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Direct and Spillover Effects of Middle School Vaccination Requirements†

By Christopher S. Carpenter and Emily C. Lawler*

We study the direct and spillover effects of state requirements that middle school youths obtain a tetanus, diphtheria, and pertussis (Tdap) booster prior to middle school entry. These mandates significantly increased Tdap vaccine take-up and reduced pertussis (whooping cough) incidence by about 32 percent. We also document cross-vaccine spillovers: the mandates significantly increased adolescent vaccination rates for meningococcal disease and human papillomavirus (HPV)—which is responsible for 98 percent of cervical cancers—by 8–34 percent, with particularly large effects for children from low SES households. We find important roles for both parents and providers in generating these spillovers. (*JEL* H75, I12, I18, I21, I28, J13)

Reductions in vaccine-preventable diseases through increased uptake of vaccinations are some of the most significant public health improvements in American history (Centers for Disease Control 1999). These improvements have been particularly striking for diseases that have historically harmed infants and young children, such as measles, mumps, and rubella. Most of the research on childhood vaccination has come from medical and public health studies, including some randomized controlled trials (RCTs). The empirical economics literature on vaccination in general, and childhood vaccination in particular, has mainly focused on how vaccination decisions respond to changes in prevalence (Philipson 1996, Oster 2016), information (Anderberg, Chevalier, and Wadsworth 2011), prices (Chang 2016a), recommendations (Lawler 2017), and vaccination mandates aimed at infants and young children prior to entry into kindergarten or childcare (Abrevaya and Mulligan 2011, Ward 2011, Luca 2014).[1]

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[1] For a comprehensive treatment of economic epidemiology issues relating to vaccine-preventable diseases, see Philipson (2000).

In this paper, we provide new evidence on the direct and spillover effects of a series of school-entry mandates that have not been previously studied in the economics literature: state requirements that adolescents obtain a Tdap (tetanus, diphtheria, and acellular pertussis) booster prior to entering middle school. In the last decade 46 states have adopted these requirements. Like prior work on childcare and kindergarten entry mandates, our study benefits from the fact that there is substantial variation in the timing of Tdap booster mandate adoption across states. Unlike the prior work on younger children, however, our focus on slightly older adolescents offers a new and fertile environment within which we can credibly test for a variety of vaccination-related spillovers.

Using provider-verified data on vaccination histories for adolescents from the National Immunization Survey-Teen (NIS-Teen) and difference-in-differences models, we examine the effects of middle school Tdap booster requirements on the likelihood of vaccination by the age of 13 for Tdap (direct effect) and for the other vaccines routinely recommended for adolescents: MCV, HPV, and influenza (possible cross-vaccine spillover effects).[2] Using the same empirical models, we also estimate mandate effects on the incidence of pertussis (which is protected against by the Tdap booster) and tuberculosis (which has a similar transmission mechanism and clinical presentation as pertussis, but is not protected against by the Tdap booster and thus cannot reflect true spillover effects) in the population and by ten-year age groups. These morbidity analyses allow us to address the extent to which population morbidity effects are due to adolescents being directly targeted by vaccine mandates versus morbidity spillover effects accruing to infants, younger children, adults, and/or the elderly (i.e., cross-age spillovers).

To preview, we find clear evidence that state laws requiring youths to obtain a Tdap booster prior to middle school entry were very effective at directly increasing Tdap booster take-up. Specifically, we find that adoption of a Tdap booster mandate increased the likelihood that an adolescent received a Tdap booster between 10 and 12 years of age by 13.5–13.7 percentage points. We also estimate substantial reductions in pertussis incidence as a result of the mandates. These reductions in pertussis morbidity are observed primarily for adolescents who were targeted by the mandates, with some additional evidence of spillovers to infants and prime age adults.

We also find strong evidence of cross-vaccination spillovers: although most state mandates only required the Tdap booster, we find significant increases in other vaccinations that were also recommended for young adults.[3] For example, we estimate that state Tdap booster requirements increased MCV vaccination rates by 2.2–2.9 percentage points. Even more striking, we find that these Tdap booster policies significantly increased HPV vaccination initiation by 4.2–4.9 percentage points and HPV vaccination completion by 2.5–3.3 percentage points. These spillover effects

[2] Vaccine recommendations in the United States are made by the Advisory Committee on Immunization Practices (ACIP). The ACIP currently recommends middle school age youths be routinely administered one dose of tetanus-diphtheria-acellular pertussis (Tdap) booster vaccine, one dose of meningococcal conjugate vaccine (MCV), the human papillomavirus (HPV) vaccine series, and an annual influenza vaccine.

[3] As of January 2016, 22 of those 46 states also required MCV vaccination for middle school entry, and 2 states had adopted requirements that students receive the HPV vaccine series. No state requires students to receive the influenza vaccine.

are larger for youths from households with low socioeconomic status (SES). Our results are the first to document that middle school vaccination requirements induced large improvements in adolescent and child health. Furthermore, given the spillover effects to HPV vaccination, there are likely to be large longer run payoffs due to reduced risk of HPV-related cancers in both men and women, especially cervical cancer.

Our paper on the direct and spillover effects of middle school vaccination requirements makes a number of important contributions to the literature on the determinants of vaccination and childhood health. First, our study provides new and credible tests of vaccination spillover effects, thereby improving our understanding of relative costs and benefits of policies aimed at increasing childhood vaccination rates. Unlike treatments studied by most prior work that affect very broad populations (e.g., information campaigns, disease prevalence, and financial incentives), school-entry vaccination mandates offer particularly powerful tests of spillover effects because they only bind for a very specific age group of children and a very specific disease or set of diseases. Thus, if outcomes for different-aged children or different diseases are affected, this is likely due to vaccination spillovers, i.e., a requirement that a child get one type of vaccination may lead her to get other vaccinations as well, or may lead other non-targeted individuals in the household to also get vaccinated.

To date, little prior work has considered the possibility of such spillovers, and among those that have, the evidence has been mixed. Oster (2016) finds that pertussis outbreaks increase whooping cough vaccination rates for school-aged children but not vaccination rates for other diseases, while Schaller, Schulkind, and Shapiro (2017) do find evidence of increases in take-up of other vaccines for infants in response to pertussis outbreaks. In the context of hepatitis A, Lawler (2017) finds no evidence that kindergarten and childcare entry mandates had spillover effects to increased vaccination rates of other vaccines. Below, we discuss several reasons why spillover effects of middle school mandates might differ from prior evidence from infants and younger children.

Second, our study provides important new evidence on the determinants of vaccination among a previously understudied group: middle school-aged adolescents. Prior work on school-entry mandates has focused almost exclusively on infants and young children, but vaccination improvements over the past two decades for middle school-age children have notably been slower and less remarkable than for elementary school-age children. For example, while HealthyPeople 2020 (HP2020) recommends maintenance of the already high vaccination rates for kindergarten age children, those same recommendations explicitly acknowledge the need to increase vaccination coverage for adolescents (Office of Disease Prevention and Health Promotion 2015).[4] A particular challenge in vaccinating adolescents is that they

[4] Of the 4 vaccines routinely recommended for adolescents, only the Tdap booster vaccination rates currently meet their HP2020 target of 80 percent. In contrast, the vaccination rate for 13–15 year olds for MCV in 2012 was 73.8 percent (target of 80 percent), and the seasonal influenza vaccination rate for children 6 months to 17 years was 46.9 percent in the 2010–2011 flu season (target of 70 percent). The case of HPV is even worse: only 35.1 percent of 13–15 year olds (50 percent of girls and 20.9 percent of boys) had initiated the HPV vaccine by 2012, far below the HP2020 target of 80 percent. We present trends in the uptake of these vaccines in Figure 1.

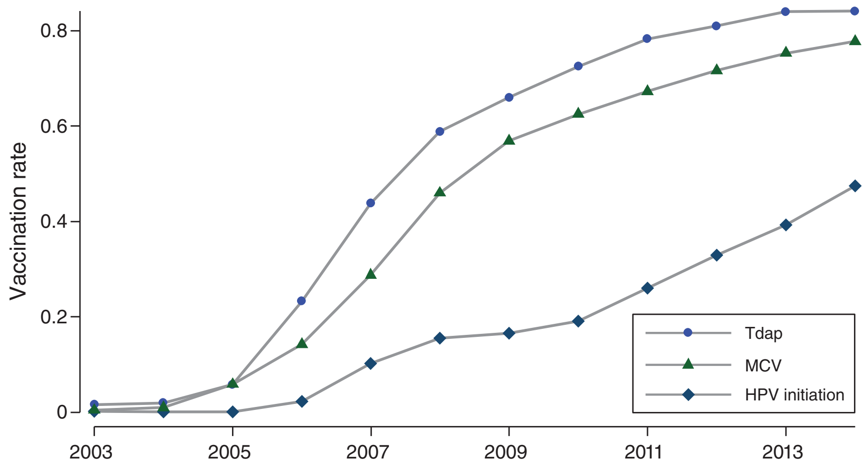

Figure 1. Trends in Adolescent Vaccination Rates for ACIP-Recommended Vaccines

Note: Vaccination status is measured directly prior to age 13, and assigned to the year in which the individual was age 12.

Source: Data are from NIS-Teen

primarily encounter healthcare providers only for acute injuries and sports-related physicals, and as a result they have much lower rates of attachment to the healthcare system than individuals in other age groups (Woodwell and Cherry 2004, Humiston and Rosenthal 2005).

Third, by estimating population-level morbidity effects of increased Tdap vaccination, our research complements and augments the existing randomized control trial (RCT) evidence on the efficacy of the Tdap vaccine.[5] In the presence of population morbidity spillovers, individual-level RCT estimates of vaccine effectiveness will understate the true reduction in pertussis in the population that may result from receipt of the Tdap vaccine. Analyses of morbidity effects at the population level, however, provide a more complete picture of the extent to which the Tdap vaccine is able to reduce disease incidence. Although we face limitations in our ability to identify the effects of the mandate on vaccination rates across all age groups, we believe our results provide important new evidence on the overall effect of the Tdap vaccine on pertussis incidence in the population.

Fourth, the literature specifically regarding determinants of adolescent HPV vaccination has largely failed to identify meaningful policy levers that could increase HPV vaccine uptake among adolescents. As the HPV vaccine has the largest gap between current and targeted immunization rates for adolescents, understanding any credible policy lever to increase HPV vaccine uptake in this age group is important. Finally, the literature on the effectiveness of public policies at promoting adolescent health is relatively underdeveloped compared to literatures on children at the younger and older ends of the age spectrum. While we know a substantial amount

[5] Randomized control trial evidence of the efficacy of the acellular pertussis vaccine among adolescents and adults estimates overall vaccine efficacy to be 92 percent, with a 95 percent confidence interval ranging from 32 to 99 percent (Ward et al. 2005).

about the causes and consequences of early child health (Almond and Currie 2011, Almond, Currie, and Duque 2017) and high school student health (Gruber 2001), there is comparatively less research on the critical period of early adolescence. In addition to the clinical changes associated with puberty, the vast majority of high risk behaviors are initiated during adolescence. Documenting the role vaccination policies play in adolescent health therefore contributes to a more complete picture of child development.[6]

Our paper proceeds as follows: Section I provides institutional background on the mandates and conditions we study, and Section II provides a brief literature review. Section III describes the data and outlines the empirical approach. Section IV presents the results, and Section V discusses and concludes.

I. Institutional Background

In this section, we briefly describe the diseases and vaccinations under study as well as the middle school mandates and the mechanisms for spillovers.[7]

A. *Conditions under Study*

Tetanus, diphtheria, and pertussis (or "whooping cough") are all diseases caused by bacteria, and vaccination against them with a combination vaccine series (currently DTaP) has been routinely recommended for young children since the 1940s and 1950s. In 2005, a booster for the series, the Tdap vaccine, was approved for use in adolescents and was recommended to be administered at age 11 or 12. Tetanus and diphtheria are now extremely rare diseases, but pertussis remains endemic in the United States. [8]

Pertussis is a respiratory disease characterized by a severe cough, and it is transmitted from person-to-person through respiratory secretions. It is believed to have remained endemic in the United States both because it is extremely contagious (a single person can infect up to 15 others), and because of waning immunity following vaccination (CDC 2017).[9] In recent decades, peak pertussis incidence in the United States has occurred among infants and adolescents 10 to 14 years of age.[10]

Among adolescents, pertussis is typically mild: it results in hospitalizations in approximately 2 percent of cases and further complications, including pneumonia, seizures, and permanent brain damage in approximately 2.5 percent of cases (Hamborsky, Kroger, and Wolfe 2015). The duration of illness is relatively long

[6] In fact, one reason why HPV-promoting public policies have been controversial is that some believe the HPV vaccine promotes sexual promiscuity.

[7] The online Appendix provides more detailed information on each condition we study.

[8] Figure 2 plots population pertussis rates in the United States from 2000–2015.

[9] Specifically, the DTaP series is considered to be approximately 90 percent effective against pertussis in the year following completion of the series, with immunity waning to closer to 70 percent by 5 years after vaccination. For the Tdap vaccine, effectiveness is estimated to be approximately 70 percent in the first year; that estimate drops to between 30 and 40 percent by 4 years after receipt of the vaccine (CDC 2017).

[10] In online Appendix Figure 2 we present the pertussis incidence by age group in the year prior to the introduction of the Tdap vaccine (2004) and in the last year of our sample (2015). In total, in 2004, there were over 25,000 cases of pertussis in the United States. Of these, 5,850 were among 0-to-4-year-olds, and 6,000 were among 10-to-14-year-olds.

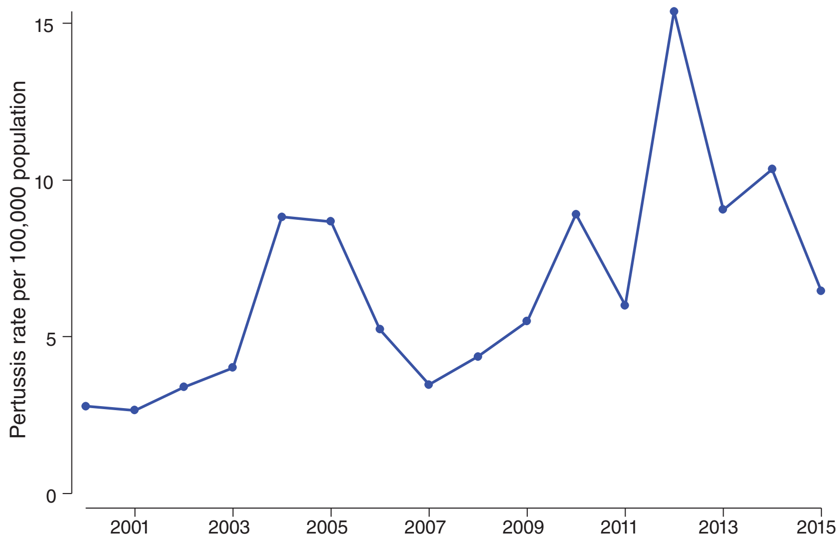

Figure 2. Trends in Population-Wide Pertussis Incidence, 2000–2015

Source: Data from the Centers for Disease Control and Prevention

however, ranging from a couple of weeks to a couple of months (Hamborsky, Kroger, and Wolfe 2015), and, on average, results in five lost school days for adolescents (Purdy et al. 2004).

For infants, however, pertussis is a much more severe illness. Infants under the age of 6 months are hospitalized in approximately 63 percent of cases, and experience severe complications in close to 13.5 percent of cases. Additionally, infants experience mortality from pertussis in approximately 1 percent of cases (CDC 2002).[11] Notably, infants are particularly vulnerable to pertussis since initiation of the DTaP series does not occur until two months of age.

Meningococcal disease includes infections of the lining of the brain and spinal cord (meningitis) and of the bloodstream (septicemia and bacteremia). We focus on the quadrivalent meningococcal conjugate vaccine (MCV4), which provides protection against four of the most common meningococcal disease serogroups and has been routinely recommended for children age 11 or 12 since 2005.

Human papillomavirus (HPV) is the most common sexually transmitted infection in the United States: the CDC estimates that nearly all sexually active men and women will get HPV at some point in their lives. Most HPV infections are asymptomatic and resolve on their own. High-risk types of HPV cause the large majority of the cancers of the cervix, vagina, penis, anus, mouth, and throat. The first HPV vaccine was licensed for use in females in the United States in June 2006, and it was further approved for males in October 2009. The vaccine is only effective if it is

[11] For other age groups, the mortality risk from pertussis is <0.1 percent, and for adolescents in particular mortality from pertussis is essentially zero.

given before an infection occurs. It is currently recommended that all youths initiate the HPV vaccine series between ages 11–12.[12]

Seasonal flu (common in fall and winter months) is an acute and highly contagious viral infection that causes mild to severe illness; among infants and the elderly there is elevated risk of death due to complications. The flu vaccine varies from season to season with respect to the particular strains of the influenza virus that it protects against. The annual influenza vaccine was routinely recommended for children over the age of six months for the first time in 2010.

B. *Middle School Vaccination Requirements and ACIP Recommendations*

There is a long history in the United States of using school-based mandatory vaccination laws as a tool to increase vaccination rates, in part because compulsory schooling laws provide an effective means for enforcement.[13] Although all states presently mandate the receipt of some vaccines, there is considerable variation in the set required for school attendance in each state (Malone and Hinman 2003).[14] As of January 2016, 46 states have adopted middle school entry requirements for the Tdap booster (Figure 3). The mandates we study apply to both private and public school students in the vast majority of states; only in four states is the treatment of private school students unclear (CDC 2016b).

In the United States, recommendations on the use of vaccines are set by the Advisory Committee on Immunization Practices (ACIP). The ACIP is a 15 member committee composed of doctors and public health professionals and was established in 1964. Their guidelines are directly linked to a number of health policies, as many states anchor their laws to current ACIP recommendations.[15] As of January 2016, the ACIP recommended that 11–12-year-olds receive an annual influenza vaccination, one dose of Tdap, the HPV vaccine series, and a single dose of quadrivalent meningococcal conjugate vaccine.[16]

[12] During our sample period the HPV vaccine was recommended to be administered as part of a three-dose series. As of December 2016 the recommendation has been updated to reflect new evidence demonstrating that receiving only the first two doses of the series is of equivalent efficacy to the full three-dose series. ACIP now recommends that individuals initiating the series before the age of 15 receive only 2 doses of the vaccine.

[13] A limitation to the effectiveness of mandates is the availability of individual exemptions. During our sample period exemptions could be obtained for individuals whose religious beliefs oppose vaccination in all but 2 states, and 20 states additionally allowed exemptions for personal/philosophical beliefs (NCSL 2017). All states grant exemptions for children who cannot be vaccinated due to medical reasons. To our knowledge there is not good evidence on how children who do not meet the vaccination requirements are induced to get the required vaccinations (i.e., how the laws are enforced). School-based nurses are unlikely to be able to fulfill the vaccination requirements, however, because most schools lack the administrative requirements to handle the billing and reimbursement for the vaccinations.

[14] There have been school vaccine mandates implemented in all 50 states and Washington DC since 1980. All states currently mandate that students receive the DTaP vaccine series prior to kindergarten entry.

[15] For example, under the Affordable Care Act (ACA) preventive care provision (effective September 23, 2010), all new insurance plans must provide all ACIP-recommended vaccines without cost sharing. Moreover, once the ACIP designates a vaccine as "routinely recommended," the Vaccines for Children (VFC) program has to pay for them. Individuals are eligible for free vaccinations under the VFC program if they are 18 years of age or younger, and are Medicaid-eligible, uninsured, American Indian or Alaskan Native, or are underinsured.

[16] Out-of-pocket cost for this bundle of vaccines is potentially high. At this time of this writing, Walgreens, for example, charged $249.99 for the first dose of the HPV vaccine, $214.99 for both the second and third doses of the HPV vaccine, $133.99 for the meningococcal vaccine, $63.99 for the Tdap booster, and $31.99 for the influenza immunization, for a total expense of nearly $700 (Walgreens 2016). Prior to the ACA, some private insurance plans

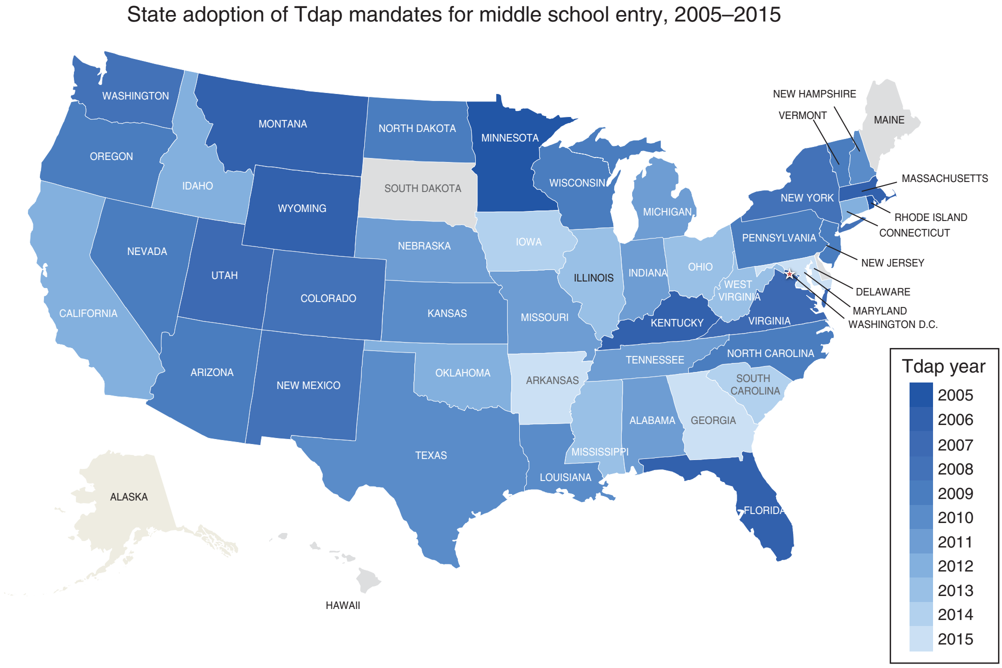

Figure 3. Timing of Tdap Mandate Policy Adoption

Note: Minnesota adopted in 1996; Rhode Island adopted in 1999.

C. *Spillovers*

In this paper we examine the direct effects of Tdap booster mandates on take-up of the Tdap booster and on pertussis morbidity among the targeted age group (5–14 year olds), but we are also interested in two types of spillover effects. First, we examine the effects of the mandates on the pertussis morbidity rates of younger and older individuals in the state. These cross-age spillovers may occur due to reduced disease transmission among the directly targeted adolescents, which is referred to as the "herd immunity" or "community" effect in the medical and public health literatures. Additionally, cross-age spillovers may occur if the middle school mandates cause behavioral spillovers that result in increased vaccination among non-targeted age groups.

The second type of spillover we study is a cross-vaccine spillover from state Tdap mandates to immunization rates for other non-mandated vaccines, such as the MCV, HPV, or flu vaccines. These types of spillovers may occur through several different channels. For example, Tdap mandates lead to an implicit price reduction for the other vaccines that are recommended for adolescents by requiring the youth to seek out a health care provider. These interactions with providers may also lead to information exchange whereby providers inform patients about and recommend receipt of other age-appropriate vaccinations. Alternatively, the mandates may directly

covered some portion of these vaccines, and several states adopted laws requiring private insurance plans in the state to cover the vaccines (see Chang 2016a for evidence on these).

increase parental knowledge about other vaccines, perhaps through local news coverage or information provided by the school or state department of health.[17]

II. Literature Review

Our paper relates to a substantial literature on the economics of infectious diseases and vaccination (Philipson 2000). Philipson (1996) shows that higher measles prevalence in an individual's state is associated with earlier age at first measles vaccination, suggesting that vaccination responds to disease prevalence. Oster (2016) finds a similar result for pertussis: whooping cough disease outbreaks increase vaccination rates of children in the following year, with effect sizes that are too large to reflect actual changes in disease risk. Schaller, Schulkind, and Shapiro (2017) also study pertussis outbreaks but focus on infants, finding that outbreaks increase infant vaccinations not only for pertussis but also for other vaccine-preventable diseases. Multiple studies have examined the vaccination effects of the MMR-autism controversy in which a study in a major medical journal in the United Kingdom suggested that the measles, mumps, and rubella vaccine might cause autism, showing that highly educated mothers responded to the information by reducing MMR vaccination rates for their children (Anderberg, Chavelier, and Wadsworth 2011; Chang 2016b).[18]

Our study of middle school vaccination requirements is also related to several quasi-experimental studies in economics that have examined similar vaccination mandates for kindergarten or childcare entry. Abrevaya and Mulligan (2011) show that such vaccination mandates for varicella were associated with significant increases in varicella vaccination rates for young children using data from the 1996–2007 National Immunization Survey (NIS). Lawler (2017) also uses NIS data to study similar requirements for hepatitis A and finds that both ACIP recommendations and state vaccination requirements significantly increased vaccination rates for hepatitis A and reduced hepatitis A morbidity. Ward (2011) and Luca (2014) both consider the implementation of the first modern school vaccination laws (adopted between 1963 and 1980) and find reductions in morbidity and mortality for the vaccine-targeted diseases.[19]

[17] Online Appendix Figure 1 shows an example of this type of information provided to parents by the Wisconsin Department of Health. Question 9 on the flyer asks "Are there any other vaccines that are recommended for my adolescent?" The answer provided instructs parents that even though Tdap is the only immunization required under law for middle school entry, adolescents in this age group are also recommended to receive MCV, HPV, and seasonal influenza vaccinations.

[18] Numerous subsequent studies have failed to confirm a link between the MMR vaccine and autism, and the original study that purported the connection was retracted in 2010.

[19] Other economics studies examine the role of non-mandate related vaccination policies. For example, Chang (2016a) finds that state insurance mandates for various childhood vaccinations significantly increased infant vaccination rates, and Ward (2014) finds that influenza immunization campaigns are effective at increasing influenza vaccination rates. A number of studies focus particularly on the HPV vaccine, although we are not aware of any quasi-experimental literature that has identified significant causal determinants of adolescent HPV vaccination rates. Moghtaderi and Adams (2016) use NIS-Teen data from 2008–2011 and find no effects of requirements that parents and/or students receive education and information about the HPV vaccine; mandates requiring the vaccine for school entry; mandates requiring private insurers to cover the HPV vaccine; laws granting pharmacists the authority to give vaccinations; and general awareness campaigns. Trogdon et al. (2016) use NIS-Teen data from 2008–2014 and also find no significant relationship between pharmacist vaccination authority and either HPV vaccine initiation or completion.

Within the medical and public health literature there are a number of papers that have considered the effects of state middle school vaccination mandates. These studies generally use only a limited number of years (e.g., 2009 and 2010 in Bugenske et al. 2012) or study the experiences of a small number of states (e.g., New York in Kharbanda et al. 2010), though it is important to note that some of these studies have explicitly examined the possibility of cross-vaccine spillovers from Tdap vaccination mandates to take-up of MCV and HPV vaccines (see, for example, Dempsey and Schaffer 2011). Our work builds on the prior work in public health by using much more comprehensive nationally representative data spanning adoption of numerous state Tdap vaccination mandates. The data and variation allow us to carefully test the parallel trends assumption required for identification in difference-in-differences models and to estimate credible event study models that trace out the immediate and medium term effects of the mandates. We also go further by directly examining age-specific morbidity effects.

III. Data Description and Empirical Approach

Data on adolescent vaccination come from the 2008–2013 waves of the National Immunization Survey-Teen.[20] The NIS-Teen is a random digit dialing telephone survey that targets adolescents between 13 and 17 years of age and includes provider-verified immunization histories and household sociodemographic characteristics. Approximately 33,500 households complete the survey each year;[21] among these households there is adequate provider data for 58.7 percent of sample teens.[22] In these data, we observe immunization status for Tdap, MCV, HPV, and seasonal influenza vaccinations, as well as for other childhood vaccines. Importantly for our analyses, these data include the age (in years) at which the child received each vaccination, even if it occurred years prior to the NIS-Teen interview. We use this information to restrict our analysis to vaccination doses received between 10 and 13 years of age—the age range for which middle school mandates are most likely to be binding. Our effective sample for vaccination outcomes is therefore individuals who were age 13 between 2004 and 2013.

Our data on pertussis disease incidence were obtained directly from the CDC. These data consist of counts of cases of a subset of nationally notifiable diseases by state, year, and ten-year age group.[23] Availability of information on age group

[20] Due to a survey revision in 2014, later waves of the NIS-Teen survey are not directly comparable to the 2008–2013 waves (NCIRD, NCHS, and NORC 2015). For completeness, however, we show that our results are robust to adding the 2014 and 2015 waves in online Appendix Table 10.

[21] Among land line samples the response rate ranges from 51.1 to 58.7 percent; among the cell phone samples (administered in addition to the land-line survey for the 2011–2013 survey waves) response rates were substantially lower and ranged from 22.4 to 23.6 percent.

[22] Teens that completed the household interview may lack adequate provider data either because the household did not provide consent to contact providers (between 23.2 and 35.1 percent of households in a given survey wave) or because the contacted providers did not have medical records for the teen. Across all survey waves provider response rates were extremely high, ranging from 92.7 to 96.3 percent.

[23] The number of cases of nationally notifiable diseases is voluntarily reported to the CDC by state and territorial jurisdictions for nationwide monitoring of disease. These data are considered the most comprehensive information available on US national disease incidence, although they only include diagnosed cases (i.e., they exclude cases where the individual did not go to a health care provider or was misdiagnosed) and thus represent a substantial undercount of true disease incidence. The reliance on provider diagnosis represents a potentially

enables us to separately estimate the direct effects (on the ages targeted by the mandates) and indirect effects (on other age groups) of the middle school mandates on disease incidence in the population. We observe morbidity outcomes for pertussis (covered by Tdap) and tuberculosis (a control condition transmitted in the same manner as pertussis, but not protected against by the Tdap vaccine) from 2000–2015. We also use population morbidity data for a range of other diseases (e.g., hepatitis A, hepatitis B, meningococcal disease, measles, Lyme disease, and salmonellosis) as additional falsification tests.

To estimate the effect of the Tdap mandates, we estimate standard difference-in-differences models that rely on plausibly exogenous variation in the timing of mandate adoption across states. Specifically, we estimate

$$
\begin{aligned}
(1) \quad Y_{ist} = \beta_0 &+ \beta_1 X_{ist} \\
&+ \beta_2 (\mathit{MIDDLE\ SCHOOL\ ENTRY\ VACCINATION\ MANDATE})_{st} \\
&+ \beta_3 Z_{st} + \beta_4 S_s + \beta_5 T_t + \beta_6 S_s \times \mathit{TREND} + \varepsilon_{ist},
\end{aligned}
$$

where Y_{ist} are the vaccination take-up outcomes available in the NIS-Teen data for individual i in state s who was age 13 in year t; X_{ist} is a vector of individual characteristics available in the NIS-Teen, including: child's gender, fixed effects for child's age at time of survey, child's race/ethnicity (Hispanic, white, black, with other as the excluded category), number of other children under 18 years old living in the home (only 1 child, 2 to 3 children, with 4 or more children as the excluded category), maternal education (less than high school, high school, some college, with college or above as the excluded category), maternal age group (34 years old or younger, 35 to 44 years old, with 45 years or older as the excluded category) and an indicator variable for whether the mother is married.[24]

The term *MIDDLE SCHOOL ENTRY VACCINATION MANDATE* is a vector of disease-specific indicator variables equal to one in the states and years in which there is a vaccination mandate in effect. Since all vaccination outcomes are observed at age 13 in year t, a vaccination mandate is considered in effect for individual i in state s if there was a binding mandate for 12-year-olds in year $t-1$ or for 11 year olds in year $t-2$ in state s.[25] This vector captures vaccination mandates for

important limitation in this context, as providers may adjust the intensity of their surveillance in the presence of a vaccine mandate, thus biasing our morbidity results. Furthermore, it is difficult to sign this bias: Tdap mandates may increase provider surveillance intensity by increasing their awareness of pertussis, or it may decrease their surveillance if they lower their expectation of encountering a patient with pertussis.

[24] The number of other children living in the home and maternal education, age group, and marital status are all observed at the time of the survey, not at the time the child was age 13. Our main results are not sensitive to removing the controls in the X vector.

[25] There is variation across states in the age for which a middle school mandate is binding. For example, some states require vaccination by age 11, while in others the requirement is by age 12. Additionally, some requirements are by grade level, in which case we consider sixth grade entry equivalent to age 11 and seventh grade entry equivalent to age 12. We assume that there is no cross-state mobility between ages 11 and the time at which the child is surveyed (age 13–17); in a robustness test we have confirmed that our results are not sensitive to restricting attention to the 78 percent of our sample whose current state of residence matches their birth state of residence.

the tetanus, diphtheria, and pertussis booster (Tdap),[26] the meningococcal vaccine (MCV), and the human papillomavirus series (HPV). These 3 vaccines are the only immunizations for which routine administration is recommended for the first time at age 11 or 12. The influenza vaccine is additionally recommended annually for children ages 6 months through 18 years, although as of 2016 no state has mandated receipt of the influenza vaccine for school attendance. Information on the timing of adoption of these mandates was taken from the Immunization Action Coalition.[27]

Additionally contained in the vector *MIDDLE SCHOOL ENTRY VACCINATION MANDATE* are indicator variables that capture if individuals faced a newly binding "catch up" middle school entry mandate for hepatitis A, hepatitis B, varicella, or a measles-containing vaccine. These vaccines are frequently required for middle school entry, although they are routinely recommended for children much younger than middle school age. Consequently, many states have companion kindergarten entry mandates for these diseases. State requirements regarding these other diseases are still relevant, however, because some share of young adults are "caught" by them (i.e., they were too old at time of implementation of the disease-specific kindergarten vaccination mandate in their state to have been treated by it).[28]

The term Z_{st} is a vector of other potentially relevant state vaccination-related public policies, some of which have been studied in prior work. These include: state mandates requiring insurance policies to cover various vaccinations (Chang 2016a) and well-child visits;[29] nonmedical exemption policy (Bradford and Mandich 2015);[30] state education requirements for the HPV and meningococcal vaccines (Moghtaderi and Adams 2016, Bugenske et al. 2012); high school and college immunization requirements for the meningococcal vaccine; immunization mandates for childcare/kindergarten entry for other diseases such as hepatitis A (Lawler 2017); and income eligibility thresholds for the state Medicaid/Children's Health Insurance Program.[31] The Z vector also includes controls for state unemployment rates and state demographic characteristics (fraction female; fraction

[26] Among the states that have Tdap booster mandates, nine previously had mandates requiring receipt of a TD-containing vaccine prior to middle school entry. In the baseline specification we consider a TD-containing mandate to be equivalent to a mandate for the Tdap booster.

[27] Only two states over our sample period ever adopted a mandate for HPV vaccination (Washington DC and Virginia). Given the well-documented challenges associated with credibly estimating difference-in-differences models with a small number of policy changes (Conley and Taber 2011, MacKinnon and Webb 2018), we do not present estimates for this variable, as they are highly sensitive to specification. Twenty two states adopted MCV vaccination requirements, and we control for these throughout. Note that a state never adopted a middle school vaccination requirement for MCV prior to adopting one for Tdap.

[28] Specifically, we consider there to be an effective (newly binding) "catch up" mandate if a child residing in state s who is age 13 in year t was subject to the mandate for middle school entry (i.e., there was a mandate effective for 12 year olds in year $t-1$ or for 11 years olds in year $t-2$) and was *not* subject to a mandate for the same vaccine prior to kindergarten entry (i.e., there was not a mandate in effect in state s for the same vaccine when the child was age 5 in year $t-8$).

[29] Due to the Affordable Care Act (ACA) preventive services rule requiring most insurance plans to cover ACIP-recommended vaccinations and well-child visits without cost-sharing beginning September 2010, we turn the insurance coverage indicator "on" for all observations in years 2011 and later.

[30] Over our sample period only two states changed their exemption policy for vaccinations; both did so by eliminating the personal belief exemption.

[31] In a series of robustness checks we verify our results are unaffected by the inclusion of several additional controls for which we have data only for a subset of our sample years. These include state Section 317 funding, state Vaccines For Children (VFC) policies, and scope of practice laws regarding pharmacist prescribing authority (Trogdon et al. 2016).

black, Hispanic, and other nonwhite races; fraction of individuals with high school degrees and college or more; fraction of individuals under 21 and between 21–64; and fraction of individuals below the federal poverty line).[32] In order to best capture the state characteristics that would have feasibly been relevant to the vaccination decisions considered here, all variables contained in the Z_{st} vector are measured in the year in which the child was 11 (year $t - 2$). We also include in the Z_{st} vector the lagged population-wide pertussis and meningococcal disease rates in the state, following Philipson (1996) and Oster (2016). All models additionally control for a full set of state and birth cohort fixed effects. In some models we further control for state-specific linear cohort trends, where we interact each state fixed effect with a variable TREND that equals 1 for individuals who were age 13 in 2004, 2 if age 13 in 2005, and so forth. We use sample weights provided by NIS-Teen, and we cluster standard errors at the state level (Bertrand, Duflo, and Mullainathan 2004).[33]

The variable β_2 represents our coefficient of interest and reflects the direct and indirect (i.e., spillover) effects of middle school vaccination requirements. The key identifying assumption in this difference-in-differences style model is that vaccination outcomes would have evolved similarly in states that did and did not adopt a middle school vaccination requirement in the absence of the mandate, or alternatively that there were no other unobserved shocks to vaccination outcomes in states coincident with adoption of the middle school vaccination requirements. In some models we replace the vector of Tdap, MCV, and HPV middle school vaccination requirements with a series of indicator variables representing years relative to adoption of the respective state vaccination requirement. This event-study style framework allows us to explicitly address and visually inspect the parallel trends assumption in the two-way fixed effects framework.

For analyses of the morbidity data, we estimate a variant of equation (1) where the outcome is the age-specific morbidity rate in state s and year t, measured as number of cases per 100,000 population.[34] Age-specific morbidity rates are calculated using the number of cases for each disease by age group (as provided to us by the Centers for Disease Control and Prevention) and age-specific population estimates from the Surveillance and Epidemiologic End Results (SEER) system. In this more aggregate level model, we include year fixed effects instead of birth cohort fixed effects, and all policies are considered in effect at the start of the calendar year following implementation. These models use age-specific state population weights.

[32] State unemployment rates come from the Bureau of Labor Statistics. State demographic characteristics are from the Census Bureau. Our main results are not sensitive to removing the controls in the Z vector.

[33] In 2011, NIS-Teen switched from single frame landline-only sampling to dual frame sampling that included landlines and cell phones, and in that year only both single and dual frame weights are provided. In all reported estimates we use dual frame weights starting in 2011. None of the main results is sensitive either to this decision or to the exclusion of weights.

[34] We note that given the nature of disease contagion, there is potential for cross-state spillovers in reduced disease incidence, which would bias our estimated effects toward zero using this identification strategy. Ideally we would test for the presence of this type of geographic spillover, however, doing so would require morbidity measures at a sub-state level, which the CDC does not release due to confidentiality concerns.

IV. Results

A. *Descriptive Statistics*

Online Appendix Table 1 presents means of key variables relating to Tdap, MCV, HPV, and influenza vaccination-related outcomes and demographic characteristics from the NIS-Teen 2008–2013 sample. By age 13, 45 percent of the NIS-Teen sample received the Tdap booster, and 35.7 percent received the MCV vaccine. These rates are, respectively, higher in states that had implemented a middle school entry mandate for the Tdap booster by 2013. Notably, MCV and HPV vaccination rates were also higher in states with Tdap vaccination requirements in place by 2013, though the same is not true for seasonal influenza vaccination rates. In the full sample, HPV and seasonal influenza vaccination rates are both substantially lower than Tdap booster vaccination rates at 23.6 and 12.2 percent, respectively. As mentioned previously, Figure 1 shows the trends in Tdap, MCV, and HPV vaccination rates for adolescents over our sample period; all have increased substantially since 2005. Online Appendix Table 1 also shows that slightly less than half the NIS-Teen sample is female, over 57 percent is white, 20 percent is Hispanic, and over 14 percent is black. At the time of the survey, over a third of the mothers in the NIS-Teen sample were college educated, while 69.6 percent were married.

B. *Direct Effects of Tdap Mandates on Tdap Vaccination and Pertussis Cases*

In Table 1, we present difference-in-differences estimates of the effects of state middle school vaccination mandates on vaccine take-up and morbidity outcomes that take explicit advantage of the plausibly exogenous variation in the timing of policy adoption across states. Columns 1 and 2 (without and with linear state trends, respectively) of Table 1 present results from separate regressions of the model specified in equation (1) where the outcome variable is receipt of the Tdap booster between ages 10 and 12. We report the coefficients on the policy indicator for the state Tdap booster requirement.

The results in columns 1 and 2 of Table 1 provide strong evidence that Tdap vaccination mandates for middle school entry were effective at increasing take-up of the Tdap vaccine. The estimate in column 1 indicates that Tdap mandates were associated with a 13.5 percentage point increase in the likelihood that an adolescent received a Tdap booster between 10 and 12 years of age, and this finding is invariant to the inclusion of smooth state-specific linear time trends. Figure 1 showed that over our sample period Tdap vaccination rates increased from about 0 to 80 percent; the estimates in columns 1 and 2 of Table 1 indicate that Tdap mandates can explain about 17 percent of this overall increase.[35] We show visually event-study-based

[35] Note that vaccination rates are not 100 percent. This is due in part to the fact that five states still have not adopted requirements for the Tdap booster as a condition of middle school entry. It is also due to some amount of noncompliance, though the channels of noncompliance are quite rare. For example, adolescents and parents can evade state Tdap booster requirements for middle school entry by homeschooling their children, though nationally the rate of homeschooling is less than 3.5 percent during our sample period (Snyder, de Brey, and Dillow 2016).

Table 1—Middle School Tdap Vaccination Requirements Increased Tdap Vaccination Rates by Age 13 and Reduced Population Pertussis Morbidity, NIS-Teen (2008–2013) and CDC Data (2001–2015)

	1 dose Tdap booster (1)	1 dose Tdap booster (2)	Pertussis morbidity (3)	Pertussis morbidity (4)
Sample mean	0.449	0.449	6.889	6.889
Δ (*final year − base year mean*)	*0.814*	*0.814*	*3.792*	*3.792*
Tdap mandate for middle school entry	0.135	0.137	−2.241	−2.220
	(0.0140)	(0.0164)	(1.262)	(1.543)
R^2	0.335	0.338	0.439	0.486
Observations	116,304	116,304	763	763
Individual characteristics?	Yes	Yes	Yes	Yes
Other policy controls?	Yes	Yes	Yes	Yes
Other state/time varying Xs?	Yes	Yes	Yes	Yes
State and year fixed effects?	Yes	Yes	Yes	Yes
Linear state trends?	No	Yes	No	Yes

Notes: Results in columns 1 and 2 are from linear probability models and use NIS-Teen sampling weights. The outcome in columns 1 and 2 is an indicator for whether the individual received the Tdap booster by age 13. Individuals are observed at ages 13–17 between 2008 and 2013. All models include controls for individual demographic characteristics (age at observation fixed effects, gender, race, number of children in the household, and mother's age, education level, and marital status); state and birth cohort fixed effects; state mandates for insurance coverage of well-child visits and vaccines; state college and high school immunization and education requirements for MCV; state HPV policies (see text for details); state immunization mandates for child care/kindergarten entry; lagged state pertussis and meningococcal disease incidence; state children's Medicaid/CHIP income eligibility thresholds; state unemployment rates; and state demographic characteristics (fraction black, Hispanic, and other races, fraction of individuals with high school degree and with some college or more, and fraction below the federal poverty level). Results in columns 3 and 4 are estimated using disease incidence data from the CDC and are weighted by state population. The dependent variable in columns 3 and 4 is the number of reported cases of pertussis per 100,000 population. These models include controls for state mandates for insurance coverage of well-child visits and vaccines; all child care/school vaccination mandates; state HPV and MCV policies; lagged pertussis incidence; state children's Medicaid/CHIP income eligibility thresholds; state unemployment rates; state demographic characteristics (fraction black, Hispanic, and other races, fraction of individuals with high school degree and with some college or more, and fraction below the federal poverty level); and state and year fixed effects. Columns 2 and 4 also include linear state trends. Standard errors are clustered at the state level.

estimates of the direct effect of Tdap mandates on Tdap-vaccine uptake in Figure 4 (the actual estimates from the event study specification are presented in online Appendix Table 2). Figure 4 shows that the Tdap mandates induced large, immediate, and significant increases in Tdap booster take-up, and there is no evidence of systematic trends prior to Tdap mandate adoption. This is consistent with the validity of the parallel trends assumption required for identification.

Were these increases in vaccination rates effective at reducing morbidity? We present difference-in-differences estimates of the effect of Tdap mandates on population-wide pertussis morbidity in columns 3 and 4 of Table 1. The outcome variable in these columns is the population incidence rate of pertussis per 100,000 population from 2001–2015.[36] The estimates in columns 3 and 4 of Table 1 provide some evidence that the Tdap booster requirements for middle school entry were effective at reducing population-wide pertussis incidence. Specifically, we estimate that adoption of a Tdap booster mandate reduced pertussis morbidity by 2.2 cases per

[36] Note that although we have disease incidence data for 2000-2015, the inclusion of a lagged measure of disease incidence in our baseline specification means that we are only able to examine disease incidence as an outcome variable for the years 2001–2015.

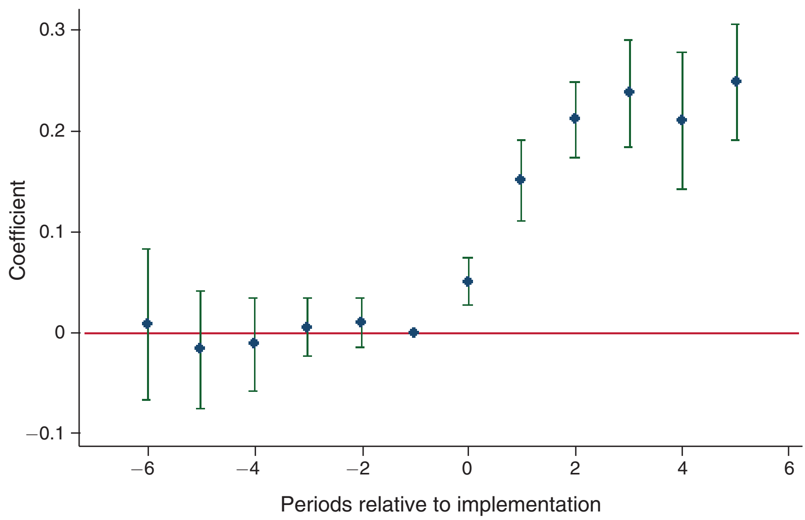

Figure 4. Event Study Estimates of the Direct Effects of Middle School Vaccination Requirements for the Tdap Booster

Notes: Coefficients are relative to the excluded group of the year prior to policy implementation. The coefficients presented for −6 periods and 5 periods relative to implementation should be interpreted as the coefficient on 6 or more years prior to implementation and 5 or more years since implementation, respectively. The vertical bars around each point estimate represent the 95 percent confidence intervals.

100,000 population, or by about 32 percent relative to the sample mean.[37] The point estimate on the Tdap booster requirement variable is statistically significant in the two-way fixed effects model of column 3; adding linear state trends in column 4 reduces the estimate somewhat and renders it statistically insignificant.[38] We additionally present event-study estimates of the effect of the Tdap mandates on population-wide pertussis morbidity in Figure 5 (coefficient estimates are presented in online Appendix Table 4).[39] Although the visual evidence of a population-wide pertussis reduction appears quite short-lived, there is no evidence that Tdap mandates were implemented in response to pertussis outbreaks in a state.[40]

[37] In additional analyses presented in online Appendix Table 3, we investigate potential nonlinearities in the effect of the mandate based on initial levels of disease prevalence. We find no significant interaction effect when we interact the mandate with baseline (2004) incidence rates, although estimates from models that include interactions with disease incidence rates in the year prior to mandate implementation suggest that mandates are especially effective at reducing pertussis in states with higher pertussis rates. When combined with the event study evidence that Tdap mandates were not systematically adopted in response to sharp upward spikes in pertussis incidence (as shown in Figure 5), this suggests the potential importance of nonlinearities in the effects of the policies.

[38] As a sensitivity check we also estimated the morbidity analyses using log (pertussis cases + 1) as the outcome variable. Our results are robust to this alternative specification.

[39] Figures 3 and 4 (event studies for Tdap vaccine take-up and pertussis morbidity, respectively) show estimates from models without linear state trends. Estimates from the models with trends were qualitatively similar (see online Appendix Tables 2 and 4).

[40] There are many reasons why a sustained increase in Tdap vaccination rates might result in only a short-term reduction in pertussis rates. One is that the immunity effect wears off after a couple of years, which is why many states require periodic vaccination "boosters." Another is that many states implemented the Tdap mandate by requiring the vaccine not only for those in sixth or seventh grade, but also for students through ninth, or in some cases twelfth, grade, with the idea that they wanted to increase Tdap vaccination as much as possible among these youths. This means that in practice, in the years after initial Tdap mandate adoption, only the new sixth or seventh grade youths (depending on the grade configuration in the state) or new enrollees would be required to be newly vaccinated.

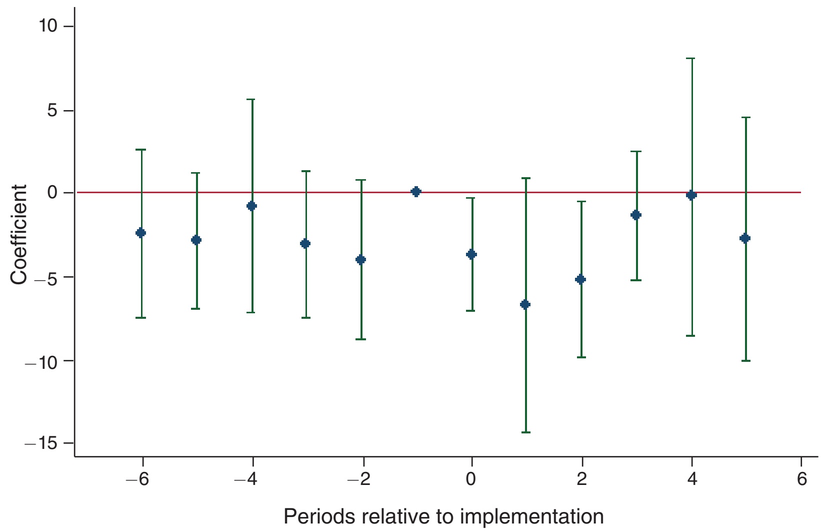

Figure 5. Event Study Estimates of Effects of Middle School Vaccination Requirements for the Tdap Booster on Population Pertussis Morbidity

Notes: Coefficients are relative to the excluded group of the year prior to policy implementation. The coefficients presented for −6 periods and 5 periods relative to implementation should be interpreted as the coefficient on 6 or more years prior to implementation and 5 or more years since implementation, respectively. The vertical bars around each point estimate represent the 95 percent confidence intervals.

We examine cross-age morbidity spillover effects in Table 2. Specifically, Table 2 makes use of age-specific morbidity data for two diseases: pertussis and tuberculosis (which is not protected against by the Tdap vaccine). With these data we estimate two-way fixed effects models as in columns 3 and 4 of Table 1, but we replace the outcome variable with an age-group specific rate of pertussis incidence. All regressions are weighted by age-group specific population measures. The results from this analysis are presented in columns 1 and 2 of Table 2, and we report only the coefficient on the single Tdap mandate indicator. Thus, each table entry is the coefficient from a separate regression, where the relevant age group is provided in the row label. All regressions include the full set of state-level controls and state and year fixed effects; column 2 adds state-specific linear time trends.

The results in Table 2 provide evidence that the middle school vaccination requirements for the Tdap booster were effective at reducing morbidity among the targeted group: 5–14-year-olds. We estimate that a Tdap mandate reduced pertussis cases of 5–14-year-olds by 9 cases per 100,000 population, and this estimate is statistically significant at the 5 percent level. Including linear state trends reduces the magnitude somewhat but continues to suggest large, though not significant, reductions in pertussis in the targeted age group when Tdap mandates are adopted. Notably, we also estimate that state Tdap mandates significantly reduced pertussis morbidity for infants age 0–4 and adults age 25–34. These findings are consistent with the possibility of herd immunity effects induced by the increased vaccination

TABLE 2—MIDDLE SCHOOL TDAP VACCINATION REQUIREMENTS REDUCED PERTUSSIS MORBIDITY, CDC DATA 2001–2015 (*Each Entry is the Coefficient on the Tdap Mandate*)

	Pertussis incidence rate (1)	Pertussis incidence rate (2)	TB incidence rate (3)	TB incidence rate (4)
Direct effect				
Age 5–14	−8.986 (4.318)	−8.242 (5.479)	−0.0950 (0.0716)	−0.0309 (0.0775)
Spillover effects				
Age 0–4	−9.490 (4.709)	−9.698 (5.650)	0.0647 (0.190)	0.0208 (0.233)
Age 15–24	−1.260 (1.324)	−1.533 (1.503)	0.205 (0.132)	0.245 (0.130)
Age 25–34	−0.861 (0.481)	−0.746 (0.525)	0.0335 (0.176)	0.153 (0.175)
Age 35–44	−0.886 (0.561)	−0.703 (0.630)	−0.130 (0.156)	−0.0754 (0.112)
Age 45–54	−0.603 (0.470)	−0.470 (0.489)	−0.0630 (0.170)	0.0511 (0.158)
Age 55–64	−0.516 (0.332)	−0.539 (0.362)	−0.129 (0.118)	−0.0258 (0.123)
Age 65+	−0.318 (0.239)	−0.349 (0.295)	0.0606 (0.171)	0.0288 (0.178)
Linear state trends?	No	Yes	No	Yes

Notes: The dependent variable is the number of reported cases of each disease per 100,000 population, separately by age group (reported in each row). Each entry is from a separate regression. All models include controls for state mandates for insurance coverage of well-child visits and vaccines; all child care/school vaccination mandates; state HPV and MCV policies; lagged pertussis incidence; state children's Medicaid/CHIP income eligibility thresholds; state unemployment rates; state demographic characteristics (fraction black, Hispanic, and other races, fraction of individuals with high school degree and with some college or more, and fraction below the federal poverty level); and state and year fixed effects. Columns 2 and 4 also include linear state trends. Regressions are weighted by age-specific state population. Standard errors are clustered at the state level.

of disease transmitters (adolescents).[41] Although the statistical significance of these estimates is somewhat affected by the inclusion of linear state trends, the estimated magnitudes are large and consistently suggest meaningful reductions in pertussis incidence.[42] Spillover effects to infant pertussis morbidity are not surprising, as

[41] As noted previously, the cross-age morbidity spillovers documented in Table 2 might not be herd immunity effects if there were cross-age *behavioral* spillovers to increased vaccination rates of non-targeted age groups. We tested this possibility directly in online Appendix Tables 5 and 6. In online Appendix Table 5 we examine the effects of the mandate on vaccination rates among 7–9-year-olds, 14–15-year-olds, and 16–17-year-olds, using NIS-Teen data and the same specification as in our baseline vaccination estimates. For the 14–15 and 16–17-year-olds we limit our sample to states that did not require the Tdap booster for any ages above 13, so that we could credibly identify behavioral spillovers. We find suggestive evidence of behavior spillovers to 16–17-year-olds, although estimates are small in magnitude (1.3–2.3 percentage points). In online Appendix Table 6, we use vaccination data from the 2003–2015 National Immunization Survey, which is a counterpart to (and precursor of) the NIS-Teen and which targets children age 19–35 months. Using a similar two-way fixed effects model as presented in equation (1), we estimate the effect of the Tdap mandates for middle school entry on the probability that a young child is up-to-date with the infant diphtheria, tetanus, and pertussis vaccine, DTaP (for infants age 19–35 this is 4 doses). We find no evidence that Tdap mandates were associated with meaningful changes in infant DTaP vaccination rates, and this null finding was not sensitive to the presence of other children in the household. In results not reported but available upon request we also estimate effects on adults using data from the CDC BRFSS from 2012–2016. For 12 states these data include answers to the question "Have you received the Tdap vaccine since 2005?" for a subset of years (for a total of 40 state-year observations). Although identification for this analysis is only based on 3 states, we do find suggestive evidence that the mandates increased Tdap vaccination rates among adults by 1.1–1.2 percentage points. Given the data limitations, however, we interpret these results cautiously.

[42] In online Appendix Figure 2, we present age group-specific pertussis incidence rates in the year prior to the vaccine development (2004) and in the last year of the sample (2015). We also visually present, in online Appendix Figure 3, the estimated proportional pertussis morbidity reduction attributable to the Tdap mandates (relative to the age-group specific 2004 mean) across the life course. Online Appendix Figure 3 confirms that the effects of the Tdap mandates for middle school entry were large across all age groups but were particularly effective for infants and prime age adults.

infants cannot be vaccinated against pertussis until two months of age, and it takes multiple doses over several months for them to develop a high level of protection.[43]

As a robustness/falsification analysis we also estimate the effects of the Tdap mandates on age-specific tuberculosis morbidity, the only other disease with a plausibly similar transmission mechanism for which we were able to obtain age-specific morbidity data at the state/year level from the CDC.[44] Tuberculosis is a relatively common infection caused by bacteria, and it is transmitted from person-to-person through the air.[45] Symptoms include a cough that typically lasts at least three weeks, chest pain, fatigue, and a fever. Tuberculosis, while similar to pertussis in transmission mode and clinical symptoms, is not prevented by the Tdap vaccine; thus, if we observed effects of the Tdap booster mandates on tuberculosis morbidity for 5–14-year-olds (or for other age groups), this would be suggestive of a model misspecification or an omitted variables problem. We present the estimates of the Tdap mandates on tuberculosis morbidity in columns 3 and 4 of Table 2. The estimates are small and statistically insignificant in nearly all models. Thus, overall we find strong evidence that the Tdap mandates for middle school entry generated large reductions in pertussis morbidity that extended beyond the directly targeted age group (5–14-year-olds). Some of these morbidity effects for other age groups—particularly infants—could be consistent with herd immunity from increased vaccinations of middle school age youths.

C. *Cross-Vaccination Spillovers*

We next consider the potential for cross-vaccination spillovers among middle school-aged children. For these analyses we take advantage of the fact that among the 46 states that mandate receipt of *any* of the vaccines routinely recommended for 11–12-year-olds prior to middle school entry, all mandate the Tdap booster, less than half mandate the MCV vaccine, only 2 mandate HPV, and none mandate seasonal influenza. In all states, Tdap was the first among this set of vaccines to be required for middle school entry. If after controlling for all other middle school vaccination mandates there is an effect of the Tdap mandate on receipt of other vaccines among middle school-aged individuals, then we interpret this as evidence of cross-vaccination spillovers from Tdap booster mandates to non-Tdap vaccination rates.

We present these findings in Table 3 for the other ACIP-recommended vaccines for adolescents: MCV (columns 1–2), HPV vaccine initiation by age 13 (columns 3–4), HPV vaccine completion by age 13 (columns 5–6), and seasonal influenza vaccine between the ages of 10 and 13 (columns 7–8) for models without and with

[43] This result is consistent with findings in the epidemiological literature, which, in a different context, similarly document that the herd immunity effects of the Tdap vaccine primarily occur for infants (Rohani, Zhong, and King 2010; Domenech de Cellès et al. 2014).

[44] We also present, in online Appendix Table 7, a set of falsification analyses using a number of other nationally notifiable diseases for which we were able to obtain morbidity data at the population level only. We find no significant effect of the Tdap mandate on any of the other disease we consider, and the estimated effects are consistently very small in magnitude.

[45] The mean rate of tuberculosis during our sample period was 4.1 cases per 100,000 population.

Table 3—Middle School Tdap Vaccination Requirements Had *Cross-Vaccine Spillovers* to Other ACIP-Recommended Vaccines for Adolescents, NIS-Teen 2008–2013

	1 dose MCV (1)	1 dose MCV (2)	Initiated HPV vaccine (3)	Initiated HPV vaccine (4)	Completed HPV vaccine (5)	Completed HPV vaccine (6)	Had influenza vaccine, age 10–13 (7)	Had influenza vaccine, age 10–13 (8)
Sample mean	0.357	0.357	0.236	0.236	0.0987	0.0987	0.122	0.122
Δ (*final year − base year mean*)	*0.724*	*0.724*	*0.306*	*0.306*	*0.139*	*0.139*	*0.436*	*0.436*
Tdap mandate for middle school entry	0.0223	0.0290	0.0490	0.0416	0.0247	0.0331	0.0123	0.00709
	(0.0159)	(0.0148)	(0.0151)	(0.0152)	(0.00863)	(0.0107)	(0.00815)	(0.00657)
R^2	0.285	0.289	0.111	0.113	0.065	0.066	0.172	0.175
Observations	116,304	116,304	57,133	57,133	57,133	57,133	116,304	116,304
Linear state trends?	No	Yes	No	Yes	No	Yes	No	Yes

Notes: See notes to Table 1 for details on the specification and control variables. Columns 3–6 are restricted to females who were age 13 between 2007–2013 and males who were age 13 between 2011–2013.

linear state trends in the odd and even-numbered columns, respectively.[46] Results in Table 3 indicate the presence of cross-vaccine spillover effects of Tdap mandates for middle school entry. The estimates in columns 1 and 2 of Table 3, for example, indicate that Tdap mandates increased the probability an adolescent received the MCV vaccine by 2.2–2.9 percentage points, and these estimates are statistically significant at the 10 percent level in models with linear state trends. Note that since the Tdap vaccine was always in the first set of vaccines to be mandated for middle school entry, the Tdap mandate effect in these models is identified from the 27 states that adopted Tdap requirements but *not* MCV requirements, as well as from the small number of states that first adopted a Tdap requirement and then years later adopted an MCV requirement.

Columns 3 through 6 of Table 3 also show striking evidence of sizable cross-vaccination spillover from Tdap mandates to HPV initiation (columns 3 and 4) and completion (columns 5 and 6).[47] Specifically, our estimates in columns 3 and 4 suggest that the Tdap mandates increased HPV vaccine initiation by 4.2–4.9 percentage points, and these estimates are statistically significant. Moreover, columns 5 and 6 indicate that the Tdap mandates also significantly increased completion of the 3-dose series of the HPV vaccine on the order of 2.5–3.3 percentage points.[48] Finally, columns 7 and 8 of Table 3 provide no evidence that Tdap mandates increased take-up of the seasonal influenza vaccine.

[46] To account for the fact that the HPV vaccine was not approved for use in males until 2009, the estimation sample for HPV vaccination outcomes is restricted to females who were age 13 between 2007–2013 and males who were age 13 between 2011–2013.

[47] For completeness we also estimated the spillover effects to the receipt of at least two doses of the HPV vaccine series, since the ACIP recently revised its guidelines to recommend that younger adolescents obtain just two doses of the HPV vaccine instead of three. Our estimates suggest that the Tdap mandates significantly increased the probability of having received at least 2 doses of the HPV vaccine series by 2.8–2.9 percentage points.

[48] Online Table 8 shows event study estimates for the Tdap mandate spillovers to MCV vaccination, HPV vaccine initiation, and HPV vaccine completion. In general, we find little evidence of systematic pre-trends in outcomes prior to Tdap mandate adoption and significant immediate increases in vaccination rates for MCV, HPV initiation, and HPV completion, none of which were mandated by the policy whose event time coefficients are reported. Online Appendix Table 9 shows that if we define cross-vaccine spillovers in a different way by considering

What might explain the null effect of the Tdap mandates on seasonal influenza vaccination? One possibility is timing. Whereas vaccines for Tdap, MCV, and HPV are generally available throughout the year—including prior to the start of the school year—the same is not true for seasonal influenza. Typically seasonal flu vaccines become available in September, after most adolescents have started the school year. Thus, it could be that when parents take their child to a healthcare provider for the required Tdap vaccine prior to middle school entry, the MCV and HPV vaccines are in stock but the seasonal flu vaccine is not.[49]

D. *Heterogeneity*

In Table 4, we investigate heterogeneity in the effects of the Tdap mandates for middle school entry on Tdap vaccination rates (the direct effect) and on vaccination rates for the other routinely recommended vaccines for youths in this age range where we find spillovers: MCV, HPV vaccine initiation, and HPV vaccine completion. In each entry of Table 4, we present the relevant subsample mean and the coefficient on the Tdap mandate (and its associated standard error) from a separate fully saturated regression model with linear state trends. The outcome variable for each regression is provided in the column header, and each row reports results for a different subsample; we reprint the results for the full sample in the top row. We separately consider the effects of the Tdap mandate on vaccination by gender of the child (rows 2 and 3), race/ethnicity (rows 4–6), and maternal education (rows 7 and 8).

Table 4 reveals several intriguing patterns with respect to heterogeneous effects. First, we find that the direct compliance effect of the Tdap mandate on Tdap vaccination rates (column 1) is larger for girls than for boys and is larger for mothers with lower education relative to mothers with higher education. This latter gradient could reflect that the children with lower educated mothers have a lower vaccination rate in the absence of the mandate and thus have further to go to achieve compliance.[50]

In terms of spillover effects, several patterns are notable. The gender difference in the direct effect (i.e., larger effects for girls) is also observed for the spillover effect of Tdap mandates to MCV and HPV vaccination. For race/ethnicity, we find that although the direct effect of the Tdap mandate is largely invariant to race/ethnicity, the spillover effects to HPV vaccine initiation are much larger for Hispanic youth

outcomes that are the combination of the Tdap booster with each of the other ACIP-recommended vaccines, we continue to find that the Tdap mandates for middle school entry had spillover effects at increasing take-up of MCV and HPV vaccines. Online Appendix Table 10 shows that our spillover estimates are robust to adding data from the 2014 and 2015 NIS-Teen, which used different criteria for determining completeness of provider vaccination data than earlier years. Online Appendix Table 11 shows that the spillover effects to MCV and HPV are largely driven by years in which the respective vaccine was ACIP-recommended for adolescents. Note that once a vaccine is ACIP-recommended, the Vaccines for Children program must pay for it for low-income children.

[49] Also, the flu vaccine is different from the other vaccines in that it was the most recent to be recommended for routine vaccination, and it is also recommended for adolescents and the rest of the members of the household on an annual basis. It could be that getting the flu vaccine is a qualitatively different experience for the family, since everyone in the household is recommended to get the influenza vaccine every year.

[50] Specifically, in states and years in which there is not an effective Tdap mandate for middle school entry, the Tdap vaccination rate by age 13 for children whose mothers have a bachelor's degree is 35.9 percent, compared to 27.8 percent of children whose mothers whose highest level of education is less than a bachelor's degree. A similar pattern holds if we stratify by household income instead of mother's education.

Table 4—Heterogeneity in the Effects of Middle School Tdap Vaccination Requirements, NIS-Teen 2008–2013 (*Each entry is the coefficient on the Tdap mandate*)

	1 dose Tdap (direct effect) (1)	1 dose MCV (spillover effect) (2)	Initiated HPV vaccine (spillover effect) (3)	Completed HPV vaccine (spillover effect) (4)
1. Full sample, mean	0.449	0.357	0.236	0.099
Tdap mandate effect	0.137	0.0290	0.0416	0.0331
	(0.0164)	(0.0148)	(0.0152)	(0.0107)
2. Girls, mean	0.448	0.355	0.265	0.117
Tdap mandate effect	0.152	0.0392	0.0349	0.0361
	(0.0170)	(0.0196)	(0.0147)	(0.0136)
3. Boys, mean	0.449	0.358	0.123	0.028
Tdap mandate effect	0.122	0.0190	−0.0609	0.0301
	(0.0167)	(0.0133)	(0.0482)	(0.0481)
4. White, mean	0.453	0.343	0.205	0.095
Tdap mandate effect	0.150	0.0378	0.0438	0.0332
	(0.0192)	(0.0182)	(0.0174)	(0.0111)
5. Black, mean	0.412	0.347	0.238	0.078
Tdap mandate effect	0.150	0.0757	0.0454	0.0637
	(0.0390)	(0.0243)	(0.0354)	(0.0224)
6. Hispanic, mean	0.456	0.389	0.303	0.118
Tdap mandate effect	0.128	0.0305	0.0972	0.0470
	(0.0142)	(0.0189)	(0.0368)	(0.0197)
7. Mother has at least BA, mean	0.509	0.403	0.206	0.094
Tdap mandate effect	0.111	0.00570	0.0290	0.0314
	(0.0207)	(0.0202)	(0.0185)	(0.0108)
8. Mother has less than BA, mean	0.418	0.333	0.252	0.101
Tdap mandate effect	0.149	0.0397	0.0474	0.0349
	(0.0180)	(0.0145)	(0.0173)	(0.0140)

Notes: Columns 3 and 4 are restricted to females aged 13 between 2007–2013, and males aged 13 between 2011–2013. See notes to Table 1 for details on the specification and control variables. All models include state trends.

compared to white youth, while the spillover effects to HPV vaccine completion are largest for black youths.

Finally, the spillover effects of Tdap mandates also vary by maternal education. Lower educated mothers are much more likely to take up the MCV vaccine and the first dose of the HPV vaccine for their children compared to highly educated mothers when their state requires their child to receive the Tdap booster. This could happen for several possible reasons, including the possibility that the information sent home to parents is more of a treatment for low-educated mothers than for highly educated mothers (who may have known about the other ACIP-recommended vaccines even in the absence of the Tdap mandate). It could also be that the low-educated mothers are complying with the Tdap mandate in qualitatively different ways than the high-educated mothers, for example, by visiting different types of providers where the interaction leads to different types of cross-vaccine spillovers.[51] Finally, it could

[51] In results not reported but available upon request, we additionally considered heterogeneity in mandate effects by type of provider and by insurance status. For provider type, the NIS-Teen data allow us to identify whether the child received her vaccines exclusively at public institutions (e.g., public clinics), exclusively at private institutions

be an income effect: if low-educated mothers are more likely to be eligible for free vaccines under the Vaccines for Children program, the increased take-up of the MCV vaccines could reflect downward sloping demand. We explore mechanisms in the next section.

E. *Mechanisms*

Our final sets of analyses attempt to disentangle mechanisms for the cross-vaccination spillovers observed in Tables 3 and 4. In addition to the implicit price reduction for the non-mandated vaccines brought about by the fact that the child has to see a provider to obtain the required Tdap vaccine, there are also possible roles for parents and providers. For example, it could be that state Tdap mandates cause parents to receive new information about other age-recommended vaccines, and this causes them to get their child vaccinated against those conditions even though it is not required. Alternatively, it could be that the Tdap mandates simply cause parents to have increased contact with the healthcare system, whereby a provider informs them about other age-appropriate vaccinations for their child. These mechanisms have different implications for the most effective policy for increasing immunizations.

We investigate these issues in a variety of ways. First, we consider a range of outcomes available in the NIS-Teen data: whether the parent had ever heard of human papillomavirus or HPV, whether the parent had ever heard of a vaccine for HPV called Gardasil or Cervarix (the trade names for the HPV vaccine), whether the parent reports that her doctor ever recommended the HPV vaccine, and whether the child had an 11–12 year old well-child visit. A positive effect of the Tdap mandates on these last two outcomes—receipt of a physician recommendation for the HPV vaccine or the likelihood that the youth had a well-child visit (and thus interacted with the healthcare system)—would provide evidence in favor of the provider mechanism. The first two outcomes, parental knowledge of HPV and of the HPV vaccine, are more ambiguous and could be affected through receipt of new information regarding vaccination from the school or through the provider channel. In the absence of other evidence for the provider mechanism, however, an effect on these outcomes would lend support for the idea that patient behavior underlies the spillover.

Table 5 presents these results for the sample of youths who were age 13 at the time of the survey (and for whom the reference window of the questions is most recent and relevant).[52] We find little evidence that Tdap mandates are significantly

(e.g., a physician's office or retail clinic), or in a mixture of public and private settings. Acknowledging that the type of setting chosen for vaccination is endogenous, we do find that the spillover effects of the Tdap mandates were significantly larger for individuals whose vaccinations were received exclusively at public providers. We also test for differential effects of the mandate in states that allow pharmacists to administer vaccines to adolescents, but we do not find evidence of a significant interaction between the two policies. Limiting our sample to adolescents aged 13 at the time of survey (since we only observe the child's insurance status at the time of the survey, not at the time of vaccination), we find no evidence of heterogeneous effects of the mandate by insurance status. We further examine, separately by child insurance status, if mandates had differential effects in states with immunization insurance mandates or after the ACA preventive services mandate went into effect. We find no evidence of heterogeneous effects of the mandates along these dimensions.

[52] Because these analyses are done using a subset of the sample used in our main vaccination analyses presented in Tables 1 and 3, we re-estimate effects on Tdap, MCV, and HPV uptake for this more limited sample. Results are presented in online Appendix Table 12 and return patterns similar to those from the full sample.

Table 5—Evidence on Mechanisms, NIS-Teen 2008–2013

	Ever heard of HPV (1)	Ever heard of HPV (2)	Ever heard of HPV shot (3)	Ever heard of HPV shot (4)	Doctor recommended HPV vaccine (5)	Doctor recommended HPV vaccine (6)	Had an 11–12 year old well-child visit (7)	Had an 11–12 year old well-child visit (8)
Sample mean	0.947	0.947	0.922	0.922	0.480	0.480	0.915	0.915
Δ (*final year − base year mean*)	*−0.001*	*−0.001*	*−0.009*	*−0.009*	*0.056*	*0.056*	*0.041*	*0.041*
Tdap mandate for middle school entry	−0.00171	0.0368	0.0236	0.0443	0.0312	0.0348	0.0331	0.0382
	(0.0178)	(0.0249)	(0.0175)	(0.0222)	(0.0222)	(0.0433)	(0.00973)	(0.0166)
R^2	0.0810	0.101	0.0879	0.0994	0.105	0.109	0.0349	0.0385
Observations	7,757	7,757	7,764	7,764	17,399	17,399	24,144	24,144
Linear state trends?	No	Yes	No	Yes	No	Yes	No	Yes

Notes: See notes to Table 1 for details on the specification and control variables. All samples are restricted to individuals who have adequate provider vaccination data and are age 13 at time of survey, as the outcomes in columns 1–6 are measured at time of interview; they are not able to be retrospectively measured at age 13. The outcomes in columns 1–4 are only reported for 2008–2011, and so the estimation sample for these outcomes is females who are age 13 at the time of survey, 2008–2011. The actual question for the outcome in columns 3 and 4 asks about the cervical cancer vaccine, genital warts vaccine, HPV shot, Gardasil, or Cervarix. The estimation sample for columns 5 and 6 consists of the set of females aged 13 at time of survey for the 2008–2013 survey waves, and males aged 13 at time of survey for the 2011–2013 survey waves.

associated with increases in the likelihood of any of the outcomes except for a robust and statistically significant increase in the likelihood of having had an 11–12-year-old well-child visit. This offers some mixed support for the provider mechanism, though in this case we would have also expected Tdap mandates to have increased the likelihood of having received a physician recommendation for the HPV vaccine.[53]

We also investigated the patient mechanism using data from Google Trends, which captures the relative popularity of specific search terms in an area from 2005 to the present. These data have been used by other scholars studying a range of topics, including vaccination (see, for example, Oster 2016). The advantage of the Google Trends data in our setting is that we can examine the popularity of searches for, say, "Tdap" to see if adoption of Tdap mandates for middle school entry at the state level is associated with meaningful increases in search behavior. Since parents far outnumber providers (and we think providers are not using Google to find out about various vaccinations), any relationship between the mandates and the search behavior is likely to reflect parent behavior. At a minimum it may suggest that information about the Tdap vaccine is disseminating broadly in the community following Tdap mandate adoption. Moreover, we can examine searches for MCV and HPV-related terms as well to provide additional tests of the role of information and parent search behavior in driving the spillover effects.

The results of the Google Trends analyses are presented in Table 6. Specifically we present coefficients on the Tdap mandate in a two-way fixed effects regression on the relative search popularity score provide by Google for each state, where each

[53] It could also be that children are receiving vaccines that they or their parents are not aware they are receiving. Anecdotally some parents follow a rule of thumb whereby they instruct the provider to give any vaccination that is recommended for their child. While vaccine information statements are required to be provided to parents, it is not obvious how much the parent/provider interaction is an informed negotiation.

Table 6—Further Evidence on Mechanisms, Google Trends 2005–2013

	Relative Google search popularity for "Tdap" (1)	Relative Google search popularity for "Tdap" (2)	Relative Google search popularity of the "Meningococcal vaccine" topic (3)	Relative Google search popularity of the "Meningococcal vaccine" topic (4)	Relative Google search popularity for "HPV" (5)	Relative Google search popularity for "HPV" (6)
Sample mean	30.82	30.82	56.63	56.63	43.83	43.83
Δ (2013 *mean* − 2005 *mean*)	*25.54*	*25.54*	*−30.98*	*−30.98*	*1.18*	*1.18*
Tdap mandate for middle school entry	4.230	7.248	2.236	3.622	2.019	1.450
	(1.763)	(1.613)	(1.875)	(1.575)	(0.875)	(0.665)
Pertussis rate in the state	0.125	0.202	0.00178	0.00801	−0.0321	−0.0310
	(0.0647)	(0.0755)	(0.0245)	(0.0210)	(0.0245)	(0.0273)
R^2	0.666	0.733	0.614	0.657	0.793	0.803
Observations	4,845	4,845	4,825	4,825	5,508	5,508
Linear state trends?	No	Yes	No	Yes	No	Yes

Notes: The outcome variable is a measure of the popularity of a given search term or topic, in which, for each state, the month of peak search volume is normalized to 100. All models include the state policy controls and state demographics as described in the notes to Table 1 as well as fixed effects for each state and for each month-year. Columns 2, 4, and 6 also include linear state trends.

state's popularity is anchored at 100 in the month/year combination for that state where the search was most popular. We also report the coefficient on the pertussis rate in the state as an additional validity check, as Oster (2016) shows using Google Trends data that disease outbreaks increase vaccination in part by increasing information. The results in Table 6 provide striking evidence in favor of an information-based mechanism driving the direct and spillover effects of Tdap mandates for middle school entry. Columns 1 and 2 (without and with linear state trends, respectively) show that a Tdap mandate for middle school entry is significantly and positively associated with increased searches for "tdap" and that the current pertussis rate in a state is also significantly and positively associated with searches for "tdap." Columns 3 and 4 and columns 5 and 6, respectively, show that the former relationship is also true for searches related to the meningococcal vaccine and HPV: the popularity of both searches in a state is estimated to increase significantly when the state adopts a Tdap mandate.[54] This is strongly consistent with parent behavior playing an important role in driving the cross-vaccine spillovers identified above.[55]

V. Discussion and Conclusion

We provide a variety of analyses showing that state mandates requiring Tdap vaccination prior to middle school entry were highly effective at significantly increasing Tdap vaccine uptake between the age of 10 and 12 by 13.5–13.7 percentage

[54] These patterns are largely confirmed in online Appendix Table 13, which shows event study versions of Table 6.

[55] We also note that the fact we find any effect of state Tdap mandates on completion of the HPV vaccine series—which over our time period required three doses, each administered during separate visits to a healthcare provider over a minimum of six months—strongly suggests that patient behavior has to play an important role. Notably, this finding contrasts with that in Lawler (2017) who finds in the context of a different vaccine (hepatitis A) that vaccination recommendations are effective at inducing initiation but not completion of a vaccine series in young children.

points. Event study analyses show that the direct vaccination effects of the mandates occur immediately and are sustained over time. Similarly specified models of population-wide morbidity suggest a population-wide reduction on the order of 32 percent of the sample mean. Disaggregated age-specific pertussis morbidity data confirm that the Tdap mandates for middle school entry substantially reduced pertussis rates among 5–14-year-olds (whose vaccination rates were directly affected), but also induced meaningful reductions in pertussis morbidity for infants and young adults. Some of these effects may have occurred due to herd immunity (i.e., the reduced transmission attributable to directly targeted adolescents).

We also find clear evidence of cross-vaccination spillovers: state requirements that middle school youths obtain the Tdap booster resulted in increases in MCV vaccination even in states that did not require MCV vaccination for middle school entry. More striking, the Tdap mandates also significantly increased HPV vaccination rates. We also find that these spillover effects are larger for females, nonwhites, and children of less educated mothers. When we investigate mechanisms, we find some evidence that the mandates increased contact with healthcare providers. There is stronger evidence that the laws increased Google search behavior for information on the Tdap booster, meningococcal disease, and HPV. Taken together these patterns suggest that both parents and providers are responsible for the remarkable cross-vaccine spillovers attributable to state Tdap mandates.

Notably, our findings on spillovers differ from two prior published studies that have examined younger children. Oster (2016) finds that although pertussis outbreaks increase whooping cough vaccination rates, there are no spillovers to vaccination rates for other diseases,[56] while Lawler (2017) finds a similar null result using variation from state mandates requiring Hepatitis A vaccination for childcare or kindergarten entry. We suspect that two factors are particularly important for explaining this divergence: first, younger children have much more contact with the healthcare system than do middle school age adolescents. This may work against spillovers for younger children and infants since most of them are already getting the recommended vaccinations at their frequent well child visits. Second, the policies we study here are likely to be more salient treatments than the kindergarten entry mandates for Hepatitis A studied in Lawler (2017). This is because the Tdap booster requirements were the first mandated vaccinations of any type for adolescents in these states, whereas Hepatitis A was never the first mandated vaccine for younger children in any state. Instead, it was one in a fairly long line of other state-mandated vaccinations that commonly included varicella, polio, and MMR.

Our results suggest that the private and social returns to middle school vaccination requirements for the Tdap booster are extremely large. Estimates from Table 2 indicate that, if implemented nationally, Tdap mandates would reduce pertussis incidence by 1,890 cases per year among 0–4 year olds (19.9 million 0–4-year-olds in US $\times$ 9.49 cases/100,000 population) and 3,700 cases per year among 5–14-year-olds. Additionally, using conservative estimates of the pertussis fatality rate, we find

[56] A working paper by Schaller, Schulkind, and Shapiro (2017) focusing on infants, however, does find that state whooping cough outbreaks are associated with increases in not only pertussis vaccination but also take-up of Hepatitis B, MMR, and varicella vaccinations for infants, consistent with cross-vaccine spillovers.

that these mandates potentially save the lives of 7–9 infants and children each year (Hamborsky, Kroger, and Wolfe 2015, Purdy et al. 2004). For adults, reductions are smaller but still substantial; we estimate the mandates would reduce pertussis incidence nationally by 380 cases per year among 25–34 year olds.

To estimate the value of this averted pertussis morbidity, we refer to Purdy et al. (2004), who provide age-group-specific cost estimates of pertussis morbidity. Their cost estimates include both direct costs due to outpatient and inpatient health care, as well as indirect costs due to lost work productivity (due to own illness or to care for sick family members). Based on their estimates, on average, each averted infant case saves approximately \$6,432, each averted child case saves approximately \$3,757, and each averted adult case saves approximately \$1,374. In total, this suggests that the reductions in pertussis morbidity resulting from national implementation of middle school Tdap mandates would generate approximately \$24.3 million per year of social savings. Reductions in pertussis mortality, valued using an estimate of the value of statistical life of \$9.1 million, would result in an additional \$65.8 million in social savings annually (Viscusi and Aldy 2003).

For estimates of policy cost we separately consider the costs of the increased vaccination and of policy enforcement. Our results in Table 1 suggest that national implementation of the Tdap mandates would increase the number of administered Tdap doses by approximately 540,000 doses per year (4 million 11 year olds in the US $\times$ 0.135). Using estimates from Whitney et al. (2014) and the CDC's Vaccine Price List (2018), we estimate the cost of each additional Tdap vaccine administered to be approximately \$112, for a total cost of approximately \$60.7 million per year. This estimate incorporates measures of the value of caregiver time and travel costs, vaccine administration costs, and the cost of the vaccine dose itself.[57] We also allow for an overall rate of vaccine wastage of 5 percent.

As an estimate of policy enforcement costs, we use personnel costs from a school-based health clinic vaccine administration study done by Kempe et al. (2012). In this study, school-based health clinic staff first checked student immunization records and then proceeded to meet with and administer vaccines to those with missing doses, for a per child average personnel cost of \$2.21. Scaling this estimate by the total number of 11 year olds in the United States suggests an upper bound on school-based enforcement costs of approximately \$8.84 million dollars per year.

Overall, our estimates suggest that national implementation of middle school Tdap booster mandates would generate approximately \$90.1 million in social savings per year (due to reductions in pertussis morbidity and mortality) while costing approximately \$69.5 million annually. These estimates imply a benefit-cost ratio of 1.30:1, or equivalently, that for each additional dollar spent, middle school Tdap mandates yield \$1.30 in social benefits.[58] Notably, this analysis likely underestimates the social benefits of the Tdap mandates, as our spillover estimates further suggest

[57] We account for the substantial differences in the price of a vaccine dose and its administration across public and private providers by using a weighted average price that reflects the distribution of adolescents across providers and the relative estimated effect sizes for adolescents that see each provider type in our sample. In our calculations we use an estimated price per dose of Tdap of \$34.67, with an associated administrative cost of \$16.57.

[58] For comparison, the estimates in Ward (2014) and White (2018) using quasi-experimental variation in influenza vaccination rates imply benefit-cost ratios in Canada and the United States of 5.18:1 and 3.54:1, respectively.

potentially large returns due to increased HPV vaccination. For example, our most conservative estimate suggests that HPV vaccine completion rates increased by 2.5 percentage points (column 5 of Table 3). Given that there are 4 million 11 year olds in the United States, this translates to about 100,000 adolescents and young adults who received 3 doses of the HPV vaccine because their state required them to get a Tdap booster prior to middle school entry. The American Cancer Society indicates that the lifetime risk of developing cervical cancer is about 0.6 percent; given that the HPV vaccine protects against the viruses that cause 70 percent of all cervical cancers, we estimate that Tdap mandates will prevent about 210 cases of cervical cancer (50,000 adolescent girls having completed the HPV vaccine due to Tdap mandates $\times$ 0.006 $\times$ 0.70). Similar calculations suggest that the Tdap booster mandates will also prevent 659 cases of throat cancer, 160 cases of anal cancer, and 74 cases of cancer of the vulva.[59]

Future work could also examine other longer term consequences of the Tdap booster mandates for middle school entry. For example, since the laws increased interactions with healthcare providers, it is possible that other adolescent health outcomes and behaviors could have been affected. And by identifying an exogenous increase in HPV vaccine uptake, our work offers a new setting for tests of the moral hazard concerns about increased risky sexual behaviors in the context of HPV vaccination. One might also imagine that the policy changes had longer term effects on preventive cancer screenings for the youths whose HPV vaccine behavior was affected.

Finally, more work is also needed to understand the broad drivers of increases in young adult vaccination more generally over our sample period. Although we estimate that state Tdap mandates for middle school entry have statistically significant effects at increasing vaccination, they accounted for only 17 percent of the overall increase in Tdap vaccination rates over our sample period. This suggests that there were also other factors that contributed to the sharp nationwide increase in Tdap booster take-up, including possible secular changes in attitudes toward vaccines. Another way to appreciate the need for more study of factors driving the increase in young adult vaccination rates is to see from Figure 1 that over our sample period the rate of MCV vaccination among youths increased by a nearly similar amount, despite that we do not find strong evidence of spillovers from Tdap mandates to MCV vaccination rates, and despite that far fewer states mandated MCV vaccination than mandated Tdap vaccination. Thus, more research is needed to understand the broad societal factors contributing to these stark increases in preventive health behaviors.

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