate by the ratio of these populations gives our national estimate.

benefit channel (IQ point gain). Including health care and special education costs averted, as well as behavioral and crime control costs, would lead to a higher estimate (Gould 2009).

4 Conclusion

Children exposed to lead have diminished life chances, experiencing "an unfolding series of adverse behavioral outcomes: behavior problems as a child, pregnancy and aggression as a teen, and criminal behavior as a young adult" (Reyes 2014). Lead exposure in children has been linked to attention-deficit and hyperactivity disorders (Nigg et al., 2010), delinquency and violence (Dietrich et al; 2001; Reyes 2007; Mielke and Zahran 2012), poor academic achievement (Reyes 2012; Miranda et al., 2007; Zahran et al. 2009) and IQ loss (Needleman 1990; Canfield et al. 2003; Jusko et al. 2008). Magnetic Resonance Imaging studies show that adults poisoned by lead as children have reduced gray matter in regions of the brain known to govern executive judgment, impulsivity and mood regulation (Cecil et al; 2008, 2011) — intellectual and socio-emotional traits that economists have linked to long-term life outcomes (Doyle et al 2013; Cunha and Heckman, 2010; Almond and Currie, 2010; Reyes 2014).

Past lead control efforts - lead was effectively banned from house paint in 1978, from plumbing in 1986, from food cans in 1995, and automobile gasoline by 1996 - have generated sizable social benefits (Grosse et al. 2002; Gould 2009; Pichery et al. 2011; Jones 2012), reducing the number of children with BLLs above the CDCs threshold for concern. Despite these lead control efforts, BLLs remain high for a sizeable fraction of children in the United States (Zahran et al., 2011). Our study provides evidence that elevated BLLs in children proximate to airports is partially attributable to avgas deposition.

Specifically, we find that the odds of a child's BLL eclipsing CDC thresholds for concern 1) increase dose-responsively in proximity to airports, 2) decline measurably in neighborhoods proximate to airports in the months following 9-11, and 3) increase dose-responsively in the flow of PEA traffic. We also show that mean BLLs in children and total PEA traffic oscillate together at the monthly time-step. Moreover, our results show that the external social damages attributable to avgas consumption are significant relative to the private cost of gasoline—at least \$8.60 per gallon compared to a pump price of \$6.30.[11] Under current regulations, these damages are unpriced. An emission fee that forced avgas consumers to internalize these costs can lead to a transition away from lead-formulated avgas by the roughly two-thirds of the existing PEA fleet for which the lead additive is non-critical (Kessler 2013). In addition, by creating incentives for technological change, the policy would potentially set the stage for the eventual phase out of lead from the aviation sector.

[11] Of course, the efficient emission tax would be applied to the lead content of gasoline, so the tax per gallon would vary for different formulations of avgas. \$8.60 applies to an average gallon of avgas sold in Michigan over the sample period. This is equivalent to \$4.55 per gram of lead.

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Table 1: Descriptive Statistics on Proportion of Children Eclipsing 5 and 10μg/dL by Covariates

	Proportion ≥ 5 μg/dL	Proportion ≥ 10 μg/dL
Distance to Airport (km)		
>$P_{.50}$	0.144	0.024
<$P_{.50}$	0.191	0.038
Piston Engine Aircraft		
>$P_{.50}$	0.227	0.053
<$P_{.50}$	0.203	0.039
Sex		
Male	0.167	0.031
Female	0.156	0.028
Age of Child		
<1 year	0.097	0.012
1 year	0.140	0.024
2 years	0.199	0.040
3 years	0.187	0.035
4 years	0.163	0.029
5 years	0.171	0.034
% Housing Built < 1950		
>$P_{.50}$	0.255	0.053
<$P_{.50}$	0.069	0.007
Season		
Winter	0.147	0.026
Spring	0.146	0.024
Summer	0.176	0.035
Fall	0.171	0.032
Population Density		
>$P_{.50}$	0.233	0.048
<$P_{.50}$	0.091	0.012
% Public Assistance		
>$P_{.50}$	0.253	0.052
<$P_{.50}$	0.072	0.008
Pb Facility < 2 km		
Yes	0.226	0.046
No	0.120	0.019
Year		
< 2005	0.216	0.044
> 2005	0.114	0.017

Table 2: Random Intercept Logistic Regression Odds Ratios Predicting Elevated Blood Pb (≥ 5 µg/dL and ≥ 10 µg/dL) in Children in Michigan Residing < 10km from an Airport

	Model 1 ≥ 5 µg/dL OR	Model 2 ≥ 10 µg/dL OR	Model 3 ≥ 5 µg/dL OR	Model 4 ≥ 10 µg/dL OR
Distance to Airport (km)	0.975***	0.970***		
	(0.005)	(0.008)		
Reference = Distance ≥ 3 km				
< 1 km			1.236***	1.437***
			(0.080)	(0.141)
1 to 2 km			1.144***	1.241***
			(0.040)	(0.068)
2 to 3 km			1.059*	1.012
			(0.035)	(0.055)
Reference = Age < 1				
Age 1	2.041***	2.862***	2.041***	2.863***
	(0.031)	(0.108)	(0.031)	(0.108)
Age 2	2.705***	3.946***	2.705***	3.946***
	(0.042)	(0.150)	(0.042)	(0.150)
Age 3	2.103***	2.864***	2.102***	2.864***
	(0.033)	(0.110)	(0.033)	(0.110)
Age 4	1.717***	2.275***	1.717***	2.275***
	(0.027)	(0.088)	(0.027)	(0.088)
Age 5	1.622***	2.380***	1.622***	2.381***
	(0.028)	(0.099)	(0.028)	(0.099)
Male	1.123***	1.140***	1.123***	1.140***
	(0.006)	(0.013)	(0.006)	(0.013)
Reference = Winter/Spring				
Summer Season	1.370***	1.559***	1.370***	1.559***
	(0.010)	(0.022)	(0.010)	(0.022)
Fall Season	1.249***	1.341***	1.249***	1.341***
	(0.009)	(0.020)	(0.009)	(0.020)
% Housing Built < 1950	1.022***	1.028***	1.021***	1.027***
	(0.001)	(0.001)	(0.001)	(0.001)
Population Density	1.019	1.140***	1.025	1.151***
	(0.016)	(0.028)	(0.016)	(0.028)
% Public Assistance	1.089***	1.096***	1.090***	1.097***
	(0.003)	(0.004)	(0.003)	(0.004)
Pb Facility < 2 km	1.020**	1.023*	1.020**	1.025*
	(0.010)	(0.014)	(0.010)	(0.014)
Year (2001=1)	0.860***	0.843***	0.860***	0.843***
	(0.001)	(0.002)	(0.001)	(0.002)
Constant	0.0311***	0.002***	0.027***	0.002***
	(0.001)	(0.000)	(0.001)	(0.000)
Log Likelihood	-386,833.01	-117,054.48	-386,832.75	-117,047.54
Wald χ^2	28,997.65	11,546.62	28,993.33	11,559.86
ρ	0.069	0.106	0.069	0.106
N	1,043,391	1,043,391	1,043,391	1,043,391
Number of tracts	2,498	2,498	2,498	2,498

Note: Standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1

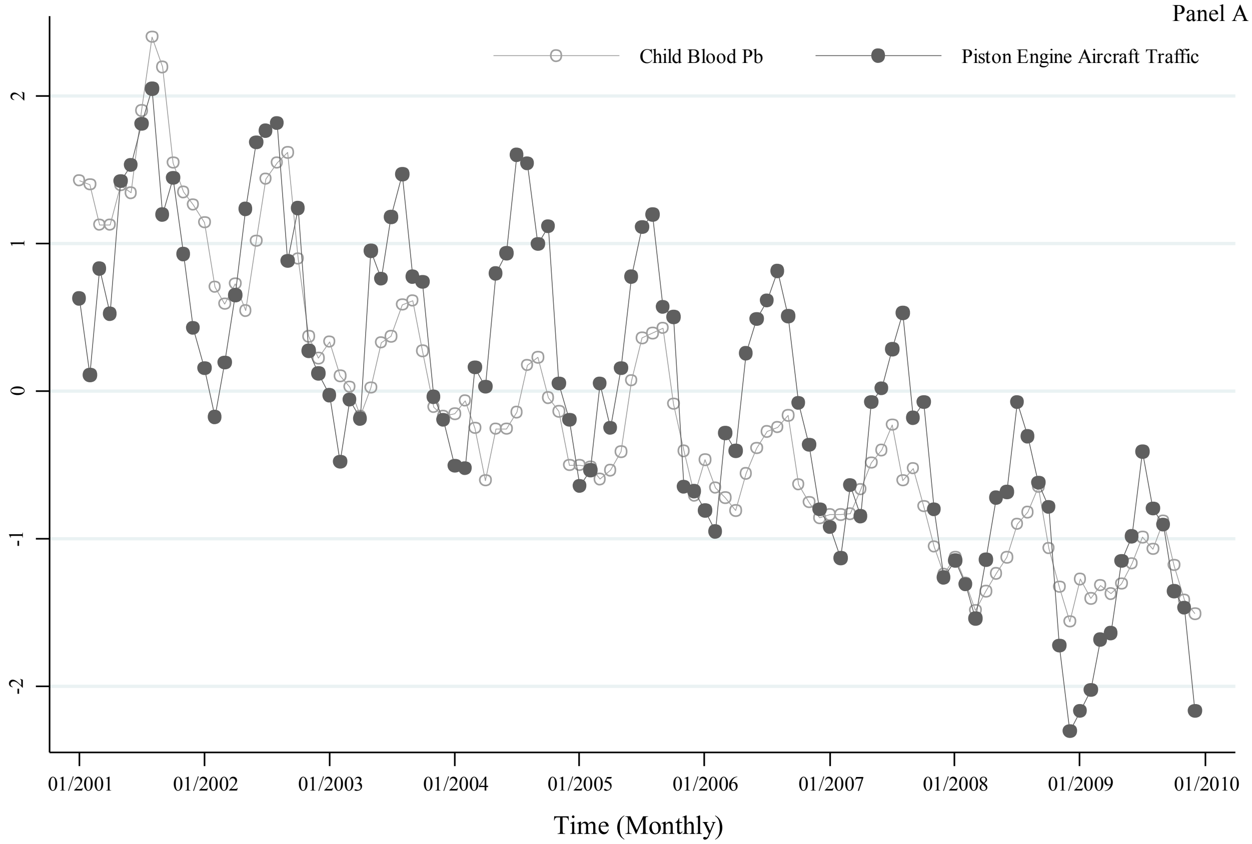
Table 3: Difference-in-Differences Random Intercept Logistic Regression Odds Ratios Predicting Elevated Blood Pb (≥ 5 μg/dL and ≥ 10 μg/dL) in Children in Michigan Residing < 10km from an Airport

	Model 1 ≥ 3 μg/dL OR	Model 2 ≥ 5 μg/dL OR	Model 3 ≥ 7 μg/dL OR	Model 4 ≥ 10 μg/dL OR
Distance to Airport (≤ 1km)	1.107	1.156**	1.202**	1.208*
	(0.080)	(0.081)	(0.096)	(0.118)
Treatment Period	1.240***	1.120***	1.158***	1.170***
	(0.030)	(0.025)	(0.029)	(0.039)
Distance × Treatment Period	0.818**	0.815**	0.785**	0.757*
	(0.077)	(0.077)	(0.089)	(0.122)
Male	1.105***	1.132***	1.162***	1.151***
	(0.007)	(0.008)	(0.010)	(0.014)
Reference Age < 1				
Age 1	2.020***	2.357***	2.684***	3.232***
	(0.028)	(0.044)	(0.071)	(0.141)
Age 2	2.778***	3.228***	3.658***	4.502***
	(0.041)	(0.062)	(0.097)	(0.198)
Age 3	2.220***	2.528***	2.785***	3.238***
	(0.033)	(0.049)	(0.075)	(0.143)
Age 4	1.821***	2.044***	2.219***	2.523***
	(0.027)	(0.039)	(0.060)	(0.113)
Age 5	1.594***	1.903***	2.215***	2.609***
	(0.027)	(0.041)	(0.065)	(0.124)
% Housing Built < 1950	1.019***	1.024***	1.027***	1.031***
	(0.001)	(0.001)	(0.001)	(0.001)
Reference = Winter/Spring				
Summer Season	1.290***	1.428***	1.473***	1.615***
	(0.010)	(0.012)	(0.016)	(0.025)
Fall Season	1.195***	1.260***	1.264***	1.358***
	(0.009)	(0.011)	(0.015)	(0.024)
Population Density	1.034	1.063**	1.053*	1.059*
	(0.026)	(0.026)	(0.029)	(0.034)
% Public Assistance	1.074***	1.084***	1.084***	1.089***
	(0.004)	(0.003)	(0.004)	(0.005)
Pb Facility < 2 km	1.033**	1.013	1.010	0.991
	(0.014)	(0.013)	(0.015)	(0.017)
Year (2001=1)	0.868***	0.850***	0.846***	0.841***
	(0.001)	(0.001)	(0.002)	(0.002)
Constant	0.187***	0.025***	0.007***	0.002***
	(0.008)	(0.001)	(0.000)	(0.000)
Log Likelihood	-304,062.44	-242,936.92	-166,064.17	-89,543.14
Wald χ^2	21,340.37	21,662.86	15,326.55	8,810.09
ρ	0.082	0.068	0.079	0.093
N	516,540	516,540	516,540	516,540
Number of tracts	891	891	891	891

Note: Observations restricted to census tracts with children observed in the treatment period (September to November 2001) and < 1km from the nearest airport. Standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1

Figure 1: Monthly Blood Pb (of Children ≤ 10 Km of Traffic Airport) and Piston Engine Aircraft Traffic in Time and Blood Lead Levels by PEA Traffic

Panel A



Panel B

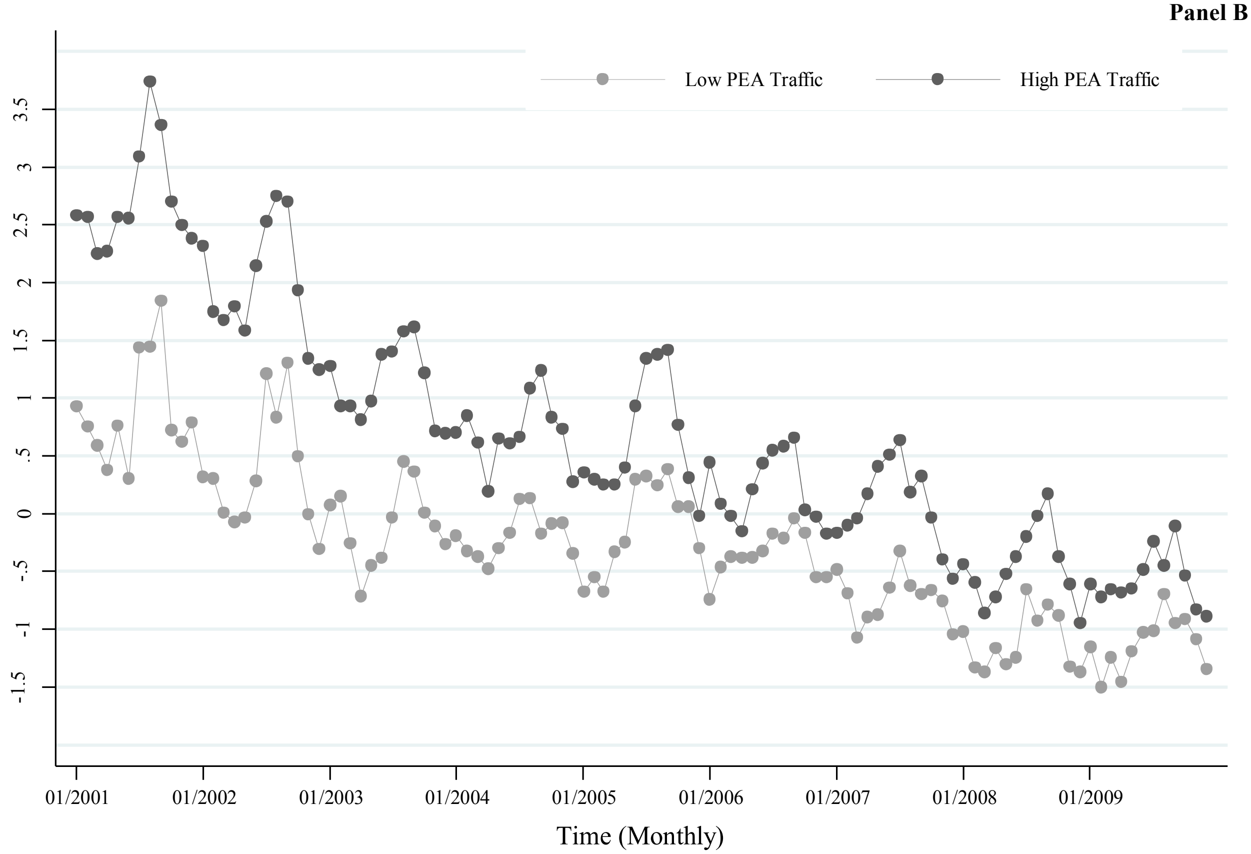


Table 4: Random Intercept Logistic Regression Odds Ratios Predicting Elevated Blood Pb (≥ 5 μg/dL and ≥ 10 μg/dL) in Children in Michigan Residing < 10km from an Airport with Validated Piston Engine Aircraft Traffic

	Model 1 ≥ 5 μg/dL OR	Model 2 ≥ 10 μg/dL OR	Model 3 ≥ 5 μg/dL OR	Model 4 ≥ 10 μg/dL OR
Distance to Airport (km)	0.962***	0.961***		
	(0.009)	(0.014)		
Piston Engine Aircraft	1.067***	1.075***	1.057***	1.064**
	(0.014)	(0.026)	(0.014)	(0.027)
Distance to Airport < 2km			1.286***	1.343***
			(0.099)	(0.145)
Distance <2km × Piston Engine Aircraft			1.122***	1.088*
			(0.033)	(0.054)
Male	1.127***	1.140***	1.127***	1.140***
	(0.010)	(0.017)	(0.010)	(0.017)
Reference = Age < 1				
Age 1	2.466***	3.486***	2.467***	3.486***
	(0.056)	(0.190)	(0.056)	(0.190)
Age 2	3.409***	5.016***	3.411***	5.018***
	(0.080)	(0.275)	(0.080)	(0.275)
Age 3	2.680***	3.626***	2.682***	3.627***
	(0.063)	(0.199)	(0.063)	(0.200)
Age 4	2.154***	2.826***	2.154***	2.827***
	(0.051)	(0.157)	(0.051)	(0.157)
Age 5	2.008***	2.851***	2.010***	2.853***
	(0.052)	(0.167)	(0.052)	(0.167)
% Housing Built < 1950	1.022***	1.030***	1.022***	1.030***
	(0.001)	(0.002)	(0.001)	(0.002)
Reference = Winter/Spring				
Summer Season	1.356***	1.523***	1.354***	1.522***
	(0.017)	(0.034)	(0.017)	(0.034)
Fall Season	1.231***	1.328***	1.230***	1.327***
	(0.014)	(0.028)	(0.014)	(0.028)
Population Density	1.146***	1.165***	1.144***	1.168***
	(0.033)	(0.047)	(0.033)	(0.047)
% Public Assistance	1.088***	1.100***	1.088***	1.099***
	(0.004)	(0.006)	(0.004)	(0.006)
Pb Facility < 2 km	1.034*	1.026	1.043**	1.036
	(0.018)	(0.024)	(0.018)	(0.024)
Year (2001=1)	0.870***	0.852***	0.871***	0.852***
	(0.002)	(0.004)	(0.002)	(0.004)
Constant	0.028***	0.002***	0.021***	0.001***
	(0.002)	(0.000)	(0.001)	(0.000)
Log Likelihood	-157,323.86	-57,071.86	-157,318.84	-57,070.75
Wald χ^2	12,915.33	5,875.20	12,874.96	5,867.77
ρ	0.078	0.111	0.079	0.111
N	374,313	374,313	374,313	374,313
Number of tracts	773	773	773	773

Note: Standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1

Figure 2: Predicted Probabilities of Elevated Blood Pb (≥ 5 μg/dL) by PEA Traffic and Distance to Nearest Airport