The Economic and Health Effects of the Chemical Spill in the Elk River

Abstract

In January 2014, Freedom Industries spilled 4-methylcyclohexylmethanol, a chemical foaming agent used in coal processing, from a storage facility into the Elk River in West Virginia. This chemical spill, one of the most significant in U.S. history, adversely affected the drinking water supply for over 300,000 individuals in the Charleston, West Virginia Metropolitan area. We use synthetic control methods to estimate the casual effects on macro-economic growth and infant health outcomes from this water crisis. We find a significant decrease in 5-minute Apgar Scores, a measure of how babies fare in birthing process and outside of the womb, after the chemical spill. We do not find significant effects for infant birthweight or gestational age. We find a statistically insignificant decrease of per capita GDP in the Charlestown, WV area compared to the synthetic control of 3% two years after the chemical spill.

Key words: Environmental disasters, synthetic controls, chemical spill, drinking water crisis.

JEL codes: A22, A23, Q25, Q51, Q53

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A safe and reliable supply of water is essential to human health (Hunter et al. 2010). Exposure to various organic or inorganic chemicals can lead to detrimental health effects, including nausea, vomiting, skin rashes, cancer, and fetal abnormalities (Hunter 1997). Water pollution exposure can also have indirect impacts to individuals, such as disease from malnutrition, hindered food production, reduced labor productivity, and increased risk of financial stress. Suffice it to say, historic water pollution events have had large effects on human communities (e.g., Schwabach 1989; Saha 2003; Shaban et al. 2009). Water insecurity can lead to increased pressure on poverty and social unrest (Sadoff and Grey, 2007) and water-related shocks can negatively influence public health and economic stability. Researchers have found evidence that economic growth is affected by large environmental disasters (Cavallo et al, 2013). Large disturbances to economic activity through the destruction of infrastructure, death, disease, and financial losses can all contribute to lower growth in both the short and long term.

Despite greater environmental protections and recent advancements in water treatment, there have been a number to large-scale contamination cases in the United States. These include the Deepwater Horizon oil spill on the Gulf Coast (Camilli et al, 2010), the Gold King Mine wastewater spill in Colorado (Parker 2015), the Flint, Michigan water crisis in 2014 (Hanna-Attisha et al. 2016), and West Virginia's Elk River Spill in early 2014.

Water safety and security increasingly relies on evaluating the risks and causal effects of contamination events. A difficulty with assessing the local impacts of a water contamination event is that there is typically only one "treated" observation. In typical regression analyses, one compares average outcomes for a series of treated observations to outcomes from observationally-similar but untreated "control" observations. However, regression analyses contain certain statistical characteristics which may over-extrapolate effects[1] (Abadie et al, 2010; Abadie et al, 2015). In the economics literature, the synthetic control method has recently been used to assess treatment effects for single treated observations (Abadie et al, 2010; Coffman and Noy, 2011; Abadie et al, 2015). This approach compares outcomes for a single treated observation to the outcomes of a "synthetic" control observation, constructed as a weighted average of the universe of potential control observations. The development of synthetic control methods provides a better statistical framework for analyzing singular events with aggregate level data.

In this paper, we apply the synthetic control method to assess the economic and public health effects of a large water contamination event: The Elk River Chemical Spill in West Virginia. In January 2014, Freedom Industries released approximately 10,000 gallons of chemicals used for processing coal into the Elk River (CSB, 2016). The river provides drinking water to multiple counties in West Virginia, including the state capital of Charleston. The spill led to a shut-down of restaurants, hotels, and the local mall and created a drinking water emergency that involved responses from local, state, and national agencies. The chemical spill led to lasting concern about contact and consumption of the Elk River water. Toxicity levels of some of the chemicals were not well understood by the scientific community which created additional concern about safe exposure limits.

The primary county affected by the Elk River spill is Kanawha County, WV, home to the state capital of Charleston. In our approach, we can make causal inferences by comparing *post-spill* economic and public health outcomes between a "synthetic" county and the real Kanawha County, WV. The synthetic Kanawha County is made up of a weighted linear combination of counties unaffected by the chemical spill and has *pre-spill* characteristics that are very similar to

[1] Abadie et al (2010, 2015) discuss the implications of weights in regression analysis, where weights not constrained to be positive and sum to one can extrapolate effects and yield less accurate results.

Kanawha County. We argue that the weighted combination of control counties can act as a better control to measure causal effects of the chemical spill on Kanawha County because the synthetic control better matches the treated unit (Abadie et al, 2010; Abadie et al, 2015; Coffman and Noy, 2011).

We use the synthetic control method to address two main questions:

1. Was economic growth of the area impacted by the Elk River Spill?
2. Were birth outcomes affected by the Elk River Spill?

The first question identifies if water-related shocks lead to dampened long-term economic growth. The effect of contamination of water supplies can lead to a host of averting costs on communities, such as bottled water consumption, treatment system costs, and lost leisure time (Abdalla et al, 1992), and previous work has suggested a high willingness to pay to avoid exposure to contamination (Collins and Steinback 1993). The second question addresses whether infant health is particularly vulnerable to in-utero exposure to water contamination (Galiani, Gertler, and Schargrodsky, 2005; Gamper-Rabindran, Khan, and Timmins, 2010; Currie and Walker, 2011; Currie and Schwandt, 2015). By focusing on pregnancy outcomes, we avoid the risk of attenuation due to avoidance behavior.

We find weak evidence of a long term effect to aggregate economic outcomes to Charleston, WV from the chemical spill, and we cannot rule out the null hypothesis of no effect. There is approximately a 3% decline in GDP per capita in Charleston, WV two years after the event which is statistically insignificant. We find suggestive evidence of a negative effect on infant health outcomes for infants born in Kanawha County after January 2014. This effect is substantial for 5-minute Apgar Scores but relatively short-lived, dissipating for birth cohorts born approximately four to five months after the Elk River Spill. Placebo tests results are supportive of a strong post-January 2014 effect relative to unaffected counties elsewhere in Appalachia. However, we do not find significant effects for other infant birth outcomes, such as birthweight and gestational length.

Background on the Elk River Spill

On January 9, 2014, a chemical leak was discovered at a chemical distribution facility in Charleston, West Virginia (Trip, 2014; Markham et al., 2016). Approximately 10,000 gallons of 4-methylcyclohexanemethanol (MCHM) and Propylene glycol phenyl ether (PPH) were discharged from Freedom Industries into the nearby Elk River, quickly infiltrating the intake and distribution plant of West Virginia American Water Company (WVAWC). WVAWC utilized a filtration system equipped with activated carbon to mitigate such incidences, but the filters became saturated and ineffective, exposing the drinking water supply to these chemicals (Howard, 2014). Figure 1 illustrates the location of the spill in relation to the city of Charleston.

Once filters could no longer handle the quantities of the chemicals in the river, WVAWC concluded that the water was unsafe to drink (Howard, 2014; Watkins and Ellis, 2016). Approximately 300,000 citizens of the Charleston, West Virginia metropolitan area were unable to use tap water for 4-9 days (Markum et al. 2016). The chemicals spilled were used to clean and wash coal before processing and had relatively unknown health effects (Trip, 2014). One day after the spill, 122 people had visited hospitals for symptoms of nausea and vomiting and 4-6 were admitted (Trip, 2014; Heyman and Fitzsimmons, 2014).

To cope with the absence of potable water, West Virginia Governor Early Ray Tomblin and President Barack Obama declared a state of emergency for nine affected counties, enabling the National Guard to bring in tanks of water for residents (Howard, 2014). The Federal Emergency Management Agency (FEMA) provided additional aid, bringing over three million liters of water to the affected area and working closely with the state "to ensure there [were] no unmet needs in helping those impacted by the incident" (FEMA, 2014). FEMA also set up Incident Management Assistance and Mobile Emergency Response teams on site in Charleston to help coordination. The National Guard began water testing on January 10th, using the 1 part-per-million benchmark suggested by the Center for Disease Control and Prevention as a safe screening standard; initial levels at the West Virginia American Water intake site were reported as high as 3.35 parts per million (Markum et al., 2016). Authorities lifted the water use ban on January 18th, almost two weeks after the spill.

Government response to the spill was extremely involved, and a wide array of partnerships[2] with local, state, federal and private organizations and agencies were initiated to help mitigate the crisis. The National Guard provided aid through troops helping staff reopen schools and businesses. A rapid-response team of National Guard troops, school officials, and health department staff was formed to address any complaints at schools across the county for several weeks (Snair, 2014).

Costs of the Spill

Although the stated emergency resulting from the MCHM spill lasted less than two weeks, many effects of the spill were longer lasting. According to a preliminary study by the Marshall University

[2] The list includes local health departments, the Kanawha-Charleston Board of Health, Kanawha County Board of Commission, Kanawha County Emergency Management, City of Charleston Emergency Management, the mayor of Charleston, leaders of other townships, the West Virginia Department of Health and Human Resources, Governor's office and Poison Control Center, along with U.S. senators and representatives, the National Guard and others (Snair, 2014).

Center for Business and Economic Research (CBER), an estimated total of $61 million in damages was incurred by local businesses and residents (CBER, 2014). Nearly 75,000 workers were unable to work during each day of the ban, representing over 40% of the working population in the area. The costs incurred by residents who bought bottled water, paid for extra childcare, and medical expenses were not included in this impact, nor were future health implications or economic disturbances.

Within a week of the spill, twenty-five lawsuits had been filed against Freedom Industries and it subsequently filed for bankruptcy (White, 2014). Lawsuits were also filed against the West Virginia American Water Company and chemical manufacturer, Eastman Chemical. One $151 million settlement – $126 million to be paid by W. Virginia Water and $25 million by Eastman – was reached in 2016 and will ultimately be distributed to affected businesses and residents (Raby, 2016).

Beyond the immediate costs are other important economic impacts, such as changes to economic activity where water is used in food preparation or is integrated into products, or longer term health effects which may decrease productivity through increased absences or decreased output at work. Perceptions of unsafe water quality to visitors may also suppress growth in the economy if business is taken elsewhere. These effects could be longer lasting than the period of the stated emergency as perceptions and illness persist.

Resident Perceptions of Water Quality

An in-person survey of sixteen households was performed after the "Do Not Use" order was lifted (Whelton et. al, 2014) which focused on water use and water quality perceptions. After the "Do Not Use" order was lifted, few households resumed their pre-spill activities. Most households did not resume drinking, showering, or washing with the water. Those that did not resume their pre-spill activities did so because they were unconvinced of water safety. The chemical MCHM is known to have a licorice odor. These avoidance behaviors were based on the licorice odor observations present after flushing their plumbing systems, self-reported symptoms, and anecdotal claims and media reports that the tap water was causing illness (Whelton et. al, 2014).

A more robust study conducted from February 7-26, 2014, achieved a much higher sample size with an online survey reaching 464 residents located within and outside of the affected spill zones (Savoia et. al, 2015). The survey was designed to measure the effects of how socio-demographic characteristics, timing of information, and risk perception influenced compliance with recommended behaviors and public views of environmental regulations. 56% of those surveyed believed getting sick from the tainted water was "very likely", even after the do-not-use order as lifted.

The initial crisis appeared to last four days, with the spill occurring on January 9th and state and federal officials releasing a statement on January 13th announcing the water was potable after following proper flushing protocols. But, January 15th saw the CDC release information cautioning pregnant women to continue to use bottled water; moreover, some experts disagreed with the testing methodology the CDC used as well as the screening levels for the MCHM (Snair, 2014). CDC officials stated in a press conference on February 5th that the water was "appropriate" to drink, but five days later, multiple expert witnesses were unable to conclusively report on the water's continued danger. "Because of the level of mistrust, the public is slow to return to using the water," said Dr. Rahul Gupta, Executive Director of the Kanawha-Charleston Health Department. "Survey data from the time of the spill until March 1 shows that less than five percent of the population are drinking or cooking with our local water, and approximately 20 percent are not using the water for any purpose. There has been a secondary wave of health impacts after the flushing which has further exacerbated the frustrations of a very anxious and suspicious community" (Snair, 2014).

Chemical Storage Policies and Regulations

A key component of the costs of avoidance is evaluating risks and the costs of reducing risks of future contamination events. The U.S. Chemical and Hazard Investigation Board (CSB) conducted a thorough investigation of the Elk River spill. CSB found a lack of effort by Freedom Industries to properly inspect and maintain equipment though they were compliance with existing state and federal regulations.

Regulations of chemical manufacturers and distributors are often difficult to navigate. The Occupational Safety & Health Administration (OSHA) classifies both MCHM and PPH, stripped, as "hazardous chemicals" (CSB, 2016). Every manufacturer or distributor storing more than 10,000 pounds of MCHM or PPH, stripped is required by the Emergency Planning and Community Right-To-Know Act to submit a form to its Local Emergency Planning Committee regarding the stored amount (CSB, 2016). At the time of the spill, Freedom Industries was subject "…to the West Virginia National Pollution Discharge Elimination System (NPDES)," a general permit for storm water discharge near industrial activity.

Other regulators such as the Environmental Protection Agency (EPA) define "hazardous chemicals" and "hazardous substances" differently, and thus the chemicals are subject to different regulations. While OSHA classifies "hazardous chemicals" as any chemical which poses physical or health hazards, the EPA's Clean Water Act defines "hazardous substances" as a substance where "the discharge of which may be harmful to the public health or the environment of the United

States" (CSB, 2016). While the EPA is required to establish regulations of these substances under the Clean Water Act, neither MCHM nor PPH, stripped are listed.

Storage container regulations are equally difficult to maneuver and enforce. At the time of the MCHM spill, aboveground storage tanks (ASTs) were inadequately regulated in West Virginia. No uniform regulation program exists for all ASTs, and states are charged with instituting regulations not addressed by the federal government. The 1984 state legislature established a "comprehensive statutory framework… regulating underground storage tanks, but it did not address ASTs" (CSB, 2016).

The CSB investigation revealed that the three tanks storing MCHM and PPH were initially installed in 1938 and held glycerin or calcium chloride prior to 2009 (CSB, 2016). American Petroleum Institute (API) certified inspectors found the tank shells and roof were constructed with a now-obsolete[3] construction; the bottoms appeared to be replacements of the originals (CSB, 2016). Two floor holes, 0.75 and 0.4 inches in diameter, were the source of the leak. Inspectors also found deep pits in the tank shell and floor, and determined the holes started as pits formed from corrosion.

Examining Freedom Industries' inspection protocols, CSB determined the manufacturer did not have a program in place that would ensure the ASTs were maintained and inspected regularly. Freedom Industries also did not keep detailed history, maintenance or inspection records for the failed tank as they were not forced to comply with regular inspections (CSB, 2016). CSB also reported on the lack of a leak detection system (LDS): "Freedom [Industries] did not have any level indication device, gauge system or measurement to capture the actual amount of MCHM

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[3] According to CSB, tank shells and roofs were constructed using a technique called lap-riveting; welding began to replace the process of riveting during the 1930s. The bottoms were lap-welded, but looked to be replacements of the originals.

leak, which contributed to the changing estimates of the spill amount. There was no West Virginia state or federal requirement that would have made the installation of an LDS mandatory for ASTs."

Compliance with additional federal regulations[4] could have indirectly prevented the leak from entering the Elk River. Freedom Industries had not been complying with these requirements, specifically for secondary containment (CSB, 2016). The proximity of the oil AST to the MCHM AST led CSB investigators to conclude secondary containment may have prevented the spill had Freedom Industries been complying.

Methodology

Many of the direct costs and risks enumerated above are known, but to understand the larger costs to the economy and risks to public health we use synthetic control method to analyze outcomes from this water crisis. The synthetic control method has had limited yet growing use in the economic literature (Abadie and Gardeazabal, 2003; Abadie et al., 2010; Cavallo et al. 2013; Abadie et al., 2015). This method is used to compare a specific region or entity exposed to an intervention. In this case study, the intervention is the Elk River Chemical Spill. The main entity exposed is the Charleston Metropolitan Area or Kanawha County, WV. The synthetic control is a weighted average of the control units; this allows for explicit inference of the "relative contribution" of the control units and explains the similarities (or differences) between the unit affected and the synthetic control. The weights of the controls can also be determined to be positive and sum to one, which can help guard against extrapolation errors.

The synthetic control model relies on a series of constructed vectors and matrices to perform the analysis. Following Abadie, Diamond, and Hainmueller (2010), the outcome variable

[4] The Spill, Prevention, Control and Countermeasure (SPCC) rule regulates various industrial chemicals and liquids; CSB identified that Freedom Industries also stored an oil on site which was under regulation of the SPCC.

investigated is observed for T periods for the region exposed to the intervention, Y_{1t}, where $t = 1, \ldots, T$ and the synthetic control, Y_{jt}, where $j = 2, \ldots, J+1$ and $t = 1, \ldots, T$. $T_1 = T - T_0$ is the number of post-intervention periods, and Y_1 is a $(T_0 \times 1)$ vector of post-intervention outcomes for only the exposed region. This leaves Y_0, a $(T_1 \times J)$ matrix, comprising the post-intervention outcomes for the control regions. Listing the treated region as the first of J regions is only done for convenience.

We let a $(T_0 \times 1)$ vector $K = (k_1, \ldots, k_{T_0})'$ be a weighting vector, and then define a linear combination of pre-exposure outcomes as $\bar{Y}_i^K = \sum_{s=1}^{T_0} k_s Y_{is}$. There can be M values of K to form any linear combination, and therefore M linear combinations defined by the vectors $K_1, \ldots K_M$.

Next, we represent the pre-intervention characteristics of the treated region with a $(k \times 1)$ vector $X_1 = (Z_1', \bar{Y}_1^{K_1}, \ldots, \bar{Y}_1^{K_1})'$. The vector Z is a set of explanatory variables that are used to predict outcomes, and which are not affected by the treatment. The pre-intervention characteristics for the unaffected regions are represented by a similar $(k \times J)$ matrix containing the same variables for the untreated areas, $X_0 = (Z_j', \bar{Y}_j^{K_1}, \ldots, \bar{Y}_j^{K_1})'$. We also let W be a $(J \times 1)$ vector of positive weights, where $W = (w_2, \ldots, w_{J+1})'$ and $w_2 + \cdots + w_{J+1} = 1$; each value of W is a weighted average of all the available control regions. To measure the difference between the treated and untreated units, we take the distance $\|X_1 - X_0 W\| = \sqrt{(X_1 - X_0 W)' V (X_1 - X_0 W)}$. Here, V is some $(k \times k)$ symmetric and positive semidefinite matrix. Our synthetic control weight $W^*$is chosen to minimize this distance, and the optimal choice for V minimizes the mean square error of the synthetic control estimator. The basic idea of this method is to construct a nearly identical county to our affected county in West Virginia in an effort to understand how outcomes like economic growth and infant health have changed because of the chemical spill.

We compute the p-value through a permutation test using equations 1 and 2, following Cavallo et al. 2013. Equation 1 defines the estimate of the difference between outcomes from the treated unit, Y_{1t}, and the synthetic control outcomes, Y_{jt}, using the set of optimal weights, w_j^*, found by minimizing the distance between pretreatment observations and controls. $\hat{\alpha}_{1t}$ is the estimator of this difference for unit 1 which is the treated unit at time *t*.

$$\hat{\alpha}_{1t} = |Y_{1t} - \sum_{j=2}^{J+1} w_j^* Y_{jt}| \qquad (1)$$

$$p - value_t = \Pr(\hat{\alpha}_{1t}^{PL} < \hat{\alpha}_{1t}) = \frac{\sum_{j=2}^{J+1} I\left(\hat{\alpha}_{1t}^{PL(j)} < \hat{\alpha}_{1t}\right)}{J} \qquad (2)$$

In equation 2, the term $\hat{\alpha}_{1l}^{PL}$ refers to the estimate for the each placebo of a donor unit used to construct the synthetic control for unit 1. There are *J* donor units which are used to construct a distribution of placebo estimates. The placebo estimate of $\hat{\alpha}_{1t}^{PL(j)}$ for each *j* donor unit, which are estimated with same choice of controls as our unit of interest, is used to determine significance of the estimate of $\hat{\alpha}_{1t}$. $I(\cdot)$ is an indicator function which returns 1 if the interior argument is true and 0 if false. This procedure provides the rank of the estimate of $\hat{\alpha}_{1t}$ compared to the distribution of placebos estimates $\hat{\alpha}_{1t}^{PL}$.

Economic Growth Data

We apply the synthetic control method to the Charleston, WV Metropolitan Statistical Area (MSA) for economic growth outcomes as defined by annual GDP per capita (Bureau of Economic Analysis, 2015). We use a combination of demographics and economic characteristics as additional controls to match our treated MSA: the percentage of bachelor's degree or higher, population count, and jobs by major industry (U.S. Census Bureau, American Community Survey, 2015)[5]. After eliminating MSAs that do not have a balanced panel over 2009 to 2015 we retain a total of 328 control units for this analysis in which to construct the synthetic Charleston, MSA. The selection of variables is based on a backwards induction search which finds a good balance between Charleston, WV and the synthetic Charlestown and has a good pre-treatment fit in predicting GDP per capita.

We choose 2009 as the starting point for the analysis because of the 2008 financial crisis, which may have caused structural shifts to regional economies. By using only post-2008 data we do not restrict the synthetic control group to match the pre and post periods of the recession as this may be asking too much of the synthetic control method. By including pre-2008 data, we are asking the method to match pre-financial crisis trends, the decline, and recovery of economic growth. The treatment period is 2014 as the chemical spill occurred in January of 2014. The occurrence of the spill in January is advantageous since all variables are captured annually, making measurement of the post treatment effects less likely to be attentuated.

Infant Health Data

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[5] We use 2013 1-Year estimates for the demographic and industry data from the U.S. Census ACS. This choice was made because of the definition of MSAs can change year to year. Importantly, in 2012 Charleston, WV was re-defined. This complicates averaging across years as is typically done with control variables, so we choose 2013 as the year to match demographic and industry data to have a consistent definition for all MSAs. The GDP per capita data from the BEA has been adjusted for the change in definition of MSAs across all years. We also found that by using 5-Year estimates from ACS survey data that our synthetic control is very similar to the results presented here.

We use a variety of monthly infant health outcomes from the National Vital Statistics System's Birth Data files from 2009 to 2014. We received restricted-use data, which describes mother demographic information and health outcomes for the universe of births in the United States. The location of the birth is provided at the mother's home county-level. Mother's home address-level data are available from the state, but we concluded that this level of disaggregation was not necessary given our identification strategy.

We estimate models for three main birth outcomes of interest. First, we use the Apgar score, a value from 1-10 indicating how well the baby performed through the birthing process and outside of the womb. Values are based on a series of respiratory, cardiovascular, muscular, reflexive, and skin color tests, conducted within minutes of the birth. Values over 7 indicate that the baby is in good health; scores lower than 7 indicate that the baby needs medical attention. Second, we use the baby's gestational age at birth. Typical gestational age at birth ranges from 37 to 42 weeks. A gestational age at birth below 37 weeks is classified as premature. Third, we use the baby's birthweight in grams. Full-term babies weigh between 2500 to 4000 grams; premature babies are small for their gestational age (U.S. National Library of Medicine).

We estimate both continuous and binary models of the variables described above. In the binary models, we define the dependent variable to equal 1 if the baby is born with a lower Apgar score (>= 7), is born at full-term (>= 37 weeks), and is not small for their gestational age (>= 2,500 grams).

We aggregate our outcomes and control variables to the county-month level. In order to create a balanced panel, we only use those counties that have monthly data from 2009 to 2014. We also only use those counties that are located within nearby states in the Appalachian region of the United States. These states include Kentucky, Maryland, Ohio, Pennsylvania, Tennessee, Virginia, and West Virginia. We use this additional restriction to lower the possibility of assigning positive weights to counties in regions of the countries with unobserved characteristics that may lead to differences in birth outcomes. Additionally, we exclude nearby counties that were also impacted by the Elk River Chemical Spill. These include Boone, Clay, Jackson, Lincoln, Logan, Putnam, Roane, and Cabell counties in West Virginia. As a note, only two of these counties – Logan and Cabell – had infant birth data for all months between 2009 and 2014. Logan County is far downstream of the Elk River Chemical Spill; the health effect may be mitigated by distance and time. Additionally, only a small part of Cabell County had their water systems impacted by the spill (Johnson 2014).

As additional controls in our infant health analyses, we use annual, county-level economic data from the U.S. Census Bureau (U.S. Census Bureau, American Community Survey, 2015). We include median household income, poverty rate, and unemployment rate as controls for regional economic conditions. We also use county-year means of the following mother characteristics from the NCHS: (1) percentage of mothers who are black; (2) percentage of mothers who are unmarried; and (3) percentage of mothers that are at least 35 years old (National Center for Health Statistics 2009-2014).

Economic Growth Results

The makeup of the synthetic Charleston, WV is listed in Table 2 as the weights given to each MSA based on pretreatment matches to the variables in Table 1. Our results, in Figure 2, suggest a divergence between the synthetic Charleston, WV and the real Charleston, WV MSA suggesting that the chemical spill may have a longer term effect on economic growth. The synthetic control shows a high degree of tracking Charleston MSA before the chemical spill and there is a high degree of balance between predictors. We find a decrease of 1% of GDP per capita in 2014 and a decrease of 3% in 2015.

To infer statistical significance of these impacts, we apply a permutation test, sometimes called a placebo test, on unaffected MSAs to see if the change in post treatment GDP per capita is large compared to the Charleston synthetic analysis. The placebo test posits that unaffected MSAs should not have significant differences in post treatment outcomes since they did not experience a water crisis, and if there are many placebos with larger differences from their synthetic controls, but good balance pre-treatment, then our measured effect is not statistically significant but within the statistical variation of the data. Figure 3 shows that we cannot reject the null hypothesis that the water crisis had no effect on longer term economic growth since there are many placebos with larger post-treatment variations than the Charleston analysis suggests. We have trimmed the placebo data to only include placebo MSAs with a root mean squared error (RMSE) within 4 times of the Charleston, WV RMSE with the goal of excluded placebos that did not have good pretreatment matches with their synthetic controls.

We follow the procedure in equations 1 and 2 to find the p-value of our estimates from the placebo tests. We find the estimated p-value is 0.372 for one-year post treatment and 0.199 for two years post treatment, which indicates that the estimated effect of the water crisis on economic growth in Charleston, WV is not statistically significant.

The strength of the synthetic control method is its ability to define a better statistical counterfactual for a singular event, such as a water crisis, and allows the effects of confounding unobserved characteristics to vary with time, unlike a fixed effect regression model. The weaknesses of this approach for our given question is the short time frame of pretreatment periods due to the concerns generated from the housing market collapse and 2008 financial crisis. Another challenge of our data is the size of shifts in GDP per capita in the Charleston, WV pretreatment period which have the potential of masking the significance of the estimate through a type II error.

Infant Health Results

We apply the same methodology to county-month level infant health outcomes from the National Center for Health Statistics. We estimate synthetic control models for 5-minute Apgar Score, birthweight (in grams), and gestational age (in weeks). We also estimate models using binary variables equal to 1 if those variables are indicative of good infant health: 5-minute Apgar Score >= 7; birthweight >= 2,500 grams; and gestational age >= 37 weeks. Our synthetic control model selects control counties using a function of 2011 to 2013 annual values of median household income, poverty rate, unemployment rate, and the health outcome of interest.

Table 3 shows the predictor variables used in construction of the synthetic controls. We choose the pretreatment average annual median household income, poverty percentage, unemployment rate, average county-year mother characteristics, and the respective health outcome as the predictor variables in the health analysis. This table shows a strong balance of the variables for all three synthetic control analyses. It also highlights the value of synthetic control analyses. Kanawha County, WV is different from other counties in Appalachia. It has a lower median household income and a lower proportion of the mother population that is black.

Table 4 lists the weights used in determining Kanawha County's synthetic control for each continuous infant health outcome. Most counties selected as components within the Kanawha County synthetic control are semi-rural counties containing towns with population size on the order of 10,000 to 100,000.

Our results suggest that Kanawha County, WV suffered a large and significant decrease in 5-minute Apgar Scores after January 2014 (Figure 4). This drop is pronounced and much larger than the decrease experienced by the synthetic control. Apgar Score trends for Kanawha County, WV match up reasonably well with the synthetic control's trends, though the data do show monthly variation. We do not find a similar drop in birthweight or gestational age. These results are available in Appendix Figures 1A and 2A. Although the pre-spill outcomes match up well, there is not a sustained drop in either birthweight or gestational age after the spill.

Using the binary outcome of Apgar Score, we can estimate the proportion or poor health outcomes caused by the chemical spill. There is an approximate 5% increase of low birth outcomes (as indicated by Apgar Score < 7) one month after the spill. Figure 3A in the Appendix highlights this result. We also estimate synthetic control models using binary versions of the birthweight and gestational age. We find no post-spill difference between Kanawha County and its synthetic control for either variable (see Figures 4A and 5A in the Appendix).

To determine statistical significance of the change in Apgar Score, we use the same method as applied to the MSA-level GDP data. In this case, we estimate synthetic control models for all counties not impacted by the Elk River Chemical Spill to see how changes in 5-minute Apgar Scores after January 2014 relate to those for Kanawha County. As before, the test is based on the premise that unaffected counties will not have casual changes in the outcome-of-interest since their water supplies were unaffected by the spill. Figure 5 highlights the results of these separate models. Each line represents the difference in outcome between each unaffected county and its synthetic control. We have again trimmed the data to only include those placebo counties with a RMSE within 4 times the Kanawha County RMSE, which leaves us with 235 placebo counties. It is clear that the post-January 2014 difference in 5-minute Apgar Scores between Kanawha County and its synthetic control is much larger and more negative than the difference for the vast majority of untreated counties across Appalachia. Additionally, the same placebo tests were conducted for birthweight and gestational age.

Table 5 highlights monthly p-values of our estimates from the placebo tests, per Equations 1 and 2. We find that the significance[6] of the effect extends out to April of 2014, which suggests that the impact of the spill was primarily significant for babies in the last trimesters of gestation. In this table, we also include p-values for the same placebo tests analyses conducted for the birthweight and gestational age models. For these models, we find no p-values that are lower than the conventional statistical significance level of 0.05.

Additionally, we explore how our 5-Minute Apgar Score result changes when we use a synthetic control based on counties across the country, beyond Appalachia. In Figure 8A in the Appendix, we show that the same relationship exists when our synthetic Kanawha County consists of counties across the United States.[7]

In summary, using the synthetic control methodology, we find suggestive evidence that the Elk River Spill had a statistically-significant negative impact on 5-minute Apgar Scores for infants born in the four months after the spill. This indicates that the health impact was felt in the later months of the pregnancy, which supports work that has also found significant health impacts of late-pregnancy exposure to pollution (e.g., Rich et al. 2015). However, there are some limitations to our analyses. Most prominently, the mechanism of impact is unclear. The decrease in Apgar Score could be related to chemical ingestion by the mother or maternal stress related to the spill itself, among potential other issues. Since the mechanism is unclear, it is difficult to understand

[6] At the conventional 5% significance level.

[7] Table 2A provides county weights for the nationwide-based synthetic control.

whether the (large) magnitude of our estimated effect is realistic. This is especially pertinent given our null results for birthweight and gestational age. These are surprising given the strong effect seen in Apgar Scores. Low birthweight and prematurity can lead to low Apgar Scores (e.g., Hegyi et al. 1998) so it is unclear why we do not see any strong effect of the spill on either variable. Future work should address the potential mechanisms between the spill and the effects we see in our results.

Conclusion

Comparative case studies provide a treasure trove of interesting evidence for learning about agricultural and environmental policies, risks, and impacts from unexpected events. We employ the synthetic control method to a water contamination tragedy to understand larger causal effects than those reported immediately after event. This method can be very beneficial when the outcomes are only available as aggregate statistics and there are few treated units affected by the event; a common property shared among comparative case studies.

In applying this method to the Elk River spill in West Virginia we hope to provide exposure to the methodology as well as a rigorous analysis of this important water contamination event. We find evidence for a sharp decrease in birth outcomes as measured by 5-minute Apgar Scores. Since exposure to toxins for babies in-utero occur at the end of pregnancy the timing of these effects are consistent with exposure from the chemical spill. It is unclear why the exposure to toxins through the water supply would only contribute to lower Apgar Scores but is undetectable in other birth outcomes. We do not find support for a long run effect on economic growth. Undoubtedly there was an effect on the economy from closed businesses immediately after the spill, though the size of this effect is not large enough to distinguish from the stochastic components of economic growth for Charleston, West Virginia.

Other lessons can be learned about how the public perceived water risks and policy measures to mitigate the probability of future contamination events. First, there are clear loopholes in chemical storage policies that need to address above-ground storage devices so that sites similar to Freedom Industries are adequately monitored. A second lesson is that the perceptions of water quality can persist if the agencies responsible are not coordinated and honest about risks. When agencies leave out important information, there may be outside experts that raise concerns which leads to distrust; and public distrust can be quite obstinate once earned.

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Tables and Figures

Table 1. Means of Predictors for GDP per capita

Variables	Charleston, WV	Synthetic Charleston	Rest of US
% of Bachelor degree or higher	22.8	22.8	26
Count of jobs in public sector	8,715	7,555	78,893
Count of jobs in health care	23,245	22,993	16,863
Total population estimate	224,727	227,342	713,147
Count of white population	202,050	195,285	521,080
GDP per capita 2009	56,765	56,742	40,485
GDP per capita 2011	59,847	59,820	41,011
GDP per capita 2013	56,163	56,135	41,432

Table 2. Weights to MSAs for Synthetic Charleston, WV

MSA	State	Weight
Casper	WY	0.448
Billings	MT	0.331
Victoria	TX	0.114
Hanford-Corcoran	CA	0.056
Portland-Vancouver-Hillsboro	OR-WA	0.050

Table 3: Predictor balance between Appalachia counties, Kanawha County, and Synthetic Kanawha Counties

			Synthetic Kanawha County		
Variable	Appalachia	Kanawha County	Apgar Score	Gestational Age	Birthweight
Mean Apgar Score					
2011	8.9	8.9	8.9		
2012	8.9	9.0	8.9		
2013	8.6	8.9	8.9		
Gestational Age (in weeks)					
2011	38.8	38.2		38.2	
2012	38.8	38.3		38.3	
2013	38.8	38.1		38.2	
Birthweight (in grams)					
2011	3,297.0	3,196.3			3,200.8
2012	3,301.9	3,226.9			3,219.3
2013	3,306.3	3,203.5			3,208.6
Med. Household Income (in '000s)					
2011	46.9	40.4	41.8	42.7	42.3
2012	48.0	45.8	45.1	45.8	45.3
2013	49.0	45.9	45.8	46.5	46.0
Poverty Percentage					
2011	16.1	17.2	16.1	16.6	16.5
2012	16.0	14.4	15.7	15.6	15.2
2013	15.8	15.3	15.4	16.0	15.6
Unemployment Rate					
2011	8.8	7.1	7.4	7.4	7.3
2012	7.9	6.6	6.6	6.7	6.5
2013	7.8	5.9	6.1	6.3	6.2
% of Mothers: Black					
2011	8.3	4.7	4.9	5.3	5.1
2012	8.3	5.5	5.5	5.3	5.5
2013	8.6	5.6	5.4	5.6	5.6
% of Mothers: Unmarried					
2011	44.1	41.8	42.3	42.0	42.0
2012	44.2	43.2	43.3	42.5	42.9
2013	44.8	44.2	43.6	45.0	45.0
% of Mothers: Age >= 35					
2011	9.6	9.5	9.6	9.9	9.7
2012	9.6	8.8	9.2	9.8	9.2
2013	9.9	9.9	9.4	9.7	9.2

Notes: Annual economic data is from the U.S. Census Bureau. Mean 5-Minute Apgar Score, birthweight, gestational age, and mother characteristic data is from the National Center for Health Statistics' Vital Statistics Natality Birth Data.

Table 4: Weights for Synthetic Kanawha County, WV for 5-minute Apgar Score analysis

County	State	Synthetic Control Weight		
		Apgar Score	Birthweight	Gestational Age
Henderson	Kentucky			4.8
Lawrence	Kentucky		0.2	
Letcher	Kentucky			0.8
Talbot	Maryland	10.9		
Auglaize	Ohio		4	
Holmes	Ohio	0.9		
Mahoning	Ohio			2.8
Mercer	Ohio	5.5		
Centre	Pennsylvania	9.1		
Elk	Pennsylvania	1.6		
Montour	Pennsylvania	1.4	25.1	27.6
Warren	Pennsylvania	16		
Coffee	Tennessee	10.4		
Hamilton	Tennessee	5	18.2	19.5
Lincoln	Tennessee		15.7	
McNairy	Tennessee			0.4
Overton	Tennessee		5.7	
Prince Edward	Virginia			0.7
Monongalia	West Virginia	5	6.9	12.1
Ohio	West Virginia	29.6	4.9	
Upshur	West Virginia	4.5		
Wood	West Virginia		19.3	31.4

Notes: The potential synthetic controls were selected from all counties within nearby Appalachian states, include Kentucky, Maryland, Ohio, Pennsylvania, Tennessee, Virginia, and West Virginia. We only used those observations that had (i) monthly birth outcome data for all months from 2009 to 2015 and (ii) annual economic data from the U.S. Census Bureau over the same time period. Independent cities in Virginia were excluded from the analysis.

Table 5: Post-Spill monthly p-values for synthetic control placebo tests

Month (in 2014)	P-Values		
	Apgar Score	Birthweight	Gestational Age
January	0.009	0.678	0.656
February	0.004	0.506	0.591
March	0.009	0.676	0.961
April	0.009	0.625	0.680
May	0.060	0.421	0.386
June	0.285	0.803	0.208
July	0.102	0.386	0.082
August	0.123	0.247	0.937
September	0.043	0.429	0.431
October	0.268	0.861	0.318
November	0.579	0.884	0.200
December	0.728	0.537	0.286

Figure 1. Location of the Spill in Charleston West Virginia

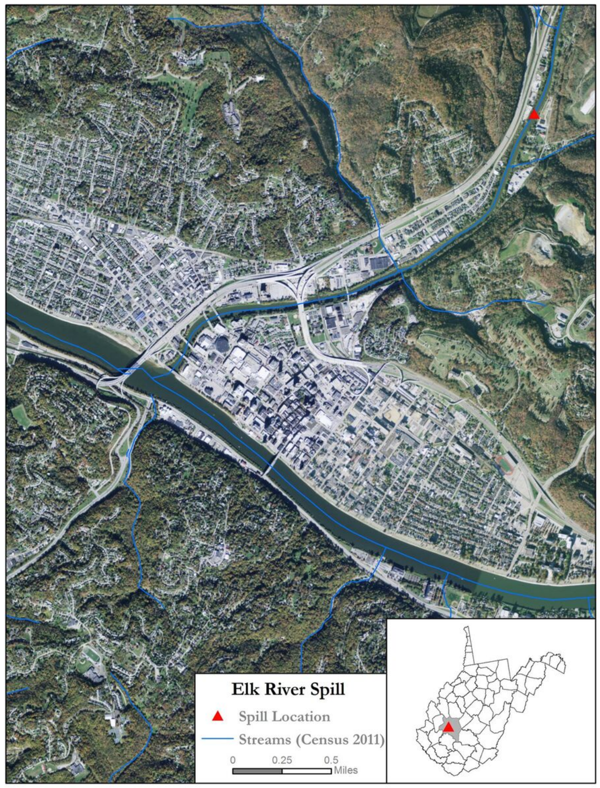


Figure 2. Trends in GDP per capita

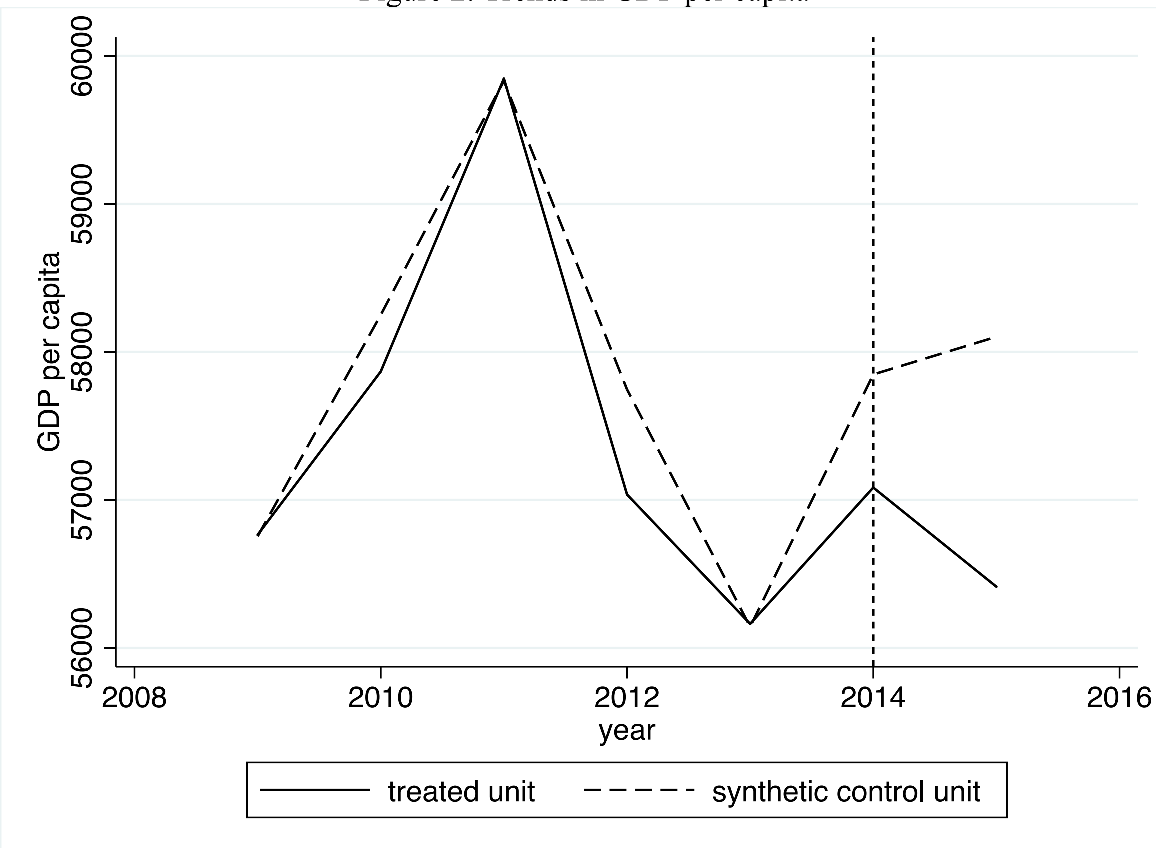
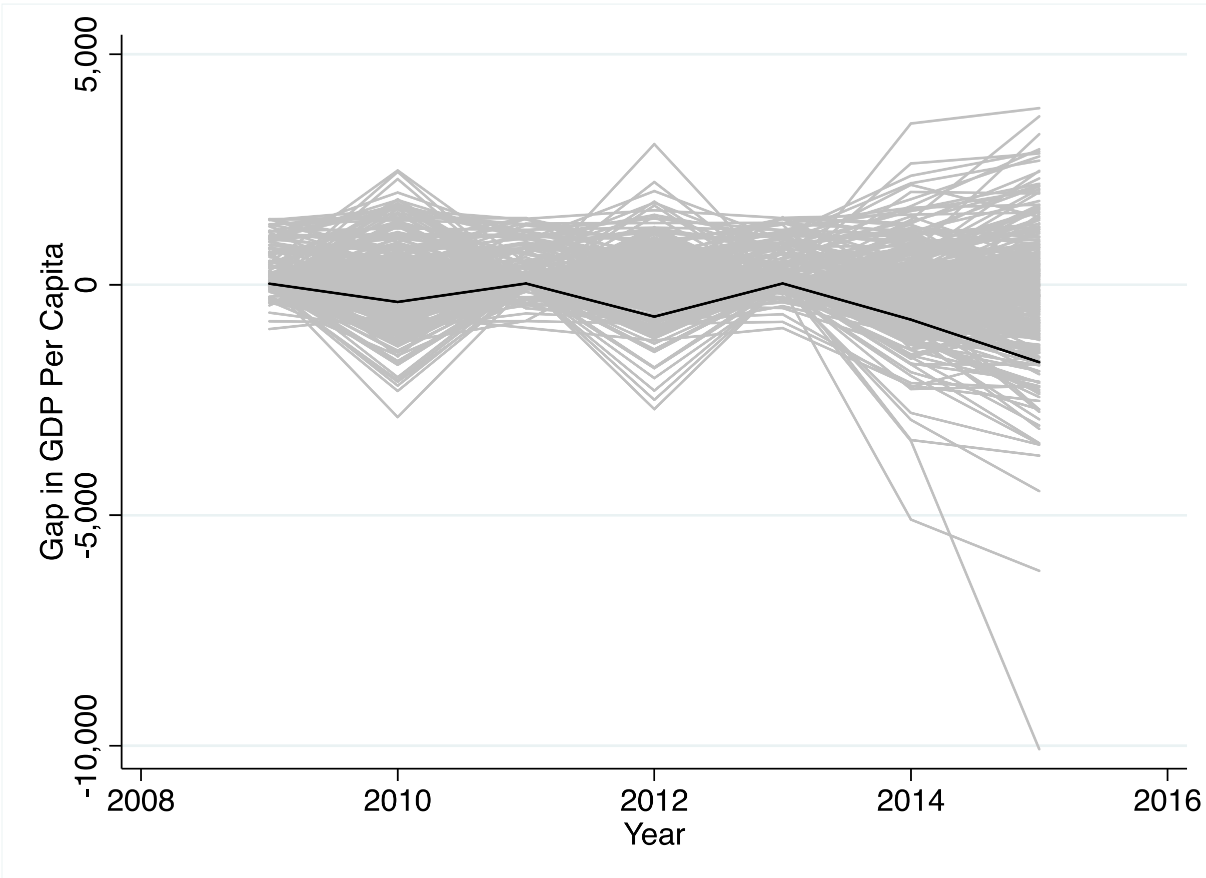


Figure 3. GDP Placebo Test



Note: This figure uses the remaining MSAs and calculates the distance from their synthetic control. We trim the placebo MSAs to only show placebos with a RMSE within 4 times of the Charleston, WV RMSE pretreatment. The black-dashed line represents the Charleston, WV MSA.

Figure 4. Trends in 5-minute Apgar Scores

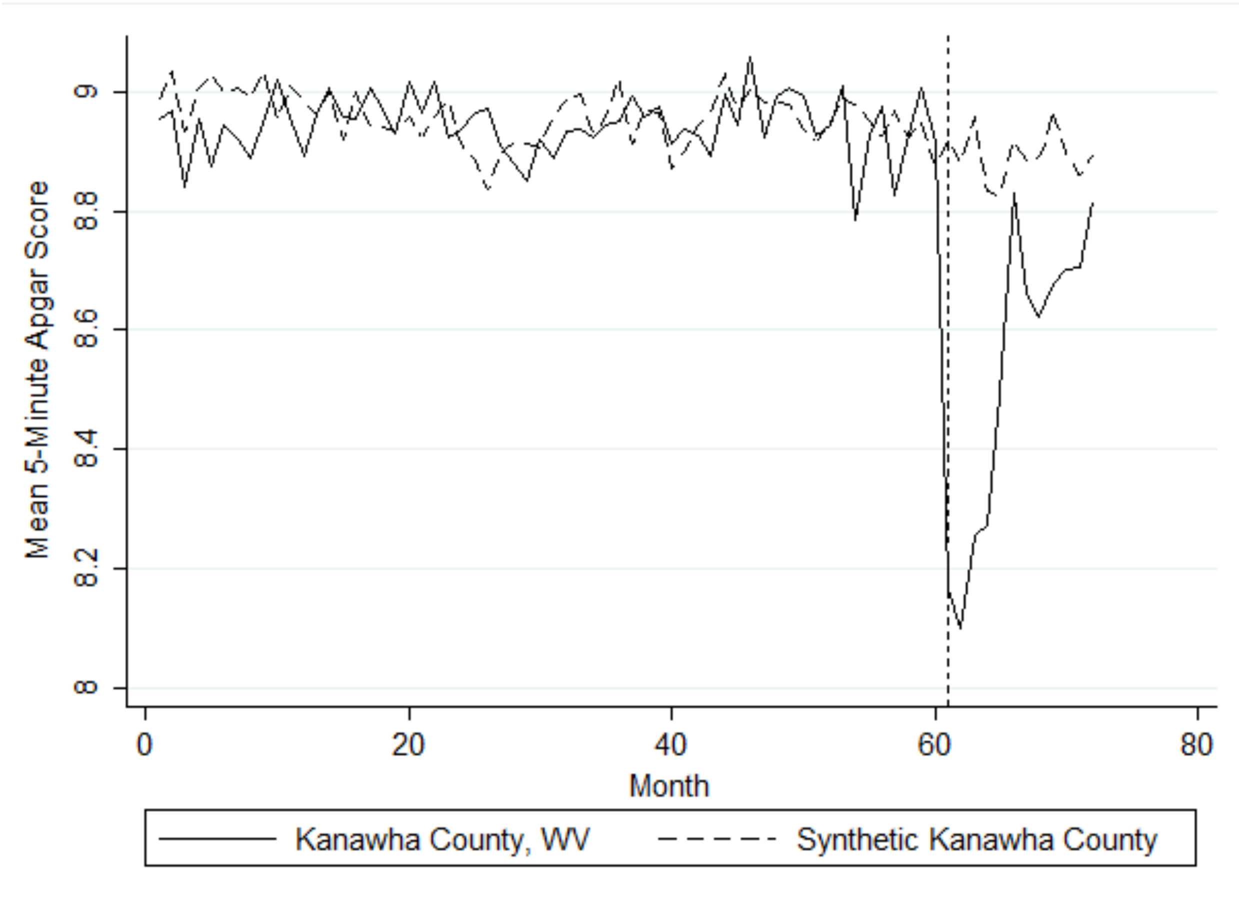
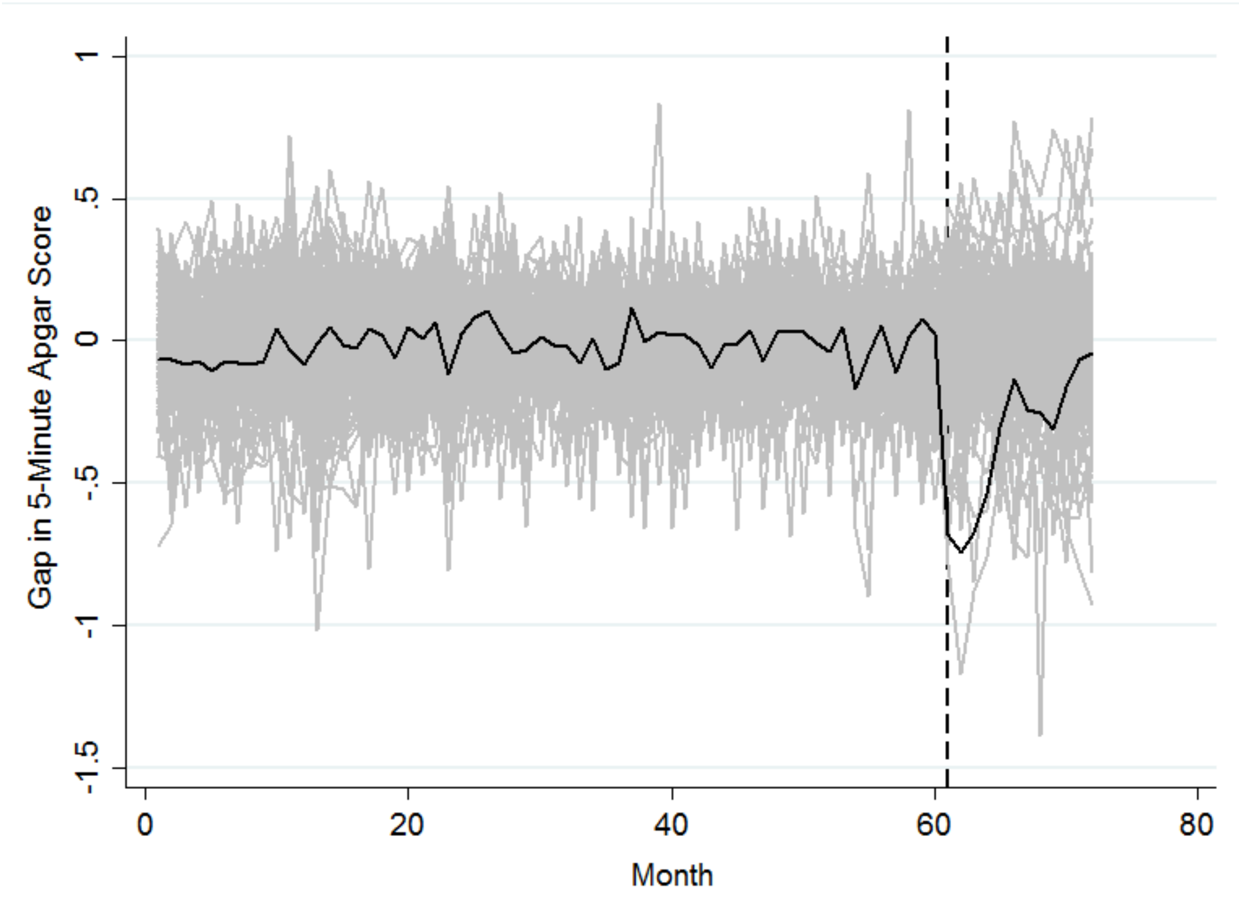


Figure 5. 5-Minute Apgar Score Placebo Test



Notes: We trim the placebo data to only include placebo MSAs with a RMSE within 4 times of the Kanawha County, WV RMSE. The black line represents Kanawha County, WV.

Appendix

Table 1A: Description of infant health outcomes

Variable	**Description**
Continuous	
Birthweight	Infant's weight at birth (in grams)
Gestational Age	Gestational age at birth (in weeks)
Apgar Score	Apgar score (on a 0 to 10 scale)
Black	Percentage of mothers that are black
Unmarried	Percentage of mothers that are unmarried
Age >= 35	Percentage of mothers that are at least 35 years old
Binary	
BWTR2500	= 1 if birthweight is greater than 2,500 grams (defined as normal)
GA37	= 1 if gestational age at birth is at least 37 months (defined as normal)
APGAR7	= 1 if Apgar score is at least 7 (defined as normal)

Notes: Annual Birth Data Files, National Center for Health Statistics, Centers for Disease Control and Prevention.

Table 2A: Weights for Synthetic Kanawha County, WV for 5-minute Apgar Score analysis (Nationwide-Based Synthetic)

County	State	Weight
Gunnison	Colorado	5.4
Otero	Colorado	3.7
Franklin	Georgia	10.1
Knox	Indiana	1.2
Allamakee	Iowa	5.5
Hamilton	Iowa	0.5
Lucas	Iowa	3.4
Ellis	Kansas	6.9
Lincoln	Maine	1.0
Nobles	Minnesota	1.1
Roseau	Minnesota	16.5
Boone	Nebraska	4.0
Otsego	New York	9.7
Stark	North Dakota	7.0
Somerset	Pennsylvania	1.2
Kershaw	South Carolina	0.6
Houston	Texas	3.4
Jim Wells	Texas	3.4
Randolph	West Virginia	1.5
Upshur	West Virginia	14.0

Figure 1A: Trends in birthweight (in grams)

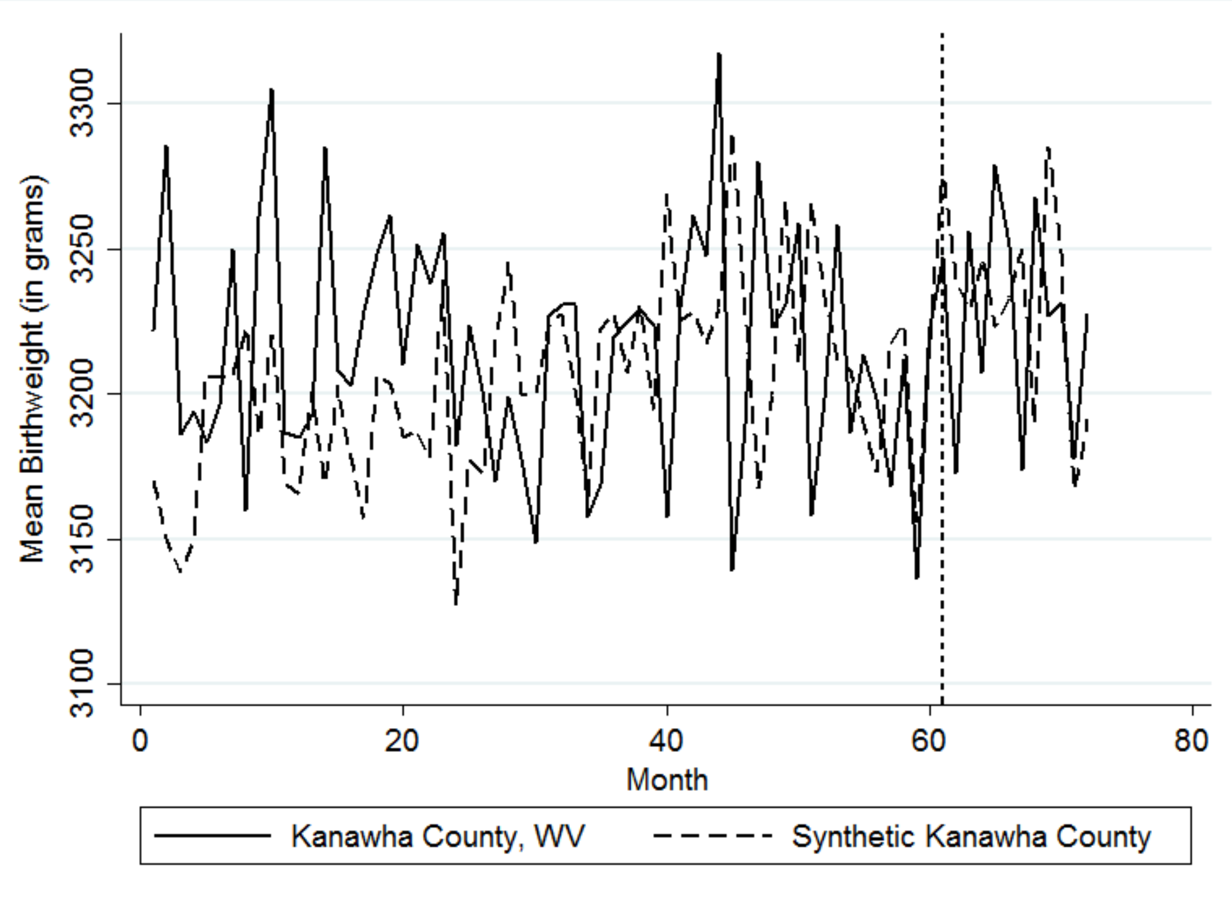


Figure 2A: Trends in gestational length (in weeks)

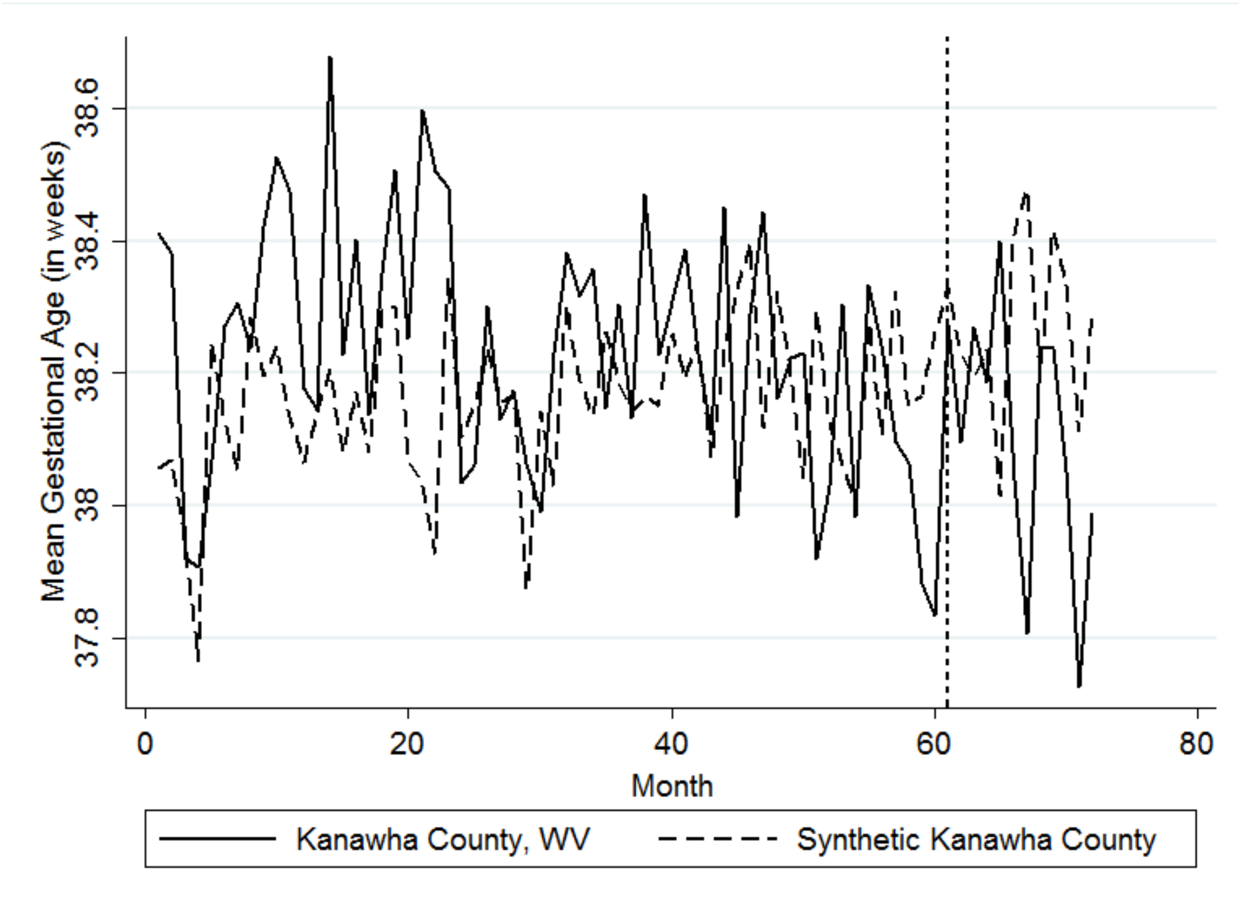


Figure 3A: Trends in percentage of infants with Apgar Scores greater than or equal to 7

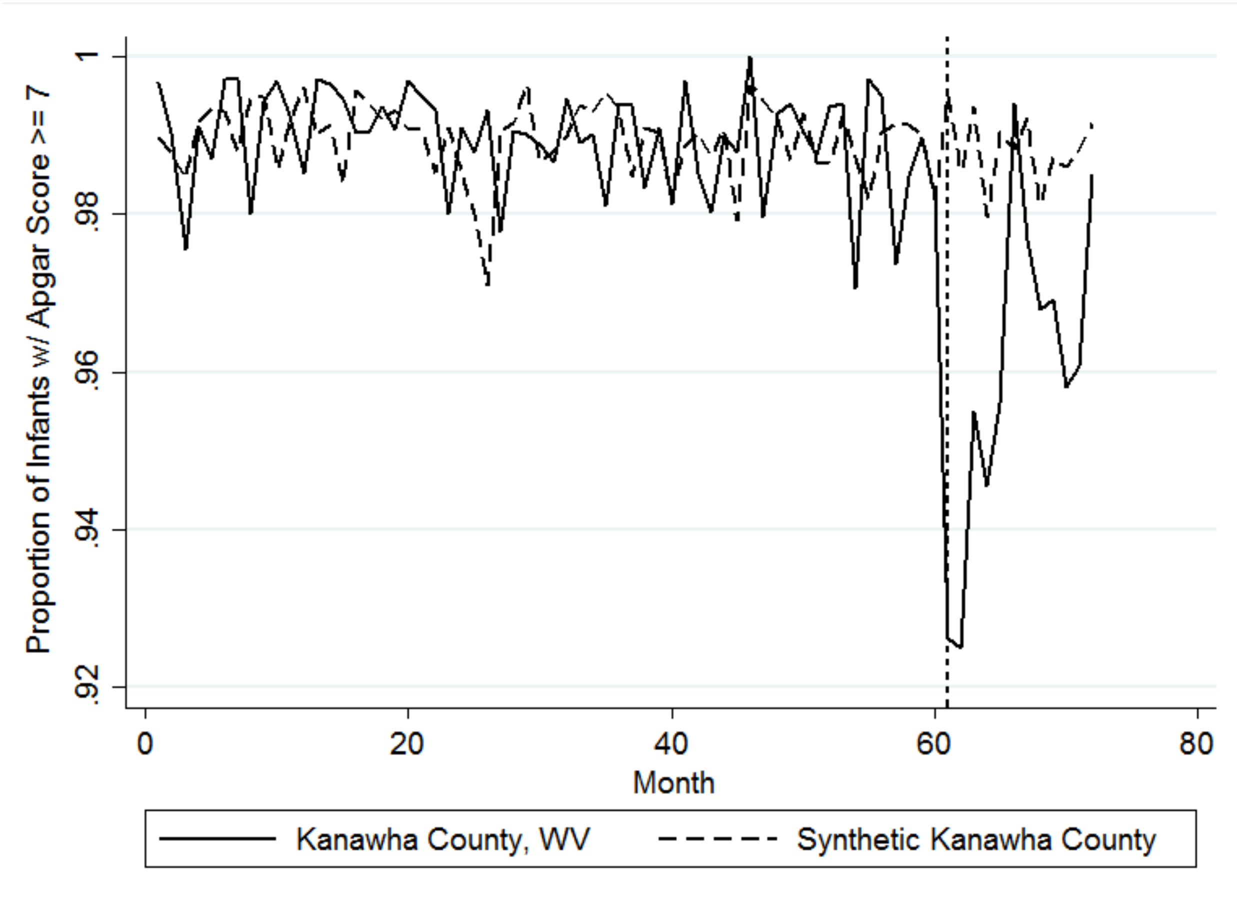


Figure 4A: Trends in percentage of infants with birthweight greater than or equal to 2,500 grams

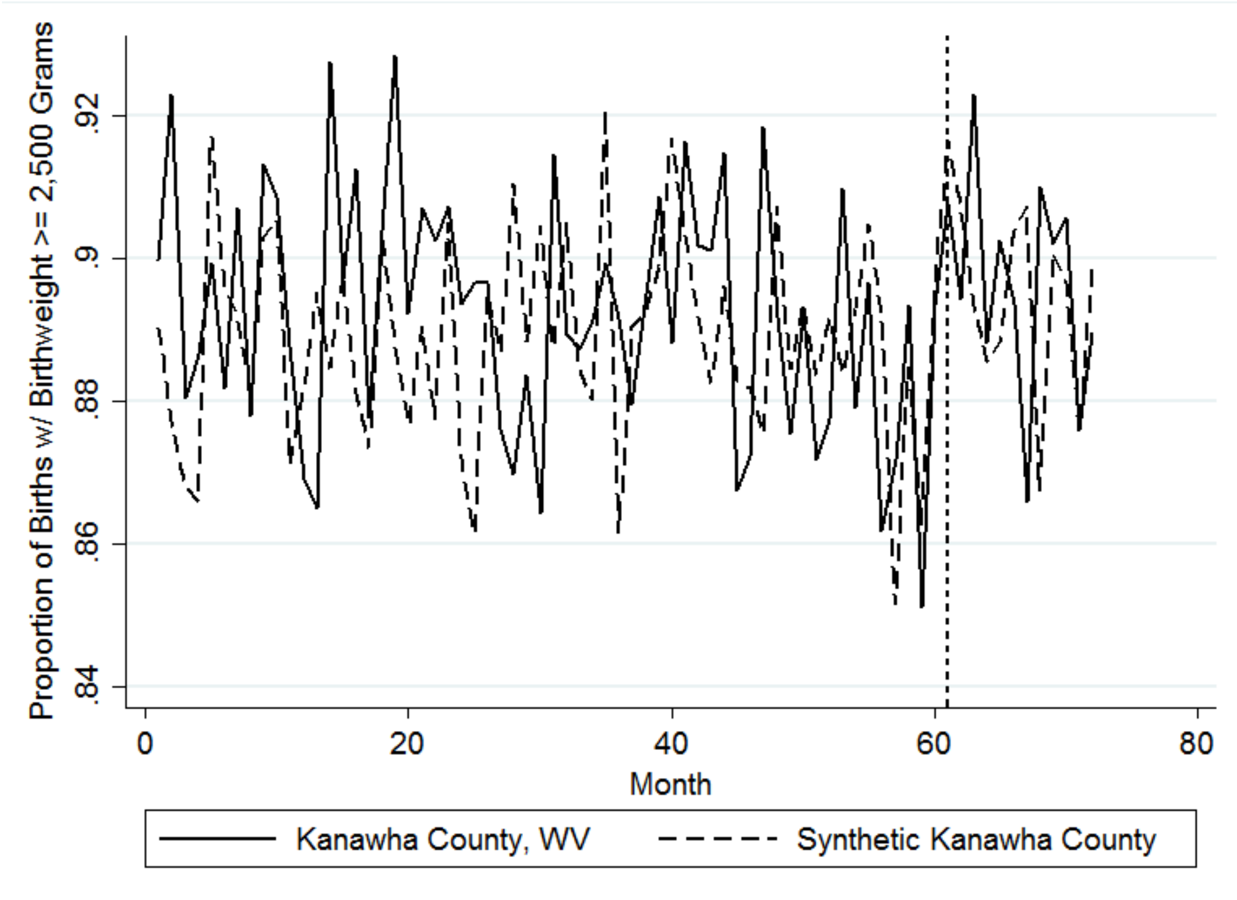


Figure 5A: Trends in percentage of infants with gestational length greater than or equal to 37 weeks

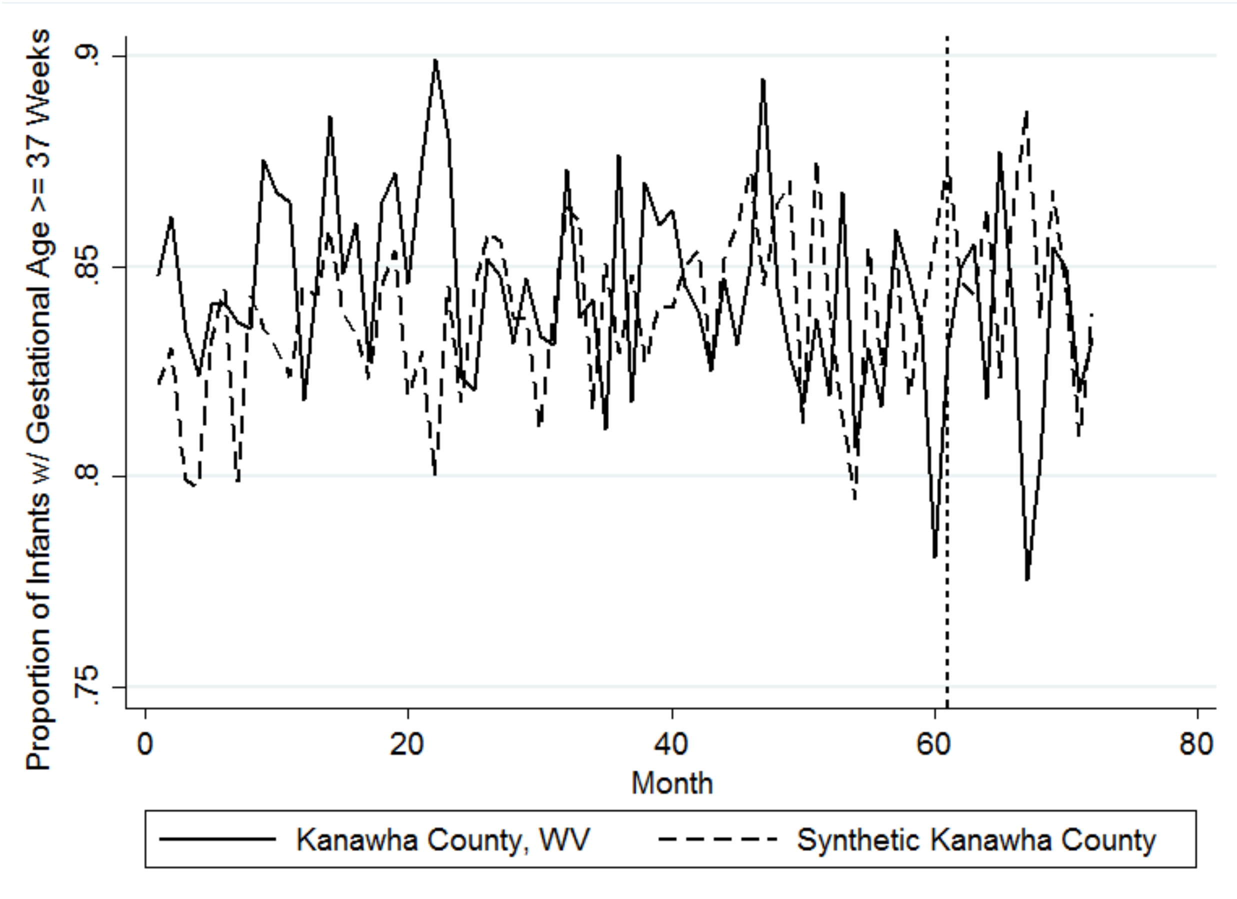
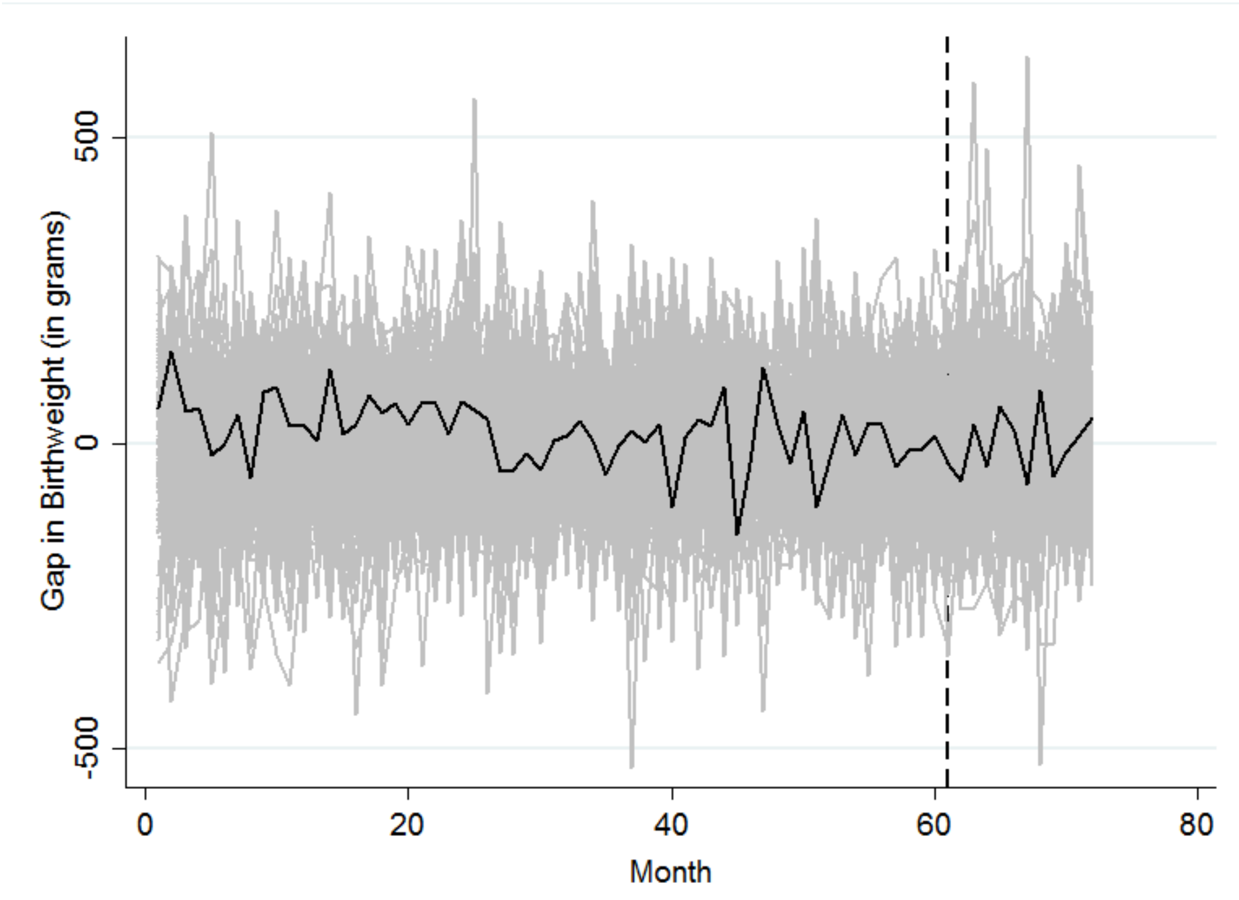
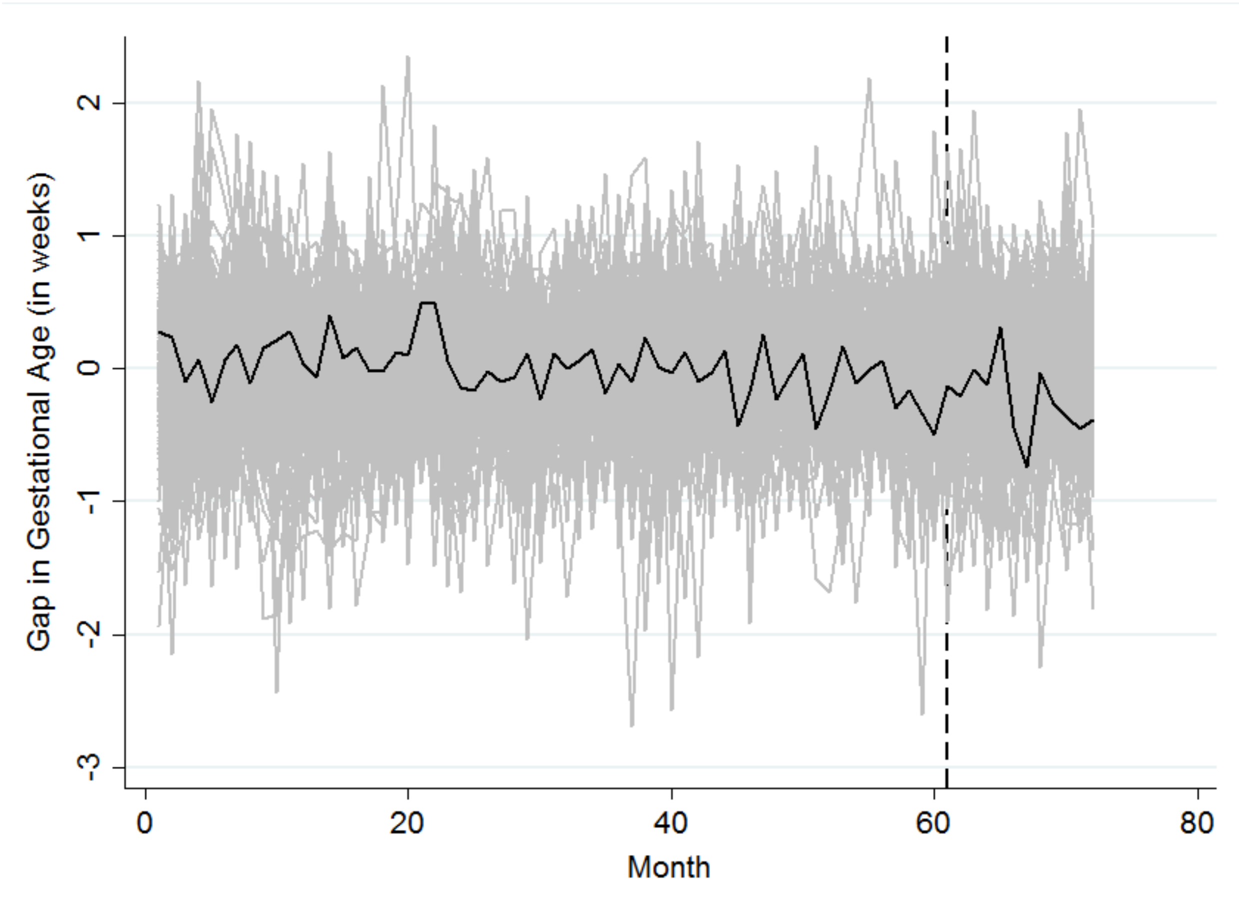


Figure 6A: 5-Minute Birthweight Placebo Test



Notes: We trim the placebo data to only include placebo MSAs with a RMSE within 4 times of the Kanawha County, WV RMSE. The black line represents Kanawha County, WV.

Figure 7A: 5-Minute Gestational Age Placebo Test



Notes: We trim the placebo data to only include placebo MSAs with a RMSE within 4 times of the Kanawha County, WV RMSE. The black line represents Kanawha County, WV.

Figure 8A: Trends in 5-minute Apgar Scores, USA-wide synthetic control