A Dynamic Model of Vaccine Compliance:

How Fake News Undermined the Danish HPV Vaccine Program

Peter Reinhard Hansen[a,c*] **Matthias Schmidtblaicher**[b]

[a] *University of North Carolina* [b] *European University Institute*

[c] *Copenhagen Business School*

January 26, 2018

Abstract

Increased vaccine hesitancy presents challenges to public health and undermines efforts to eradicate diseases such as measles, rubella, and polio. The decline is partly attributed to misconceptions that are shared on social media, such as the debunked association between vaccines and autism. Perhaps, more damaging to vaccine uptake are cases where trusted mainstream media run stories that exaggerate the risks associated with vaccines. It is important to understand the underlying causes of vaccine hesitancy, because these may be prevented, or countered, in a timely manner by educational campaigns. In this paper, we develop a dynamic model of vaccine compliance that can help pinpoint events that disrupted vaccine compliance. We apply the framework to Danish HPV vaccine data, which experienced a sharp decline in compliance following the broadcast of a controversial TV documentary.

Keywords: Vaccine Uptake, Fake News, Score-Driven Model

JEL Classification: C22, I12, I18.

[*]We thank Statens Serum Institute for providing the data, and we thank Gridt Vig Find for collecting data on Danish media websites. We also thank Anna Lunde for explaining how vaccinations are reported by physicians and how this protocol has changed over time. Finally we thank seminar participants at University of Konstanz, PUC in Rio de Janeiro, and the European University Institute and conference participants at the 28th EC2 conference in Amsterdam for valuable comments.

1 Introduction

Increased hesitancy to vaccine programs presents an important challenge to public health. To counter the misinformation that circulates about vaccines, health authorities find it necessary to devote resources to educational campaigns that would have been better spent on actual health care. A better understanding of the causes of vaccine hesitancy, would enable health authorities to take appropriate counter measures in a timely manner. It is therefore important to understand the underlying mechanisms that drive vaccine hesitancy and identify events that can undermine a vaccine program.

In this paper we develop an econometric time-series model of the time-variation in vaccine compliance. We apply the model to Danish Human Papilloma Virus (HPV) vaccine data, which yields a time series of vaccine compliance. The variation in this time series can be used to identify the events that likely caused sudden changes in vaccine compliance. Our empirical results show that declines in vaccine compliance began after media coverage that associated the vaccine with serious side effects. A single TV documentary that aired on TV2 Denmark on March 26th, 2015, had the largest impact on compliance, and the Danish HPV vaccine program collapsed immediately after the program was aired. Vaccine compliance fell from about 95% to just over 30%, immediately after the TV2 documentary, entitled "De Vaccinerede Piger – Syge og Svigtede", which translates to "The Vaccinated Girls – Sick and Abandoned". For cohort 2003 alone, we estimate that more than 11,000 unvaccinated girls can be directly attributed to the increased vaccine hesitancy that followed this TV documentary. While compliance has recently increased to about 80%, many of the girls in the affected cohorts continue to be unvaccinated. We estimate that the decline in vaccine uptake that followed the TV2 documentary will result in as many as 93 additional cases of cervical cancer and 25 additional deaths for cohort 2003 alone.

Harald zur Hausen discovered that cervical cancer was caused by HPV, for which he was awarded the Nobel prize in medicine in 2008. HPV denotes a family with more than 100 types of viruses. About 40 HPV types are sexually transmitted and at least 13 types can cause cancer, with cervical cancer being the most common form of cancer caused by HPV, see WHO (2016). HPV infections are quite common, with prevalence of 50% or higher among young men and women, see e.g. Oliver et al. (2017). HPV is responsible for all cases of cervical cancer, and a large percentage of other types of cancer. The discovery led to the development of vaccines that offers protection against HPV related cancers, and the first HPV vaccine was approved by the Food and Drug Administration (US) and the European Medicines Agency in 2006.

Evidence for the efficacy of the HPV vaccine is strong. A recent study of Scottish women aged 20-21 found that the prevalence of HPV types 16 and 18 (which is responsible for 70% of all cases of cervical cancer) was reduced from 30% to 4.5%, see Kavanagh et al. (2017). Another study of some of the first women to get vaccinated in an early randomized trial (FUTURE II), found that none of the 2,084 women had been diagnosed with cervical cancer and none of them had been found to have CIN2+ cell anomalies, which is the pre-stage to cervical cancer, see Kjaer et al. (2018). The efficacy of the vaccine was also documented in Ferris et al. (2017), who concluded that HPV vaccine continues to be highly effective and safe after 10 years, and a Japanese study found that women who where HPV vaccinated had a significantly lower rate of abnormal cervical cytology results, see Tanaka et al. (2017). The HPV vaccine is known to be safe, as large studies have shown that the prevalence of adverse events is not significantly different from that of the general population, see Arnheim-Dahlström et al. (2013), Lehtinen et al. (2016), and Feiring et al. (2017).

There is plenty of fake news about vaccines to be found on the internet, and an abundance of frightening stories that are shared on social media. However, such stories need not have much impact on vaccine programs, because the general public is well aware that the internet is rich with unfiltered nonsense. Most individuals will therefore greet such scaremongering with a healthy level of skepticism. In contrast, a single negative story from a trusted media outlet has the potential to sway the opinion of many, even if the story is unsubstantiated and ignores the scientific consensus on the matter.

This is well exemplified by the TV program "DPT: Vaccine Roulette" that initially aired in 1982 on an NBC affiliate, WRC-TV, and then national wide on The Today Show. The program associated the pertussis component of the DTP vaccine with brain damage, and the TV program was followed by extensive media coverage in the US, which speculated that the pertussis vaccine was responsible for epilepsy, mental retardation, physical disabilities, and even death, see Offit (2011, chapter 3). The association between the pertussis vaccine and the serious medical conditions have long been debunked by science. Large empirical studies found no relation between the vaccine and brain damage, see e.g. Shields et al. (1988). The last piece of the puzzle was discovered in 2006, where it was discovered that a genetic disorder was responsible for many cases of severe epilepsy and mental retardation that had previously been blamed on the vaccine, see Berkovic et al. (2006). Media coverage of this non-sensational discovery was scant, and this lack of coverage may explain that the false association between the pertussis vaccine and mental retardation continues to creep into media articles.[1] The Danish experience with the HPV vaccine program is very similar to the onset of the pertussis vaccine scare in the US. Our empirical analysis reveals a rapid decline in vaccine compliance immediately after a HPV vaccine critical TV documentary that aired on March 26th, 2015 on TV2 Denmark. As had been the case for the "Vaccine Roulette" program in the US, the Danish documentary was followed by a large number of newspaper articles on the topic. Moreover, the TV2 documentary seems to have influenced vaccine uptake beyond the Danish borders. An Irish documentary, entitled "Cervical Cancer Vaccine - Is it safe?", aired on December 14, 2015 on Channel TV3 in Ireland. The Irish documentary included many segments from the Danish documentary with English subtitles, and HPV vaccine compliance fell from 89.7% for the cohort vaccinated before the documentary aired to 55.8% for the cohort vaccinated the after the documentary.

The fact that a single TV program can cause much harm is important, because it highlights the responsibility of the trusted media in their coverage of topics such as vaccine programs. Editors who slack on the vetting of absurd assertions, and editors who fall victim to the false equivalence of two sides to an argument, can damage public health in ways that are unintended. Scientific truth is not define by a single research paper that contradicts the existing body of evidence, nor is the truth defined by the view of the last individual who offered his or hers wisdom to the media. News coverage on many topics, including the benefits and risks associated with vaccines, ought to reflect on the entire body of evidence, rather that a single source.

Medicine, including vaccines, do have side effects. For vaccines the most common side effects are benign soreness after the vaccine is given. However, there are cases where vaccines have caused serious adverse events. Fortunately, a serious side effect caused by a vaccine, must necessarily be extremely rare, because it has to slip undetected through the pre-approval test studies. In fact, vaccines can be expected to be safer than non-vaccine drugs, because clinical trials on vaccines tend to have larger sample sizes and vaccines are constantly monitored, post-licensure, by health authorities. An example of a vaccine that caused rare and severe side effects is the oral poliovirus vaccine (OPV), which is also known as the sugar-cube polio vaccine. The OPV vaccine used a weakened poliovirus, which is now believed to cause polio in about 1 out of 2,900,000 doses administered, see Alexander et al. (2004). Similarly, Pandemrix, a swine

[1] For instance, an article in a Danish Newspaper on January 19, 2017 stated that a case of brain damage was caused by the pertussis vaccine. BT: "Husker du 'Tomas - et barn du ikke kan nå'? - Lone Hertz kæmper for sin søn" (in Danish).

flu vaccine, is believed to have caused narcolepsy in 3 out of 100,000 vaccinated individuals. Recently, a dengue vaccine was suspended because it is suspected of increasing the likelihood of severe cases of the disease for some individuals. These extremely rare side effects were not discovered by journalists, but by science-based safety mechanisms that were put in place for monitoring vaccines. It is, in fact, quite impressive that side effects this rare are discovered at all.

At the time of this writing, more than 300 million doses of the HPV vaccine have been given worldwide, without statistical evidence to show that the HPV vaccine is responsible for serious medical conditions. While this does not prove that the vaccine is not responsible for any severe side effects, it does show that if such exists they will have to be extremely rare.

2 Data and Preliminary Analysis

We obtained weekly cohort specific HPV vaccination data from the Statens Serum Institute (SSI), and cohort size data from Statistics Denmark. SSI is responsible for the purchase and supply of vaccines to the Danish national vaccination programs, and SSI collects data on vaccination uptake. Two types of HPV vaccine were given in the sample period from early 2009 to mid 2017, Gardasil and Cervarix. The HPV vaccines were initially licensed with 3-dose schedules, but are now administered with just two doses for young adolescents. Our empirical analysis will focus on the number of girls receiving the first dose of the HPV vaccine, which we denote by HPV1. Specifically, we will model the number of girls in cohort c, that receive HPV1 in week t.[2]

Let X_t denote the aggregate number of girls who have received HPV1 by week t, out of a cohort with N_c girls. The basic idea is that the fraction of vaccinated girls, at time $t = 0, \ldots, T$, is approximately given by

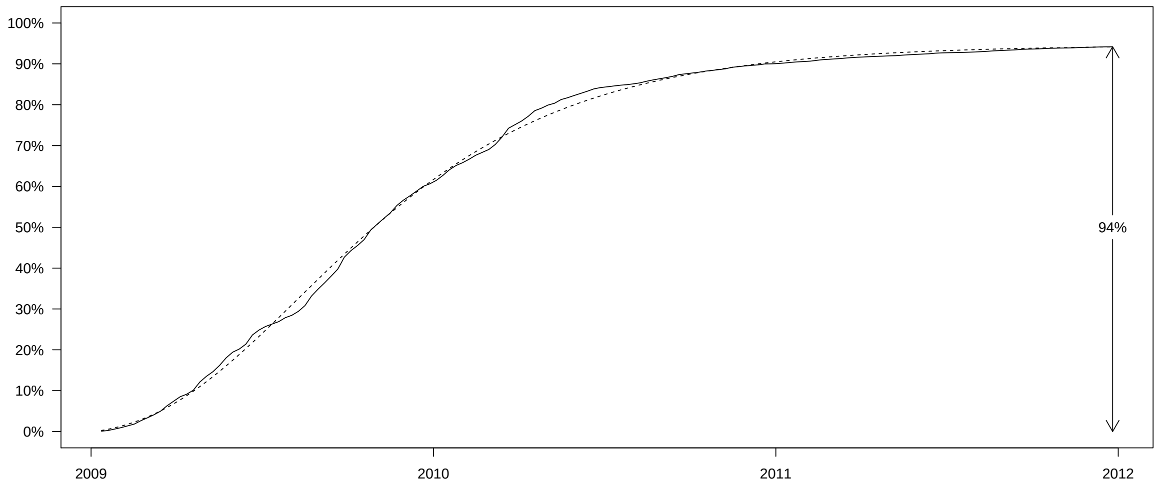
$$X_t/N_c \approx \delta \times \Lambda(\tfrac{t}{T}),$$

where $\Lambda(a)$ is an increasing function with $\Lambda(0) = 0$ and $\Lambda(T) = 1$, and where δ is a scalar between zero and one. The parameter δ is key in our analysis, because it can (in a steady state) be interpreted as the vaccine compliance/coverage by the end of sample period.

The simple structure, where δ is constant is illustrated in Figure 1, where the solid line

[2] Our data also includes the number of individuals that received the second and third dose by week and cohort. Attempts to include these data in our analysis proved difficult for several reasons. First, the anonymized data does not inform us when individuals receiving the 2nd or 3rd dose had received earlier doses, which is relevant for the modeling. Second, the changes in dose schedule induced additional irregularities in these data.

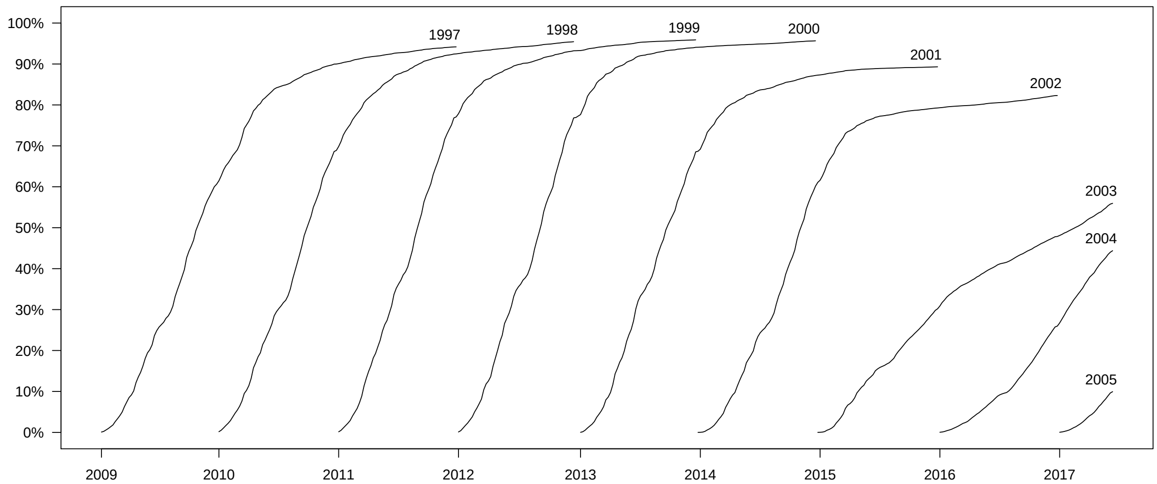
Figure 1: HPV Vaccine Coverage for Cohort 1997 (1st dose)



shows the percentage of girls, born in 1997, that has received the first dose of the HPV vaccine over a three year period. The dotted line is a curve that is fitted to the data, using the shifted Gompertz distribution to specify $\Lambda(a_t)$, where a_t is the age of cohort 1997 at time t. In conjunction with the estimate of δ (about 94%) the simple model provides an approximation to the vaccine uptake over time for this cohort.

Figure 2 shows the vaccine compliance over time for nine cohorts. We observe large discrepancies across cohorts, with a high degree of hesitancy for the youngest cohorts. For the four oldest cohorts, 1997-2000, vaccine adoption was high and slightly increasing over time. This was followed by a period of declining compliance starting with cohort 2001. Evidently, it is not possible to accurately describe all cohorts with a common specification such as that in Figure 1. But, as we shall see, a modified specification that allows for time variation in the compliance rate does describes the data well. The cornerstone of our model is the weekly number of vaccinations for each cohort, which (in a static model) has the expected value, $\delta[\Lambda(a_t^c) - \Lambda(a_{t-1}^c)] \times N_c$, where a_t^c is the age of cohort c at time t and N_c is the cohort size. We generalized this model by allowing for time-variation in δ, so that the expected number of vaccinations in week t for cohort c is given by $\delta_t[\Lambda(a_t) - \Lambda(a_{t-1})] \times N_c$.

Figure 2: HPV Vaccine Coverage (1st dose) by Cohort



3 Statistical Model

Recall that $x_{c,t}$ is the number of girls in cohort c that receive HPV1 in week t. The number of vaccinated girls in cohort c at time t is given by $X_{c,t}$, where $X_{c,t} = X_{c,t-1} + x_{c,t}$ with $X_{c,0} = 0$. The number of unvaccinated girls in cohort c that are eligible to receive the vaccine by the end of week t is denoted by $N_{c,t}$.

The age-variable, a_t^c, for cohort c at time t, is, without loss of generality, normalized so that $a = 0$ denotes the beginning of the three year period and $a = 1$ by the end of the three year period. To take an example, for those born in year 2000, we have the weekly number of vaccinations for the period primo 2012 to ultimo 2014, such that $a_t^{2000} = 0$ at the beginning of 2012 and $a_t^{2000} = 1$ by the end of 2014. The beginning of the three year period is motivated by the design of the Danish HPV vaccination program, where girls are only offered the vaccine for free once they turn twelve years old. The number of girls vaccinated before their 12th birthday is therefore negligible.

The basic structure of our model is that the number of vaccinated girls in week t is binomially distributed

$$x_{c,t}|\mathcal{F}_{t-1} \sim \text{bin}(N_{c,t-1}, p_{c,t}), \tag{1}$$

where the dependence across time and cohorts and seasonal effects are embedded in the structure of $p_{c,t}$. Our model for $p_{c,t}$ is given by

$$p_{c,t}(\theta) = \delta_t(\alpha)\lambda_{c,t}(\beta), \qquad \text{with} \quad \lambda_{c,t}(\beta) = \tfrac{N_c}{N_{c,t-1}}[\Lambda(\beta; a_t^c) - \Lambda(\beta; a_{t-1}^c)], \tag{2}$$

where $\theta = (\alpha', \beta')'$ is the vector of unknown parameters.

The first component $\delta_t(\alpha) \in (0, 1)$ defines the vaccine compliance at time t, whereas the second component, $\lambda_{c,t}(\beta)$, only depends on t though the age of the cohort, a_t^c. So the second term defines the part of $p_{c,t}(\theta)$, which all cohorts have in common, and if vaccine compliance was constant over time, then all cohorts would have similar vaccine uptake. This is evidently not the case, as demonstrated in Figure 2.

Given the binomial specification, (1), it follows that the log-likelihood for cohort c in period t is given by

$$\ell_{c,t}(\theta) = \log \binom{N_{c,t-1}}{x_{c,t}} + x_{c,t} \log p_{c,t}(\theta) + (N_{c,t-1} - x_{c,t}) \log(1 - p_{c,t}(\theta)). \tag{3}$$

Thus given specifications for $\Lambda(\beta; a)$ and $\delta_t(\alpha)$, the maximum likelihood estimators are obtained by maximizing

$$\ell(\theta) = \sum_{c,t} \ell_{c,t}(\theta),$$

with respect to the vector of parameters, $\theta = (\alpha', \beta')'$.

To complete the model we need to adopt specifications for $\Lambda(\beta; a)$ and $\delta_t(\alpha)$. Our choice for $\Lambda(\beta; a)$ is the cumulative distribution function (cdf) for the shifted and truncated Gompertz distribution, which is given by

$$\Lambda(\beta; a) = \tfrac{1}{C(\beta)}(1 - e^{-\beta_0 a}) \exp(-\beta_1 e^{-\beta_0 a}), \qquad a \in [0, 1],$$

where $C(\beta) = (1 - e^{-\beta_0}) \exp(-\beta_1 e^{-\beta_0})$ is a normalizing constant. Other, more flexible, specification could be used, and in a preliminary analysis we also experimented with specifications based on the Weibull distribution and the Beta distribution. The shifted Gompertz was adopted because it tended to have the best empirical fit.

Next we discuss specifications for $\delta_t(\alpha)$ which embodies the vaccine compliance across time. In our modeling of δ_t, it is often convenient to invoke a simple logit transformation

$$\tilde{\delta} = \log\left(\tfrac{\delta}{1-\delta}\right),$$

which is a one-to-one mapping of the unit interval, $(0, 1)$, to the real line, $\mathbb{R}$. This transformation allows us to model $\tilde{\delta}_t$ as an unrestricted parameter, and the inverse transformation, $\delta = e^{\tilde{\delta}}/(1+e^{\tilde{\delta}})$, will ensure that δ stays with its boundaries between zero and one.

Before we turn to our dynamic model of δ_t, we consider some simple specifications for δ_t, that provide crude insight about the variation in vaccine compliance.

3.1 Simple Specifications for Vaccine Compliance

First we estimate δ_t using two relatively simple approaches. The first approach has δ_t to be piecewise constant with structural changes, where the time of the structural changes are estimated. The second approach takes δ_t to be a function of time, t, using some parametric specification. Figure 3 presents the empirical results for a specification with four structural changes (upper panel), and the a specification where $\tilde{\delta}_t$ is modeled as a trigonometric polynomial in t, $\tilde{\delta}_t = \alpha_0 + \sum_{j=1}^{2}[\alpha_{2j-1}\cos(2\pi j \frac{t}{T}) + \alpha_{2j}\sin(2\pi j \frac{t}{T})]$. Full details are presented in the appendix, where we also present additional empirical results using other deterministic specifications and models with fewer structural changes. In the appendix we also detail the way seasonal effects are accounted for in these models.

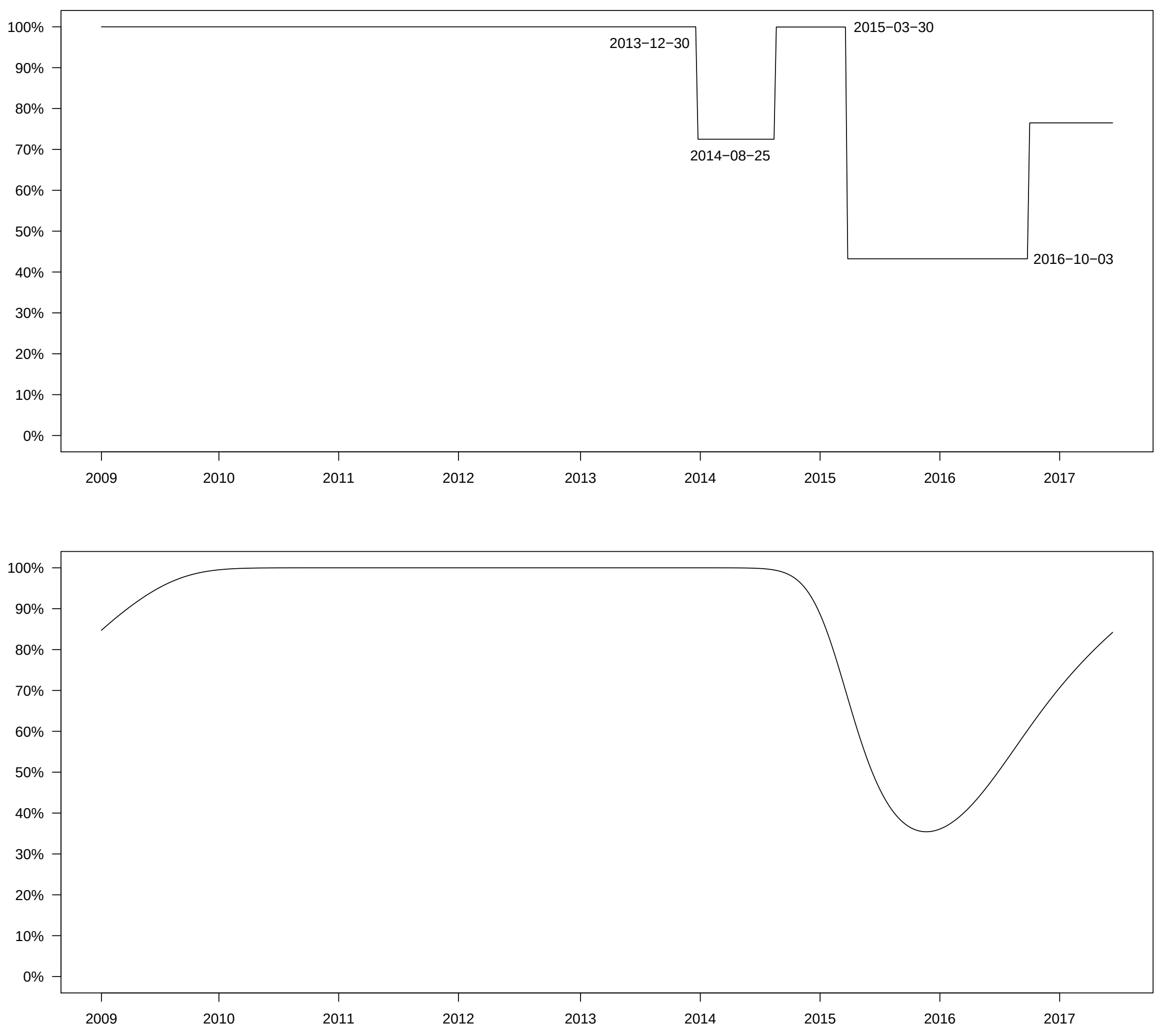
The results in Figure 3 gives us a rough idea about the variation in δ_t over time. Both specifications have $\hat{\delta}_t$ to be high until sometimes in 2013. The piecewise constant model detects the first break at the end of 2013, when compliance drops to about 80%. Compliance recovers to its previous level at the second break during the summer of 2014, then fall distinctly in early 2015, followed with a partial recovery in late 2016.

3.2 Score-Driven Model for $\delta_t(\alpha)$

In this section we present our preferred model for δ_t, which is an observation driven model based on the generalized autoregressive score model by Creal et al. (2013). Score-driven models have been very successful in modeling time-varying parameters in econometric models.[3] The score-driven model permits a more flexible variation in δ_t than the simpler methods we used in the previous section. In the present context, the score-driven model adjusts the value of δ_t directly in response to the number of vaccinations, $x_{c,t}$, deviating from the expected number. The adjustment is defined by the score, which is the derivative of the log-likelihood, suitably scaled by the expected curvature. Whenever the number of vaccinations is larger, or smaller,

[3] The popular GARCH models for modeling financial volatility, see Bollerslev (1986, 2010), can (in most cases) be interpreted as variations of score-driven models.

Figure 3: Models with Simple Specifications for Vaccine Compliance, δ



than the expected number, the score-driven model will make an adjustment to $\tilde{\delta}_t$, where the magnitude of this adjustment is estimated from the data.

The time-variation in vaccine compliance, δ, is generated by an autoregressive model of order one:

$$\tilde{\delta}_t = \alpha_0 + \alpha_1 \tilde{\delta}_{t-1} + \alpha_2 \tilde{s}_{t-1},$$

where $\tilde{s}_t$ represents a data-driven signal about the direction in which δ_t is likely to have changed. We detail the choice for $\tilde{s}_t$ below. The vector of unknown parameters in $\delta_t(\alpha)$, is here given by $\alpha = (\alpha_0, \alpha_1, \alpha_2, \delta_0)'$, where δ_0 is the starting value for δ_t. Here α_1 is a measure of the persistence in δ_t and α_2 measures how strongly the model responds to the signal provided by $\tilde{s}_t$. There is typically a high degree of persistence in score-driven models, so we also consider the restricted variant of the model, where $(\alpha_0, \alpha_1) = (0, 1)$, which imposes $\tilde{\delta}_t$ to be a very persistent process that is know as the local-level model.

The signal, $\tilde{s}_t$, is key in this model. If, for instance, the number of vaccinated girls exceeds the expected number of vaccinations, it will indicate that δ_t may have increased in value, and intuitively we would want (α_2 times) $\tilde{s}_t$ to be positive in this situation. The score-framework by Creal et al. (2013) employs an intuitive signal provided by the score of the log-likelihood function, $s_t = \partial \ell_t / \partial \tilde{\delta}$, weighted by a term that is defined by the curvature of the log-likelihood, $h_t = \partial^2 \ell_t / \partial \tilde{\delta}^2$. Specifically,

$$\tilde{s}_t = \frac{\sum_c s_{c,t}}{\sqrt{-\sum_c \mathbb{E}_{t-1} h_{c,t}}} = \frac{1}{\sqrt{\sum_c \frac{\lambda_{c,t}^2 N_{c,t-1}}{p_{c,t}(1-p_{c,t})}}} \sum_c \lambda_{c,t} N_{c,t-1} \left(\frac{\hat{p}_{c,t}}{p_{c,t}} - \frac{1-\hat{p}_{c,t}}{1-p_{c,t}} \right), \tag{4}$$

where $\hat{p}_{c,t} = x_{c,t} / N_{c,t-1}$. The expression (4) is derived in Appendix A.1, but the interpretation of the expression is quite intuitive, and is the following: In a week where more individuals are vaccinated than expected, i.e. $\hat{p}_{c,t} > p_{c,t}$ for all c, then $\tilde{s}_t > 0$, and this would be a signal suggesting that δ_t may have increased in value, and visa versa in the event $\tilde{s}_t < 0$. So we should expect the estimate of α_2 to be positive, which is indeed the case in our empirical analysis.

Our empirical analysis revealed that there was a need to account for some particular seasonal variation in the weekly vaccination rate. The most obvious seasonal effect in the weekly vaccination data, is that associated with the summer vacation and winter holidays, where the number of vaccinations is distinctly below that of neighboring weeks. This seasonal effect is pronounced and can be seen in Figures 1 and 2. The second seasonal effect is specific to the way in which the weekly vaccination data were collected over time. During the first part of the sample period, the reported number of vaccinations is higher towards the end of the month. This effect is not very pronounced and we only detected it after investigated the scores of an earlier version of our model. After conferring with a medical professional, we discovered that the way in which vaccines are recorded has changed during the sample period. Before November 15, 2015, vaccines were recorded when physicians billed for the vaccines, which resulted in an over-recording of vaccines towards the end of the month. The introduction of an electronic vaccine registry (Det Danske Vaccinationsregister) resolved this issue, starting November 15, 2015.

Due to these seasonal effects, we enhance the model for $p_{c,t}$ with a third component that accounts for seasonality. The binomial parameter is now decomposed as

$$p_{c,t}(\theta) = \delta_t(\alpha)\lambda_{c,t}(\beta)\eta_t(\gamma), \tag{5}$$

so that the parameter vector is given by $\theta = (\alpha', \beta', \gamma')'$.

To account for time variation in seasonality, we model $\tilde{\eta} = \log(\eta)$ by a separate score-driven model

$$\tilde{\eta}_t = g_{0,t} \sin(2\pi(z_t^m + g_{1,t}))(1 - z_t^a) + \gamma_2 z_t^a,$$

where $g_{i,t} = g_{i,t-1} + \gamma_i \tilde{s}_{g,i,t-1}$ for $i = 0, 1$. Analogous to (4), $\tilde{s}_{g,i,t-1}$ is the scaled score with respect to the seasonality parameters $g_{0,t}$ and $g_{1,t}$. Specifically,

$$\tilde{s}_{g,0,t} = \tilde{s}_t \text{sign}(\sin(2\pi(z_t^m + g_{1,t})))(1 - z_t^a), \tag{6}$$

and

$$\tilde{s}_{g,1,t} = \tilde{s}_t \text{sign}(g_{0,t} \cos(2\pi(z_t^m + g_{1,t})))(1 - z_t^a). \tag{7}$$

The expressions for (6) and (7) are derived in the appendix. In the estimation of the model, we treat the initial values for $(g_{0,0}, g_{1,0}) = (\gamma_3, \gamma_4)$ as free parameters, with domains, $\gamma_3 \geq 0$ and $\gamma_4 \in [0, 1]$, respectively.

The seasonal variables, z_t^m and z_t^a, are defined as follows. First, z_t^m represents the location of week t in the month, as defined by the date of the Monday of that week, divided by the number of days in the months. For example, a week with a Monday on January 12th, translates into $z_t^m = 12/31$. Second, z_t^a is a binary variable that takes the value one during the summer vacation period (week numbers 28 to 31) as well as the two weeks around Christmas/New Year (week numbers 52 and 1).

Figure 4: Vaccine Compliance Score-Driven Model

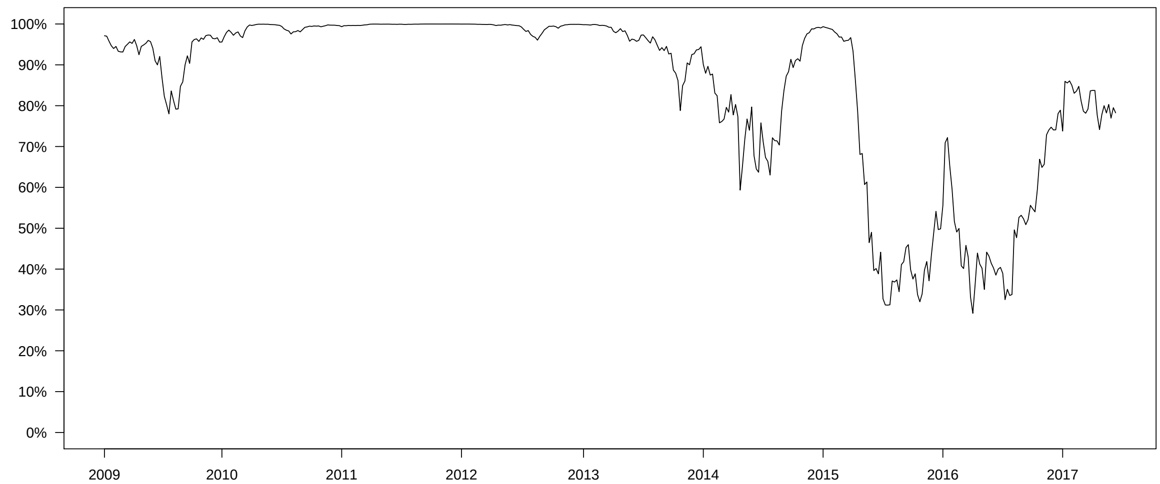


Table 1: Estimates for Score-Driven Model

$\hat{\alpha}_0$	$\hat{\alpha}_1$	$\hat{\alpha}_2$	$\hat{\delta}_0$	$\hat{\beta}_0$	$\hat{\beta}_1$	$\hat{\gamma}_0$	$\hat{\gamma}_1$	$\hat{\gamma}_2$	$\hat{\gamma}_3$	$\hat{\gamma}_4$	$\ell(\hat{\theta})$
0.007	0.987	0.056	0.971	7.230	3.000	0.001	0.002	−0.727	0.308	0.436	−20111
(0.026)	(0.036)	(0.006)	(0.001)	(0.034)	(0.026)	(0.000)	(0.000)	(0.033)	(0.0290)	(0.0290)	
0.000	1.000	0.071	0.890	7.250	3.010	0.001	0.002	−0.604	0.300	0.376	−20613
		(0.030)	(0.002)	(0.025)	(0.025)	(0.000)	(0.000)	(0.030)	(0.035)	(0.031)	

Note: Standard errors in brackets.

Figure 4 shows the time series for δ_t that is implied by the estimated score-driven model and Table 3.2 displays the parameter estimates. We also report the results for the model where we impose the restrictions $\alpha_0 = 0$ and $\alpha_1 = 1$.

We estimate vaccine compliance to be a bit lower during the first year in our sample, as was the case for the simple trigonometric polynomial model for $\tilde{\delta}_t$. Then compliance increases and stays above 95% for a three year period. The first noticeable decline in $\hat{\delta}_t$ is seen in 2013 and vaccine compliance is relatively low and volatile until the fall of 2014, after which compliance recovers to about 95% again. The most drastic movement in compliance is observed in the second quarter of 2015 where $\hat{\delta}_t$ abruptly falls to just over 30%. Compliance stays low for an extended period, aside from a brief spike in early 2016. Only in late 2016 does compliance begin to recover. Towards the end of the sample period, June 2017, it hovers at about 80%. In Section 4 we analyze the variation in δ in greater details by relating it to media data.

3.3 Refinements and Robustness Analysis

The HPV vaccine is, in Denmark, only given for free after the twelfth birthday. So the number of girls that are eligible for their first vaccine dose (HPV1) increases gradually over the year in which the cohort turns twelve. We adapt the definition of $N_{c,t}$ accordingly. Specifically we let the number of unvaccinated girls be $N_{c,t} = \lfloor g(a_t^c)N_c \rfloor - X_{c,t}$ where $g(a_t^c)$ is a positive and increasing function that fulfills $g(0) = 0$ and $g(a) = 1$ for $a \geq \frac{1}{3}$ and where $\lfloor \cdot \rfloor$ is the integer part operator.

We do not have information about the birthday of individuals in our anonymized data, but we can approximate the distribution of birthdays over the year for each cohort. Monthly birth statistics show that the birth distribution over the calendar year is almost identical across cohorts. So we estimate $g(a)$ using daily births for 2007. These data were obtained from Danmarks Statistik. The estimation of $g(a)$ is fully detailed in the appendix.

It is worth mentioning that this time-of-birth correction has only a negligible effect on the estimation results. In fact, we also estimated the model using $g(a) = 1$ for $a \in [0, 1]$ (which assumes all girls are eligible for the vaccine when $a = 0$), and well as with $g(a) = \min(3a, 1)$, which assumes an even distribution of births over the year, and the none of the empirical results changed in an important way. So our conclusions are insensitive to the choice for g.

As an additional robustness check, we have also estimated the model where $x_{c,t}$ is assumed to be conditionally Poisson distributed (rather than conditionally Binomially distributed). These results were also very similar to the ones reported here with the Binomial specification. Finally, we also experimented with the specification for $\Lambda(\beta; a)$, and obtained very similar results with a truncated Weibull cumulative distribution function.

4 The Influence of Media

In this section we discuss the Danish media coverage of the HPV vaccine and quantify the impact that the TV2 Documentary had on vaccine uptake, and the implications this will have. In addition to the coverage in mainstream media, it is possible that social media also played a role in the variation in vaccine compliance. However, there is evidence to suggest that fake news on social media is largely irrelevant. For instance, in a study of fake stories that had circulated on social media, Allcott and Gentzkow (2017) found that survey respondents are not more likely to believe in fake stories from social media, than they are likely to believe in fabricated stories that had not been circulated.

Table 2: Danish Media Articles: HPV Vaccine Efficacy and Side Effects

Source	Number of "Negative" Articles	Readership
Metroxpress	35	303
Politiken	21	90 (117)
Kristligt Dagblad	17	26
Berlingske	12	76 (87)
BT	10	47 (66)
Information	7	20
Ekstrabladet	4	46 (61)
Jyllandsposten	1	84 (109)
Weekendavisen	0	– (46)

Note: Number of Danish media articles on the HPV vaccine that involve possible side effects or raising doubt about the vaccines effectiveness (2009 - June 207). Figures for weekday readership are in thousands (for 2014) with Sunday/Weekend edition readership figures in brackets. Source: Dansk Oplagskontrol.

We searched the internet domain of the major Danish newspapers for keywords related to the HPV vaccine to identify articles on the topic. Articles that mentioned an association between the HPV vaccine and serious side effects, as well as articles that raised doubt about the benefits of the vaccine were included in our analysis. The newspaper websites we searched are listed in Table 2 along with the number of articles (up until June 2017) and the readership in thousands in 2014 for each newspaper. Metroxpress, which is a free newspaper, had the largest number of articles on the HPV vaccine with a negative sentiment and Politiken had the second most. The only newspaper domain that did not result in any articles that meet our criteria was Weekendavisen. The complete list of articles, along with date, source, and title, is presented in the Appendix in Table B.1. Most of these articles are merely reporting on the adverse events that some associate with the vaccine or reporting on the declining vaccine uptake that has resulted from this concern. Others articles can appropriately be labeled as “fake news”. For instance, by running a headline that asserts that the vaccine causes 1 in 500 vaccinated to get seriously sick, and articles that rely on quotes from individuals with ties to the anti-vaccine movements.

It is well known that media coverage can influence public sentiment on the HPV vaccine. For instance, Faasse et al. (2017) documented that the number of monthly news articles on the HPV vaccine predicts the number of reported cases of adverse events in New Zealand. Table 3 reports the number of Danish newspaper articles (listed in Table 2) by year, along with the number of reported adverse events (AE) (related to the HPV vaccine), as well as the the number of AE per

10,000 vaccine doses. For comparison, we include the annual number of AE per 10,000 vaccines for Norway. The Table indicates a relationship between media coverage and the reporting of AE in Denmark, which is similar to that reported in Faasse et al. (2017) for New Zealand.

Table 3: Media Coverage and Number of Adverse Events Reports

Year	Media Count	Adverse Events (AE)	AE per 10k doses	AE per 10k Norway
2010	0	67	13	17
2011	0	43	3	12
2012	0	95	3	11
2013	8	512	10	8
2014	4	192	17	11
2015	67	822	153	12
2016	18	307	61	10

Note: Danish annual figures on: HPV vaccine related newspaper articles; Adverse events (AE) reported for the HPV vaccine; and AE per 10,000 doses of HPV vaccine given. For comparison, we include the number of AE per 10,000 doses of HPV vaccine in Norway, based on an estimated 76,000 doses per year.

Our internet search for HPV vaccine related keywords on Danish language website reveals that the Danish media coverage of the HPV vaccine was overwhelmingly positive until April 2013, and that negative stories about the vaccine were confined to anti-vaccine websites.[4] The first article in a mainstream media that associated the HPV vaccine with serious side effects was published in Politiken, a leading Danish newspaper, on April 17th, 2013. The article had a story about a girl who had a number of symptoms, including frequent headache, dizziness, and tiredness, which her parents said were caused by the HPV vaccine.[5] The article was followed by a series of articles in Politiken that discussed the possibility of a link between the HPV vaccine and serious adverse events, and an article that raised doubt about the efficacy of the vaccine, by quoting "one of the most recognized HPV experts in the world" and "a prominent medical professor". However, the same article failed to mention that these individuals are known to have controversial views on vaccines and that their views contradict those of the World Health Organization (WHO), the Centers for Disease Control and Prevention (CDC), and the European Medicines Agency (EMA). The two "experts" are quoted in several subsequent newspaper articles, including BT (Aug. 3, 2014), Metroxpress (May 19, 2015), and Information (May 30, 2016), and while the articles are rich with applauding credentials, none of the articles mentioned the controversial nature of these individuals, nor their ties to the anti-vaccine movement.[6] This

[4]Earlier that year, on February 28th, Politiken had an article that was critical of medical doctors that were advocating the HPV vaccine, while receiving side income from the GlaxoSmithKline, which is the producer of one of the HPV vaccine.

[5]According to the mother, the parents learned that their daughters sickness was caused by the HPV vaccine from a homeopathy healer.

[6]One of the "experts" have had multiple articles on vaccines retracted, and is also a frequent speaker at

was despite the fact that an 2003 article in Journalisten, which is published by the Danish Union of Journalists, had been critical of some media coverage of the HPV vaccine, and referred to one of these individuals as controversial, see Albrecht (2013). The timing of the first vaccine-critical newspaper articles coincides with the onset of vaccine hesitancy. After this initial decrease, vaccine compliance was volatile and relatively low, until it recovered again during the second half of 2014. The sharpest and most pronounced decline in vaccine compliance occurred in 2015, and we focus on this event next.

4.1 Vaccine Hesitancy following the TV2 Documentary

On September 9th, 2013 the 7:00 pm News on TV2 Denmark had a story about the HPV vaccine and alleged side effects. The story received much criticism, because it left the viewer with an impression that serious side effects after HPV vaccination were very common. When Journalisten covered the story on September 20, 2013, the responsible TV2 editor, Jacob Nybroe, agreed that "emotions took up too much space and facts too little" and continued to say (what translates into) "we lost to emotions and next time we will remember [what we learned from this morass]", see Albrecht (2013). However, TV2 Denmark went on to produce the documentary, "The Vaccinated Girls – Sick and Abandoned", on the same topic. The documentary had no shortage of emotions, and this time an element of conspiracy theory was added to the coverage, as it was suggested that health authorities had not been forthcoming about what they knew about adverse events related to the vaccine.

Figure 5 presents the estimated compliance for the year 2015, where the pronounced decline in compliance is in accordance with the structural breaks model for δ_t, which pointed to a large decline in δ_t towards end of March 2015. The vertical line denotes the week starting on March 30, and the abrupt decline in $\hat{\delta}_t$ occurs immediately after the airing of the TV2 documentary. The controversial program was nominated for a prestigious Danish journalist award and received much attention. TV2 Denmark keeps its programs behind a paywall, but the documentary was, exceptionally, made available for free on Youtube.[7] Given the attention and impact that the documentary had, it is reasonable to attribute the decline in vaccine compliance to this TV2 documentary and the subsequent negative coverage in the Danish media.

Autism-One conferences that also feature individuals such as Jenny McCarthy and Andrew Wakefield. The other individual was a speaker at a 2009 conference organized by National Vaccine Information Center, which is an anti-vaccine organization in America, than has roots in the unfounded claims that the pertussis vaccine causes autism.

[7] TV2 removed the documentary from Youtube in October 2017, but unauthorized copies are still available on Youtube and elsewhere.

Figure 5: Vaccine Compliance Score-Driven Model for 2015

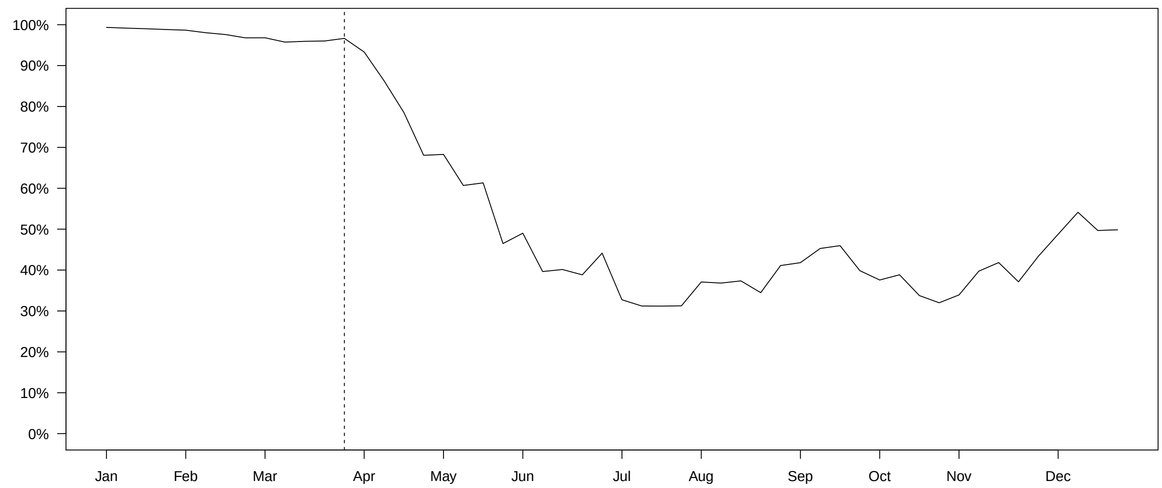
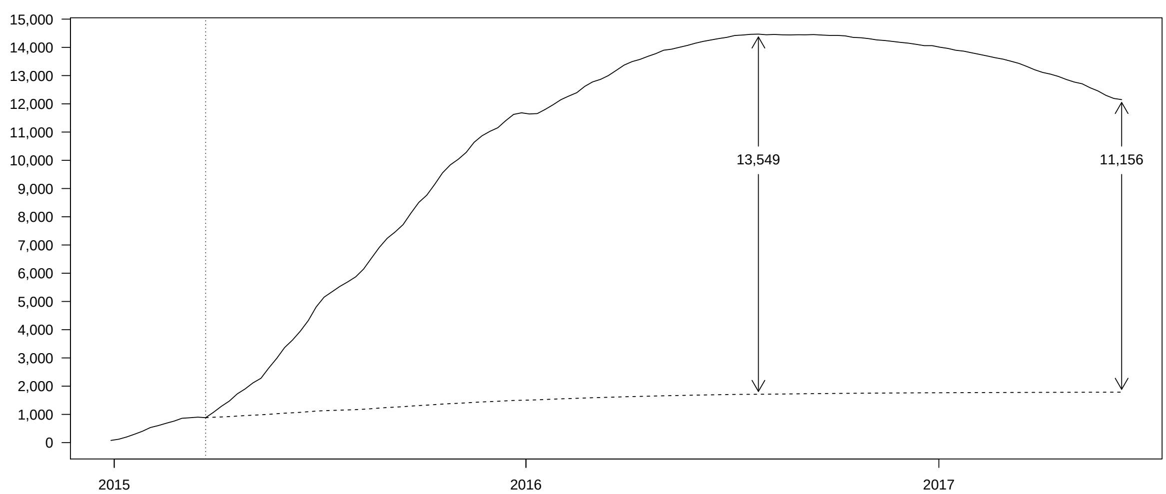


Figure 6: Missing Vaccinations for Cohort 2003



The solid line in Figure 6 shows the difference between $\Lambda(a_t^c) \times N_c$ and $X_{c,t}$ for cohort 2003. This represents the difference between the expected number of vaccinated girls under full compliance ($\delta = 1$) and the actual number of vaccinated girls. By the end of March 2015 the estimated score-driven model has $\hat{\delta}_t = 96\%$, and the dotted line is the hypothetical number of unvaccinated girls, had δ_t stayed constant at the value 96%. Under this hypothetical scenario, there would have been less than 2000 unvaccinated girls in cohort 2003. Rather than staying constant, δ_t fell rapidly in the period after the TV2 documentary aired, and the compliance rate fell to just over 30% in July 2015. As a result, the number of unvaccinated girls ended up being many times larger. The implications of the increased vaccine hesitancy that following the TV2 documentary, resulted in additional unvaccinated girls. At its peak, there were more than 13,000 additional unvaccinated girls in cohort 2003 alone, relative to the hypothetical scenario where compliance had remained constant at 96%.

A recent information campaign succeeded in increasing vaccine uptake. However the excess number of unvaccinated women in cohort 2003 was still above 11,000 by the end of our sample period (June 2017), and other cohorts were also affected. It may be worth evaluating the implications of 11,000 unvaccinated girls. A typical cohort, with about 31,000 women, has about 6,000 cone biopsies due to abnormal cervical cell changes, about 375 cases of cervical cancer, with 100 women dying from cervical cancer. The HPV vaccines that were offered in the Danish vaccine program (during our sample period) protect against the HPV virus types 16 and 18, that are responsible for about 70% of the cases of cervical cancer. So if we assume the vaccine to be 100% effective against HPV types 16 and 18, then 11,000 unvaccinated girls translates into about 93 cases of cervical cancer and 25 deaths that could have been prevented by the HPV vaccine. The actual number could be larger because low vaccine uptake forgoes additional benefits from heard immunity, that protects unvaccinated individuals. The actual number could also be smaller for a number of reasons. For instance, if the vaccine rate increases in the near future, if the vaccine turns out to be less effective than expected, or if decease and death can be prevented through improved treatments.

The TV2 documentary may have negatively influenced vaccine compliance beyond the Danish borders. In Ireland the HPV vaccine is offered for free to girls during their first year of secondary school. On December 14, 2015, the Irish Channel TV3 aired a documentary, entitled "Cervical Cancer Vaccine - Is it safe?". This documentary was quite similar to the Danish TV2 documentary, and included several segments from the Danish documentary with English subtitles. This impact on HPV vaccine compliance was similar to that in Denmark. In the school-year before the documentary aired, 2014/2015, 89.7% received HPV1, whereas in the the school-year that followed the documentary, 2016/2017, this figure had fallen to 55.8%, according to the Irish Health Protection Surveillance Center.

5 Discussion

In this paper we have developed a dynamic model for vaccine compliance, which is driven by the information provided by vaccination data. We estimated the model using Danish HPV vaccination data, which has experienced a great deal of variation in vaccine uptake since the vaccine was introduced, and the estimated path for vaccine compliance quantifies this variation.

Our empirical results strongly suggest that the onset of HPV vaccine hesitancy in Denmark can be attributed to Danish media, with the main culprit being a TV documentary that aired in March 2015 on TV2 Denmark. The program generated much attention and instigated a large number of newspaper articles on the topic. Many of these articles promoted the idea that the vaccine is potentially dangerous or that the vaccine is ineffective and may not protect against cervical cancer.

It is unlikely that the journalists, who wrote these newspaper articles and edited the TV documentary, intended to undermine a vaccine program that can prevent cancer and save many lives. However, the empirical analysis leaves little doubt that the media coverage did persuade thousands of girls to decline the HPV vaccination, and there is no ambiguity about the tragic implications this will have for many unvaccinated women and their families in the years to come. The main culprit was the TV documentary that aired on TV2 Denmark in March 2015. We estimate this documentary and the media activity that followed, to have dissuaded an additional 13,549 girls in the 2003 cohort to postpone vaccination. Some of these girls were vaccinated at a later date, but at the end of our sample period, in June 2017, more than 11,000 of these 13,549 had still not received the first dose of the HPV vaccine.

In May 2017, the Danish health authorities started a campaign, "Stop HPV", in an attempt to rehabilitate the HPV vaccine program. The latest data, as of January 2018, shows that the campaign has had some success in bringing vaccine compliance up again. For example, 36% of cohort 2005 received HPV1 during 2017 (the year they turned twelve). This figure compares favorably to 30% and 26%, which were the corresponding percentages for cohorts 2003 and 2004, respectively, but it well short of 77% which was the corresponding percentage for both cohort

1999 and 2000. The campaign has also had an impact on cohort 2003, but is still far from bringing coverage back to previous levels. As of January 2018, there are 11,185 unvaccinated girls in cohort 2013 (out of 32,747). Had HPV vaccine compliance for cohort 2003 been the same as that for cohorts 1998-2000, this figure would have been just 2,639.

The problem with the TV documentary and numerous newspaper articles is that they mislead their audience by headlining anecdotal evidence, the views of a single physician, or a single research paper, as if the headline is a fact. The discrepancy between the scientific consensus on the HPV vaccine and the sentiment that was promoted in Danish media, may be explained by a failure to understand how science arrives at objective truths. Facts are not produced by a single research paper, nor is it produced by the views of a single researcher. The media's desire to break a story, carries a temptation to run an attention-catching headline. Sensational headlines on health related issues, including vaccines, are almost always based on a single study or the views of a few individuals. In contrast, the emergence of a scientific fact is typically a very slow and incremental process that rarely calls for a sensational headline. A single research paper, or the views of a single expert, should obviously be contrasted with the entire body of evidence. When journalists neglect this important aspect, the resulting news reporting can be misleading and potentially harmful to the general public.

The dynamic model developed here allows us to pinpoint changes in vaccine compliance when applied to vaccination data at relative high frequency, such as weekly date used in this paper. It could be interesting to apply the methodology to Irish HPV vaccination data, because the country has experienced a similar increase in vaccine hesitancy surrounding a TV documentary. The present framework could be used to estimate the number of girls the documentary discouraged from receiving the vaccine, from which the implication to decease and death could be inferred.

Our empirical analysis of Danish HPV vaccination data, is based on anonymized data, which limits a deeper analysis of the individuals that declined HPV vaccination. It would be interesting to investigate whether vaccine compliance varies with socio-economic characteristics, similar to those that were observed during other vaccine crises. Following the infamous (and since retracted) study that led the public to suspect a relationship between the MMR vaccine and autism, vaccine compliance fell throughout the UK (and elsewhere). Interestingly, Anderberg et al. (2011) found that decline in MMR vaccine compliance was more pronounced in areas with a higher fraction of educated individuals and a higher average income. Whether the

Danish skepticism towards the HPV vaccine is more prevalent in families with relatively more education is currently unknown. It would also be interesting to investigate geographic variation in vaccine compliance. There is some evidence that compliance rates have been higher in rural areas, which may be related to the relative readership that newspapers have across geographical regions. Vaccine hesitancy may also, in this case of Denmark, be related to political affiliation, because a well-known politician, who chairs the Health Committee of the Danish Parliament, has been very critical of HPV vaccine and called for the vaccine program to be suspended.

References

Albrecht, J. (2013), 'Seerredaktør: TV 2 overdriver vaccinationers bivirkninger (in danish)', *Jounalisten, Sept. 20, 2013* .

Alexander, L. N., Seward, J. F., Santibanez, T. A., Pallansch, M. A., Kew, O. M., Prevots, D. R., Strebel, P. M., Cono, J., Wharton, M., Orenstein, W. A. and Sutter, R. W. (2004), 'Vaccine policy changes and epidemiology of poliomyelitis in the united states', *Journal of the American Medical Association* **292**, 1696–1701.

Allcott, H. and Gentzkow, M. (2017), 'Social media and fake news in the 2016 election', *Journal of Economic Perspectives* pp. 211–236.

Anderberg, D., Chevalier, A. and Wadsworth, J. (2011), 'Anatomy of a health scare: Education, income and the MMR controversy in the UK', *Journal of Health Economics* **30**, 515–530.

Arnheim-Dahlström, L., Pasternak, B., Svanström, H., Sparén, P. and Hviid, A. (2013), 'Autoimmune, neurological, and venous thromboembolic adverse events after immunisation of adolescent girls with quadrivalent human papillomavirus vaccine in Denmark and Sweden: cohort study', *BMJ* **347**.

Berkovic, S. F., Harkin, L., McMahon, J. M., Pelekanos, J. T., Zuberi, S. M., Wirrell, E. C., Gill, D. S., Iona, X., Mulley, J. C. and Scheffer, I. (2006), 'De-Novo mutations of the sodium channel gene SCN1A in alleged vaccine encephalopathy: A retrospective study', *Lancet Neurol* **6**, 488–492.

Bollerslev, T. (1986), 'Generalized autoregressive heteroskedasticity', *Journal of Econometrics* **31**, 307–327.

Bollerslev, T. (2010), Glossary to ARCH (GARCH), *in* T. Bollerslev, J. R. Russell and M. Watson, eds, 'Volatility and Time Series Econometrics: Essays in Honour of Robert F. Engle', Oxford University Press, Oxford, UK, pp. 137–164.

Creal, D. D., Koopman, S. J. and Lucas, A. (2013), 'Generalized autoregressive score models with applications', *Journal of Applied Econometrics* **28**, 777–795.

Faasse, K., Porsius, J. T., Faasse, J. and Martin, L. R. M. (2017), 'Bad news: The influence of news coverage and Google searches on Gardasil adverse event reporting', *Vaccine* **35**, 6872–6878.

Feiring, B., Laake, I., Bakken, I. J., Greve-Isdahl, M., Wyller, V. B., Håberge, S. E., Magnus, P. and Trogstad, L. (2017), 'HPV vaccination and risk of chronic fatigue syndrome/myalgic encephalomyelitis: A nationwide register-based study from Norway', *Vaccine* **35**, 4203–4212.

Ferris, D. G., Samakoses, R., Block, S. L., Lazcano-Ponce, E., Restrepo, J. A., Mehlsen, J., Chatterjee, A., Iversen, O.-E., Joshi, A., Chu, J.-L., Krick, A. L., Saah, A. and Das, R. (2017), '4-valent human papillomavirus (4vhpv) vaccine in preadolescents and adolescents after 10 years', *Pediatrics* **140**.

Kavanagh, K., Pollock, K. G., Cuschieri, K., Palmer, T., Cameron, R. L., Watt, C., Bhatia, R., Moore, C., Cubie, H., Cruickshank, M. and Robertson, C. (2017), 'Changes in the prevalence of human papillomavirus following a national bivalent human papillomavirus vaccination programme in scotland: a 7-year cross-sectional study', *The Lancet Infectious Diseases* **17**, 1293–1302.

Kjaer, S. K., Nygård, M., Dillner, J., Marshall, J. B., Radley, D., Li, M., Munk, C., Hansen, B. T., Sigurdardottir, L. G., Hortlund, M., Tryggvadottir, L., Joshi, A., Das, R. and Saah, A. J. (2018), 'A 12-year follow-up on the long-term effectiveness of the quadrivalent human papillomavirus vaccine in 4 nordic countries', *Clinical Infectious Diseases* p. forthcoming.

Lehtinen, M., Eriksson, T., Apter, D., Hokkanen, M., Natunen, K., Paavonen, J., Pukkala, E., Angelo, M.-G., Zima, J., David, M.-P., Datta, S., Bi, D., Struyf, F. and Dubin, G. (2016), 'Safety of the human papillomavirus (hpv)-16/18 as04-adjuvanted vaccine in adolescents aged 12-15 years: Interim analysis of a large community-randomized controlled trial', *Human vaccines & immunotherapeutics* **12**, 3177–3185.

Offit, P. A. (2011), *Deadly Choices: How the Anti-Vaccine Movement Threatens Us All*, Basic Books, New York.

Oliver, S. E., Unger, E. R., Lewis, R., McDaniel, D., Gargano, J. W., Steinau, M. and Markowitz, L. E. (2017), 'Prevalence of human papillomavirus among females after vaccine introduction – national health and nutrition examination survey, united states, 2003-014', *The Journal of Infectious Diseases* **216**, 594–603.

Shields, D., Nielsen, C., Buch, D., Jacobsen, V., Christenson, P., Zachau-Christiansen, B. and Cherry, J. D. (1988), 'Relationship of pertussis immunization to the onset of neurologic disorders: A retrospective epidemiologic study', *The Journal of pediatrics* **113**, 801–805.

Tanaka, H., Shirasawa, H., Shimizu, D., Sato, N., Ooyama, N., Takahashi, O. and Terada, Y. (2017), 'Preventive effect of human papillomavirus vaccination on the development of uterine cervical lesions in young japanese women', *Journal of Obstetrics and Gynecology* **43**, 1597–1601.

WHO (2016), 'Human papillomavirus (hpv) and cervical cancer', *World Health Organization Fact Sheet* .

A Appendix: Derivations of Various Results

A.1 Score for Vaccine Compliance

In this section we establish the result in (4). We seek the first and second derivatives of the log-likelihood function with respect to $\tilde{\delta}$. First observe that

$$\frac{\partial p_{c,t}}{\partial \tilde{\delta}_t} = \frac{\partial}{\partial \tilde{\delta}_t} \frac{e^{\tilde{\delta}_t}}{1 + e^{\tilde{\delta}_t}} \lambda_{c,t} \eta_t = \frac{e^{\tilde{\delta}_t}}{(1 + e^{\tilde{\delta}_t})^2} \lambda_{c,t} \eta_t,$$

where $\lambda_{c,t} = \frac{N_c}{N_{c,t-1}}[\Lambda(\beta; a_t^c) - \Lambda(\beta; a_{t-1}^c)]$. Thus from (3) we have that

$$s_{c,t} = \frac{\partial \ell_{c,t}}{\partial \tilde{\delta}_t} = \frac{\partial p_{c,t}}{\partial \tilde{\delta}_t} \left[\frac{x_{c,t}}{p_{c,t}} - \frac{N_{c,t-1} - x_{c,t}}{1 - p_{c,t}} \right] = \frac{e^{\tilde{\delta}_t}}{(1 + e^{\tilde{\delta}_t})^2} \lambda_{c,t} \eta_t N_{c,t-1} \left[\frac{\hat{p}_{c,t}}{p_{c,t}} - \frac{1 - \hat{p}_{c,t}}{1 - p_{c,t}} \right],$$

where $\hat{p}_{c,t} = x_{c,t}/N_{c,t-1}$. The score for $\tilde{\delta}_t$ is therefore given by

$$s_t = \sum_c s_{c,t} = \frac{e^{\tilde{\delta}_t}}{(1 + e^{\tilde{\delta}_t})^2} \sum_c \lambda_{c,t} \eta_t N_{c,t-1} \left[\frac{\hat{p}_{c,t}}{p_{c,t}} - \frac{1 - \hat{p}_{c,t}}{1 - p_{c,t}} \right].$$

Next, for the second derivative, we have

$$h_{c,t} = \frac{\partial^2 \ell_{c,t}}{\partial \tilde{\delta}_t^2} = \frac{\partial}{\partial \tilde{\delta}_t} \frac{e^{\tilde{\delta}_t}}{(1+e^{\tilde{\delta}_t})^2} \lambda_{c,t} \eta_t N_{c,t-1} \left[\frac{\hat{p}_{c,t}}{p_{c,t}} - \frac{1-\hat{p}_{c,t}}{1-p_{c,t}} \right].$$

Now

$$\frac{\partial}{\partial \tilde{\delta}_t} \frac{e^{\tilde{\delta}_t}}{(1+e^{\tilde{\delta}_t})^2} = \frac{e^{\tilde{\delta}_t}(1+e^{\tilde{\delta}_t})^2 - e^{\tilde{\delta}_t} e^{\tilde{\delta}_t} 2(1+e^{\tilde{\delta}_t})}{(1+e^{\tilde{\delta}_t})^4} = \frac{-e^{3\tilde{\delta}_t} + e^{\tilde{\delta}_t}}{(1+e^{\tilde{\delta}_t})^4} = \frac{e^{\tilde{\delta}_t}}{(1+e^{\tilde{\delta}_t})^2} \frac{1-e^{\tilde{\delta}_t}}{1+e^{\tilde{\delta}_t}},$$

and

$$\frac{\partial}{\partial \tilde{\delta}_t} \left[\frac{\hat{p}_{c,t}}{p_{c,t}} - \frac{1-\hat{p}_{c,t}}{1-p_{c,t}} \right] = -\frac{e^{\tilde{\delta}_t}}{(1+e^{\tilde{\delta}_t})^2} \lambda_{c,t} \eta_t \left[\frac{\hat{p}_{c,t}}{p_{c,t}^2} + \frac{1-\hat{p}_{c,t}}{(1-p_{c,t})^2} \right].$$

Using that $\mathbb{E}_{t-1}(\hat{p}_{c,t}) = p_{c,t}$, we have

$$\begin{aligned} -\mathbb{E}_{t-1} h_{c,t} &= \frac{e^{\tilde{\delta}_t}}{(1+e^{\tilde{\delta}_t})^2} \lambda_{c,t} \eta_t N_{c,t-1} \frac{e^{\tilde{\delta}_t}}{(1+e^{\tilde{\delta}_t})^2} \lambda_{c,t} \eta_t \frac{1}{p_{c,t}(1-p_{c,t})} \\ &= \left[\frac{e^{\tilde{\delta}_t}}{(1+e^{\tilde{\delta}_t})^2} \right]^2 \frac{\lambda_{c,t}^2 \eta_t^2 N_{c,t-1}}{p_{c,t}(1-p_{c,t})}, \end{aligned}$$

hence

$$\begin{aligned} \left(-\sum_c \mathbb{E}_{t-1} h_{c,t} \right)^{-1/2} &= \left(\left[\frac{e^{\tilde{\delta}_t}}{(1+e^{\tilde{\delta}_t})^2} \right]^2 \sum_c \frac{\lambda_{c,t}^2 \eta_t^2 N_{c,t-1}}{p_{c,t}(1-p_{c,t})} \right)^{-1/2} \\ &= \frac{(1+e^{\tilde{\delta}_t})^2}{e^{\tilde{\delta}_t}} \Big/ \sqrt{\sum_c \frac{\lambda_{c,t}^2 \eta_t^2 N_{c,t-1}}{p_{c,t}(1-p_{c,t})}}. \end{aligned}$$

Thus

$$\begin{aligned} \tilde{s}_t &= \left(-\sum_c \mathbb{E}_{t-1} h_{c,t} \right)^{-1/2} \sum_c s_{c,t} = \frac{\sum_c \lambda_{c,t} \eta_t N_{c,t-1} \left(\frac{\hat{p}_{c,t}}{p_{c,t}} - \frac{1-\hat{p}_{c,t}}{1-p_{c,t}} \right)}{\sqrt{\sum_c \frac{\lambda_{c,t}^2 \eta_t^2 N_{c,t-1}}{p_{c,t}(1-p_{c,t})}}}. \\ &= \frac{\sum_c N_c \tilde{\lambda}_{c,t} \left(\frac{\hat{p}_{c,t}}{p_{c,t}} - \frac{1-\hat{p}_{c,t}}{1-p_{c,t}} \right)}{\sqrt{\sum_c \frac{N_c^2}{N_{c,t-1}} \frac{\tilde{\lambda}_{c,t}^2}{p_{c,t}(1-p_{c,t})}}} \simeq \frac{\sum_c \tilde{\lambda}_{c,t} \left(\frac{\hat{p}_{c,t}}{p_{c,t}} - \frac{1-\hat{p}_{c,t}}{1-p_{c,t}} \right)}{\sqrt{\sum_c \frac{1}{N_{c,t-1}} \frac{\tilde{\lambda}_{c,t}^2}{p_{c,t}(1-p_{c,t})}}}, \end{aligned}$$

where $\tilde{\lambda}_{c,t} = \Lambda(\beta; a_t^c) - \Lambda(\beta; a_{t-1}^c)$.

A.2 Score for Seasonal Component

In this section we derive the results in (6) and (7) for the case $z_t^a = 0$. We seek the first and second derivatives of the log-likelihood function with respect to $g_{0,t}$ and $g_{1,t}$. First note that

$$\frac{\partial p_{c,t}}{\partial g_{0,t}} = p_{c,t} \sin\left(2\pi(z_t^m + g_{1,t})\right)$$

and

$$\frac{\partial p_{c,t}}{\partial g_{1,t}} = p_{c,t} g_{0,t} 2\pi \cos\left(2\pi(z_t^m + g_{1,t})\right).$$

From (3) we have that

$$s_{g,1,c,t} = \frac{\partial \ell_{c,t}}{\partial g_{0,t}} = \frac{\partial p_{c,t}}{\partial g_{0,t}} \left[\frac{x_{c,t}}{p_{c,t}} - \frac{N_{c,t-1} - x_{c,t}}{1 - p_{c,t}}\right] = p_{c,t} N_{c,t-1} \left[\frac{\hat{p}_{c,t}}{p_{c,t}} - \frac{1 - \hat{p}_{c,t}}{1 - p_{c,t}}\right] \sin\left(2\pi(z_t^m + g_{1,t})\right)$$

and

$$s_{g,2,c,t} = \frac{\partial \ell_{c,t}}{\partial g_{1,t}} = p_{c,t} N_{c,t-1} \left[\frac{\hat{p}_{c,t}}{p_{c,t}} - \frac{1 - \hat{p}_{c,t}}{1 - p_{c,t}}\right] g_{0,t} 2\pi \cos\left(2\pi(z_t^m + g_{1,t})\right).$$

For the second derivatives, note that

$$\frac{\partial}{\partial g_{0,t}} \left[\frac{\hat{p}_{c,t}}{p_{c,t}} - \frac{1 - \hat{p}_{c,t}}{1 - p_{c,t}}\right] = -p_{c,t} \left[\frac{\hat{p}_{c,t}}{p_{c,t}^2} + \frac{1 - \hat{p}_{c,t}}{(1 - p_{c,t})^2}\right] \sin\left(2\pi(z_t^m + g_{1,t})\right)$$

and

$$\frac{\partial}{\partial g_{1,t}} \left[\frac{\hat{p}_{c,t}}{p_{c,t}} - \frac{1 - \hat{p}_{c,t}}{1 - p_{c,t}}\right] = -p_{c,t} \left[\frac{\hat{p}_{c,t}}{p_{c,t}^2} + \frac{1 - \hat{p}_{c,t}}{(1 - p_{c,t})^2}\right] g_{0,t} 2\pi \cos\left(2\pi(z_t^m + g_{1,t})\right).$$

Since $\mathbb{E}_{t-1}(\hat{p}_{c,t}) = p_{c,t}$, we therefore have that

$$-\mathbb{E}_{t-1} \frac{\partial^2 \ell_{c,t}}{\partial g_{0,t}^2} = N_{c,t-1} \frac{p_{c,t}^2}{p_{c,t}(1 - p_{c,t})} \sin^2\left(2\pi(z_t^m + g_{1,t})\right)$$

and

$$-\mathbb{E}_{t-1} \frac{\partial^2 \ell_{c,t}}{\partial g_{1,t}^2} = N_{c,t-1} \frac{p_{c,t}^2}{p_{c,t}(1 - p_{c,t})} g_{0,t}^2 4\pi^2 \cos^2\left(2\pi(z_t^m + g_{1,t})\right).$$

Hence

$$\left(-\sum_c \mathbb{E}_{t-1} \frac{\partial^2 \ell_{c,t}}{\partial g_{0,t}^2}\right)^{-1/2} = \left(\sin^2\left(2\pi(z_t^m + g_{1,t})\right) \sum_c \tfrac{p_{c,t}^2 N_{c,t-1}}{p_{c,t}(1-p_{c,t})}\right)^{-1/2}$$

and

$$\left(-\sum_c \mathbb{E}_{t-1}\frac{\partial^2 \ell_{c,t}}{\partial g_{1,t}^2}\right)^{-1/2} = \left(g_{0,t}^2 \cos^2\left(2\pi(z_t^m + g_{1,t})\right)\sum_c \frac{p_{c,t}^2 N_{c,t-1}}{p_{c,t}(1-p_{c,t})}\right)^{-1/2}.$$

Finally,

$$\begin{aligned}
\tilde{s}_{g,0,t} &= \left(-\sum_c \mathbb{E}_{t-1}\frac{\partial^2 \ell_{c,t}}{\partial g_{0,t}^2}\right)^{-1/2}\sum_c s_{g,1,c,t} = \frac{\sum_c \lambda_{c,t}N_{c,t-1}\left[\frac{\hat{p}_{c,t}}{p_{c,t}} - \frac{1-\hat{p}_{c,t}}{1-p_{c,t}}\right]\sin\left(2\pi(z_t^m + g_{1,t})\right)}{\sqrt{\sin^2\left(2\pi(z_t^m + g_{1,t})\right)\sum_c \frac{\lambda_{c,t}^2 N_{c,t-1}}{p_{c,t}(1-p_{c,t})}}} \\
&= \tilde{s}_t \operatorname{sign}(\sin\left(2\pi(z_t^m + g_{1,t})\right)),
\end{aligned}$$

and, similarly,

$$\tilde{s}_{g,1,t} = \tilde{s}_t \operatorname{sign}(g_{0,t}\cos\left(2\pi(z_t^m + g_{1,t})\right)).$$

In the case where $z_t^a = 1$, we define $\tilde{s}_{g,0,t} = \tilde{s}_{g,1,t} = 0$.

B Additional Empirical Results and Details

The list of media stories are listen in Table B.1.

B.1 Estimation of Figure 1

We set the estimate of the static parameter δ to match X_T/N_0, i.e. 94%. The estimate of $\Lambda(t)$ is determined by minimizing the discretized version of the Anderson Darling statistic

$$\int_0^T \frac{(X_t/N_0 - \hat{\delta}\Lambda(t))^2}{\Lambda(t)(1-\Lambda(t))}\mathsf{d}\Lambda(t).$$

B.2 Birthday Correction

Figure B.1 plots daily births as a fraction of the total number of births over the year. We fit a cubic polynomial $b(\tau)$ to the fraction of daily births by least squares, where $\tau = \frac{i}{365}$, $i = 1, \ldots, 365$ denotes the time of the year. The fitted values are drawn as a dotted line in the figure. The daily measure of births is quite noisy and exhibits seasonal effects at the weekly and monthly frequency. Still, the estimated function predicts a higher number of births in late summer and few births at the end of December, which is in line with stylized facts from other countries. The cumulative number of birthdays is given by $B(\tau) = \int_0^\tau b(u)\mathrm{d}u$, so that the fraction of girls in that have turned twelve at time a_t^c is given by

Table B.1: Danish Media Articles: HPV Vaccine Efficacy and Side Effects

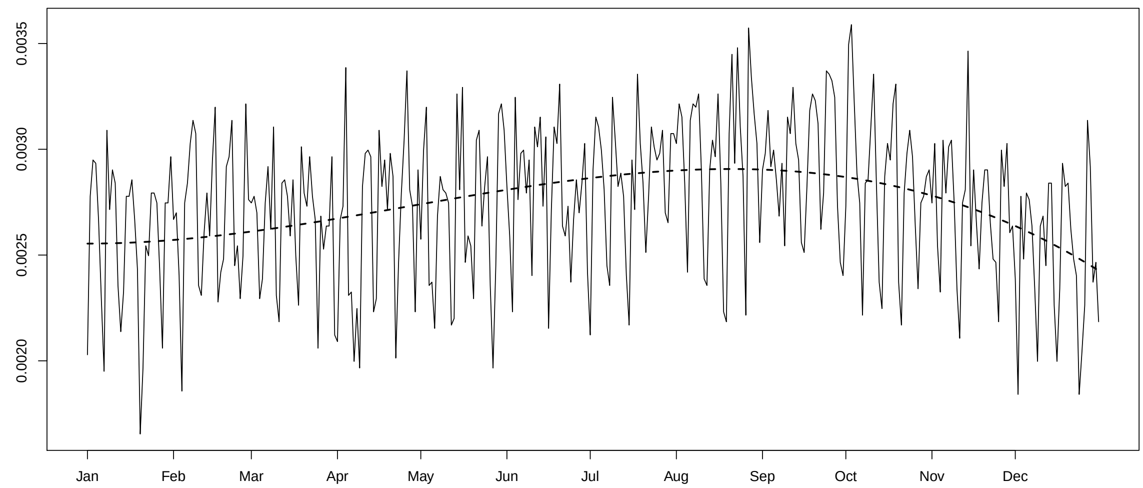
Date	Source	Title
17-Apr-13	Politiken	Frustrerede forældre: HPV-vaccine har gjort vores datters liv til et ...
3-May-13	Politiken	HPV-vacciner giver meget få, men alvorlige skader
3-May-13	Politiken	Internationale eksperter: Danmark oversælger fordelene ved HPV
3-May-13	Berlingske	Få men alvorlige skader efter HPV-vaccine
11-Jul-13	Politiken	Forening: Flere oplever bivirkninger efter HPV-vaccine
28-Jul-13	BT	400.000 piger i fare: HPV-Vaccinen kan give alvorlige bivirkninger | BT ...
5-Sep-13	Politiken	Vi lader en rådden industri bruge vores børn som forsøgsdyr
5-Sep-13	Kr.-Dagblad	Vaccine skaber usikkerhed hos unge kvinder
13-Jul-14	Berlingske	Se alvoren med HPV-vaccinen i øjnene
3-Aug-14	BT	Ramt af bivirkning: Signe får erstatning efter HPV-vaccine
3-Aug-14	BT	Ekspert: Danske piger har fået for høj dosis
25-Mar-15	Politiken	Efter voldsom kritik: Hjælp på vej til unge kvinder med smerter efter ...
25-Mar-15	Kr.-Dagblad	Regioner opretter særafdelinger for HPV-vaccinerede
25-Mar-15	Metroxpress	Læger advarer: Frygter bivirkninger ved HPV-vaccine
26-Mar-15	Politiken	Astrids far om hpv-bivirkninger: “Andre synes, at man er helt tosset ...
26-Mar-15	Politiken	Læge: Piger med vaccinebivirkninger skal tages alvorligt
26-Mar-15	Kr.-Dagblad	Læge om HPV: På tide at bivirkninger tages alvorligt
26-Mar-15	Information	Læge om HPV: På tide at bivirkninger tages alvorligt
26-Mar-15	Information	Vi kan aldrig være skråsikre på vacciner’
26-Mar-15	Metroxpress	HPV-vaccinen gjorde Katrine kronisk syg
17-Apr-15	Information	Hvornår tager man HPV-vaccinens ofre alvorligt?
5-May-15	Berlingske	Overlæge: Advar sportsaktive piger mod HPV-vaccinen - Berlingske
5-May-15	Berlingske	16-årige Natasja blev voldsomt syg efter HPV-vaccine: Har ikke været ...
5-May-15	BT	Overlæge advarer: Disse piger får flest bivirkninger af HPV-vaccinen ...
5-May-15	BT	HPV-vaccine eller ej? Her er forskerens fire ’forbudte’ råd
5-May-15	BT	16-årige Natasja blev voldsomt syg efter HPV-vaccine: Har ikke været ...
5-May-15	BT	Politikere: Danskerne skal advares om HPV-vaccinen
5-May-15	Kr.-Dagblad	Overlæge: Myndigheder bør gøre mere for vaccineofre
6-May-15	Ekstrabladet	Trist pige: Fik HPV-vaccine og så virkede læber og tunge ikke
6-May-15	Politiken	Overlæge om HPV-advarsel: Vi er nødt til at undersøge bivirkninger
6-May-15	Kr.-Dagblad	Færre takker ja til vaccine mod livmoderhalskræft
6-May-15	Metroxpress	Far kæmper for sin datter: Så syg blev Astrid efter HPV-vaccine
18-May-15	Berlingske	Eksperter: Vi ved ikke, om HPV-vaccinens virkning er varig
19-May-15	Berlingske	Forsker bag HPV-vaccinen: Vil ikke give den til mine børn
19-May-15	BT	Forskeren bag omstridt HPV-vaccine: Jeg vil ikke give den til mine ...
19-May-15	Metroxpress	Forsker bag HPV-vaccinen: - Jeg vil ikke give den til mine børn
11-Jun-15	Berlingske	Læger: En ud af 500 piger bliver alvorligt syg efter HPV-vaccine
11-Jun-15	Metroxpress	Læger: En ud af 500 piger bliver alvorligt syg af at få HPV-vaccinen ...
12-Jun-15	Metroxpress	Nanna blev syg og tabte sig 18 kilo efter HPV-vaccinen: Læs hendes ...
25-Jun-15	Kr.-Dagblad	Indberetningsbunke over HPV-vaccines bivirkninger vokser
26-Jun-15	Berlingske	Frygt for bivirkninger får piger til at droppe HPV-vaccination
27-Jun-15	Politiken	Da besvimelser, kørestol og manglende skolegang blev hverdag for ...
27-Jun-15	Berlingske	Vaccinen der deler vandene
1-Jul-15	Politiken	Læger i stor strid om hpv-pigerne
6-Jul-15	Metroxpress	HPV-piger: Vi blev ikke advaret om bivirkninger
31-Aug-15	Politiken	Unge piger vælger i stigende grad HPV-vaccinen fra
31-Aug-15	Berlingske	Nu er der færre der får HPV-vaccinen end MFR
31-Aug-15	BT	Mette fik HPV-vaccinen for seks år siden og kan stadig ikke leve et
31-Aug-15	Kr.-Dagblad	1100 piger skal checkes for mistanke om HPV-bivirkninger
31-Aug-15	Metroxpress	Lange ventelister: Over 1.100 syge piger bestormer HPV-centre
1-Sep-15	Metroxpress	Blev afvist på HPV-center: 15-årige Katrine besvimer hele tiden
7-Sep-15	Metroxpress	Heidi HPV-vaccineret som 32-årig: Jeg er ikke den mor, jeg var før ...
8-Sep-15	Metroxpress	Læger: Stop med at HPV-vaccinere kvinder over 26 år
22-Sep-15	Kr.-Dagblad	Hundredvis med mistanke om HPV-bivirkninger venter på hjælp
24-Sep-15	Politiken	Indberettede HPV-bivirkninger slår alle rekorder
24-Sep-15	Kr.-Dagblad	Over 1500 piger har formodede HPV-bivirkninger
24-Sep-15	Metroxpress	Over 1500 piger har formodede HPV-bivirkninger
29-Sep-15	Metroxpress	Eksperter: Ny HPV-vaccine er ikke mere sikker
14-Oct-15	BT	Danske piger er ikke alene om HPV-plager: Udlandet oplever også ...
14-Oct-15	Metroxpress	SE KORTET: Hele verden har syge HPV-piger
21-Oct-15	Metroxpress	Vaccine-fortalere afgør syge HPV-pigers fremtid
26-Oct-15	Berlingske	Firma bag HPV-vaccinen underdrev omfanget af alvorlige bivirkninger
5-Nov-15	Politiken	Kronisk hovedpine, lammelser og krampeanfald er dagligdag for ...
5-Nov-15	Metroxpress	Førende svensk HPV-forsker: Mistanken om Pots er ikke undersøgt ...
7-Nov-15	Kr.-Dagblad	Færre vaccineres mod livmoderhalskræft
9-Nov-15	Metroxpress	TV: Her er HPV-pigernes symptomer
10-Nov-15	Metroxpress	Læge til Stine på HPV-center: Jeg er fløjtende ligeglad og ikke selv ...
10-Nov-15	Metroxpress	BLOG: Sådan er livet som POTS-syg mor til tre
		continues...

(Table B.1 continued).

Date	Source	Title
10-Nov-15	Metroxpress	Stor stigning: Over 100 danske piger har POTS
12-Nov-15	Metroxpress	HPV-kritisk læge: Styrelsen driver klapjagt på mig
12-Nov-15	Metroxpress	BLOG: Fyringer på HPV-center bekræfter min mistanke
12-Nov-15	Metroxpress	BLOG: Hvorfor ville I ikke undersøge mig for POTS?
17-Nov-15	Metroxpress	HPV-piger: Lægerne siger, vi er tossede
20-Nov-15	Metroxpress	BLOG: Er lægen styret af frygt eller lægeløftet?
24-Nov-15	Metroxpress	Smertesyndrom sendte 15-årig badminton-pige i kørestol
25-Nov-15	Metroxpress	BLOG: Piger med vaccineskader og læger på herrens mark
26-Nov-15	Politiken	Liselott Blixt affejer HPV-rapport: "Lavet af betalt lobby"
27-Nov-15	Politiken	Kritiseret HPV-center: "Hvilket ærinde har lægemiddelmyndighederne ...
1-Dec-15	Metroxpress	HPV: Alvorlige bivirkninger bliver aldrig indberettet
1-Dec-15	Metroxpress	Astrid opgav at indberette: Det var mega uoverskueligt
3-Dec-15	Metroxpress	Udskældt HPV-læge: Sundhedsstyrelsens uvidenhed er dybt...
8-Dec-15	Metroxpress	Førende forsker: Forsøg med HPV-vaccinen skjuler alvorlige bivirkninger
15-Dec-15	Metroxpress	Ekspert: Danske piger misinformeret i HPV-forsøg
17-Dec-15	Politiken	HPV-høring: Vi ser altså nye signaler
17-Dec-15	Politiken	Analyse: HPV-kritikken vil ikke dø
18-Dec-15	Berlingske	Trods videnskabelig modvind: Blixt tror stadig på HPV-bivirkninger
4-Feb-16	Kr.-Dagblad	Overlæge efterlyser behandling af HPV-pigers symptomer
4-Feb-16	Information	Overlæge efterlyser behandling af HPV-pigers symptomer
31-Mar-16	Information	Sundhedsstyrelsen er utroværdig'
15-Apr-16	Ekstrabladet	Stadig flere piger sig nej til hpv-vaccinen
15-Apr-16	Kr.-Dagblad	Stadig flere piger sig nej til hpv-vaccinen
23-Apr-16	Kr.-Dagblad	Flere danske klager over HPV-vaccine end norske og svenske
23-Apr-16	Kr.-Dagblad	OVERBLIK: Danmark klager mest over hpv-vaccine
27-Apr-16	Ekstrabladet	Flere piger i hovedstadsområdet siger nej til hpv-vaccine
27-Apr-16	Kr.-Dagblad	Flere piger i hovedstadsområdet siger nej til hpv-vaccine
28-Apr-16	Information	Det er en svær beslutning at HPV-vaccinere sit barn
28-Apr-16	Metroxpress	Vi har nu set 500 piger med symptomer efter HPV-vaccinen
26-May-16	Politiken	HPV-rapport kaldes uacceptabelt, ringe videnskabeligt håndværk...
26-May-16	Metroxpress	Forskere og politiker klager over EU-frifindelse af HPV-vaccinen
30-May-16	Kr.-Dagblad	OVERBLIK: Hpv-vaccine til diskussion igen
30-May-16	Information	Ekspert anklager styrelse for at vildlede om HPV-vaccine
19-Jun-16	Metroxpress	Nyt HPV-kritisk magasin sætter fokus på bivirkninger ved vaccinen...
5-Aug-16	Ekstrabladet	Syg mor fortryder: Forkælede sig selv med HPV-vaccine til 3500 kr
4-Oct-16	Kr.-Dagblad	Brug af den kontroversielle hpv-vaccine er halveret
7-Apr-17	Politiken	Fortsat skepsis: Hver femte føler sig utryg ved hpv-vaccinen
28-Jun-17	Politiken	Overlæge afviser frikendelse af hpv-bivirkninger trods nyt studie...

Note: Danish media articles on the HPV vaccine that either reports on a possible association with serious side effects, or articles that raise doubt about the efficacy of the vaccine.

Figure B.1: Daily births as a fraction of total births in 2007



$$g(a) = \tfrac{1}{B(1)} B(3a), \qquad a \in (0, \tfrac{1}{3}],$$

with $g(a) = 0$ for $a \leq 0$ and $g(a) = 1$ for $a \geq \frac{1}{3}$. The number of girls in cohort c, which is eligible to receive HPV1 by the end of week t is given by the girls who have turned twelve, less those that have already received HPV1, i.e.,

$$N_{c,t} = g(a_t^c) N_c - X_{c,t}.$$

B.3 Simple Specifications for $\delta_t(\alpha)$

In this section we describe simple models for $\delta_t(\alpha)$. We use two simple approaches. One where δ_t is piecewise constant, but subject to structural changes, and one in which the time-variation in δ_t is given by a deterministic function. In the first approach, the change-points are unknown parameters that are to be estimated from the data. Thus α represents the (vector) of change point(s) during the sample period and the values that δ_t takes before, between, and after change points. The second approach takes δ_t to be a simple deterministic function of time.

As explained in the main part of the paper, we need to accommodate seasonality at both annual and monthly frequency. For the simple specifications, we model seasonality as

$$\tilde{\eta}_t = \gamma_0 \sin(2\pi(z_t^m + \gamma_1))(1 - z_t^a) + \gamma_2 z_t^a,$$

where z_t^m, z_t^{sum} and z_t^{win} are the seasonal indicators described in Section 3.2.

We estimated the piecewise constant model with one, two, three, and four breakpoints, and we consider the following four different deterministic specifications where δ is a simple function of t: Hinge functions, Hermite polynomials, Trigonometric polynomials and natural cubic splines. Table B.3 gives the exact expressions for the different specifications. The Hinge function approximation is piecewise linear and the free parameters are the slopes and the knots at which the slope changes. The natural cubic spline basis function is cubic between knots and linear beyond boundary knots with knots placed at equally spaced intervals. For each function, we choose a flexible specification: the Hinge model, the Trigonometric polynomial and the natural cubic spline model each allow for nine free parameters in α. In the estimation of the Hermite polynomial model, four turned out to be the maximum order that was numerically feasible. Table B.3 presents the estimates of all eight simple specifications for δ_t.

Figure B.2 plots the estimated vaccine compliance, $\hat{\delta}_t$, for the different piecewise constant specifications. All models detect a break in the last week of March or the first week of April 2015. At that change point, compliance drops dramatically by 40 to 50 percentage points. The models that allow for a second change point determine it in the first week of October 2016. At that second change point, compliance recuperates to about 70%. The models with three and four change points also detect a break in late 2013, when compliance falls from close to 100%. The model with four break points also finds a break in late 2014, when compliance rises again to close to 100%. Estimates for $\hat{\delta}_t$ for the different approximations to deterministic functions are plotted in Figure B.3. The estimated compliance paths all have similar shapes as the one for the model with three break points. The Trigonometric polynomial model however also detects an initial uptake of compliance early in the sample.

While these simple specifications give some insight into dynamics of vaccination compliance in the data, the score-driven model has many advantages. First, for the simple specifications, the path of vaccine compliance depends on the arbitrary choice of basis function. Second, the simple specifications do not allow for dynamic updating of the compliance parameter. Third, the score-driven model fits the data (in terms of the log-likelihood) better even though the score-driven model has fewer free parameters.

Table B.2: Overview of simple specifications

model	specification
(1) One break	$\delta_t = \alpha_0 \mathbb{1}_{t<\alpha_2} + \alpha_1 \mathbb{1}_{\alpha_2 \le t}$
(2) Two breaks	$\delta_t = \alpha_0 \mathbb{1}_{t<\alpha_2} + \alpha_1 \mathbb{1}_{\alpha_2 \le t<\alpha_4} + \alpha_3 \mathbb{1}_{\alpha_4 \le t}$
(3) Three breaks	$\delta_t = \alpha_0 \mathbb{1}_{t<\alpha_2} + \alpha_1 \mathbb{1}_{\alpha_2 \le t<\alpha_4} + \alpha_3 \mathbb{1}_{\alpha_4 \le t<\alpha_6} + \alpha_5 \mathbb{1}_{\alpha_6 \le t}$
(4) Four breaks	$\delta_t = \alpha_0 \mathbb{1}_{t<\alpha_2} + \alpha_1 \mathbb{1}_{\alpha_2 \le t<\alpha_4} + \alpha_3 \mathbb{1}_{\alpha_4 \le t<\alpha_6} + \alpha_5 \mathbb{1}_{\alpha_6 \le t<\alpha_8} + \alpha_7 \mathbb{1}_{\alpha_8 \le t}$
(5) Hinge basis	$\tilde{\delta}_t = \alpha_0 + \sum_{j=1}^{4} \alpha_{2j-1} \max(0, t - \alpha_{2j})$
(6) Hermite polynomial	$\tilde{\delta}_t = \alpha_0 + \alpha_1 \mathrm{He}_1(t) + \alpha_2 \mathrm{He}_2(t) + \alpha_3 \mathrm{He}_3(t) + \alpha_4 \mathrm{He}_4(t)$
(7) Trigonometric polynomial	$\tilde{\delta}_t = \alpha_0 + \sum_{j=1}^{2} \left(\alpha_{2j-1} \cos(2\pi \times j \times t/T) + \alpha_{2j} \sin(2\pi \times j \times t/T)\right)$
(8) Natural cubic spline	$\tilde{\delta}_t = \alpha_0 + \sum_{j=1}^{8} \alpha_j \mathrm{B}_j(t)$

Note: $\mathrm{He}_j(t)$ refers to the j'th Hermite polynomial in t.
$\mathrm{B}_j(t)$ refers to the j'th natural B-spline basis function in t. Knots of the spline are placed at equally spaced intervals.

Table B.3: Estimates for simple specifications

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$\hat{\beta}_0$	7.1734	7.2100	7.1954	7.1702	7.1510	7.1773	7.1558	7.1619
$\hat{\beta}_1$	2.9653	2.9965	2.9966	2.9463	2.9773	2.9946	2.9469	2.9482
$\hat{\gamma}_0$	0.1861	0.1886	0.1952	0.1916	0.1948	0.1930	0.1909	0.1925
$\hat{\gamma}_1$	0.5345	0.5324	0.5370	0.5350	0.5362	0.5350	0.5342	0.5295
$\hat{\gamma}_2$	-0.8055	-0.7877	-0.7630	-0.7516	-0.7595	-0.7636	-0.7916	-0.8350
$\hat{\alpha}_0$	0.9918	0.9906	0.9999	0.9999	6.5833	5.1009	9.8359	48.4335
$\hat{\alpha}_1$	0.5384	0.4328	0.8641	0.7249	0.0123	0.0052	-9.9975	23.2094
$\hat{\alpha}_2$	324	324	238	259	74.9574	0.0003	7.6581	70.7022
$\hat{\alpha}_3$		0.7692	0.4290	0.9994	-0.0477	-0.0000	1.8361	99.7050
$\hat{\alpha}_4$		403	325	293	131.2689	0.0000	-2.4958	-38.5700
$\hat{\alpha}_5$			0.7676	0.4324	0.0351			-50.3722
$\hat{\alpha}_6$			403	324	346.9837			-58.2845
$\hat{\alpha}_7$				0.7649	0.0546			-18.0657
$\hat{\alpha}_8$				403	390.3151			-66.7822
$\ell(\hat{\theta})$	-22917	-21468	-21008	-20608	-21819	-22026	-21779	-21843

B.4 Simple Specifications for $\delta_t(\alpha)$ without monthly seasonality correction

In this section we document estimates for the simple specifications for $\delta_t(\alpha)$ that do not control for seasonality on a monthly basis. We include these results to demonstrate that the monthly correction does not spuriously introduce patterns in the estimates of $\hat{\delta}_t$. The seasonal model is simply

$$\tilde{\eta}_t = \gamma z_t^a,$$

where z_t^a is defined as before.

As specifications for $\delta_t(\alpha)$, we use those listed in Table B.3. Figure B.4 plots the estimated

Figure B.2: Models with Structural Changes in Vaccine Compliance, δ

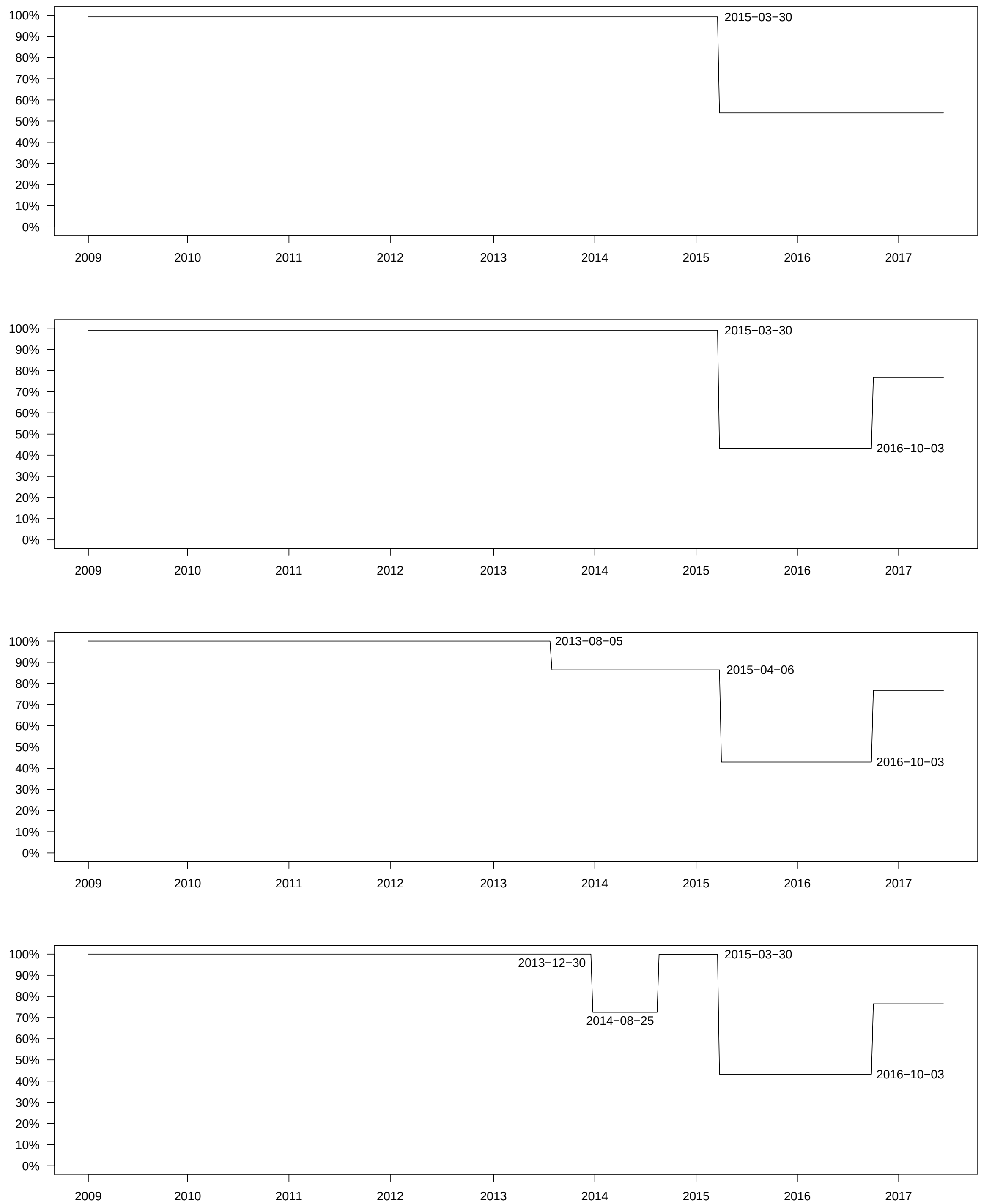
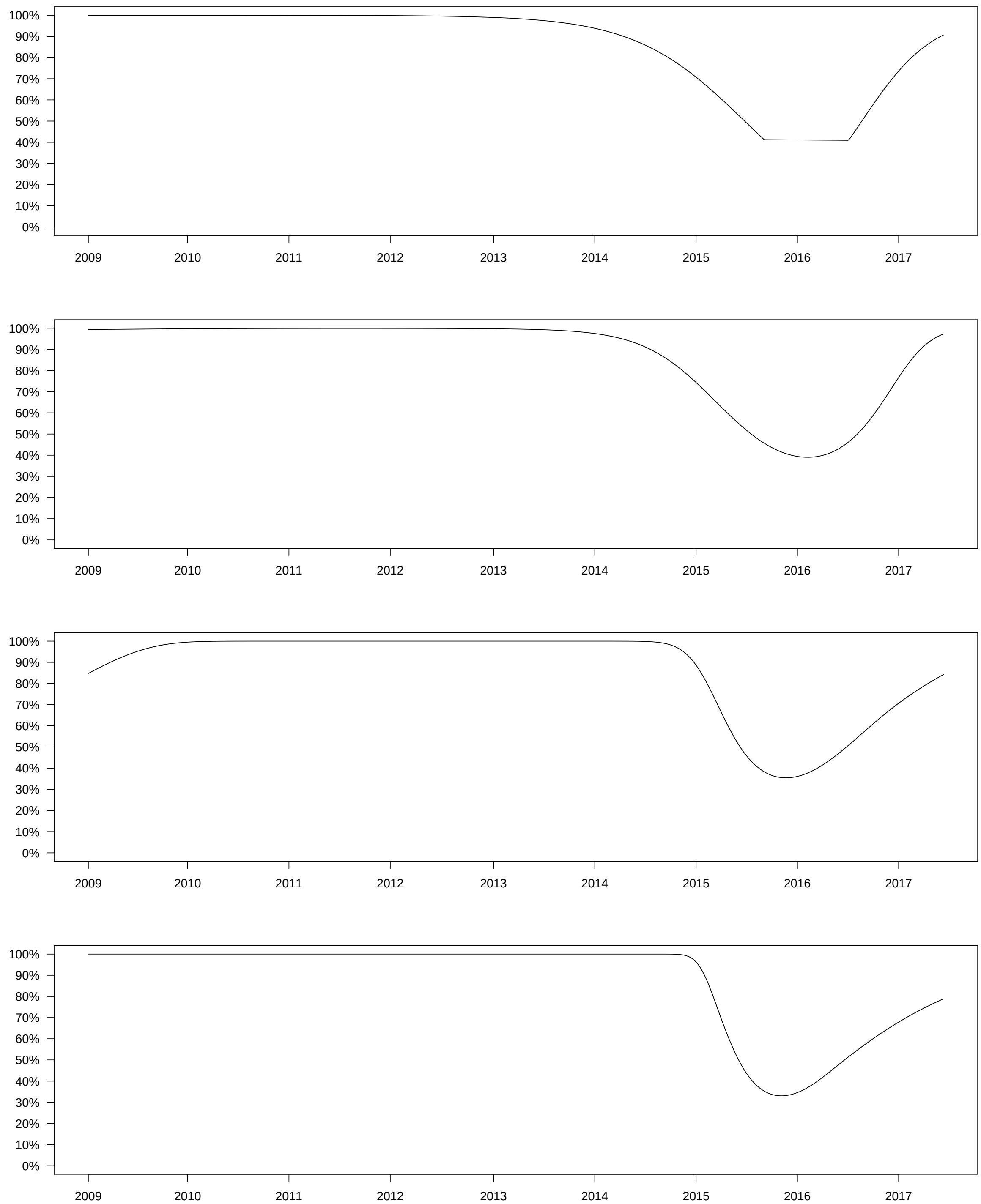


Figure B.3: Simple Models with Time-Varying Vaccine Compliance, δ



vaccine compliance, $\hat{\delta}_t$, for the different piecewise constant specifications. Figure B.5 plots vaccine compliance for the simple specifications. The estimated time paths of $\hat{\delta}_t$ are very similar to those in Table B.3. The only differences in terms of estimated break dates are that now the last break is determined to be one week later than in the model with monthly seasonality correction and that the model with three breaks sets the first break date a month earlier. Similarly, $\hat{\delta}_t$ in the different simple models are very much alike to those in Figure B.3. Table B.4 displays the estimates. For each specification, the log likelihood is considerably lower than the respective value in Table B.3, so even a static correction for monthly seasonality offers great improvements in the empirical fit of the data.

Table B.4: Estimates for simple specifications without monthly seasonality correction

$\hat{\beta}_0$	7.1586	7.1969	7.1904	7.1730	7.1067	7.1570	7.1452	7.1485
$\hat{\beta}_1$	2.9549	2.9887	2.9905	2.9475	2.9474	2.9757	2.9384	2.9552
$\hat{\gamma}$	-0.8128	-0.7962	-0.7575	-0.7531	-0.7557	-0.7788	-0.7919	-0.7960
$\hat{\alpha}_0$	1.0000	0.9991	1.0000	0.9999	7.8439	6.8556	9.9062	70.3525
$\hat{\alpha}_1$	0.5418	0.4382	0.8758	0.7270	-0.0185	0.0044	-10.000	7.1016
$\hat{\alpha}_2$	324	324	234	259	29.8815	0.0003	7.7324	-49.1731
$\hat{\alpha}_3$		0.7755	0.4344	0.9999	-0.0677	-0.0000	1.8084	-70.7593
$\hat{\alpha}_4$		404	325	293	300.9243	0.0000	-2.4927	-64.9370
$\hat{\alpha}_5$			0.7753	0.4374	0.0865			-71.0927
$\hat{\alpha}_6$			404	324	341.5531			-78.5973
$\hat{\alpha}_7$				0.7736	0.0472			-46.5433
$\hat{\alpha}_8$				404	381.5049			-83.3784
$\ell(\hat{\theta})$	-24774	-23358	-22962	-22527	-23633	-23988	-23735	-23683

B.5 Seasonality correction in score-driven model

Figure B.6 plots the paths of $\hat{\eta}_t$ and of the time varying seasonality parameters $\hat{g}_{0,t}$ and $\hat{g}_{1,t}$. During most of the sample period, monthly seasonality is strong, with estimated propensity during peaks being about 50% higher than during troughs. The monthly seasonal effect diminishes after 2015 and is not very pronounced towards the end of the sample period. The attenuation of the seasonal effect in the late sample period can also be seen in the graph of $\hat{g}_{0,t}$, the time varying parameter that governs the amplitude of the sine function. The score-driven seasonal model reliably detects the change in the seasonal pattern induced by the end of the over-recording of vaccinations after the introduction of the electronic vaccine registry on November 15, 2015. The third panel of Figure B.6 plots $\hat{g}_{1,t}$, the estimated time path of the phase shift in the sine function. $\hat{g}_{1,t}$ takes values between about 0.4 and 0.7 during the sample period, corresponding to over-recording towards the end of the month.

Figure B.4: Models with Structural Changes in Vaccine Compliance without monthly seasonality correction, δ

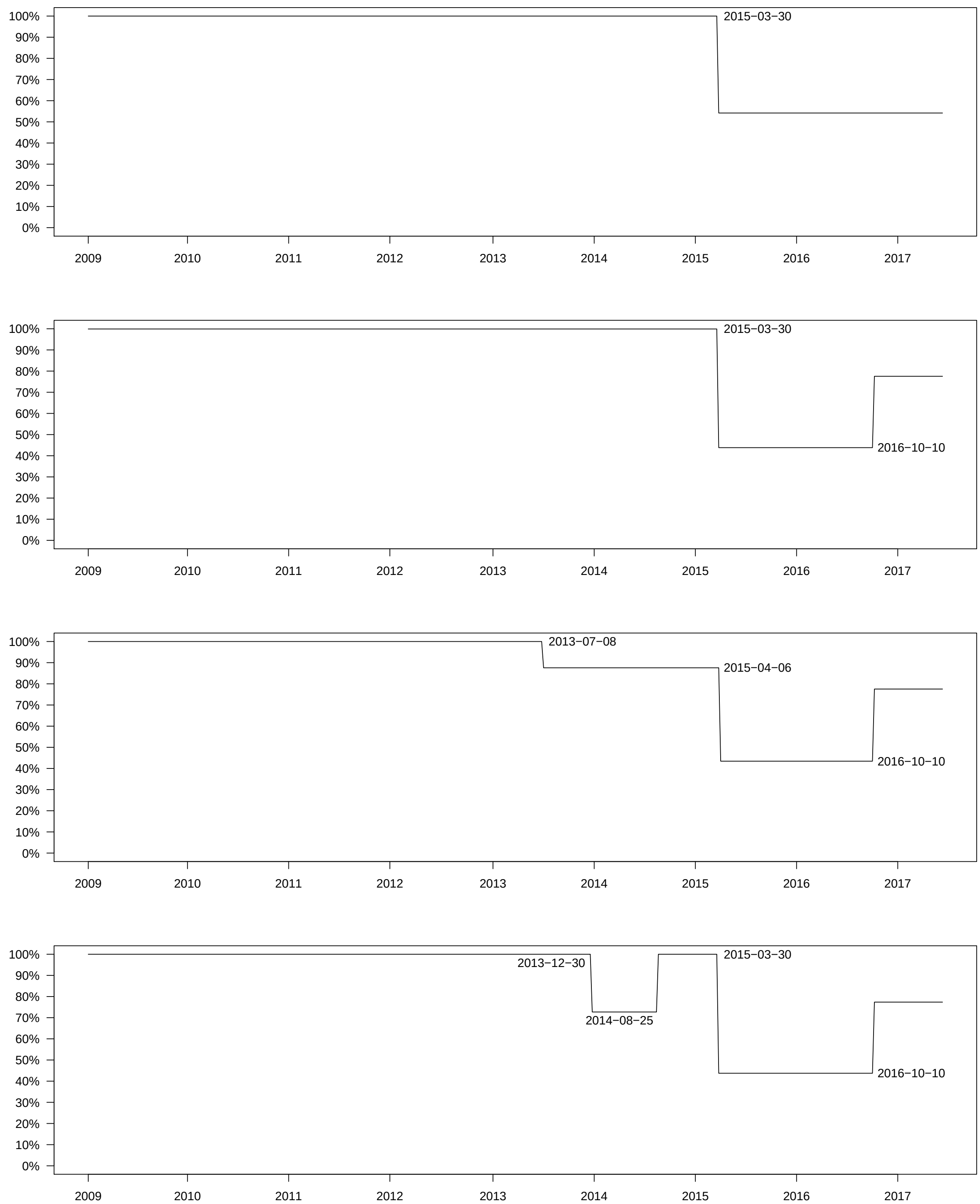


Figure B.5: Simple Models with Time-Varying Vaccine Compliance without monthly seasonality correction, δ

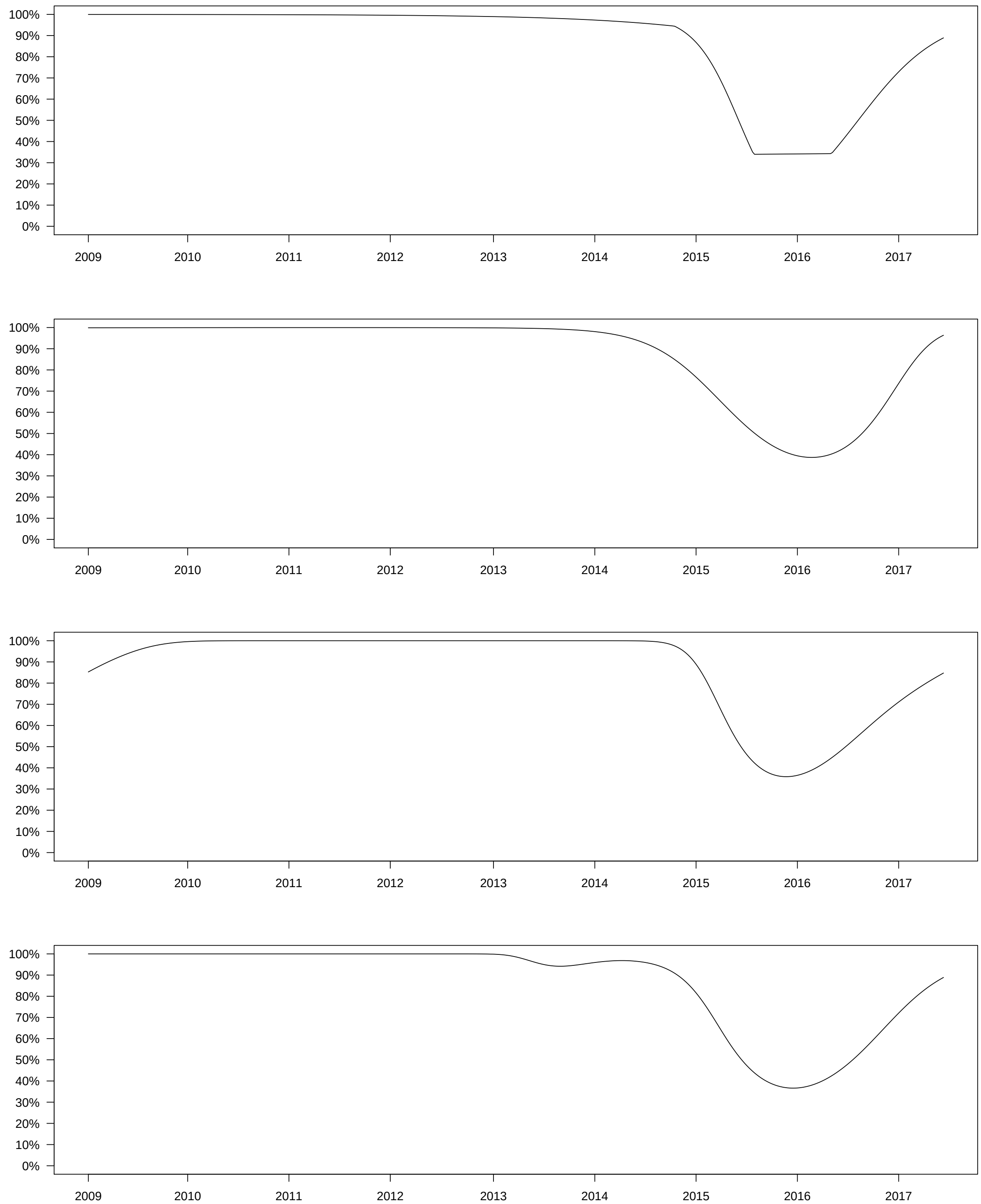


Figure B.6: Time paths of $\hat{\eta}_t$ (upper panel), $\hat{g}_{0,t}$ (middle panel) and $\hat{g}_{1,t}$(lower panel)