Consequences of a Shortage and Rationing: Evidence from a Pediatric Vaccine

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Abstract

Shortages and rationing are common in health care, yet we know little about the consequences. We examine an 18-month shortage of the pediatric Haemophilus Influenzae Type B (Hib) vaccine. Using insurance claims data and variation in shortage exposure across birth cohorts, we find that the shortage reduced uptake of high-value primary doses by only 4 percent and low-value booster doses by 26 percent. This suggests providers largely complied with rationing recommendations. In the long-run, catch-up vaccination occurred but was incomplete: shortage-exposed cohorts were 4 percentage points less likely to have received their booster dose years later. We also find that the shortage and rationing caused provider switches, extra provider visits, and negative spillovers to other care.

Keywords: rationing, shortage, vaccine, Haemophilus Influenzae Type B
JEL Codes: I12, I18, L65

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1 Introduction

Drug shortages are an "urgent public health crisis," according to the American Medical Association (2020). The Food and Drug Administration (FDA) reported 41 new shortages of drugs and vaccines in 2021 and 83 shortages that continued from previous years (FDA, 2022). Addressing drug shortages is a priority among policymakers in the United States.[1] While a common policy response in the face of shortages is recommending the rationing of supply (Hantel et al., 2019), there is limited empirical evidence on the effects of such policies. Understanding these effects is important, because the welfare effects of a shortage depend not only on the effect on quantities, but also on the allocation of quantities and on patient and provider behavior.

In this article we examine the effects of a vaccine shortage and subsequent rationing on the welfare and behavior of patients. We study this question in the context of an 18-month shortage of the pediatric Haemophilus Influenzae Type B (Hib) vaccine. The Hib vaccine shortage began in December 2007 when manufacturer Merck announced it could not guarantee the sterility of its Hib vaccine and stopped production. At the time, there was only one other approved Hib vaccine maker in the U.S., Sanofi Pasteur, which supplied about half the market. Because of the shortage, the Centers for Disease Control and Prevention (CDC) recommended delaying Hib booster doses in favor of primary series doses (CDC, 2007).

Measuring the welfare effects of a shortage presents empirical challenges, but several features of the Hib vaccine market allow us to overcome these obstacles. First, in other markets it is difficult to estimate counterfactual product demand in the absence of a shortage, due to demand fluctuations, substitution across products, and, in the case of drug markets, changes in market size resulting from variation in disease incidence. The Hib vaccine, however, is recommended for all children. Thus, the market size is straightforward to calculate. Moreover, pediatric immunization rates are remarkably stable over time and other childhood vaccines are recommended to be received on a similar schedule to the Hib vaccine, providing additional information about what uptake of the Hib vaccine might have been in the absence of a shortage. Second, in other markets it is challenging to determine if rationing during a shortage is efficient, because the value of the product to each consumer is

[1] For example, in 2018 the FDA created an inter-agency Drug Shortages Task Force to study and reduce drug shortages (Food and Drug Administration, 2019). Additionally, members of Congress have introduced legislation to address drug shortages, including S.2595: the Drug Shortages Prevention and Quality Improvement Act of 2021.

unknown. For the Hib vaccine series, however, primary doses have higher marginal benefit than booster doses (Griffiths et al., 2012),[2] allowing us to see whether rationing encourages higher-value uses.

A shortage of the Hib vaccine is also important to study in its own right. The Hib vaccine is highly effective and provides protection against Hib bacterial infections, which can cause severe brain damage, nerve damage, and death. Before the Hib vaccine was available, Hib was a leading cause of childhood meningitis and pneumonia in the United States, and approximately 20,000 children had serious Hib disease and about 1,000 died annually (CDC, 2022b). After the Hib vaccine became widely used, incidence of Hib disease rapidly declined by more than 99 percent and has remained low. Notably, from 2009 to 2018 there were only 36 Hib cases in patients younger than age 5 recorded by CDC surveillance sites (Oliver, Moro, and Blain, 2020).[3]

For our analyses we first estimate the effects of the Hib shortage and rationing on vaccination uptake in the short- and long-run. This allows us to examine how well providers adhered to the CDC recommendation to delay the booster dose and whether children caught up after delayed vaccines. The CDC recommended delaying care to prioritize the higher-value primary series vaccine, assuming that delayed children would catch up. While these types of recommendations are common, there is little observational evidence on whether providers adhere to the recommendations or on the long-term consequences of delayed vaccination.

We next consider how a shortage alters care decisions by patients.[4] There are many decisions a patient could make in response to a shortage which have different costs and spillover effects. A patient could wait to see a doctor until the shortage has resolved, which might delay other care that would have otherwise been given on the same visit. Alternatively, a patient could receive other recommended preventive care on schedule and arrange a later visit for the Hib vaccine, adding to crowding in the health care system and inconvenience for patients. Finally, a patient could search for a different provider who has Hib vaccine available and is willing to administer it. Seeing an additional provider—who is less familiar with the patient's history—fragments care. Fragmented care delivery has

[2] The first two primary doses of the Hib vaccine have cumulative efficacy of about 92%; the booster dose provides little added efficacy (Griffiths et al., 2012).

[3] Given this low number of documented Hib cases, we do not estimate the impacts of the shortage on Hib morbidity or mortality.

[4] We will refer to decisions made by patients, children, infants, or parents interchangeably. In the case of pediatric care, the decisions are typically made by adults on behalf of children.

been shown in other contexts to increase health care costs and reduce quality of care (Agha, Frandsen, and Rebitzer, 2019; Agha, Ericson, and Zhao, Forthcoming).[5]

Finally, we conduct provider-level analyses to explore supply-side factors that impacted the shortage. For this analysis we explore whether providers who used Merck vaccine doses prior to the shortage differently reduced their primary and booster series relative to those providing Sanofi vaccine doses prior to the shortage. This helps us to understand supply frictions and whether compliance to the CDC recommendation was uniform. Likewise, we explore whether providers in counties where mostly Merck doses were used prior to the shortage were differentially impacted by the shortage. This would suggest localized supply issues or differential compliance with the CDC recommendation.

We conduct these analyses using commercial insurance claims data from the Merative™ MarketScan® Research Databases, 2004-2017. We compare children who were of age to receive Hib vaccine doses during the shortage period to children from earlier or later birth cohorts. The sharp timing of the shortage combined with the recommended vaccination schedule generates clear predictions about which cohorts the Hib vaccine shortage affected. Our identification strategy assumes that in the absence of the shortage, outcomes for the shortage-exposed cohorts would have been similar to outcomes for non-exposed children. We support this assumption by showing that pre- and post-shortage outcomes are stable across cohorts and by showing that other childhood vaccines recommended to be received on a similar schedule as Hib, but which were not in shortage, did not experience the same changes during the shortage period.[6]

We find evidence of broad adherence to the CDC recommendation to delay Hib booster doses and prioritize primary doses. Among shortage-exposed cohorts, there was only a 4 percentage point reduction in children receiving their primary doses, while there was a 26 percentage point reduction in children receiving their booster dose. Our results also show that following the shortage there was significant catch-up vaccination, although it was imperfect. Years after the shortage ended shortage-exposed children were fully caught up on the primary series, but remained 4 percentage points less likely to have ever received a booster dose.

[5]Switching providers during a vaccine series can result in incomplete and inaccurate vaccine records, which can cause unnecessary health care visits and immunizations (CDC, 2017).

[6]We also show that our results are robust to difference-in-differences specifications in which the one vaccine recommended on the *identical* schedule (pneumococcal vaccine) is used as a control for the Hib vaccine. To the extent that the shortage had negative spillover effects on the uptake of the pneumococcal vaccine, this will bias our difference-in-differences estimates towards zero.

Supplemental analyses using nationally representative National Immunization Survey-Child data, 2002-2019, suggest that during the shortage Hib doses were distributed fairly equitably across the population. We find no significant differences across race/ethnicity, household income, or maternal education. We also find that the shortage had similar effects on vaccination uptake for children regardless of whether they were privately insured, supporting the external validity of our MarketScan results.

We next examine how patients altered care decisions in the face of the shortage. We show that shortage-exposed children were about 3 percentage points less likely to be up-to-date at 18 months on the vaccine recommended to be received on the same schedule as Hib (pneumococcal vaccine) and they made 0.3 more provider visits for vaccinations by age 5 than children in surrounding cohorts. These results suggest some patients delayed their preventive care visit during the shortage, while others made additional visits to receive the missed Hib dose. We also find that children in shortage-exposed cohorts were 3 percentage points more likely to switch providers during the Hib vaccine series, consistent with patients searching for new providers in order to obtain the Hib vaccine. Extrapolating these coefficient estimates to the entire population suggests that patients were delayed receiving more than 160,000 pneumococcal vaccine doses, and there were more than 1.5 million extra provider visits and more than 140,000 provider switches.

Finally, our provider-level analyses show that the depth of the shortage varied significantly across providers. We find that providers who mostly used Merck Hib vaccines prior to the shortage reduced administration of primary series doses by about 25 percentage points (relative to the number of pneumococcal vaccines they gave) in the first six months of the shortage, and by 9 percentage points in the last year of the shortage. For providers who used mostly the Sanofi Hib vaccine prior to the shortage, however, we find no reduction in the number of primary series doses given during the shortage. This suggests provider-level supply constraints may have been an issue throughout the shortage. For the booster series, we find both types of providers had similar levels of compliance in terms of rationing the booster doses, but areas with more Merck provider reduced their booster doses more quickly.

This article builds on several important literatures. First, we provide novel comprehensive evidence of the short- and long-run immunization effects of a vaccination shortage. The existing empirical literature on the impacts of drug and vaccine shortages has primarily

focused on short-run quantity effects.[7] If catch-up vaccination occurs (or supply frictions persist) after the end of a shortage, focusing on the short-run may over- (or under-) state the effects of the shortage of vaccine coverage in the population. Most closely related to our work, Santibanez et al. (2012) and White, Pabst, and Cullen (2011) examine the short-term effects of the Hib vaccine shortage and find evidence that the primary and booster series quantities fell substantially at the onset of the shortage. We extend these analyses over a longer time period and additionally show that there is substantial reallocation and catch-up vaccination in the long-run. Our use of longer time series of data also allows us to examine the stability of childhood vaccination rates among pre- and post-shortage cohorts, thus providing evidence in support of our identifying assumption.

We also build on the existing literature by providing the first evidence on the broader health care effects of the Hib vaccine shortage. By analyzing the spillover effects to other preventive care, number of vaccination visits, and patient switching across providers, we capture costs of the vaccine shortage that have previously been unexamined.[8] In general, the current literature on the behavioral response of patients to drug and vaccine shortages is sparse; to our knowledge only two other articles have examined this question (de Janvry, Sadoulet, and Villas-Boas, 2010; Fitzpatrick, 2022).[9] We complement these articles by considering a distinct context (U.S. pediatric vaccine shortage) and by leveraging claims data with more than 300,000 patient observations to provide large-scale evidence of the patient response and health care impacts of a shortage.

This article additionally expands the literature examining the demand-side of the vaccine market. Our findings on the effects of the CDC rationing recommendations are consistent with evidence from Lawler (2017) and Lawler (2020) showing that, in non-shortage contexts, CDC vaccination recommendations can be effective at impacting immunization uptake.[10] Similarly, our findings complement existing evidence of important spillover ef-

[7] For example, Alpert and Jacobson (2019) document quantity effects for various chemotherapy drug shortages using claims data. They note that a minority of chemotherapy treatments designated as in shortage experience declines in quantities, and hypothesize that in many cases providers are able to mitigate the shortage through other means.

[8] Several other studies descriptively document the harms of vaccine shortages by surveying immunization program managers, physicians, and hospital staff (Chamberlain et al., 2012; Kaakeh et al., 2011; Kempe et al., 2010).

[9] de Janvry, Sadoulet, and Villas-Boas (2010) analyze the impact of a flu vaccination shortage in the context of a college campus and find that providing information about the shortage actually increased uptake of the vaccine, and this increase was driven by lower-risk individuals. Fitzpatrick (2022) examines the impact of anti-malarial drug shortages in Uganda, and finds evidence of patient search and changes in the composition of customers.

[10] Other existing work on the determinants of vaccination have considered a broad set of factors, including

fects of other vaccination shocks (Andersson et al., 2021; Carpenter and Lawler, 2019; Schaller, Schulkind, and Shapiro, 2019).

Our study also contributes to the literature showing how government policies can exacerbate or mitigate drug and vaccine shortages. Although rationing recommendations are a common policy response, existing work has primarily focused on the impacts of reimbursement rates (Woodcock and Wosinska, 2013; Ridley, Bei, and Liebman, 2016; Yurukoglu, Liebman, and Ridley, 2017), or interventions targeting manufacturers (Lee et al., 2021). Recent evidence from the COVID-19 pandemic shows that governments can be effective at rationing vaccines (Kim and Lee, 2022). More broadly, our work also relates to the literature examining physician adherence to practice recommendations (Alalouf, Miller, and Wherry, 2019; Buchmueller and Carey, 2018).

2 Hib vaccine and shortage background

The Hib vaccine protects against Hib bacterial infections, which can cause severe brain damage, nerve damage, and death. Prior to the approval of the Hib conjugate vaccine in 1990, approximately one in 200 children under the age of 5 developed Hib infections (Oliver, Moro, and Blain, 2020), and about one thousand children died each year as a result (CDC, 2022b). After introduction of the Hib vaccine, Hib infections fell by more than 99 percent, and nearly 90 percent of Hib cases occurred among children that had not received the full vaccine series.

Before the 2007-2009 Hib vaccine shortage began, there were two manufacturers serving the U.S. market —Sanofi Pasteur and Merck —and each manufacturer served about half of U.S. children.[11] The Sanofi Pasteur Hib vaccine (brand names ActHIB or TriHIBit) is a 3-dose primary series, to be administered at 2, 4, and 6 months of age. The Merck Hib vaccine (brand name PedvaxHIB or Comvax) is a 2-dose primary series, to be administered at 2 and 4 months of age.[12] Following completion of the Hib primary vaccines series, a booster dose of any Hib vaccine is recommended to be received at 12-15 months of age

vaccination mandates (Carpenter and Lawler, 2019; Churchill, 2021; White, 2021), insurance coverage (Chang, 2016), information shocks (Chang, 2018), and disease incidence (Oster, 2018; Schaller, Schulkind, and Shapiro, 2019).

[11] Based on author calculations using MarketScan Data.

[12] The CDC recommends that children receive the same vaccine type (Merck or Sanofi Pasteur) for all primary series doses, although they can be used in combination. If the Sanofi Pasteur vaccine is administered as either the first or the second dose of the primary series, a total of three doses of the Hib vaccine are needed to complete the series (CDC, 2007).

(Table 1). Catch-up vaccination is recommended for children between the ages of 15 and 59 months who are not up-to-date. Healthy children over the age of 59 months are not recommended to receive the Hib vaccine, because the risk of Hib is primarily for infants (Oliver, Moro, and Blain, 2020).

The Hib vaccine is one of ten vaccines routinely recommended for infants between birth and 18 months of age. However, only the pneumococcal conjugate vaccine (PCV) has a recommended dosing schedule that fully aligns with the Hib vaccine (Table 1).[13] Prior to the shortage, infants in our sample received their first two doses of pneumococcal and Hib vaccines on the same day more than 95 percent of the time.

Table 1: Recommended Vaccine Schedule

	Age in Months		
	Hib (Merck)	Hib (Sanofi Pasteur)	Pneumococcal
First Primary Dose	2	2	2
Second Primary Dose	4	4	4
Third Primary Dose	N/A	6	6
Booster Dose	12-15	12-15	12-15

Notes: Catch-up vaccination for the Hib and pneumococcal vaccines is recommended for children between the ages of 15 and 59 months who are not up-to-date. Healthy children over the age of 59 months are not recommended to receive the Hib or pneumococcal vaccine, even if they have not previously received any doses. Source: Centers for Disease Control and Prevention.

The Hib vaccine shortage began on December 13, 2007, when Merck suspended production of its Hib vaccines due to uncertainty about the sterility of its manufacturing equipment. On December 18, 2007, the CDC issued the recommendation that the Hib booster dose be delayed until the shortage resolved, except for high-risk groups (CDC, 2007).[14] According to the CDC, the risk of deferring the booster dose was low if primary series coverage remained high, especially given the low rates of Hib disease prevalence.

Eighteen months later, on June 25, 2009, Sanofi Pasteur announced increased produc-

[13] We provide the full recommended vaccination schedule for children aged 0-24 months in Appendix Table A1. Two other vaccines, diphtheria-tetanus-pertussis (DTaP) and polio, are on schedules similar but not exactly matching the Hib vaccine schedule. Therefore, we do not examine them in the main text, but include robustness checks using these vaccines in Appendix Section A3.

[14] Children at high risk for Hib were those with "asplenia, sickle cell disease, human immunodeficiency virus infection and certain other immunodeficiency syndromes, and malignant neoplasms" and American Indian/Alaska Natives (CDC, 2007).

tion of its Hib vaccines.[15] Shortly afterwards, on July 1, 2009, the CDC declared that the shortage had ended and recommended resuming administration of the Hib booster dose. The CDC also recommended "limited catch-up," meaning older children with a delayed booster dose should wait to receive it until their next routinely scheduled visit (CDC, 2009d). In September 2009, the CDC updated their advice and recommended broad catch-up, with providers actively recalling patients that were in need of a booster dose (CDC, 2009c). In the fourth quarter of 2009, Merck Hib doses once again became available and Merck returned to full supply in the first quarter of 2010 (CDC, 2010).[16]

3 Data

Our main data are commercial health insurance claims from Merative™ MarketScan® Research Databases. We extend our analyses to publicly-insured and uninsured children using data from the National Immunization Survey-Child. To control for time-varying county-level characteristics, we use data from the American Community Survey and Robert Wood Johnson Foundation County Health Rankings Dataset. We provide more detail about each data source below.

3.1 MarketScan

For our primary analyses we use data from Merative™ MarketScan® Research Databases for 2004-2017. MarketScan data are a convenience sample of patients enrolled in commercial health insurance. For enrolled patients, the data include all patient claims, as well as patient demographic characteristics, such as year of birth, gender, and county of residence. Each claim includes information on billed services (captured by CPT-4 codes), date of service, patient identifiers, and provider identifiers. Receipt of a vaccine dose is identified using the recorded CPT codes.[17] Because the recommended vaccination schedule for the Hib vaccine is based on child age in months, for each child in our sample we assign month

[15] This included the introduction of the new Sanofi Pasteur Pentacel vaccine (combination vaccine containing DTaP, polio, and Hib) which was introduced in June 2008.

[16] Also contributing to the end of the shortage, in October 2009 GlaxoSmithKline began shipping the monovalent Hib conjugate vaccine Hiberix which had previously only been available outside the U.S. (CDC, 2007).

[17] The Merck and Sanofi Pasteur Hib vaccines have different CPT codes because the technology and recommended dosing schedules differ. The CPT codes we use to identify the Hib vaccine are: 90644, 90645, 90646, 90647, 90648, 90748, 90698, 90696, 90697, 90720, 90721, 90737. The CPT codes corresponding to the Merck Hib vaccine are 90647 and 90748.

of birth as the minimum of the first date at which we observe a claim and the first month the child appears in the enrollment file.[18]

We restrict our sample to the set of children who were continuously enrolled between 0 and 5 years of age, to allow us to construct individual vaccination histories and up-to-date measures. To ensure that we are observing births rather than new plan enrollment, we only include children whose parents were enrolled for longer than the child in the child's birth year. For our preferred sample, we also exclude children for whom we never observe any vaccines,[19] and children living in states where the Vaccines For Children (VFC) Program supplies childhood vaccines for free to all children, as this affects provider incentives for filing insurance claims for vaccines and leads to under-reporting of vaccination.[20] Overall, this leaves a sample of 322,784 commercially-insured children born between the years of 2005 and 2010.[21]

For each infant in our sample we construct a series of binary variables separately capturing receipt of any Hib doses, two or more doses, and up-to-date (UTD) status for the Hib vaccine at 9, 18, and 62 months of age. These ages correspond to the key thresholds in the immunization schedule (age of primary series completion, age of booster dose completion, and age beyond which catch-up vaccination is no longer recommended), plus a three month lag. We use a three-month lag to allow for measurement errors in month of birth and to capture infants that are only a month or two behind schedule.[22] Vaccination up-to-date measures are constructed based on the type of Hib vaccine received (i.e. 3 primary doses

[18] For 57% of children the claim-based measure and the enrollment-based measure agree on the birth month, while for 91% of children these measures are within one month of each other.

[19] This includes not observing any vaccines for pneumococcal, Hib, polio, rotavirus, hepatitis B, hepatitis A, or DTaP.

[20] The federal Vaccines For Children (VFC) Program supplies states with childhood vaccines to be administered at no charge for Medicaid-eligible, American Indian/Alaskan Native, uninsured, or underinsured children. During our sample period 14 states (accounting for 10 percent of the children in our data) supplement the federal VFC program and implement a "Universal" VFC program, in which free vaccines are also provided for privately insured children (CDC, 2016). In these states, providers are not reimbursed by insurance for the vaccines and therefore have less of an incentive to file a claim. In our data, vaccination rates constructed from claims are much lower in these states and often observed prices are zero when a claim is recorded.

[21] We check that our results are robust to these sample restrictions, tables are available on request.

[22] The fraction of children in our sample that receive vaccines one to three months behind schedule (based on our assigned month of birth) even in the absence of the shortage is high. For example, for the pneumococcal vaccine in 2006 (pre-shortage), only 41 percent of infants were up-to-date on the booster by age 15 months as recommended, whereas 60 percent were up-to-date by 18 months. Beyond 18 months the percent continues to increase but at a much slower rate: only 66 percent are up-to-date by 21 months of age.

are required if the Sanofi Pasteur Hib vaccine was administered for any of the primary series doses, otherwise only 2 primary doses are required) and the age at which each dose was received.

3.2 Plots of MarketScan data

We illustrate the dynamics of the Hib vaccine shortage using plots of the MarketScan data. In Figure 1 we plot primary versus booster doses, and in Figure 2 we show Merck versus Sanofi Pasteur doses. For the plots, we divide the number of doses of the Hib vaccine (which were short starting in December 2007) by the number of pneumococcal doses (which were not short). Pneumococcal vaccine doses are recommended to be administered at the same ages as the Hib vaccine doses, and therefore serve as a proxy for how many children would be expected to need a Hib vaccine in a given month. If patients also delayed receipt of the pneumococcal vaccine as a result of the Hib shortage, these figures will *understate* the depth of the shortage.[23]

Figure 1 shows that during the shortage primary doses were relatively stable while booster doses declined. For booster doses, the ratio of Hib to pneumococcal doses administered was about 1 in December 2007, falling to 0.79 in January 2008, and 0.43 in June 2008. After the shortage ended in June 2009, there was a spike in booster dose administration, with over 1.5 Hib booster doses administered per pneumococcal booster dose for the months of August 2009 to January 2010.

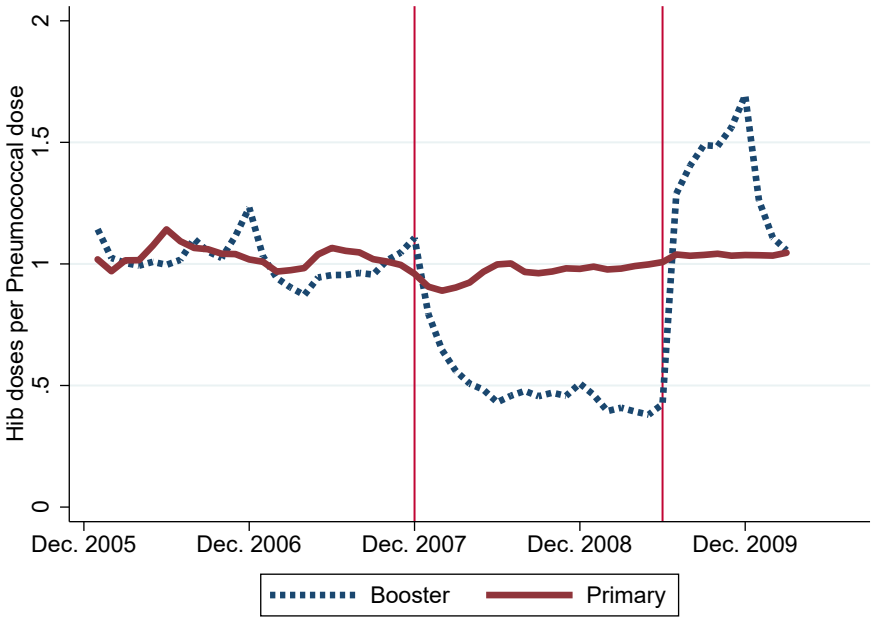
These trends suggest providers largely adhered with CDC recommendations to (1) delay booster doses following the start of the shortage in December 2007 and (2) administer catch-up doses following the conclusion of the shortage in June 2009. However, adherence was initially gradual, and this appears to be associated with a short-run reduction in the number of primary series doses administered at the start of the shortage.[24]

Figure 2 examines trends in Hib vaccination separately by manufacturer (combining primary and booster doses). The top line shows total Hib doses per pneumococcal dose and the lower two lines disaggregate the results into Sanofi Pasteur and Merck doses. At the beginning of the shortage there was an immediate reduction in the number of Merck doses administered while the number of Sanofi Pasteur doses administered increased during the

[23] In Appendix Figure A3, we graph the number of Hib doses divided by the average number of 6-month-old children in the MarketScan data in a year. The overall patterns are consistent regardless of denominator.

[24] The recommendation during the shortage was to continue administering the booster dose to high-risk children. Therefore, we should not expect zero Hib booster doses to be administered.

Figure 1: Ratio of Hib to Pneumococcal Doses Administered per Month



Notes: The outcome variable is Hib doses divided by pneumococcal doses in that month in the MarketScan data. Doses are split into primary series and booster doses based on a child's observed history. Primary series Merck doses count as 1.5 doses to account for Merck's two dose series.

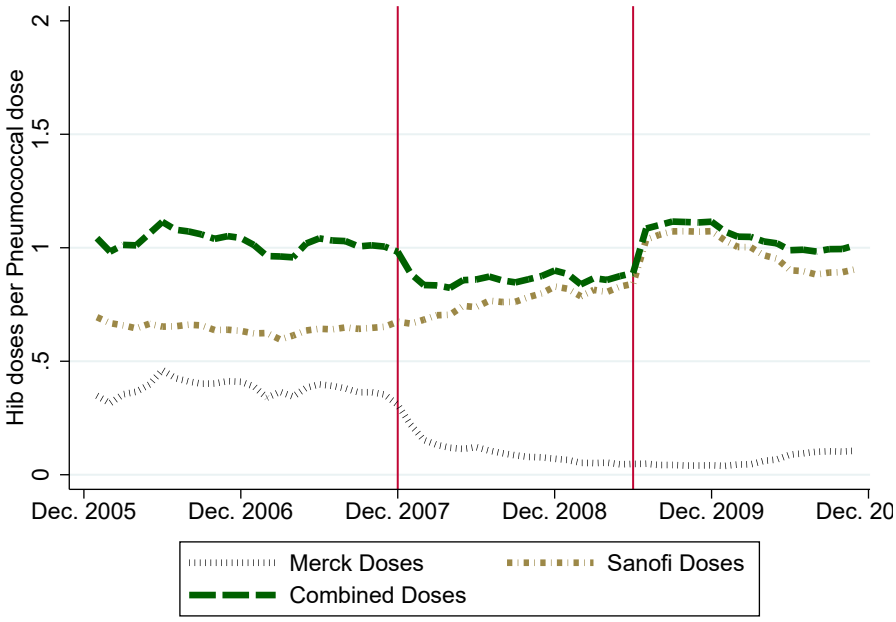
shortage period. Notably, the Merck supply was short, but not zero, as expected given that the shelf life of a Hib vaccine is at least two years if kept cold (World Health Organization, 2000).

3.3 National Immunization Survey-Child

We supplement our primary analyses using data from the National Immunization Survey-Child (NIS-Child), 2002-2019 (CDC, 2021). The NIS-Child is a nationally representative random digit dialing survey that targets children aged 19 to 35 months old. The survey includes provider-verified vaccination histories, as well as demographic information such as insurance status, income, education, and race. We provide more details about the survey in Appendix Section A5.

Unlike the MarketScan data, the NIS-Child data contain immunization information regardless of child insurance status or provider billing decision. Thus, these data allow us

Figure 2: Ratio of Hib to Pneumococcal Doses Administered per Month



Notes: The outcome variable is Hib doses divided by pneumococcal doses in that month in the MarketScan data. Doses are split between Merck and Sanofi Pasteur. Primary series Merck doses count as 1.5 doses to account for Merck's two dose series.

to examine the effects of the shortage on vaccination rates for a nationally representative population, as well as examine heterogeneity by insurance status and other demographics. These heterogeneity analyses are important for understanding whether rationed doses were distributed equitably and the external validity of our main results.

The primary outcomes we examine in these data are indicator variables capturing whether the child has received at least one, two, or three doses of the Hib vaccine by age 18 months. These data do not distinguish between Merck or Sanofi Pasteur manufactured Hib vaccines, thus we are unable to construct more precise measures of up-to-date status, or to differentiate between primary and booster series doses. An additional limitation of the NIS-Child data is that for each child we only know year of survey and age in years at time of survey, which creates substantial measurement error in our assignment of shortage exposure.

3.4 Other data sources

We use measures from the American Community Survey (ACS) and the Robert Wood Johnson Foundation (RWJF) County Health Rankings Dataset as controls in some specifications. We use the ACS data from 2012 to create county-level measures of income conditional on being privately insured and under-65, to match our claims sample (Ruggles et al., 2022; University of Wisconsin Population Health Institute, 2022). We obtain demographics and various health system controls in the RWJF data. These controls include the number of primary care physicians per 100,000 (a measure of physician capacity), the share of people receiving diabetic screening (a measure of a health system's adherence to quality guidelines), and other demographics like education and racial composition.

In addition, there are important state level policies which we incorporate into our analyses. We collected data on whether a state mandates children be up-to-date with the pneumococcal vaccine at the time of child care entry from Immunization Action Coalition and author's review of state statutes (IAC,2020).[25] Finally, we use data from the annual VFC Program Management Survey 2001-2010 to determine the generosity of a state's VFC program (CDC, 2015).

4 Methods

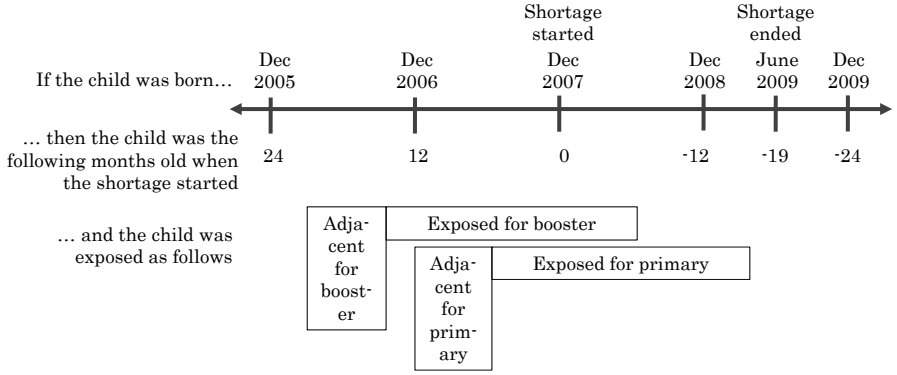
Our main source of identifying variation is differences in exposure to the shortage across birth cohorts. We define cohorts as "shortage-exposed" for a given vaccine dose if the timing of the shortage (December 2007 through June 2009) overlapped with when a child would have been of age to receive the dose. As shown in Figure 3, infants born between June 2007 and April 2009 were 2 to 6 months of age while the shortage was ongoing and therefore were exposed for the primary series. Likewise, infants born between September 2006 and June 2008 were 12 to 15 months old while the shortage was ongoing and therefore were exposed for the booster dose.

Because some children receive vaccine doses behind schedule even in the absence of a shortage, those born slightly before the directly exposed cohorts were partially impacted by the shortage.[26] Thus, we allow for these partially-treated cohorts to be differentially

[25] All states have mandates requiring children to be up-to-date on the Hib vaccine prior to daycare entry, and these mandates were adopted prior to the start of our sample period.

[26] For example, a child born 8 months before the shortage starts would not be "exposed" for their dose scheduled at 6 months of age. However, prior to the shortage, 26 percent of children received their 6 month

Figure 3: Mapping for Calendar Time to Cohort Time



Notes: The shortage occurred from December 2007 to June 2009. Following the recommended vaccination schedule, children born between June 2007 and April 2009 were exposed to the shortage for the primary series. Children born between September 2006 and June 2008 were exposed for the booster dose.

affected through the inclusion of a "shortage-adjacent" indicator that is equal to one for the cohorts that were born 6 months or less before the shortage-exposed cohorts, and is equal to zero otherwise. To most cleanly identify the impact of the shortage, however, throughout the paper we focus only on the estimated impact for the shortage-exposed cohorts.

Our main regression specification is as follows:

$$\mathrm{Y}_{cm} = \beta_0 + \beta_1 \mathbb{1}(Exposed_m) + \beta_2 X_c + \epsilon_{cm} \tag{1}$$

where Y_{cm} is the outcome observed for child c born in month-year m; X_c is a vector of observable child characteristics. In our preferred specification this vector includes calendar month-of-birth fixed effects, to control for seasonality in health and vaccination uptake (Currie and Schwandt, 2013; Worsham, Woo, and Jena, 2020), an indicator variable capturing if the child was in a shortage-adjacent cohort, and Census region fixed effects.[27] $\mathbb{1}(Exposed_m)$ represents an indicator variable that is equal to one if the birth cohort was

dose later than 8 months of age. For those children, the late dose they would have received at 8 months of age may not be available during the shortage. Thus, these partially treated cohorts consist of a mixture of individuals who got the vaccine on time (before the shortage) and individuals who were behind schedule and therefore were affected by the shortage.

[27] In Appendix Section A4, we check that our results are robust to adding county-level demographic controls.

directly exposed to the shortage, and is zero otherwise. Thus, the coefficient on this variable is our treatment effect of interest, as it represents the difference in outcomes between the shortage-exposed and non-shortage exposed cohorts, net of birth month effects and other controls. Standard errors are clustered at the birth month-year level, as the availability of vaccines is the source of our treatment variation (Abadie et al., 2017). For robustness, we also report p-values from the wild cluster bootstrap procedure described in Cameron, Gelbach, and Miller (2008).

The identifying assumption for this model is that in the absence of the shortage, the level of the outcomes for those affected by the shortage would have been similar to those not affected by the shortage. To support this assumption we (1) show graphically that outcomes for pre-shortage and post-shortage cohorts are stable, and (2) in each regression we run a specification with a pre-shortage linear trend, to demonstrate that there were no significant linear trends in the outcomes for pre-shortage cohorts. For these pre-trend regressions we keep data only for pre-shortage cohorts and then regress each outcome (after netting out calendar month-of-birth fixed effects) on a month-year linear trend and vector of region fixed effects.[28] Formally, the regression equation is:

$$\mathrm{Y}_{cm} = \beta_0 + \beta_1 BirthMonth_m + \gamma_r + \epsilon_{cm} \tag{2}$$

where $BirthMonth_m$ is the month-year of birth and γ_r represents region fixed effects. For all analyses, we report the pre-trend regression results in the same table, in a panel below the main results.

We also provide support for the identification assumption by examining effects of the shortage on uptake of the pneumococcal, DTaP, and polio vaccines, which are administered on the same or similar schedule as the Hib vaccine but not directly affected by the shortage. These analyses provide evidence that any changes we see during the shortage for the Hib vaccine were not present (or not as large) for other vaccines, helping to rule out concurrent frictions that might explain our results. Although the Hib shortage may plausibly have spillover effects to other vaccines (e.g. if households delay well-child visits), these effects should be relatively smaller in magnitude than observed changes for the Hib vaccine.

[28] In our main specification we include calendar month fixed effects to address seasonality in health and vaccination uptake (Currie and Schwandt, 2013; Worsham, Woo, and Jena, 2020). For this truncated sample, we net out calendar month effects by running an initial regression with the full sample of the outcome on just calendar month fixed effects. We then predict the outcome net of the calendar month fixed effects, and use these predicted values for our pre-trends analysis.

Finally, in Appendix Section A6, we also implement a difference-in-differences estimation strategy where we explicitly use pneumococcal immunization rates as a control. If there are spillover effects to the pneumococcal vaccine, this difference-in-differences strategy should underestimate the true effects of the shortage on uptake of the Hib vaccine.

5 Results

5.1 Summary statistics

For the MarketScan data, the unit of observation is an individual patient. We report statistics for the full sample, as well as separately for the cohorts exposed to the shortage for the primary series, the cohorts exposed for the booster dose, and those never exposed to the shortage (Table 2). Some cohorts are exposed to the shortage for both the primary and booster doses (Figure 3), so there is overlap between the individuals in columns 2 and 3. Across all cohorts, by 9 months of age 92 percent of infants had received at least 1 Hib vaccine dose and 72 percent had received the full primary series.

We see the effect of the shortage and rationing on booster doses in the summary statistics. At 18 months, 62 percent of infants in cohorts that were never exposed to the shortage were up-to-date on the Hib booster dose, compared to only 35 percent of those exposed. These disparities are not present for the pneumococcal vaccine (Appendix Table A2). In Appendix Table A7, we present summary statistics for the county-level control variables we use. For all measures, the three different cohort groups have very similar observables.

Table 2: Summary Statistics

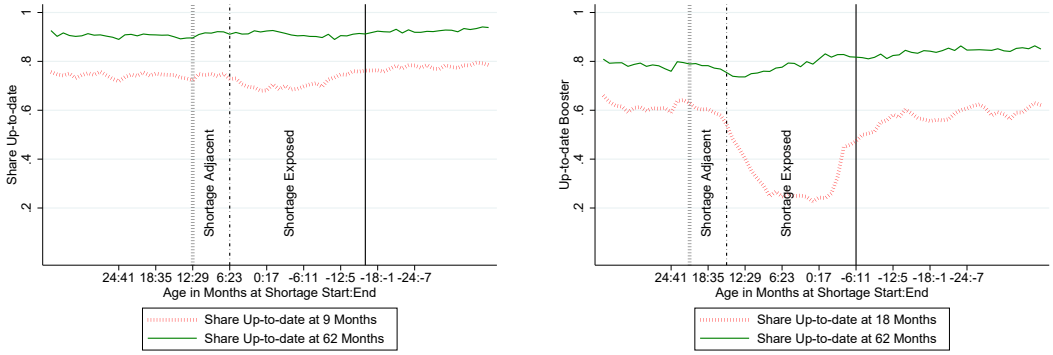
	(1) Full Sample	(2) Exposed during Primary	(3) Exposed during Booster	(4) Never Exposed
Shortage Exposed Primary	0.334	1.000	0.600	0.000
	(0.472)	(0.000)	(0.490)	(0.000)
Shortage Exposed Booster	0.306	0.550	1.000	0.000
	(0.461)	(0.498)	(0.000)	(0.000)
Any Hib Doses, 9 Months	0.917	0.911	0.918	0.920
	(0.276)	(0.285)	(0.274)	(0.271)
Hib UTD Primary, 9 Months	0.721	0.693	0.694	0.739
	(0.448)	(0.461)	(0.461)	(0.439)
Hib UTD Booster, 18 Months	0.526	0.433	0.346	0.615
	(0.499)	(0.495)	(0.476)	(0.487)
Any Hib Doses, 62 Months	0.954	0.951	0.959	0.955
	(0.210)	(0.216)	(0.199)	(0.207)
Hib UTD Primary, 62 Months	0.899	0.895	0.897	0.902
	(0.302)	(0.306)	(0.304)	(0.298)
Hib UTD Booster, 62 Months	0.793	0.797	0.766	0.803
	(0.405)	(0.402)	(0.423)	(0.398)
Observations	322784	107833	98739	175470

Notes: Summary statistics for outcomes and treatments for different samples using MarketScan data aggregated to the child level. The mean is listed with the standard deviation in parentheses below. Children could have been exposed during the primary series and the booster series, so columns 2-4 do not add up to the full sample of 322,784 observations. See Figure 3 for details. "UTD" indicates up-to-date.

5.2 Effect of shortage and rationing on up-to-date rates

Descriptive trends in Hib up-to-date rates are plotted in Figure 4. Panel (b) shows that the shortage and rationing reduced the share of children who were up-to-date on booster doses at 18 months. Furthermore, we can see that most patients caught up with booster dose by the time they were 62 months old (at least two years after the shortage for all exposed cohorts). We see similar, though less pronounced, patterns for the primary series (Panel (a)).

Figure 4: Up-to-Date Rates Netting Out Calendar Month of Birth



(a) Primary Series

(b) Booster Dose

Notes: This figure presents variation in up-to-date rates for the Hib vaccine for children born in different month-years in the MarketScan data. We present results after netting out birth month effects. In Panel (a), the dotted orange line and the solid green line are share up-to-date for primary series at 9 months and 62 months, respectively. In Panel (b), the dotted orange line and the solid green line are share up-to-date for the booster dose at 18 months and 62 months, respectively.

To quantify these descriptive effects, we estimate Equation 1 and report the results in Table 3, Panel A. These results show that shortage-exposed children were 26 percentage points less likely to be up-to-date on the booster dose at age 18 months (column 3), relative to individuals in other birth cohorts. The effect for the primary doses was smaller: at 9 months of age shortage-exposed cohorts were 4.5 percentage points less likely to be fully up-to-date on the primary series (column 2) and were only 0.9 percentage points less likely to have received any Hib doses (column 1).[29]

We also demonstrate that over time patients caught up on missed vaccine doses, though not completely. By age 62 months (at least two years after the end of the shortage for all cohorts), the exposed cohorts were still 4.4 percentage points less likely to be up-to-date on the Hib booster dose (column 6). These estimates are smaller than those at 18 months, indicating catch-up vaccination occurred. However, given that CDC recommendations for routine catch-up vaccination only extend through 59 months (thus making Hib vaccination after that age unlikely), our results imply that the Hib shortage had long-run effects on Hib vaccination coverage. Importantly, at 62 months of age we find no evidence of a statistically significant reduction in uptake of the primary series doses, based on either the

[29]For completeness we present in Appendix Table A3 estimated effects on age (in months) at receipt of each Hib dose. While a limitation of these analyses is that age is observed only among those that eventually receive the vaccine, we continue to find robust evidence that the shortage delayed receipt of Hib doses.

any dose measure (column 4) or the up-to-date measure (column 5).

Table 3: The Effect of the Shortage on Hib Vaccine Up-to-Date Rates

	(1) Any doses 9 months	(2) Primary UTD 9 months	(3) Booster UTD 18 months	(4) Any doses 62 months	(5) Primary UTD 62 months	(6) Booster UTD 62 months
Panel A						
Shortage Exposed	-0.009***	-0.045***	-0.258***	-0.003	-0.005	-0.044***
	(0.002)	(0.006)	(0.022)	(0.002)	(0.002)	(0.007)
	[0.000]	[0.000]	[0.000]	[0.219]	[0.098]	[0.000]
Mean	0.92	0.72	0.53	0.95	0.90	0.79
Observations	322784	322784	322784	322784	322784	322784
Panel B						
Pre-Trend	-0.000	-0.000	-0.000	0.000	-0.001*	-0.001
	(0.000)	(0.000)	(0.002)	(0.000)	(0.000)	(0.001)
	[0.892]	[0.204]	[0.858]	[0.415]	[0.063]	[0.206]
Pre-Shortage Mean	0.92	0.72	0.63	0.95	0.89	0.77
Observations	88740	88740	45594	88740	88740	45594

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Each column of each panel presents coefficient estimates from a separate regression using MarketScan data aggregated to the child level. The outcome variable is given in the column header and captures receipt of a given dose of the Hib vaccine. The indicator variables *Shortage Exposed* and *Shortage Adjacent* capture if a child's birth cohort was of age to receive a given vaccine dose during the shortage, or in an adjacent cohort. See Figure 3 for details. Robust standard errors, shown in parentheses, are clustered at the month-year of birth level. Wild clustered bootstrapped p-values are reported in brackets.

In Appendix Section A4, we include county-level demographics. Results are quantitatively similar. Our findings are also robust to the inclusion of state fixed effects and state level trends (available upon request).

5.3 Pre-trends

The identifying assumption in our estimation strategy is that, in the absence of the shortage, outcomes for shortage-exposed cohorts would have been similar to those for cohorts not affected by the shortage. While Figure 4 provides graphical evidence that outcomes for the pre-shortage and post-shortage cohorts are stable, we also estimate Equation

2 to test for linear trends in the outcome variables for the pre-shortage birth cohorts. These estimates, reported in Table 3, Panel B, are consistently small in magnitude, and only one is even marginally significant. These results provide evidence in support of our assumption that, in the absence of the shortage, Hib vaccination rates across cohorts would have remained stable.

5.4 Using National Immunization Survey - Child data

In this section we use NIS-Child data to examine the effects of the shortage on a nationally representative sample of children. Also, with the NIS-Child data we can examine heterogeneity in the effects of the shortage based on socio-economic status, including by race, income, maternal education, and by state VFC policy. The NIS-Child data are helpful because our main data include only commercially-insured children and lack socio-economic status. We present these results in Appendix Section A5.

These results show that states with Universal VFC programs experienced substantially larger reductions in uptake of the booster dose during the shortage. While the cause of this heterogeneity is unclear, one hypothesis is that in Universal VFC states, governments are able to more closely regulate vaccine supply and induce compliance with the recommended rationing policy.[30] Importantly, since we omit these states from our main analyses,[31] this result suggests that, if anything, our MarketScan results likely understate the true depth of the shortage.

We find no evidence of heterogeneity across the other dimensions we consider, including child insurance status, race, household income, or maternal education. These results suggests that the regulatory rationing implemented resulted in relatively equitable distribution of the Hib doses across the population. These findings also provide evidence of the external validity of our MarketScan results. We note, however, that because of limitations in the NIS data we cannot as granularly assign birth months and individual exposure to the shortage. This measurement error attenuates our estimates and weakens our ability to detect small amounts of heterogeneity.

[30] For example, the New York VFC program limited provider VFC orders of the Hib vaccine to be 75 percent of what the practice usually ordered, and only allowed providers to order Hib vaccines once a month (Blog, 2008).

[31] Recall that in universal VFC states recommended childhood vaccines are supplied by the government for free to all children, thus reducing the incentive for a provider to file an insurance claim and the probability that we observe vaccines in our data.

5.5 Pneumococcal vaccination

We next explore whether the shortage and rationing affected other health care. The Hib vaccine shortage and rationing could cause some patients to delay their vaccination visit until the Hib vaccine was available (thus delaying the receipt of other recommended preventive care), add a provider visit once the Hib vaccine became available, or switch providers in search of the Hib vaccine.

We begin our examination of health care spillovers by looking at the effects of the Hib shortage on uptake of the pneumococcal vaccine. Recall that the CDC recommends administering the pneumococcal vaccine on the same schedule as the Hib vaccine, but the pneumococcal vaccine supply was not short during our sample period. Thus, reductions in uptake of the pneumococcal vaccine among shortage-exposed cohorts is likely due to households delaying their vaccination visit until the Hib vaccine became available.[32] Results from the estimation of Equation 1 are presented in Table 4 and show no decline in up-to-date rates for pneumococcal primary doses.[33] We do find, however, a modest 2.9 percentage point reduction in the probability of being up-to-date on the pneumococcal booster dose at 18 months of age (column 3),[34] which translates to about 160,000 children receiving a delayed pneumococcal booster dose.[35] Table 4 Panel B consistently shows precisely estimated null pre-trends in pneumococcal vaccination, providing evidence for our identifying assumption that vaccination outcome *levels* during the shortage would have remained stable in the absence of the shortage.

Overall, the small to null results for pneumococcal are suggestive of the lack of a concurrent friction which would have also affected Hib vaccination, even in the absence of the shortage. This suggests an alternative identification strategy for measuring the shortage effect on Hib vaccination, where the pneumococcal vaccine is treated as the counterfactual for the Hib vaccine. Using pneumococcal as a counterfactual will account for other fac-

[32] One potential confounder is that, around the time of the Hib shortage, some states passed mandates that require the pneumococcal vaccine prior to enrolling in child care. To address this, for these analyses we drop states that passed pneumococcal mandates between 2006 and 2008, although our results are not sensitive to this decision. For completeness, we also verify that our main Hib results are robust to not including these states. These tables are available upon request.

[33] Figure A1 in the appendix presents the analog of Figure 4 for the pneumococcal vaccine.

[34] Appendix Table A4 presents the estimated effects on age (in months) at receipt of each pneumococcal dose. In Appendix Section A3, we also do a similar analysis with the DTaP and polio vaccines, which are on a similar, though not identical schedule as Hib. While they experience declines, they are much smaller in magnitude than those we see with the pneumococcal vaccine.

[35] There are about 3.75 million children born every year and the shortage lasted 1.5 years. Hence, $3.75 \text{ million} \times 1.5 \times 0.029 \approx 160,000$.

tors that could affect vaccination, although it may slightly understate the effects on the Hib vaccine due to spillover effects. In Appendix Section A6 we present results from a difference-in-differences analysis in which the pneumococcal vaccine is explicitly treated as the counterfactual. Our results are consistently robust to this alternative modeling strategy.

Table 4: The Effect of the Shortage on Pneumococcal Vaccine Up-to-Date Rates

	(1) Any doses 9 months	(2) Primary UTD 9 months	(3) Booster UTD 18 months	(4) Any doses 62 months	(5) Primary UTD 62 months	(6) Booster UTD 62 months
Panel A						
Shortage Exposed	-0.003	-0.005	-0.029***	-0.002	0.012*	0.012
	(0.004)	(0.006)	(0.006)	(0.004)	(0.005)	(0.007)
	[0.578]	[0.394]	[0.000]	[0.718]	[0.023]	[0.097]
Mean	0.90	0.71	0.67	0.94	0.89	0.82
Observations	177351	177351	177351	177351	177351	177351
Panel B						
Pre-Trend	0.000	0.000	-0.001	0.001**	0.001**	-0.000
	(0.000)	(0.000)	(0.001)	(0.000)	(0.000)	(0.001)
	[0.338]	[0.182]	[0.492]	[0.006]	[0.012]	[0.747]
Pre-Shortage Mean	0.87	0.69	0.62	0.91	0.86	0.74
Observations	48640	48640	24570	48640	48640	24570

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Each column of each panel presents coefficient estimates from a separate regression using MarketScan data aggregated to the child level; the outcome variable is given in the column header and measures receipt of a given dose of the pneumococcal vaccine (which was not in shortage). Robust standard errors, shown in parentheses, are clustered at the month-year of birth level. Wild clustered bootstrapped p-values are reported in brackets. For this analysis, we drop states that implemented pneumococcal mandates between 2006 and 2008.

5.6 Effects on number of visits

We next consider whether shortage-exposed children made additional doctors visits for vaccination. If patients are unable to receive a Hib vaccine dose during their routine preventive care visit due to the shortage, then they might need to return to their providers for additional visits. Additional visits can require copays, travel time, and hassle for patients, while increasing gridlock for providers.

Our measure of vaccination visits is defined as the number of observed visits where the infant received at least one dose of a set of childhood vaccines (Hib, pneumococcal, hepatitis A, DTaP, or polio).[36] We count visits with non-Hib vaccines in our measure because delayed Hib doses might be given during later routine vaccination visits, in which case the effect on congestion and hassle costs would be minimal. For this analysis, we define infants as shortage-exposed if they were of age to receive the Hib booster dose during the shortage, as these were the cohorts that experienced the largest changes in vaccination. We also limit our sample to those who are up-to-date on the pneumococcal and Hib booster at 62 months of age, to avoid attenuating our results by including children who never returned to receive delayed doses.

Table 5 presents evidence of the effect of the shortage on the number of vaccination visits; Figure A2 in the appendix presents the associated descriptive trends. These results show that, on average, shortage-exposed patients made 0.27 additional vaccination visits (Panel A, column 1), relative to non-exposed cohorts. This corresponds to roughly 1.5 million additional visits. Moreover, the results in column 2, in which the sample is restricted to children whose provider primarily used the Sanofi Pasteur vaccine prior to the shortage, demonstrates this increase in vaccination visits was not driven by individuals who would have received the 2-dose Merck primary vaccine series in the absence of the shortage, but now must receive the 3-dose Sanofi Pasteur vaccine series.

[36] When constructing this outcome we do not count doses of rotavirus, MMR, varicella, or hepatitis B vaccines, as these were either newly introduced or they experienced changes in the recommended schedule during our sample period.

Table 5: Effect of the Shortage on the Number of Visits by 62 Months

	(1) All Providers	(2) Provider Used Mostly Sanofi
Panel A		
Shortage Exposed	0.273***	0.282***
	(0.018)	(0.022)
	[0.000]	[0.000]
Mean	7.11	7.11
Observations	111741	60910
Panel B		
Pre-Trend	0.001	-0.000
	(0.002)	(0.003)
	[0.698]	[0.946]
Pre-Shortage Mean	6.93	6.93
Observations	17118	9756

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Each column of each panel presents coefficient estimates from a separate regression using MarketScan data aggregated to the child level. The outcome variable is the number of vaccine visits a child has at 62 months old, conditional on being up-to-date on the Hib and pneumococcal vaccine. Robust standard errors, shown in parentheses, are clustered at the month-year of birth level. Wild clustered bootstrapped p-values are reported in brackets.

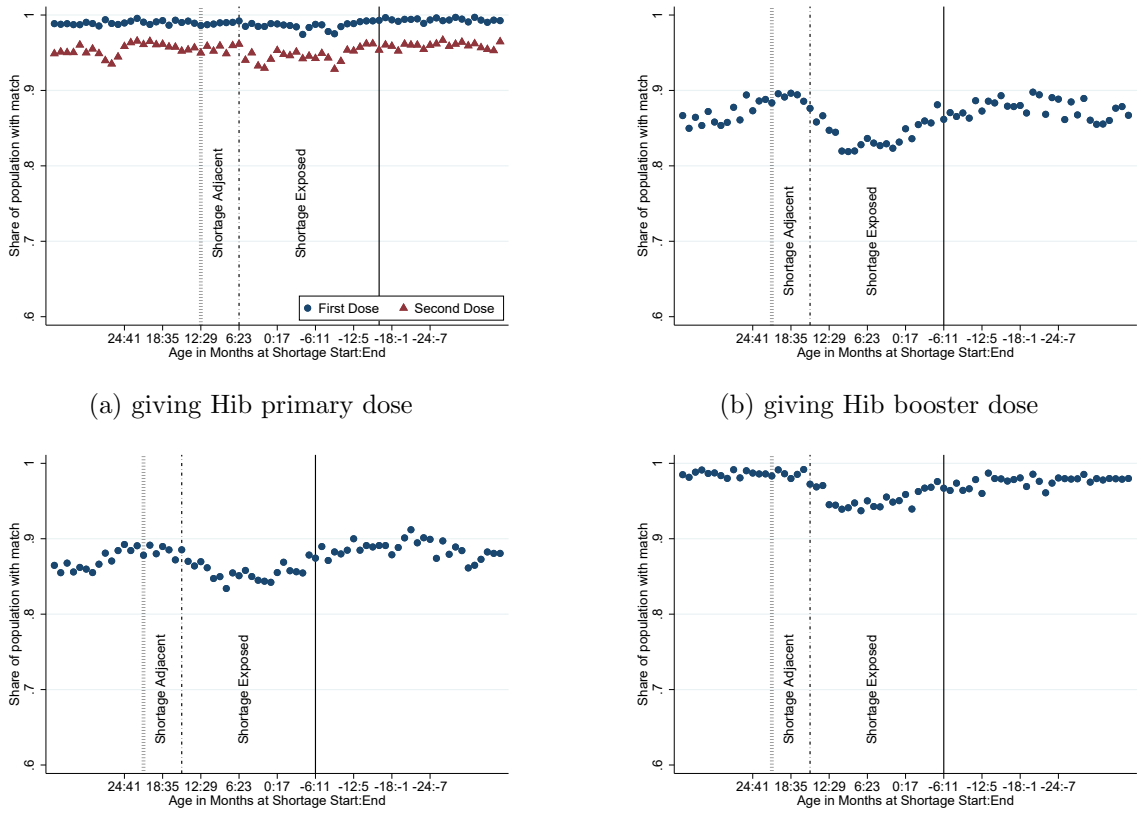
5.7 Effects on continuity of care

We next examine whether patients switched providers. Our primary measures of patient switching of providers are a series of indicator variables that capture if the provider that gave the infant their first *pneumococcal* vaccine dose was the same as the provider that gave that infant a subsequent vaccine. For each specification, the sample is limited to the set of patients who received both doses of interest, and had a valid provider identifier for both doses.

Results are presented in Figure 5 and Table 6. Across all doses considered, being in the shortage-exposed cohort reduces the probability that a patient sees the same provider for the index pneumococcal dose and for a given Hib dose. Prior to the shortage 99% of first Hib doses are given by the same provider as the first pneumococcal dose; this is 0.5 percentage points lower for individuals in shortage-exposed cohorts (blue circles in top left

of Figure 5 and Column 1 of Table 6). Reductions are larger for the booster doses of both the pneumococcal and Hib vaccine. On average, 87 percent of the pre-shortage cohort received both the pneumococcal and Hib booster doses from the same provider who administered the index pneumococcal dose. For the shortage-exposed cohorts the probability of receiving the booster dose from the same provider is 3.2 percentage points lower for Hib and 2.6 percentage points lower for the pneumococcal vaccine. In percentage terms, this is a 25 percent increase in the amount of switching for the Hib vaccine, as only 13 percent of children were switching providers before the shortage.

Figure 5: Probability That a Child Saw the Same Provider for the First Pneumococcal Dose and Later Doses



(a) giving Hib primary dose

(b) giving Hib booster dose

(c) giving pneumo. booster dose

(d) giving Hib booster dose, conditional

Notes: This figure presents variation in whether the provider who gave a child their first pneumococcal vaccine also gave the vaccine referenced in the caption or legend. Panel d is conditional on booster pneumococcal provider matching the first dose provider.

To identify the extent to which these were "one-off" switches in search of the Hib vaccine, we also look at whether the Hib booster dose was given by the same provider as the first pneumococcal dose, conditional on the pneumococcal booster dose being given by the first pneumococcal provider. This analysis shows that, among individuals that saw the same provider for their first and booster pneumococcal doses, there was a 2.5 percentage point decline in the probability of seeing that same provider for their Hib booster dose for the shortage exposed cohorts. (Table 6, column 5).

Table 6: Effect of the Shortage on the Probability That a Child Saw the Same Provider for the First Pneumococcal Dose and Later Doses

	(1)	(2)	(3)	(4)	(5)
	1st Hib	2nd Hib	Hib Booster	Pneumo Booster	Hib Booster Conditional on Pneumo
Panel A					
Shortage Exposed	-0.005***	-0.010***	-0.032***	-0.026***	-0.025***
	(0.001)	(0.002)	(0.004)	(0.003)	(0.003)
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
Mean	0.99	0.95	0.87	0.87	0.97
Observations	143739	134389	92842	101359	74770
Panel B					
Pre-Trend	0.0001*	0.0007***	0.0028***	0.0026***	0.0003*
	(0.0001)	(0.0001)	(0.0005)	(0.0004)	(0.0001)
	[0.0210]	[0.0000]	[0.0130]	[0.0060]	[0.0120]
Pre-Shortage Mean	0.99	0.96	0.87	0.87	0.99
Observations	48143	44590	15364	15436	11476

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Each column of each panel presents coefficient estimates from a separate regression using MarketScan data aggregated to the child level; the outcome variable is an indicator variable that measures whether the provider who gave a child their first pneumococcal vaccine dose also gave the vaccine dose referenced in the column header. Robust standard errors, shown in parentheses, are clustered at the month-year of birth level. Wild clustered bootstrapped p-values are reported in brackets.

5.8 Provider-Level Analyses

In our final set of analyses we characterize supply-side factors influencing the shortage depth. For these analyses, we compare provider-level Hib vaccination rates during the shortage to their rates during the two prior years. We allow the depth of the shortage to vary based on two pre-shortage provider characteristics: percent of Hib vaccines administered by the provider that were manufactured by Merck and percent of Hib vaccines administered in the county that were manufactured by Merck (omitting that provider's own doses).[37]

For each provider we approximate their Hib vaccination rate by dividing the number of

[37] In our data, providers tend to only use one type of vaccine: prior to the shortage 77% percent of providers used at least 80% Merck vaccines or 80% Sanofi Pasteur vaccines.

Hib doses by the number of pneumococcal vaccine doses the provider administered over the same time period. Although we document in Section 5.5 that the Hib shortage had modest negative spillover effects to uptake of the pneumococcal vaccine, those effects occurred only for the booster dose. Thus, for the booster dose analyses, we view these estimates as a lower bound on the true reduction in Hib immunization rates. See Appendix A7 for more details on the methodology.

Results from the provider-level analyses are presented in Appendix Table A18. These results show that the reduction in receipt of Hib primary doses was entirely driven by providers who predominantly used the Merck vaccine (for which production halted) prior to the shortage, suggesting that provider-level supply frictions are important and persistent. For Sanofi providers there was no measurable effect on the primary series.

For booster doses, on the other hand, providers increasingly reduced their use throughout the shortage. While we do not find a differential impact of reducing boosters by providers who used mostly Merck versus those who used mostly Sanofi, we do find that *counties* that used mostly Merck vaccines reduced their use of the booster more than other counties. This result is consistent with the idea that information about the shortage and recommended rationing policy took some time to disseminate, but was disseminated more rapidly in areas with more Merck-supplied providers, as a higher share of physicians likely knew directly about the issue.

6 Conclusions

We examine the effects of a Hib vaccine shortage and rationing. Our analysis has four main takeaways. First, we provide evidence that the rationing recommendation was effective. Providers mostly followed the rationing plan, reducing low-value booster doses to increase high-value primary doses. Only four percent of children fell behind on primary doses, whereas twenty-six percent fell behind on booster doses. In Appendix A8 we compute counterfactual analyses comparing the actual allocation of doses during the shortage to the best-case (full compliance) and worst-case (no compliance) scenarios. These counterfactuals suggest that the reallocation to primary doses was close to the best case scenario where physicians comply perfectly.

In many settings with scarce resources, economists recommend rationing using prices rather than regulatory rationing. However, price rationing typically fails to account for externalities, such as the external benefits of vaccination against an infectious disease, and

can be inequitable if vaccines are allocated based on ability to pay. Our results, though, show that regulatory rationing successfully reallocated many booster doses to higher-value primary series doses.[38] Moreover, heterogeneity analyses using the NIS-Child suggest that these doses were also distributed fairly equitably across the population. We find no evidence of consistent differences across race/ethnicity, household income, or maternal education.

Second, we show the long-run effects of the shortage on Hib vaccination rates. We find that many patients caught up. However, years after the shortage resolved, shortage-exposed cohorts remained 4 percentage points less likely to have received their booster dose. Understanding these long-run effects is important given that the level of population immunity directly affects the probability of disease transmission. These results also suggest that polices such as vaccine reminder letters, which have been effective in other contexts (Hirani, 2021; Milkman et al., 2021), may be a useful policy complement to regulatory rationing.

Third, while the regulatory rationing appears effective, the shortage was broadly disruptive in the healthcare system. Our results suggest that the shortage caused patients to delay receipt of the pneumococcal vaccine, make additional vaccination visits, and switch providers in search of available Hib doses. Quantifying these patient responses may help policymakers to be aware of these other costs when crafting future rationing plans.

Finally, our provider level analyses suggest that attention to supply chain frictions may be important. For Sanofi providers there was no measurable effect on Hib primary series vaccination. However, providers who used mostly Merck vaccines prior to the shortage gave fewer primary series doses throughout the entire shortage, with the largest effects during the first six months.

While these takeaways apply to many drug and vaccine shortages, we advise caution when extrapolating to other contexts, including the COVID-19 vaccine shortage. The COVID-19 vaccine shortage followed a demand shock, whereas the Hib vaccine shortage followed a supply shock. Also, the COVID-19 vaccine shortage occurred during a period with high burden of disease, whereas the Hib vaccine shortage occurred during a period with low burden of disease. Nevertheless, for both Hib and COVID-19, government agencies had success rationing vaccines toward high-value uses.

[38] We find no change in the prices of these vaccines during the sample period, as shown in Figure A4.

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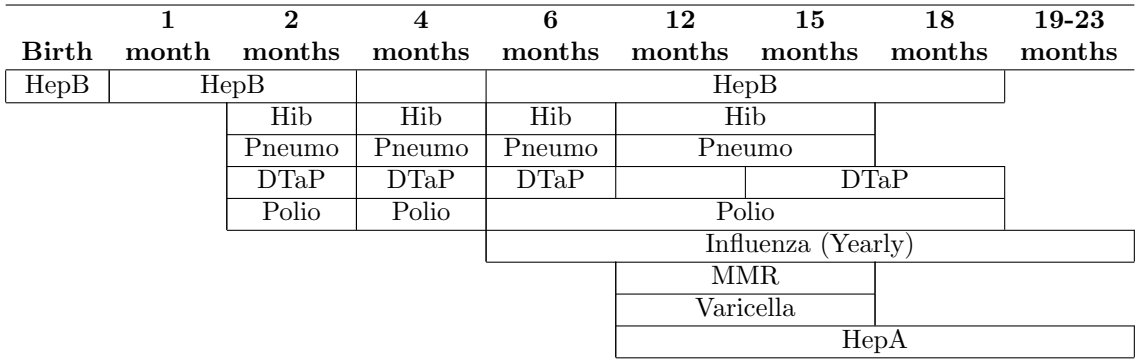
A1 Other Analyses Referenced in the Text

Table A1: Recommended vaccinations from birth to 24 months.



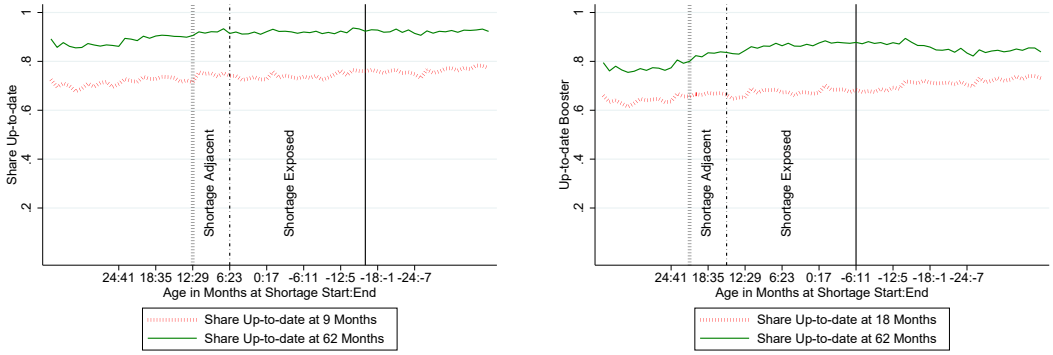
Notes: DTaP is a diphtheria, tetanus, and pertussis vaccine; HepA is a hepatitis A vaccine; HepB is a hepatitis B vaccine; Hib is a Haemophilus influenzae type b vaccine; MMR is a measles, mumps, and rubella vaccine; Pneumo is a pneumococcus vaccine; and RV is a rotavirus vaccine. Source: Centers for Disease Control and Prevention.

Table A2: Summary Statistics for Pneumoccocal Vaccine Outcomes

	(1) Full Sample	(2) Exposed during Primary	(3) Exposed during Booster	(4) Never Exposed
Any Pneumo Doses, 9 Months	0.896	0.893	0.890	0.900
	(0.305)	(0.309)	(0.313)	(0.300)
Pneumo UTD Primary, 9 Months	0.720	0.715	0.709	0.724
	(0.449)	(0.452)	(0.454)	(0.447)
Pneumo UTD Booster, 18 Months	0.663	0.657	0.646	0.671
	(0.473)	(0.475)	(0.478)	(0.470)
Any Pneumo Doses, 62 Months	0.930	0.927	0.925	0.932
	(0.255)	(0.260)	(0.264)	(0.252)
Pneumo UTD Primary, 62 Months	0.884	0.889	0.884	0.880
	(0.321)	(0.314)	(0.320)	(0.324)
Pneumo UTD Booster, 62 Months	0.809	0.831	0.819	0.794
	(0.393)	(0.375)	(0.385)	(0.404)
Observations	177351	60636	54475	95303

Notes: Summary statistics for outcomes and treatments for different samples using Marketscan data aggregated to the child level. The mean is listed with the standard deviation in parentheses below. Children could have been exposed during the primary series and the booster series, so columns 2-4 do not add up to the full sample of observations. See Figure 3 for details. For this table, we drop stats that implemented pneumococcal mandates between 2006 and 2008. "UTD" indicates up to date.

Figure A1: Up-to-Date Rates Netting Out Birth Month for Pneumococcal Vaccine

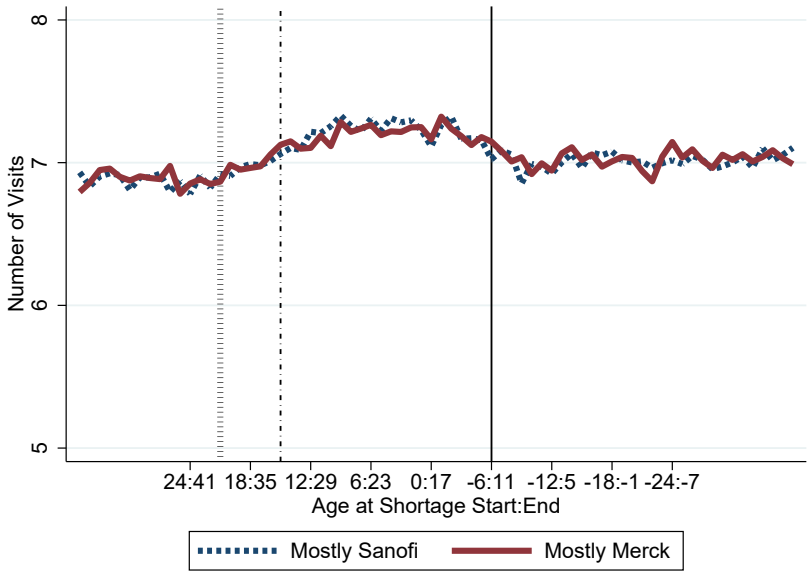


(a) Primary Series

(b) Booster Series

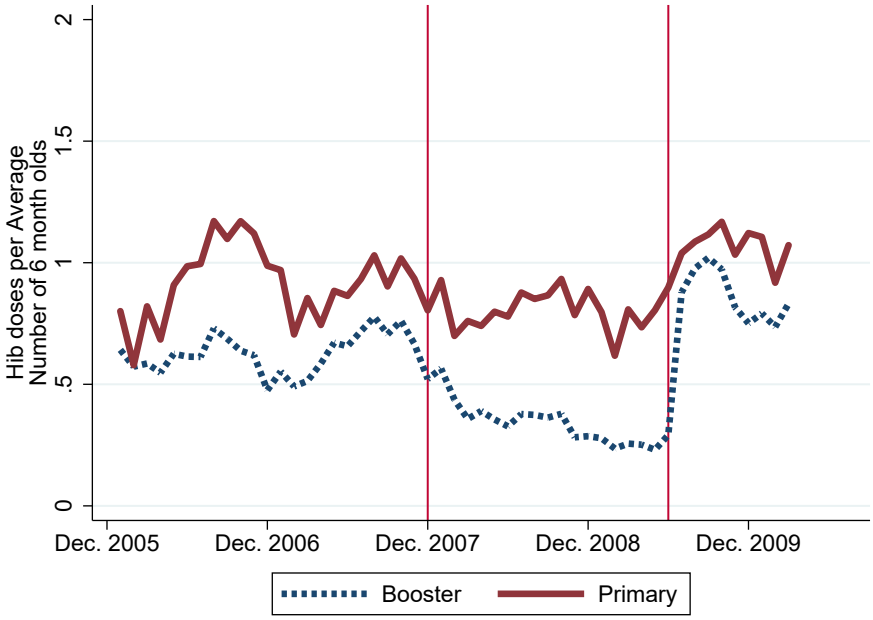
Notes: This figure presents variation in up-to-date rates for the pneumococcal vaccine (which was *not* in shortage) for children born in different month-years in the MarketScan data. We present results after netting out birth month effects. In Panel (a), the dotted orange line and the solid green line are share up-to-date for primary series at 9 months and 62 months, respectively. In Panel (b), the dotted orange line and the solid green line are share up-to-date for booster series at 18 months and 62 months, respectively.

Figure A2: Number of Vaccination Visits



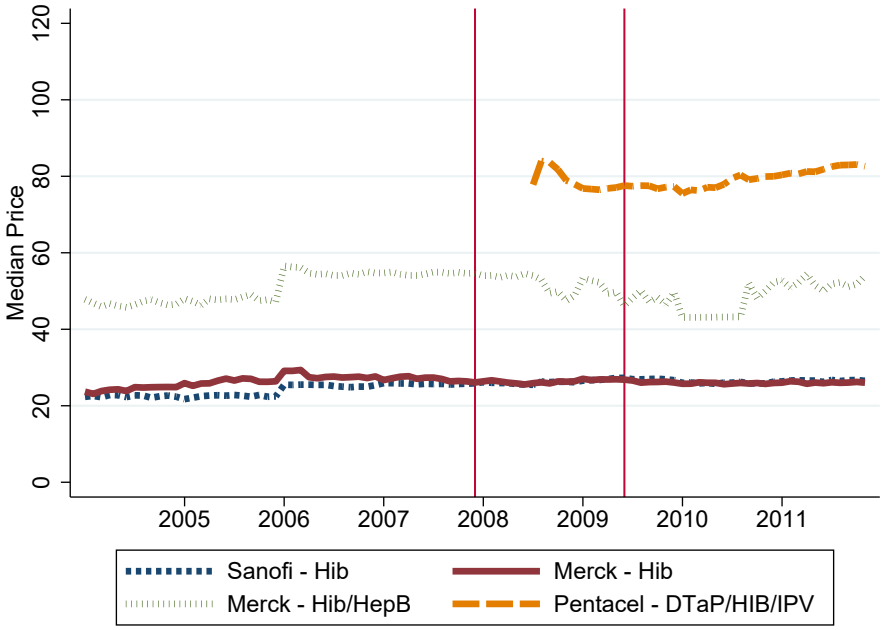
Notes: This figure plots the average number of visits at which a child in a given birth cohort received at least one dose of the hepatitis A, Hib, pneumococcal, or DTaP vaccine, net of calendar month of birth fixed effects. Inclusion in the sample is conditional on being up-to-date on Hib and pneumococcal at 62 months, to avoid counting fewer visits for those missing vaccines. The dashed blue line represents children whose provider primarily administered Sanofi Hib vaccines during the pre-shortage period; the solid red line represents children whose provided primarily administered Merck manufactured Hib vaccines during the pre-shortage period.

Figure A3: Number of Hib doses per child administered per month



Notes: The outcome variable is Hib doses administered in a given month, divided by the average number of 6-month-old children in the MarketScan data in a year. The vertical axis is scaled by the number of doses in each series, so the value of one approximates a child being up-to-date in the series. A series is two primary doses of the Merck vaccine, three primary doses of the Sanofi Pasteur vaccine, or one booster dose.

Figure A4: Median Monthly Price Per Dose for Leading Hib Vaccines



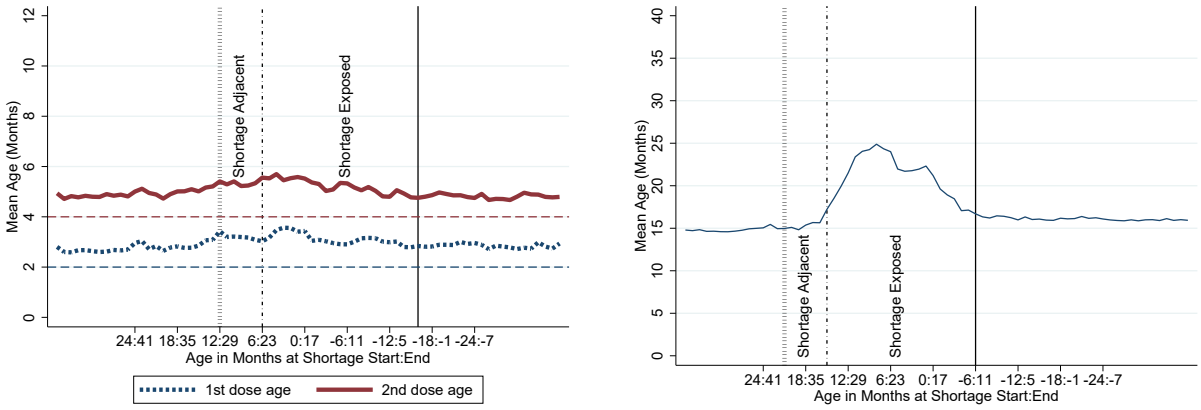
Notes: This figure presents prices, in nominal dollars (not adjusted for inflation), for various vaccines, at the monthly level, throughout our sample period.

A2 Effects on timing of care

In this section, we estimate the effect of the Hib vaccine shortage on the patient's age (in months) at receipt of the Hib and pneumococcal vaccines. While this measure has the advantage of allowing us to quantify how long care receipt was delayed as a result of the shortage, it is only observed for those that ever receive a dose of the vaccine.

Figures A5 and A6 graphically present the mean age at receipt for the booster dose of the Hib and pneumococcal vaccine series, conditional on receiving the relevant dose. There is a large visual increase in the mean age for Hib booster dose; the increase for pneumococcal booster and Hib primary series is more muted, but still visible.

Figure A5: Age of Receipt (in Months) for Hib Doses

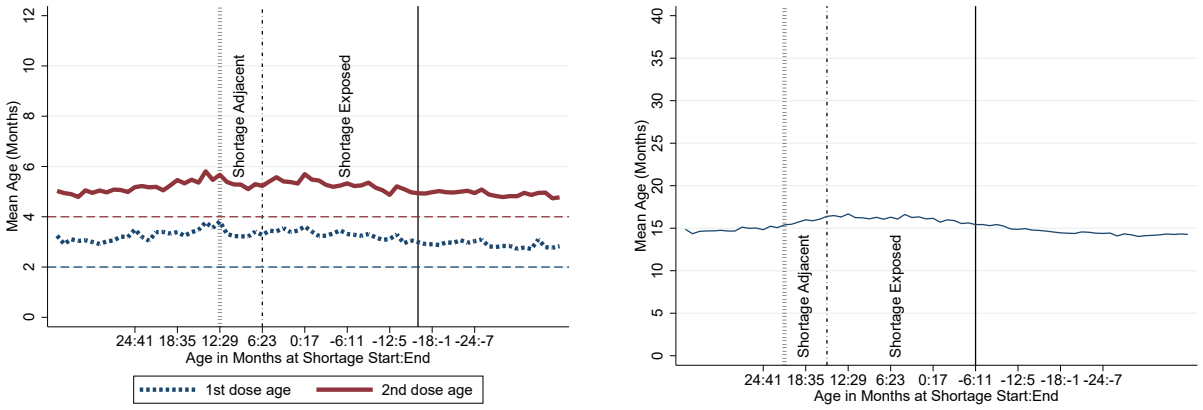


(a) Primary Series Doses

(b) Booster Series

Notes: Each figure shows variation in the mean age of receipt for the vaccine given in the panel label in the MarketScan data. The dashed horizontal lines refer to the primary dose schedule.

Figure A6: Age of Receipt (in Months) for Pneumococcal Doses



(a) Primary Series Doses

(b) Booster Series

Notes: Each figure shows variation in the mean age of receipt for the vaccine given in the panel label in the MarketScan data. The dashed horizontal lines refer to the primary dose schedule.

The results from estimating Equation 1 are presented in Tables A3 and A4. These results show that, conditional on receiving a booster dose of the Hib vaccine, shortage-exposed individuals were on average 5.1 months older at the time of receipt than individuals in the non-exposed cohorts (column 3) of Table A3. Consistent with the figures, we find significant, though smaller, increases in the age at which infants receive the pneumococcal booster dose: children in shortage-exposed cohorts are on average 1.5 months older when they receive the booster dose of the pneumococcal vaccine, relative to non-exposed cohorts.

Notably, analyses of the pre-trends in these outcomes (Panel B) does suggest that the mean age of receipt was increasing for both of the vaccines even prior to the shortage. This may be because those born just before the shortage adjacent cohort may still receive doses later than they would have if they would have received the doses during the shortage. Still the magnitudes of these trends, for the booster doses, are sufficiently small that, on average, they explain only 4 and 25 percent of the estimated main effect on age at Hib and pneumococcal booster vaccine receipt, respectively.[39] Therefore, these analyses overall suggest that the Hib vaccine shortage caused families to delay provider encounters, thus negatively affecting timely receipt of other pediatric vaccines and increasing vulnerability to other diseases.

[39]Given that the shortage lasted 18 months, the average magnitude of the pre-trend was calculated as 9 months $\times$ pre-trend coefficient estimate.

Table A3: Effect of Shortage on Age at Receipt of a Hib Dose, Conditional on Receipt

	(1) Age 1st Dose	(2) Age 2nd Dose	(3) Age Booster Dose
Panel A			
Shortage Exposed	0.277***	0.346***	5.086***
	(0.041)	(0.052)	(0.571)
	[0.000]	[0.000]	[0.000]
Mean	2.89	5.02	17.18
Observations	307973	293297	230472
Panel B			
Pre-Trend	0.012***	0.014***	0.023*
	(0.003)	(0.003)	(0.010)
	[0.000]	[0.000]	[0.073]
Pre-Shortage Mean	2.72	4.93	14.82
Observations	84599	80463	32630

Note: Each column presents coefficient estimates from a separate regression using MarketScan data aggregated to the child level; the outcome variable is the age in months of a child receiving the dose of the Hib vaccine referenced in the header. Robust standard errors, shown in parentheses, are clustered at the month-year of birth level. Wild clustered bootstrapped p-values are reported in brackets.

Table A4: Effect of Shortage on Age of Dose – Pneumococcal, Conditional on Receipt

	(1) Age 1st Dose	(2) Age 2nd Dose	(3) Age 3rd Dose	(4) Age Booster Dose
Panel A				
Shortage Exposed	0.205***	0.216***	0.266***	1.535***
	(0.047)	(0.044)	(0.056)	(0.078)
	[0.000]	[0.000]	[0.000]	[0.000]
Mean	3.11	5.14	7.79	15.19
Observations	302753	289919	276970	244335
Panel B				
Pre-Trend	0.027***	0.031***	0.030***	0.044***
	(0.003)	(0.004)	(0.003)	(0.008)
	[0.000]	[0.000]	[0.000]	[0.000]
Pre-Shortage Mean	3.21	5.20	7.83	14.83
Observations	81875	77943	73840	31746

Note: Each column presents coefficient estimates from a separate regression using MarketScan data aggregated to the child level; the outcome variable is the age in months of a child receiving the dose of the pneumococcal vaccine referenced in the header. Robust standard errors, shown in parentheses, are clustered at the month-year of birth level. Wild clustered bootstrapped p-values are reported in brackets.

A3 DTaP and Polio Placebos

To provide further support that the declines in Hib up-to-date rates were driven by the shortage, as opposed to other unobserved shocks (e.g changes in access to vaccines or vaccination hesitancy), we also examine changes in up-to-date rates for the DTaP and polio vaccines. The recommended schedule for these vaccines is shown in Table A1, and while it is similar to the schedule for the Hib vaccine, there are some differences. Notably, the third dose of the polio vaccine is recommended between the ages of 6 and 18 months, overlapping with the timing of both the 3rd and booster Hib doses (recommended at 6 and 12-15 months, respectively). For DTaP, the 4th dose is recommended at 15-18 months, overlapping with the Hib booster dose timing.

Our outcome variables for these analyses are indicator variables capturing if a patient is up-to-date with either the DTaP or polio vaccine.[40] One important limitation of the

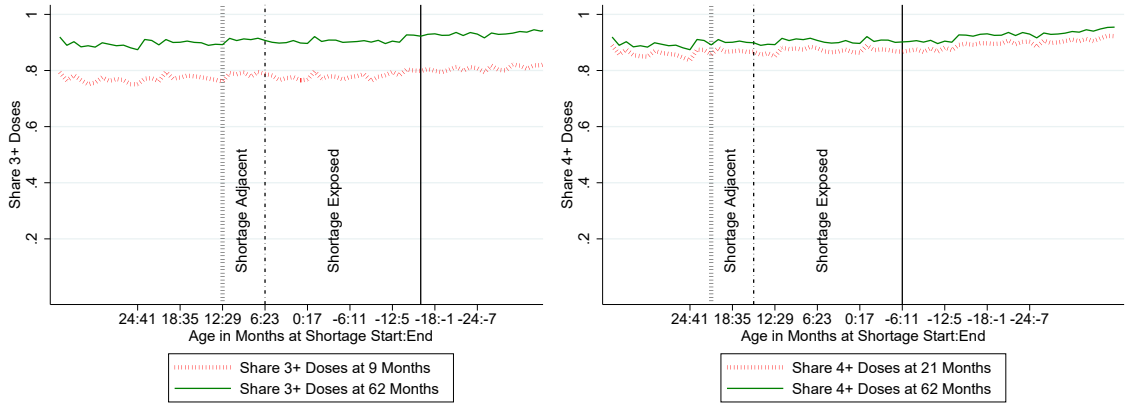
[40]For the Hib and pneumococcal vaccines we examined up-to-date rates 3 months after the age of rec-

analyses examining up-to-date rates of the polio vaccine is that, independently of the Hib shortage, the age of receipt was likely changing over our sample period due to the introduction of a combination vaccine, Pentacel, in June 2008. The Pentacel vaccine contains DTaP, polio, and Hib, and is recommended to be received at ages 2, 4, 6, and 15-18 months. While this dose schedule aligns exactly with the recommended schedule for DTaP, it implies that the third dose of polio (recommended between ages 6-18 months) will be received relatively earlier (i.e. close to 6 months) for children who receive their polio doses from the Pentacel combination vaccine. This would bias our results to be more negative for the third polio dose as children would have received this dose earlier, after the shortage ends. To address this, we also tried a specification which includes a post period indicator. Results are similar and the table is available upon request.

The results examining the effects of the shortage on up-to-date rates for the DTaP vaccine are presented in Figure A7 and Table A5; Figure A8 and Table A6 present results for polio. Overall, during the Hib shortage, we see significant declines in up-to-date rates for the DTaP and polio vaccines. These reductions, however, are consistently small in magnitude, particularly relative to the magnitude of the corresponding estimate for the Hib vaccine. Across all outcomes we also find no evidence of a pre-existing linear trend (Panel B). Therefore, these analyses provide support for the idea that the large reductions observed in uptake of the Hib vaccine are driven by the shortage, as opposed to other unobserved shocks or pre-existing trends.

ommended vaccine administration, to allow for measurement error in the age of the child in months and to capture children who received their vaccine doses only a couple of months late. For the DTaP and polio vaccines, because the 4th and 3rd doses are respectively recommended to be received by 18 months of age, we use 21 months (18 + 3 month buffer) as our endpoint for those doses.

Figure A7: Share receiving 3 and 4 doses of a DTaP containing vaccine



(a) Third DTaP Dose

(b) Fourth DTaP Dose

Notes: This figure presents variation in up-to-date rates for the third and fourth doses of the DTaP vaccine for children born in different month-years in the Marketscan data.

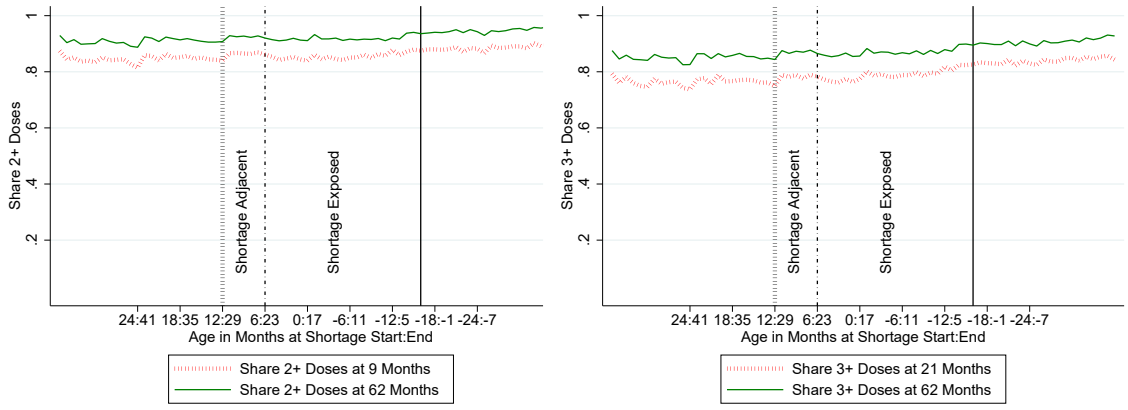
Table A5: Effect of the Shortage on Up-to-Date Rates for DTaP

	(1) Any doses 9 months	(2) Three doses 9 months	(3) Four doses 21 months	(4) Any doses 62 months	(5) Three doses 62 months	(6) Four doses 62 months
Panel A						
Shortage Exposed	-0.006*	-0.007	-0.016***	-0.010***	-0.007*	-0.014***
	(0.003)	(0.004)	(0.003)	(0.003)	(0.003)	(0.003)
	[0.034]	[0.095]	[0.000]	[0.004]	[0.051]	[0.000]
Mean	0.91	0.75	0.85	0.97	0.89	0.89
Observations	322784	322784	322784	322784	322784	322784
Panel B						
Pre-Trend	-0.000	-0.000	-0.001	0.000	-0.000	-0.001
	(0.000)	(0.000)	(0.001)	(0.000)	(0.000)	(0.001)
	[0.638]	[0.779]	[0.232]	[0.817]	[0.634]	[0.374]
Pre-Shortage Mean	0.90	0.73	0.84	0.96	0.88	0.88
Observations	88740	88740	45594	88740	88740	45594

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Each column of each panel presents coefficient estimates from a separate regression using MarketScan data aggregated to the child level; the outcome variable is given in the column header and captures receipt of a given dose of the DTaP vaccine. Robust standard errors, shown in parentheses, are clustered at the month-year of birth level. Wild clustered bootstrapped p-values are reported in brackets.

Figure A8: Share receiving 2 and 3 doses of a polio containing vaccine



(a) Second Polio Dose

(b) Third Polio Dose

This figure presents variation in up-to-date rates for the second and third doses of the polio vaccine for children born in different month-years in the Marketscan data.

Table A6: Effect of the Shortage on Up-to-Date Rates for Polio

	(1) Any doses 9 months	(2) Two doses 9 months	(3) Three doses 21 months	(4) Any doses 62 months	(5) Two doses 62 months	(6) Three doses 62 months
Panel A						
Shortage Exposed	-0.009***	-0.009*	-0.011	-0.008**	-0.008*	-0.008
	(0.002)	(0.004)	(0.007)	(0.003)	(0.003)	(0.005)
	[0.000]	[0.034]	[0.133]	[0.008]	[0.030]	[0.121]
Mean	0.90	0.84	0.77	0.97	0.91	0.86
Observations	322784	322784	322784	322784	322784	322784
Panel B						
Pre-Trend	-0.000	-0.000	-0.000	0.000	-0.000	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
	[0.738]	[0.459]	[0.402]	[0.905]	[0.569]	[0.405]
Pre-Shortage Mean	0.89	0.82	0.74	0.95	0.89	0.83
Observations	88740	88740	88740	88740	88740	88740

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Each column of each panel presents coefficient estimates from a separate regression using MarketScan data aggregated to the child level; the outcome variable is given in the column header and captures receipt of a given dose of the polio vaccine. The indicator variables *Shortage Exposed* and *Shortage Adjacent* capture if a child's birth cohort was of age to receive a given vaccine dose during the shortage, or in an adjacent cohort, respectively. See Figure 3 for details. Robust standard errors, shown in parentheses, are clustered at the month-year of birth level. Wild clustered bootstrapped p-values are reported in brackets.

A4 Including county-level controls

Table A7: Summary Statistics for Other Demographics

	(1) Full Sample	(2) Exposed during Primary	(3) Exposed during Booster	(4) Never Exposed
Family Size	3.777	3.801	3.797	3.764
	(1.189)	(1.216)	(1.216)	(1.171)
Income ($10,000s)	6.823	6.817	6.775	6.845
	(1.471)	(1.460)	(1.442)	(1.489)
% Rural	0.208	0.207	0.212	0.207
	(0.239)	(0.237)	(0.240)	(0.239)
% African American	0.141	0.140	0.141	0.140
	(0.129)	(0.129)	(0.129)	(0.129)
% Hispanic	0.146	0.146	0.148	0.145
	(0.155)	(0.155)	(0.156)	(0.155)
% College	0.609	0.609	0.606	0.610
	(0.104)	(0.104)	(0.104)	(0.104)
% High School	0.800	0.799	0.801	0.801
	(0.079)	(0.079)	(0.078)	(0.079)
PCPs	89.376	89.390	87.968	89.912
	(42.700)	(43.002)	(41.622)	(43.010)
Teen Births	42.526	42.462	43.359	42.160
	(17.495)	(17.420)	(17.578)	(17.455)
% Diabetic Screening	0.824	0.824	0.823	0.825
	(0.038)	(0.038)	(0.039)	(0.038)
Merck Share	0.414	0.417	0.413	0.414
	(0.402)	(0.400)	(0.399)	(0.404)
Observations	322784	107833	98739	175470

Notes: The mean is listed with the standard deviation in parentheses below. Source: Authors' using Marketscan and Robert Wood Johnson County Health Rankings.

Table A8: Effect of the Shortage on Hib Vaccine Up-to-Date Rates, including county-level controls

	(1) Any doses 9 months	(2) Primary UTD 9 months	(3) Booster UTD 18 months	(4) Any doses 62 months	(5) Primary UTD 62 months	(6) Booster UTD 62 months
Panel A						
Shortage Exposed	-0.008**	-0.038***	-0.254***	-0.002	-0.001	-0.038***
	(0.002)	(0.005)	(0.022)	(0.002)	(0.002)	(0.008)
	[0.009]	[0.000]	[0.000]	[0.530]	[0.702]	[0.000]
Mean	0.92	0.72	0.53	0.95	0.90	0.79
Observations	263069	263069	263069	263069	263069	263069
Panel B						
Pre-Trend	-0.000	-0.000	-0.000	0.000	-0.001*	-0.001
	(0.000)	(0.000)	(0.002)	(0.000)	(0.000)	(0.001)
	[0.864]	[0.210]	[0.861]	[0.427]	[0.081]	[0.207]
Pre-Shortage Mean	0.92	0.72	0.63	0.95	0.89	0.77
Observations	88740	88740	45594	88740	88740	45594

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Each column of each panel presents coefficient estimates from a separate regression using MarketScan data aggregated to the child level; the outcome variable is given in the column header and captures receipt of a given dose of the Hib vaccine. Robust standard errors, shown in parentheses, are clustered at the month-year of birth level. Wild clustered bootstrapped p-values are reported in brackets.

A5 National Immunization Survey-Child data results

Data: We supplement our primary analyses using data from the National Immunization Survey-Child (NIS-Child), 2002-2019. The NIS-Child is a nationally representative random digit dialing survey that targets children aged 19 to 35 months old. This survey is conducted in two parts: (1) a household survey that collects information on household and child characteristics, and (2) a survey of the child's healthcare provider(s) that collects detailed information on the child's vaccination history. The vaccination information collected from providers includes number and type of vaccine doses received at the time of survey, as well as age in days for each of the doses. Due to changes in the availability of individual level characteristics over time, for our regression analyses we restrict out sample to the 2005-2015 survey waves;[41] this corresponds to children born from 2002 through 2014. We also restrict our sample to exclude Alaskan residents, as Alaskan natives are considered to be a high risk group for Hib and therefore were not included in the CDC recommendation to delay the booster series (CDC, 2007). Overall, in our final sample there are approximately 14,500 to 21,000 children each year with both a completed household survey and adequate provider data.

The primary outcomes we examine in these data are indicator variables capturing whether the child has received at least one, two, or three doses of the Hib vaccine by age 18 months. Unfortuantely, these data do not consistently distinguish between Merck or Sanofi Pasteur manufactured Hib vaccines, so we are unable to construct more precise measures of up-to-date status or to differentiate between primary and booster series doses. Importantly, however, unlike the MarketScan data, the NIS-Child data contain immunization information regardless of child insurance status or provider billing decision. Thus, these data allow us to examine the effects of the shortage on vaccination rates for a nationally representative population.

To determine whether a given child was exposed to the shortage, we first assign each child a birth year, based on their year of interview and age at the time of interview (available in bins: 19-24 months, 25-29 months, and 30-34 months).[42] We then define those born in either 2007 or 2008 to be shortage-exposed. Descriptive trends in the outcome variables

[41] Specifically, family income is only available after 2005. The mother's binned age is not available after 2015.

[42] For those who are interviewed when 19-24 months old, we set their birth year equal to their interview year minus one. For those 25-29 months old or 30-34 months old, we set their birth year equal to their interview year minus two.

across birth cohorts are plotted in Figure A9. This figure shows a sharp drop in the share of children receiving 3+ Hib doses by age 18 months, corresponding with the timing of the shortage. Notably, Hib vaccination rates are relatively stable before and after the shortage.

Methods: For these analyses we estimate the following modified version of Equation 1:

$$Y_{cm} = \beta_0 + \beta_1 \mathbb{1}(Exposed_m) + \beta_2 X_c + \gamma_s + \epsilon_{cm} \tag{A1}$$

Where our outcome, Y_{cm}, is an indicator variable capturing whether child c in birth cohort m has had at least one, two, or three Hib containing vaccinations at the age of 18 months old.[43] $\mathbb{1}(Exposed_m)$ is an indicator for whether the child is in the shortage-exposed cohort, defined as being born in either 2007 or 2008. In this specification we omit the $\mathbb{1}(Shortage\ Adjacent_m)$ indicator because birth cohorts are measured less precisely, relative to MarketScan. X_c is a vector of child-level characteristics observed at the time of survey, including measures of household demographics and socioeconomic status;[44] γ_s are state fixed effects. All results use survey weights and standard errors are clustered by birth year. We also compute p-values using a wild clustered bootstrap. As in our baseline model, identification is based on the assumption that, in the absence of the shortage, the outcomes would have been similar for shortage-exposed and non-exposed cohorts.

To test for heterogeneity in the effects of the shortage, we additionally include the interaction between $\mathbb{1}(Exposed_m)$ and a measure of a given individual-level characteristic, Z_c, as follows:

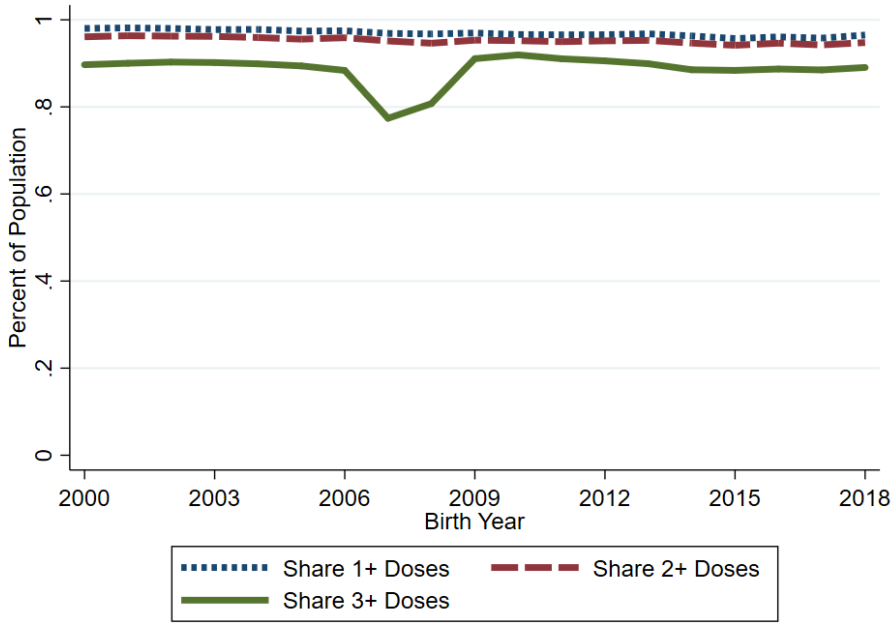
$$Y_{cm} = \beta_0 + \beta_1 \mathbb{1}(Exposed_m) + \beta_2 \mathbb{1}(Exposed_m) \times Z_c + \beta_3 X_c + \gamma_s + \epsilon_{cm} \tag{A2}$$

Where Z_c represents one characteristic out of the vector X_c. The coefficient on the interaction term, β_2, measures whether certain groups were differentially affected by the

[43] We limit to 18 months old because children begin to be interviewed at 18 months. If we used an older age (e.g. 21 months), then we might miss children vaccinated between 18 and 21 months, but interviewed at 18 months. We focus on 3 doses because many do not receive a 4th dose due to Merck not requiring it.

[44] We use the following variables as controls: education of the mother, the race of the child, family income (binned as below poverty, above poverty but below \$75k, and above \$75k), the number of people in the household, whether the child was breast fed, whether the child received WIC, the language the interview was conducted in, the mother's age. We do not include insurance variables as controls because they only began being asked in 2007, limiting our pre-period. However, we do check for heterogeneity by insurance status.

Figure A9: Number of Hib Doses per Child in the NIS Data



Notes: This figure presents variation in the share of children having received 1, 2, or 3 of the Hib vaccine in the NIS data. Number of doses is measured at 18 months because some children were interviewed as early as 19 months old. Birth year is fuzzy as only age in months at time of interview is reported in 6 month bins and we only know the interview year.

shortage.

Results: Table A9 presents results without the interaction term, which provide a baseline for the national average decline in up-to-date rates. All later results provide evidence on individual groups deviations from a baseline group. We observe no statistically significant decline in one or two doses received, and a 9.7-9.9 percentage point decline in the probability of having received 3 or more doses by age 18 months. Note that the lack of precision in the definition of which cohorts are shortage-exposed and the lack of information about whether a child is on a two or three dose primary series means we are averaging over many different birth cohorts who may be differently affected. This should attenuate our results.

Table A9: Effect of the Shortage on Hib Vaccine Receipt, NIS-Child

	1+ Doses	1+ Doses	2+ Doses	2+ Doses	3+ Doses	3+ Doses
Shortage Exposed	-0.00192	-0.00138	-0.00449	-0.00342	-0.0992***	-0.0970***
	(0.002)	(0.002)	(0.004)	(0.004)	(0.010)	(0.009)
	[0.489]	[0.595]	[0.447]	[0.540]	[0.000]	[0.000]
State Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Other Controls	No	Yes	No	Yes	No	Yes
Sample Mean	0.98	0.98	0.96	0.96	0.89	0.89
Observations	182407	182405	182407	182405	182407	182405

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Each column presents coefficient estimates from a separate regression using NIS data at the child level. The outcome variable is an indicator for whether a child has received at least the number of Hib doses as specified in the column header. Odd columns only include state fixed effects, while even columns include additional control variables. Shortage exposed means that a child was born in 2007 or 2008, based on our fuzzy assignment of birth years. Robust standard errors, shown in parentheses, are clustered at the birth-year. Wild clustered bootstrapped p-values are reported in brackets.

Tables A10 through A16 present results examining heterogeneity across different demographic groups. For each table, the excluded group is listed in the header. Briefly, these results show that there were larger reductions in uptake of the Hib vaccine in states with universal VFC programs (Table A16). Because we omit these states from our main analyses (given that providers have reduced incentive to file insurance claims when vaccines are being provided by the government), this result suggests that, if anything, our main results likely understate the true depth of the shortage. Across all of the other characteristics we consider, including race, maternal education, household income, and insurance status, we find no evidence of significant heterogeneity once we bootstrap standard errors. These findings provide support for the external validity of our MarketScan results.

Table A10: Effect of the Shortage on Hib Vaccine Receipt: Heterogeneity by Maternal Education
Omitted Category: Less than 12 years of education

	1+ Doses	1+ Doses	2+ Doses	2+ Doses	3+ Doses	3+ Doses
Shortage Exposed	-0.00279	-0.00191	-0.00764	-0.00573	-0.0813***	-0.0772***
	(0.005)	(0.005)	(0.006)	(0.006)	(0.005)	(0.006)
	[0.626]	[0.769]	[0.301]	[0.433]	[0.003]	[0.010]
Shortage Exposed × =12 years	-0.00202	-0.00287	0.000832	-0.000864	-0.0213	-0.0244
	(0.005)	(0.005)	(0.005)	(0.005)	(0.013)	(0.014)
	[0.745]	[0.602]	[0.882]	[0.890]	[0.237]	[0.138]
Shortage Exposed × >12 years	0.00687	0.00619	0.0119	0.0102	-0.0132*	-0.0175**
	(0.003)	(0.003)	(0.006)	(0.006)	(0.005)	(0.005)
	[0.158]	[0.171]	[0.172]	[0.171]	[0.144]	[0.102]
Shortage Exposed × College Grad	0.00157	0.000734	0.00394	0.00201	-0.0248	-0.0292
	(0.004)	(0.005)	(0.005)	(0.006)	(0.014)	(0.014)
	[0.756]	[0.881]	[0.490]	[0.738]	[0.099]	[0.082]
State Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Other Controls	No	Yes	No	Yes	No	Yes
Sample Mean	0.98	0.98	0.96	0.96	0.89	0.89
Observations	182407	182405	182407	182405	182407	182405

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Notes: Each column presents coefficient estimates from a separate regression using NIS data at the child level. The outcome variable is an indicator for whether a child has received at least the number of Hib doses as specified in the column header. Odd columns only include state fixed effects, while even columns include additional control variables. Shortage exposed means that a child was born in 2007 or 2008, based on our fuzzy assignment of birth years. Robust standard errors, shown in parentheses, are clustered at the birth-year. Wild clustered bootstrapped p-values are reported in brackets.

Table A11: NIS-Child regression results: Heterogeneity by Household Income
Omitted Category: Income above $75k

	1+ Doses	1+ Doses	2+ Doses	2+ Doses	3+ Doses	3+ Doses
Shortage Exposed	-0.00373*	-0.00343*	-0.00838**	-0.00778**	-0.113***	-0.112***
	(0.001)	(0.001)	(0.002)	(0.002)	(0.024)	(0.024)
	[0.148]	[0.142]	[0.068]	[0.088]	[0.000]	[0.001]
Shortage Exposed × Above Poverty, <=$75k	0.00125	0.00161	0.00705	0.00767*	0.0214	0.0226
	(0.002)	(0.002)	(0.003)	(0.003)	(0.027)	(0.027)
	[0.596]	[0.542]	[0.185]	[0.156]	[0.575]	[0.559]
Shortage Exposed × Below Poverty	0.00436	0.00450	0.00474	0.00516	0.0216	0.0226
	(0.004)	(0.004)	(0.003)	(0.003)	(0.013)	(0.013)
	[0.507]	[0.462]	[0.227]	[0.239]	[0.183]	[0.093]
State Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Other Controls	No	Yes	No	Yes	No	Yes
Sample Mean	0.98	0.98	0.96	0.96	0.89	0.89
Observations	175311	175310	175311	175310	175311	175310

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Each column presents coefficient estimates from a separate regression using NIS data at the child level. The outcome variable is an indicator for whether a child has received at least the number of Hib doses as specified in the column header. Odd columns only include state fixed effects, while even columns include additional control variables. Shortage exposed means that a child was born in 2007 or 2008, based on our fuzzy assignment of birth years. Robust standard errors, shown in parentheses, are clustered at the birth-year. Wild clustered bootstrapped p-values are reported in brackets.

Table A12: Effect of the Shortage on Hib Vaccine Receipt: Heterogeneity by Child Race
Omitted Category: White

	1+ Doses	1+ Doses	2+ Doses	2+ Doses	3+ Doses	3+ Doses
Shortage Exposed	-0.00148	-0.000995	-0.00458	-0.00348	-0.103***	-0.101***
	(0.002)	(0.002)	(0.003)	(0.004)	(0.009)	(0.009)
	[0.497]	[0.641]	[0.301]	[0.417]	[0.000]	[0.000]
Shortage Exposed × Black Only	-0.000809	-0.000692	0.00598*	0.00620**	0.0151	0.0159
	(0.002)	(0.002)	(0.002)	(0.002)	(0.009)	(0.009)
	[0.713]	[0.760]	[0.147]	[0.102]	[0.239]	[0.139]
Shortage Exposed × Other/Multi	-0.00273	-0.00230	-0.00768	-0.00697	0.00950	0.0108
	(0.007)	(0.007)	(0.007)	(0.007)	(0.008)	(0.009)
	[0.660]	[0.702]	[0.491]	[0.598]	[0.469]	[0.423]
State Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Other Controls	No	Yes	No	Yes	No	Yes
Sample Mean	0.98	0.98	0.96	0.96	0.89	0.89
Observations	182407	182405	182407	182405	182407	182405

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Notes: Each column presents coefficient estimates from a separate regression using NIS data at the child level. The outcome variable is an indicator for whether a child has received at least the number of Hib doses as specified in the column header. Odd columns only include state fixed effects, while even columns include additional control variables. Shortage exposed means that a child was born in 2007 or 2008, based on our fuzzy assignment of birth years. Robust standard errors, shown in parentheses, are clustered at the birth-year. Wild clustered bootstrapped p-values are reported in brackets.

Table A13: Effect of the Shortage on Hib Vaccine Receipt: Heterogeneity by Employer Insurance Coverage
Omitted Category: Covered by Employer or Union

	1+ Doses	1+ Doses	2+ Doses	2+ Doses	3+ Doses	3+ Doses
Shortage Exposed	-0.00150	-0.000874	-0.00204	-0.00104	-0.105***	-0.103***
	(0.001)	(0.002)	(0.003)	(0.004)	(0.014)	(0.013)
	[0.388]	[0.577]	[0.668]	[0.803]	[0.000]	[0.000]
Shortage Exposed × Not Covered by Emp or Union	0.000406	0.000640	-0.00263	-0.00208	0.00725	0.00869
	(0.003)	(0.003)	(0.003)	(0.003)	(0.009)	(0.008)
	[0.914]	[0.849]	[0.472]	[0.488]	[0.621]	[0.517]
State Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Other Controls	No	Yes	No	Yes	No	Yes
Sample Mean	0.98	0.98	0.96	0.96	0.89	0.89
Observations	142008	142008	142008	142008	142008	142008

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Notes: Each column presents coefficient estimates from a separate regression using NIS data at the child level. The outcome variable is an indicator for whether a child has received at least the number of Hib doses as specified in the column header. Odd columns only include state fixed effects, while even columns include additional control variables. Shortage exposed means that a child was born in 2007 or 2008, based on our fuzzy assignment of birth years. Robust standard errors, shown in parentheses, are clustered at the birth-year. Wild clustered bootstrapped p-values are reported in brackets.

Table A14: Effect of the Shortage on Hib Vaccine Receipt: Heterogeneity by Medicaid Coverage Status
Omitted Category: Covered by Medicaid

	1+ Doses	1+ Doses	2+ Doses	2+ Doses	3+ Doses	3+ Doses
Shortage Exposed	-0.00107	-0.000326	0.0000913	0.00178	-0.0934***	-0.0901***
	(0.004)	(0.004)	(0.004)	(0.005)	(0.014)	(0.014)
	[0.802]	[0.943]	[0.978]	[0.735]	[0.005]	[0.003]
Shortage Exposed × Not Covered by Medicaid	-0.00233	-0.00201	-0.00565	-0.00535	-0.00162	-0.00126
	(0.003)	(0.004)	(0.004)	(0.005)	(0.011)	(0.012)
	[0.551]	[0.609]	[0.303]	[0.439]	[0.841]	[0.847]
State Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Other Controls	No	Yes	No	Yes	No	Yes
Sample Mean	0.98	0.98	0.96	0.96	0.89	0.89
Observations	84387	84387	84387	84387	84387	84387

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Notes: Each column presents coefficient estimates from a separate regression using NIS data at the child level. The outcome variable is an indicator for whether a child has received at least the number of Hib doses as specified in the column header. Odd columns only include state fixed effects, while even columns include additional control variables. Shortage exposed means that a child was born in 2007 or 2008, based on our fuzzy assignment of birth years. Robust standard errors, shown in parentheses, are clustered at the birth-year. Wild clustered bootstrapped p-values are reported in brackets.

Table A15: Effect of the Shortage on Hib Vaccine Receipt: Heterogeneity by Uninsurance Status
Omitted Category: Was Uninsured

	1+ Doses	1+ Doses	2+ Doses	2+ Doses	3+ Doses	3+ Doses
Shortage Exposed	-0.0124	-0.0125	-0.00756	-0.00682	-0.120***	-0.118***
	(0.006)	(0.006)	(0.005)	(0.005)	(0.016)	(0.016)
	[0.115]	[0.144]	[0.244]	[0.247]	[0.011]	[0.021]
Shortage Exposed × Never Uninsured	0.0135*	0.0139*	0.00599	0.00586	0.0220*	0.0212
	(0.006)	(0.006)	(0.006)	(0.006)	(0.009)	(0.009)
	[0.124]	[0.122]	[0.400]	[0.476]	[0.147]	[0.176]
State Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Other Controls	No	Yes	No	Yes	No	Yes
Sample Mean	0.98	0.98	0.96	0.96	0.89	0.89
Observations	136219	136219	136219	136219	136219	136219

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Notes: Each column presents coefficient estimates from a separate regression using NIS data at the child level. The outcome variable is an indicator for whether a child has received at least the number of Hib doses as specified in the column header. Odd columns only include state fixed effects, while even columns include additional control variables. Shortage exposed means that a child was born in 2007 or 2008, based on our fuzzy assignment of birth years. Robust standard errors, shown in parentheses, are clustered at the birth-year. Wild clustered bootstrapped p-values are reported in brackets.

Table A16: Effect of the Shortage on Hib Vaccine Receipt: Heterogeneity by State VFC Policy
Omitted Category: Not in Universal VFC state

	1+ Doses	1+ Doses	2+ Doses	2+ Doses	3+ Doses	3+ Doses
Shortage Exposed	-0.00138	-0.000829	-0.00390	-0.00278	-0.0900***	-0.0877***
	(0.002)	(0.002)	(0.004)	(0.004)	(0.008)	(0.008)
	[0.619]	[0.757]	[0.563]	[0.651]	[0.000]	[0.000]
Shortage Exposed × Universal VFC	-0.00460*	-0.00470*	-0.00506	-0.00548	-0.0786***	-0.0790**
	(0.002)	(0.002)	(0.003)	(0.004)	(0.017)	(0.018)
	[0.145]	[0.138]	[0.261]	[0.411]	[0.000]	[0.000]
State Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Other Controls	No	Yes	No	Yes	No	Yes
Sample Mean	0.98	0.98	0.96	0.96	0.89	0.89
Observations	182407	182405	182407	182405	182407	182405

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Notes: Each column presents coefficient estimates from a separate regression using NIS data at the child level. The outcome variable is an indicator for whether a child has received at least the number of Hib doses as specified in the column header. Odd columns only include state fixed effects, while even columns include additional control variables. Shortage exposed means that a child was born in 2007 or 2008, based on our fuzzy assignment of birth years. Robust standard errors, shown in parentheses, are clustered at the birth-year. Wild clustered bootstrapped p-values are reported in brackets.

A6 Difference-in-differences analyses using pneumococcal as a control

In this section, we estimate the effects of the Hib vaccine shortage using a difference-in-differences framework, in which the change in uptake of the pneumococcal vaccine over time is explicitly treated as the counterfactual for how uptake of the Hib vaccine would have evolved in the absence of the shortage. This approach has the advantage of allowing us to relax the identification assumption of our baseline model that the *level* of Hib vaccination uptake would have remained constant in the absence of the shortage. However, if the Hib shortage had negative spillovers to uptake of the pneumococcal vaccine (because, for example, households delayed all vaccinations until Hib was available), then our coefficient estimates from the difference-in-differences model will *understate* the true impacts of the shortage on uptake of the Hib vaccine.

A6.1 Methods

For these analyses, we use data from MarketScan and estimate the effect of the Hib vaccine shortage by comparing changes in uptake of the Hib vaccine to concurrent changes in uptake of the pneumococcal vaccine. Our difference-in-differences specification is as follows, where the unit of observation is at the child-vaccine level:

$$\begin{aligned} Y_{cvm} = \beta_0 + \beta_1 \mathbb{1}(Hib\ Vaccine_v) + \beta_2 \mathbb{1}(Adjacent_m) \times \mathbb{1}(Hib\ Vaccine_v) \\ + \beta_3 \mathbb{1}(Exposed_m) \times \mathbb{1}(Hib\ Vaccine_v) + \beta_4 X_c + \epsilon_{cvm} \end{aligned} \tag{A3}$$

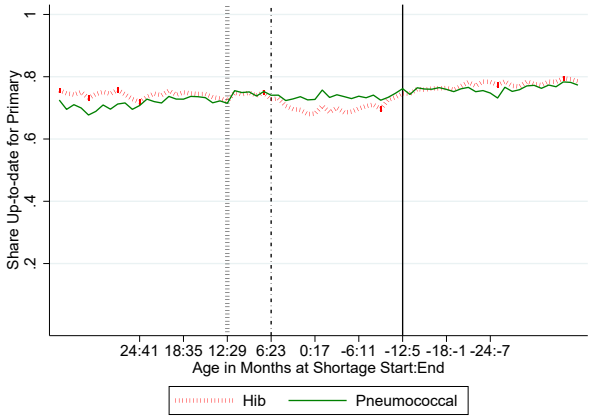
Y_{cvm} represents the vaccination outcome measure for child c in birth month-year cohort m for vaccine type $v \in \{Hib, pneumococcal\}$. The outcome variables of interest are indicators for having at least one dose of the specified vaccine, being up to date on the primary series, and being up to date on the booster series. $\mathbb{1}(Hib\ Vaccine_v)$ is an indicator variable equal to one if the given observation is for the Hib vaccine, and is equal to zero otherwise; X_c is a vector of birth cohort fixed effects (defined at the month-year level), which flexibly controls for cross-cohort differences in vaccination behavior, and census region fixed effects. Standard errors are clustered at the birth-month cohort level. We also report wild cluster bootstrapped p-values.

This empirical strategy leverages variation in shortage exposure across birth cohorts and across vaccines. The identifying assumption in this model is that changes in the pneumococcal conjugate vaccination (PCV) outcomes represent a valid counterfactual for how Hib vaccination would have evolved in the absence of the shortage. Descriptive trends in up-to-date rates for the two vaccines, shown in Figure A10, provide empirical support for this assumption by showing that for cohorts not exposed to the shortage, PCV and Hib vaccination outcomes are very similar in terms of both trends *and* levels. Notably prior to the shortage 95% of infants received their pneumococcal and Hib vaccines on the same day, for the first two doses.

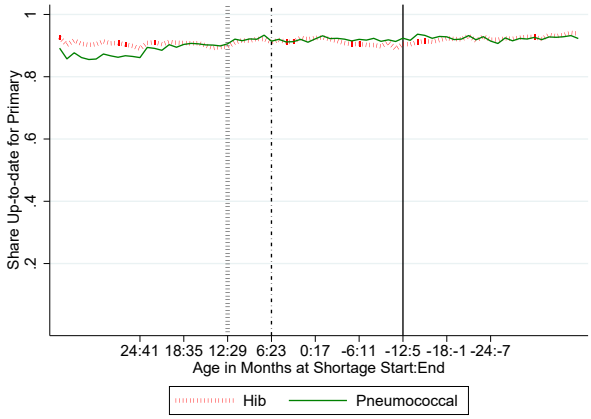
A6.2 Results

The results from estimating Equation A3 are presented in Table A17; the regression coefficients are averages of the dynamic effects shown graphically, for each of the various periods in our sample (shortage-adjacent or shortage-exposed). The estimates suggest that, at 9 months of age, shortage exposed cohorts were 0.68 percentage point less likely to have received any Hib doses than any pneumococcal doses (column 1) and 2.4 percentage points less likely to be fully up-to-date on the Hib primary series (column 2); at 18 months of age, shortage-exposed infants are 27.9 percentage points less likely to be up-to-date on the Hib booster series (column 3).

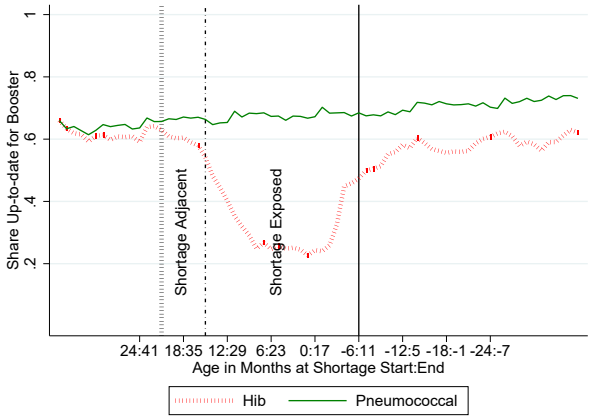
Figure A10: Share of birth cohort up-to-date, Hib and Pneumococcal Vaccines



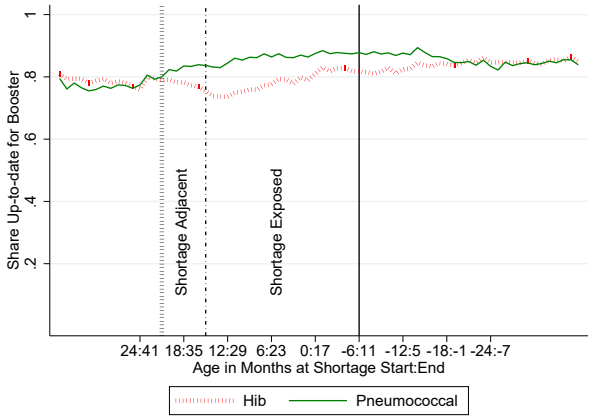
(a) Primary series at 9 months



(b) Primary series at 62 months



(c) Booster series at 18 months



(d) Booster series at 62 months

Notes: This figure presents variation in up-to-date rates for the Hib and Pneumococcal vaccine for children born in different month-years in the Marketscan data. In all figures, we present results after netting out birth month effects.

The results in columns 4-6 examine the effect of the shortage on vaccination outcomes measured at age 62 months. These results demonstrate that cohorts exposed to the shortage had persistently lower uptake of the Hib vaccine, even well after the shortage resolved. Specifically, at 62 months of age, the directly exposed cohorts were 1.7 percentage points less likely to be up-to-date on the Hib primary series (column 5), and 8.3 percentage points less likely to be up-to-date on the booster dose (column 6), relative to the pneumococcal

vaccine. Compared to the estimated effect of the shortage on vaccination uptake by age 9 or 18 months, these estimates are substantially smaller, suggesting catch-up vaccination *did* occur in the interim. However, given that CDC recommendations for routine catch-up vaccination only extends through 59 months (thus making Hib vaccination after that age unlikely), these results also imply that the Hib shortage had long-run effects on Hib vaccination coverage.

Relative to the results from our baseline model (presented in Table 3), the difference-in-difference results are similar or larger in magnitude. This provides further support that the effects we estimate are the result of the shortage, as opposed to the effect of some other unobserved shock impacting vaccination uptake more broadly.

Table A17: Difference-in-Differences Estimates of the Effect of the Shortage on Hib Up-to-Date Rates

	(1)	(2)	(3)	(4)	(5)	(6)
	Any doses 9 months	Primary UTD 9 months	Booster UTD 18 months	Any doses 62 months	Primary UTD 62 months	Booster UTD 62 months
Shortage Exposed × 1(Hib)	-0.00680***	-0.0239***	-0.279***	-0.00473***	-0.0169***	-0.0831***
	(0.002)	(0.007)	(0.027)	(0.001)	(0.004)	(0.008)
	[0.001]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
Sample Mean	0.96	0.74	0.60	0.99	0.94	0.83
Observations	87868	87868	87868	87868	87868	87868

A7 Provider-Level Analyses

A7.1 Methods

To characterize the dynamics of the shortage and supply-side factors influencing the shortage depth, we conduct provider-level analyses. For these analyses, we compare provider-level Hib vaccination rates during the shortage to their rates during the two prior years. Since the Hib vaccine and the pneumococcal vaccine are recommended to be received on the same vaccination schedule, the number of pneumococcal doses administered approximates the number of Hib-vaccine eligible children visiting a providers practice in a given quarter. Thus, we approximate the Hib vaccination rate by dividing the number of Hib doses by the number of pneumococcal vaccine doses the provider administers over the same time period. Motivated by Figure 1, we allow for different effects in the first two quarters (six months) of the shortage versus the remaining shortage period (quarters 3 through 6 of the shortage).

We formalize the provider-level analyses by estimating the following regression equation:

$$\begin{aligned}\text{Hib to Pneumococcal Ratio}_{pq} =& \beta_0 + \beta_1 \mathbb{1}(ShortageQuarters1-2_q) \\ &+ \beta_2 \mathbb{1}(ShortageQuarters3-6_q) + \gamma_r + \gamma_p + \epsilon_{pq},\end{aligned} \tag{A4}$$

where the dependent variable is the ratio of Hib to pneumococcal doses administered by physician p in quarter q, defined separately for the primary and booster series. We aggregate the data to the quarterly level because for some providers we see only a small number of monthly doses.[45] As previously discussed, we allow the shortage to have a different effect in the very short-run, thus, $\mathbb{1}(ShortageQuarters1-2_q)$ is an indicator for the first two quarters of the shortage and $\mathbb{1}(ShortageQuarters3-6_q)$ is an indicator for the rest of the shortage; we exclude post-shortage observations from these analyses. Each indicator variable captures the average effect of the shortage on vaccine administration, relative to the two years prior to the shortage. γ_r is a vector of calendar quarter fixed effects, and controls for seasonality; γ_p are physician fixed effects and control for time invariant physician characteristics. Standard errors are clustered at the quarter-year, although since we have relatively few clusters we also report p-values from the wild cluster bootstrap

[45] We shift our quarter definition up by one month to account for the shortage starting in December 2007. Therefore, December 2007 to February 2008 is the first quarter of the shortage.

procedure described in Cameron, Gelbach, and Miller (2008). The regressions are weighted by the number of pneumococcal doses administered by a given physician in a given quarter, to account for the fact that there is variation across physicians in practice size.[46]

To decompose the impact of physician-level factors on the realized depth of the shortage, we augment the above equation with interactions between the *Shortage Quarters* indicators and the following two pre-shortage provider characteristics: percent of Hib vaccines administered by the provider that were manufactured by Merck and percent of Hib vaccines administered in the county that were manufactured by Merck (omitting that provider's own doses). Providers tend to only use one type of vaccine: prior to the shortage 77% percent of providers used at least 80% Merck vaccines or 80% Sanofi Pasteur vaccines. The provider's vaccine manufacturer at the start of the shortage directly impacts their short-run access to the vaccine, and therefore also their incentives to reduce booster administration. It also influences the probability that they experienced frictions at the start of the shortage, for example due to negotiating a new contract or joining a new physician buying group. Geographic-specific variation might affect vaccination rates if it changes the degree of information about the shortage and the rationing policy or if it changes access to Sanofi Pasteur doses for patients and providers.

A7.2 Provider-Level Results

For our first set of analyses we examine the dynamics of the shortage by comparing provider-level vaccination rates during the shortage to their rates during the two prior years, as formalized in equation A4. Results for the primary series are shown in Table A18, columns 1-3; the booster dose results are presented in columns 4-6.

The results in column 1 show that while the shortage significantly reduced receipt of primary series doses, this reduction was concentrated in the first part of the shortage. During the first two quarters of the shortage 0.08 fewer Hib primary doses were administered per pneumococcal dose, while there is no economically or statistically significant reduction in primary doses during the remainder of the shortage. If we allow the effect of the shortage to vary based on the provider's pre-shortage Merck share (i.e. the share of pre-shortage Hib vaccines they administered that were manufactured by Merck), we find that the reduction was significantly larger for physicians that administered primarily Merck doses prior to the

[46] Results are robust when we do not include weights. They are also similar when leaving the data at the monthly level.

shortage (column 2). Indeed, providers who used Sanofi vaccines prior to the shortage did not reduce the number of primary series doses they gave at any point during the shortage.

Column 3 additionally allows the effects of the shortage on primary series vaccination rates to vary based on whether *other* providers in the county initially used mainly Merck or Sanofi vaccines. We find no evidence that having relatively more Merck (or Sanofi) providers in a county impacts the physician-level shortage depth. These results suggest both that physician-level supply frictions drive the reduction in primary vaccinations and that local supply is unable to mitigate the physician-specific supply issues.

Table A18: Hib Doses Per Pneumococcal Dose

	(1) Primary Hib Per Pneumococcal	(2) Primary Hib Per Pneumococcal	(3) Primary Hib Per Pneumococcal	(4) Booster Hib Per Pneumococcal	(5) Booster Hib Per Pneumococcal	(6) Booster Hib Pneumoco
Shortage Quarters 1-2	-0.082***	0.015	0.007	-0.337***	-0.338***	-0.301**
	(0.013)	(0.015)	(0.017)	(0.020)	(0.056)	(0.060)
	[0.340]	[0.467]	[0.721]	[0.053]	[0.080]	[0.066]
Shortage Quarters 3-6	-0.009	0.024	0.015	-0.498***	-0.509***	-0.491**
	(0.012)	(0.016)	(0.017)	(0.017)	(0.026)	(0.032)
	[0.684]	[0.352]	[0.458]	[0.017]	[0.002]	[0.004]
Shortage Quarters 1-2						
× Physician Merck Share		-0.255***	-0.255***		0.004	0.024
		(0.034)	(0.033)		(0.129)	(0.126)
		[0.013]	[0.009]		[0.967]	[0.804]
Shortage Quarters 3-6						
× Physician Merck Share		-0.090**	-0.092**		0.033	0.050
		(0.029)	(0.028)		(0.048)	(0.046)
		[0.013]	[0.007]		[0.448]	[0.237]
Shortage Quarters 1-2						
× County Merck Share			0.020			-0.131**
			(0.014)			(0.039)
			[0.187]			[0.054]
Shortage Quarters 3-6						
× County Merck Share			0.026			-0.067
			(0.018)			(0.050)
			[0.172]			[0.151]
Sample Mean	0.98	0.98	0.98	0.63	0.63	0.63
Observations	44167	43157	40983	24033	23759	22637

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Each column presents coefficient estimates from a separate regression using MarketScan data aggregated to the provider-quarter level. For these analyses, data are weighted by the number of pneumococcal vaccines given in a quarter and we only include data from before and during the shortage. Robust standard errors, shown in parentheses, are clustered at the quarter-year level. Wild clustered bootstrapped p-values are reported in brackets.

The results for the booster dose (columns 4-6) consistently show that the shortage resulted in larger relative reductions in vaccine administration than for the primary series doses, as expected given the CDC's recommended rationing policy. Additionally, the dynamics of the reduction differ for the booster dose relative to the primary series: for the booster dose the reduction was larger in the later shortage period (0.5 fewer Hib doses per pneumococcal dose in quarters 3 through 6) relative to the first two quarters (0.34 fewer Hib doses). These dynamics suggest that providers took time to learn about and comply with the recommended rationing policy.

Results on the interactions with physician and county Merck share are qualitatively different for the booster dose than the primary dose as well. There is no evidence that the reduction in the relative number of Hib booster vaccinations significantly differed between physicians who were primarily supplied with Merck versus Sanofi vaccines prior to the shortage (column 5). This finding is consistent with the idea that observed reductions in the administration of the booster dose were driven by response to the rationing policy, as opposed to realized supply constraints. However, we do find that physicians practicing in counties with more Merck providers were relatively more likely to reduce the administration of booster doses during the first six months of the shortage, perhaps suggesting that information about the shortage and recommended rationing policy was disseminated more rapidly in areas with more Merck-supplied providers, as a higher share of physicians know directly about the issue.[47]

A8 Counterfactuals

To draw policy implications from our analysis of the shortage and rationing, we report three sets of counterfactual calculations. Our first two counterfactual calculations focus on the short-run effects of the CDC rationing policy on primary series vaccination, conditional on the shortage occurring. For these analyses, we compare the actual outcome to a best-case counterfactual in which providers perfectly comply with the rationing recommendation, and to a worst-case counterfactual in which providers continue administering

[47] A potential alternative explanation for this pattern of results is that in areas with more Merck providers patients are less able to switch from their original provider to get their booster dose, and therefore it is less costly for a provider to reduce the number of boosters administered (i.e. providers are less at risk of losing a patient if they refuse to administer booster doses). However, this is inconsistent with our result that mostly-Merck and mostly-Sanofi providers equally reduced booster dose administration during the first six months of the shortage.

booster doses as usual. These two counterfactuals demonstrate that the actual market outcome much more closely resembled the best case (full compliance) scenario. Finally, our third counterfactual compares the costs of the actual outcome to the costs of a counterfactual in which policymakers try to avoid vaccine shortages by paying higher prices for vaccines. We conclude that, in our context, experiencing the shortage was less costly than counterfactual avoidance.

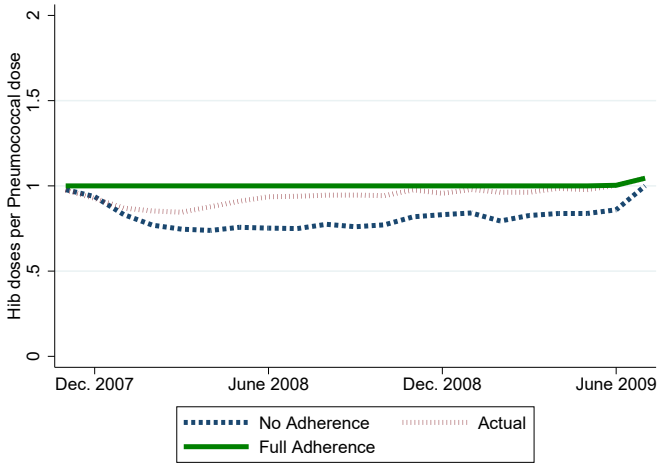
A8.1 Full adherence counterfactual

First, we compare the actual outcome to an ideal counterfactual in which providers perfectly comply with the rationing recommendation. This allows us to examine whether there was sufficient supply for the realized 4.5 percentage point reduction in Hib primary dose receipt to have been avoided with reduced administration of the booster dose. Given that the vaccination guidelines recommend individuals receive two to three times as many primary Hib doses as booster doses, it is possible that even with reallocation of all booster doses there would not have been sufficient supply.

To construct this counterfactual, in each sample month we hypothetically reallocate Hib vaccine doses that were given as boosters to be primary doses. This reallocation continues until the number of Hib primary doses per month match the number of primary series pneumococcal doses actually administered, or until all Hib booster doses have been reallocated to the primary series. The number of pneumococcal primary series doses administered serves as our proxy for the number of infants needing a Hib primary dose in a given month.

The dashed red line in Figure A11 shows the actual number of Hib primary series doses given per pneumococcal primary series dose during each month of the shortage. The solid green line shows the result of reallocating booster doses to primary doses under the full adherence counterfactual. Across all shortage months, we find that there were sufficient doses available to give one Hib primary series dose for every pneumococcal primary dose. Thus, the green line is always at or above one. To achieve full primary series vaccination, about half of the booster doses given in the first six months of the shortage would have needed to be reallocated to primary doses. Later in the shortage, the amount of hypothetical reallocation is smaller as doctors appear to have independently reallocated more vaccine doses to the primary series.

Figure A11: Counterfactual Primary Series Vaccination



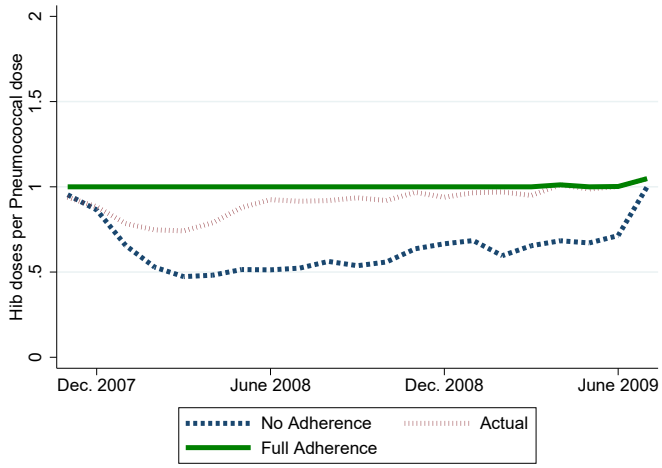
Notes: The dashed red line shows the number of Hib primary series doses per pneumococcal dose in the MarketScan data. The solid green line shows the full adherence counterfactual, where we hypothetically reallocate Hib doses from booster to primary series until the number of Hib primary series doses matches the number of pneumococcal primary series doses or until there are no remaining booster doses. For the no adherence counterfactual, which is the blue dotted line, we assume that Sanofi Pasteur providers did not shift any doses to Merck providers and Merck providers used Hib primary and booster doses in the same ratio as pneumococcal primary and booster doses.

A8.2 No adherence counterfactual

Second, in Figure A12 we compare the actual outcome to a worst-case counterfactual in which providers continue administering booster doses as usual. In this counterfactual, we assume that health-care providers that used Sanofi Pasteur Hib doses prior to the shortage do not decrease administration of booster doses and do not reallocate doses to health-care providers that had used Merck Hib doses. Instead, we assume that those providers give as many Hib doses (primary and booster) as pneumococcal doses. In this counterfactual, we also assume that health-care providers that used Merck Hib doses prior to the shortage do not prioritize primary doses, but instead administer Hib primary and booster doses in the same ratio as pneumococcal primary and booster doses.

Across the entire shortage, we estimate that providers would have given only 0.8 Hib primary series doses per pneumococcal primary series dose if there had been no adherence with the CDC-recommended reallocation of doses from booster to primary series. In reality, providers gave 0.93 Hib primary series doses per pneumococcal primary series dose.

Figure A12: Counterfactuals for Merck Providers Only



Notes: The dashed red line show the number of primary series doses a "Merck provider" gave. For the no adherence counterfactual, which is the blue dotted line, we assume that Sanofi Pasteur providers did not shift any doses to Merck providers and Merck providers used Hib primary and booster doses in the same ratio as pneumococcal primary and booster doses. The solid green line shows the full adherence counterfactual, where we hypothetically reallocate Hib doses from booster to primary series until the number of Hib primary series doses matches the number of pneumococcal primary series doses or until there are no remaining booster doses.

Hence, the reallocation increased primary doses by 13 percentage points. Notably, the difference between the actual outcome and the no adherence counterfactual was smaller during the first six months of the shortage: during this period providers gave 0.88 primary series doses for each pneumococcal primary series dose, representing only an 8 percentage point improvement over the no adherence counterfactual. Additionally, if we focus on providers who used mostly Merck vaccines prior to the shortage (and therefore were most directly impacted by the supply shock), we estimate that the primary series vaccination rate would have been 20 percentage points lower than the realized rate under the no adherence counterfactual.

Using these estimates, we calculate that over the shortage period, full adherence would have corresponded to 1.2 million additional primary doses given, relative to what we actually observed. On the other hand, had there been no adherence, we calculate that 2.2 million fewer primary series doses would have been administered than actually were.[48] This, in turn, translates to at least seven hundred thousand children not receiving the full primary series in the absence of adherence to the rationing recommendation (2.2 million doses $\div$ 3 primary doses per child).

Based on this counterfactual analysis, we find that the actual outcome of this shortage was much closer to the full adherence case, compared to no adherence case. This demonstrates the impact of the CDC rationing plan that prioritized the primary doses. Notably, however, for the first six months, the actual outcome was closer to the no adherence case, potentially suggesting supply chain or information frictions which eventually subsided.

While the number of doses given was closer to the full adherence counterfactual, it is worth noting that the consequences of these counterfactuals may not be symmetric. Limited evidence of large increases in Hib infection may be because most children still received the primary series on time or with minimal delay (Centers for Disease Control and Prevention, 2009b). The risk of a serious outbreak and associated morbidity and mortality might have been greatly increased in the no adherence case.

[48] In the no adherence case primary series doses decreased by 13 percentage points. In the full adherence case, doses increased by 7 percentage points. If 3.75 million children are born each year and needed three primary series Hib vaccine doses during the shortage, then that would translate to 16.875 million doses during the 1.5 year shortage. Therefore, a 7 percentage point increase in doses represents 1.2 million additional doses (0.07×16.875 million); a 13 percentage point decrease translates to 2.2 million fewer doses.