Vaccination strategies and transmission of COVID-19: evidence across leading countries

Dongwoo Kim*
Simon Fraser University

Young Jun Lee†
University of Copenhagen

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Abstract

Vaccination has been perceived as a key to reaching "herd immunity" in the current COVID-19 pandemic. This paper examines effectiveness of different vaccination strategies. We investigate the effects of two key elements in mass vaccination, which are allocations and timing of first and second doses and types of vaccines, on the spread of COVID-19. Amid limited supply of approved vaccines and constrained medical resources, the choice of a vaccination strategy is fundamentally an economic problem. We employ standard time-series and panel data models commonly used in economic research with real world data to estimate the effects of progress in vaccination and types of vaccines on health outcomes. Potential confounders such as government responses and people's behavioral changes are also taken into account. Our findings suggest that the share of people vaccinated with at least one dose is significantly negatively associated with new infections and deaths. Conditioning on first dose progress, full vaccination offers no further reductions in new cases and deaths. For vaccines from China, however, we find weaker effects of vaccination progress on health outcomes. Our results support the extending interval between first and second dose policy adopted by Canada and the UK among others for mRNA-based vaccines. As vaccination progressed, people's mobility increased and it offset the direct effects of vaccination. Therefore, public health measures are still important to contain the transmission by refraining people from being more mobile after vaccinated.

*Department of Economics, Simon Fraser University, 8888 University Drive, Burnaby, BC, V5A 1S6, Canada. Email: dongwook@sfu.ca

†Department of Economics, University of Copenhagen, Øster Farimagsgade 5, Building 26, DK-1353 Copenhagen K, Denmark. Email: yjl@econ.ku.dk.

1 Introduction

In the current COVID-19 pandemic, vaccination has been perceived as a key to reaching "herd immunity". This paper investigate the effects of two key elements in mass vaccination which are allocations and timing of first and second doses and types of vaccines. Mass vaccination programs have launched in leading countries since the UK first approved the use of the Pfizer–BioNTech vaccine in December 2020. Due to the very limited supply of approved vaccines in the early stage, however, even the wealthiest countries in the world had difficulties to quickly roll out the vaccine doses. COVID-19 vaccines require two doses to be administered per person within a recommended time window by manufacturers. Three or four weeks are recommended for the Pfizer–BioNTech and Moderna vaccines and 8-12 weeks for the AstraZeneca-Oxford vaccine. Under the supply constraints, leading countries adopted different vaccine roll-out strategies. UK and Canada extended the interval between first and second doses of COVID-19 vaccines up to 12-16 weeks in order to maximize the share of (at least partially) vaccinated people, whereas Israel and the US followed the recommended dosing interval. Some developing countries such as Bahrain, Chile, Turkey, UAE and Uruguay relied on less widely approved vaccines developed by Chinese firms.

Implementing a longer interval between doses has sparked a heated debate among medical experts and policy makers. In the UK, the British Medical Association (BMA) strongly stood against the idea of delaying the second dose (Mahase (2020)) as there is no clinical evidence that this strategy works. A similar criticism arose in Canada (CBC (2021)). Nonetheless, both governments implemented longer intervals to vaccinate as many people as possible. There have been handful of papers in the medical literature that suggest extending the interval between two doses might be beneficial. Moghadas *et al.* (2021) use an agent-based modeling to compare the vaccination strategies. They found that delaying the second dose can avert more infections, hospitalizations and deaths than the standard dosing if the efficacy of the first dose does not wane before the delayed second dose. Similar results using simulations-based methods are found by Romero-Brufau *et al.* (2021) and Tuite *et al.* (2021). As the vaccination programs have progressed longer than half a year, it is important to evaluate different vaccination strategies using real world data. To our best knowledge, however, there is no research on real world outcomes across different leading countries. This paper aims to provide observational cross country evidence on the effectiveness of vaccination strategies.

When it comes to types of vaccines used in mass vaccination programs, there have been rising concerns over the efficacy of some less widely approved products. After inoculating more than a half of the population, a few countries such as Chile, UAE, and Seychelles still experienced high rates of infection. These countries heavily rely on Chinese vaccines (Sinopharm, Sinovac Biotech, and CanSino) in their national inoculation programs. Vaccines from China can be a useful tool to fight the pandemic for low and middle income countries as the supply of vaccines developed in the US and Europe is limited and they cannot compete with the wealthiest countries to secure enough stocks of those vaccines. We include countries having relied on Chinese vaccines

in our analysis to see whether those vaccines have contributed to mitigating transmission of the infectious disease.

The choice of a vaccination strategy is essentially an economic problem in the sense that the resources for mass vaccination are constrained. Not only the supply of vaccines is limited but also medical facilities and healthcare workers that administer the vaccine doses are capacity constrained. Therefore, policy makers should devise an optimal strategy to allocate these limited resources for the best possible social outcomes. In this paper, we investigate whether the interval between first and second doses matters to contain the transmission of COVID-19. We also take the types of vaccines used in mass vaccination into account. As Kitagawa and Wang (2021) mentioned, optimal allocations and timing between the doses is a relevant and important problem. We rely on standard econometric approaches with real world data to answer this question. And thereby, we contribute to the literature by providing a large scale observational study on this important issue.

We employ standard time-series and panel data econometric frameworks with cross-country data to estimate the effects of the first and second dose vaccination on the COVID-19 transmission conditional on potential confounders. There are recent research papers that examine the impacts of public policies on health outcomes such as lockdown (see Acemoglu *et al.* (2020), Bjørnskov (2020), Born *et al.* (2021) and Cho (2020). Allen (2021) and Herby (2021) provide extensive literature review), and mandatory mask wearing (see Chernozhukov *et al.* (2021) and Karaivanov *et al.* (2021)). We first estimate time-series models of new infections for 8 selected leading countries (Canada, Israel, the US, the UK, Chile, Uruguay, UAE and Bahrain). Then we closely follow the approaches employed by Chernozhukov *et al.* (2021) and Karaivanov *et al.* (2021) for cross-country panel data analysis, in which we investigate the impact of vaccination on new cases and deaths, and people's behavior. Member countries in OECD and European Union that publicly release daily epidemiological data are considered. Bahrain and Uruguay are added to the country panel to evaluate the differentiating effects of vaccines from China along with Chile and Turkey that are already included in OECD.[1]

The main findings from our empirical analysis are as follows. Firstly, progress in vaccination with at least one dose is significantly negatively associated with the growth of new infections and deaths. Larger reductions in both health outcomes are found for countries delaying the second dose (Canada and the UK). Conditional on the first dose progress, full vaccination progress does not give further reductions in new cases and deaths. These findings are consistent in both time-series and panel data analyses. For the countries heavily relying on vaccines from China, no reductions in health outcomes are found for first dose progress. Full vaccination progress offers significant but weaker negative effects on new cases. Secondly, we find that progress in vaccination induces people to be more mobile. As higher mobility leads to more new infections and deaths, this indirect effect of vaccination offsets its direct effect. Lastly, our counterfactual experiments for selected countries suggest that extending the interval between

[1]Other countries that heavily rely on Chinese vaccines such as UAE and Seychelles are omitted in the panel data analysis as they do not provide daily vaccination statistics.

two doses substantially reduces weekly new cases and deaths.

Our findings can be useful to draw policy implications for low and middle income countries that fall behind in mass vaccination. According to McKensay and Company (2021), only 1% of inhabitants in low income countries had been given at least one dose of vaccines as of July 14, 2021. Since the supply of mRNA-based vaccines and alternative less widely used vaccines will continue to be limited, it is important to vaccinate as many people as possible with one dose using secured vaccine stocks. Our analysis along side with the evidence found in the medical literature suggests that extending the dosing interval is an effective strategy to mitigate the transmission of COVID-19. Especially in low income countries, not only the supply of vaccines is constrained but also the medical capacity to administer the vaccine doses, this strategy can further help maximize the level of protection among the population more quickly. As observed in many leading countries, the progress in single dose vaccination starts bending at a certain point. Thus, countries can begin to vaccinate with the second doses as resources become available. Public health measures are still very important amid vaccination progress as it can further contain the spread of the virus by reducing mobility and potential interactions among people. There is some caveat for the use of vaccines from China in our findings. It is shown that the single dose vaccination is not enough to alleviate the spread of the virus. Therefore, the importance of the second dose vaccination should be acknowledged if those vaccines are used in a significant part of mass vaccination.

The reminder of this paper is structured as follows. Section 2 describes the rationale behind delaying the second dose idea. Section 3 provides empirical analysis using time series and panel data models. Section 4 discusses the robustness of our findings. Section 5 presents counterfactual experiments for selected countries using hypothetical vaccine allocations. Section 6 concludes. Additional empirical results using alternative data frequency/model specifications and additional counterfactual experiments are provided in the Appendix.

2 Rationale Behind Delaying the Second Dose

The UK government decided to extend the interval between the first and second doses of the Pfizer-BioNTech vaccine up to 12 weeks at the end of December, 2020. Two letters sent to health professionals (NHS (2020) and Department for Health and Social Care (2020)) lay out the rationale for delaying the second dose. The main reason is that the great majority protection comes after the first dose. The second does is important for duration of protection but in the short run the additional protection afforded by the second dose is likely to be marginal. Later in Canada, National Advisory Committee on Immunization (2021) recommended that the mRNA-based vaccines and the AstraZeneca-Oxford vaccine should be given to as many people as possible by extending the dosing interval up to 4 months.

These decisions are based on three assumptions; 1. the first dose provides good enough protection; 2. the protection after the first dose does not wane too quickly; 3. the delayed second dose does not lower the efficacy of full vaccination. Under these assumptions, we conduct

a very simple thought experiment without a complicated epidemiological model. Suppose that a country secures an amount of mRNA-based vaccines that can inoculate 70% of the population with one dose. There will be a second batch of vaccines delivered to this country in 12-16 weeks. The country has to allocate its vaccine stocks to the first and second doses before the delivery of the second batch. We consider two cases in which the level of protection from the first dose substantially varies. In Case 1, the first dose provides 90% of vaccine efficacy (VE) which does not wane in 12-16 weeks, whereas the first dose VE is only 50% in Case 2. In both cases, the second dose offers 95% efficacy. Case 1 resembles the vaccine efficacy results for the mRNA-based vaccines from the clinical trials.[2] Case 2 supposes a situation where variants of the virus substantially lower the efficacy of the first dose.

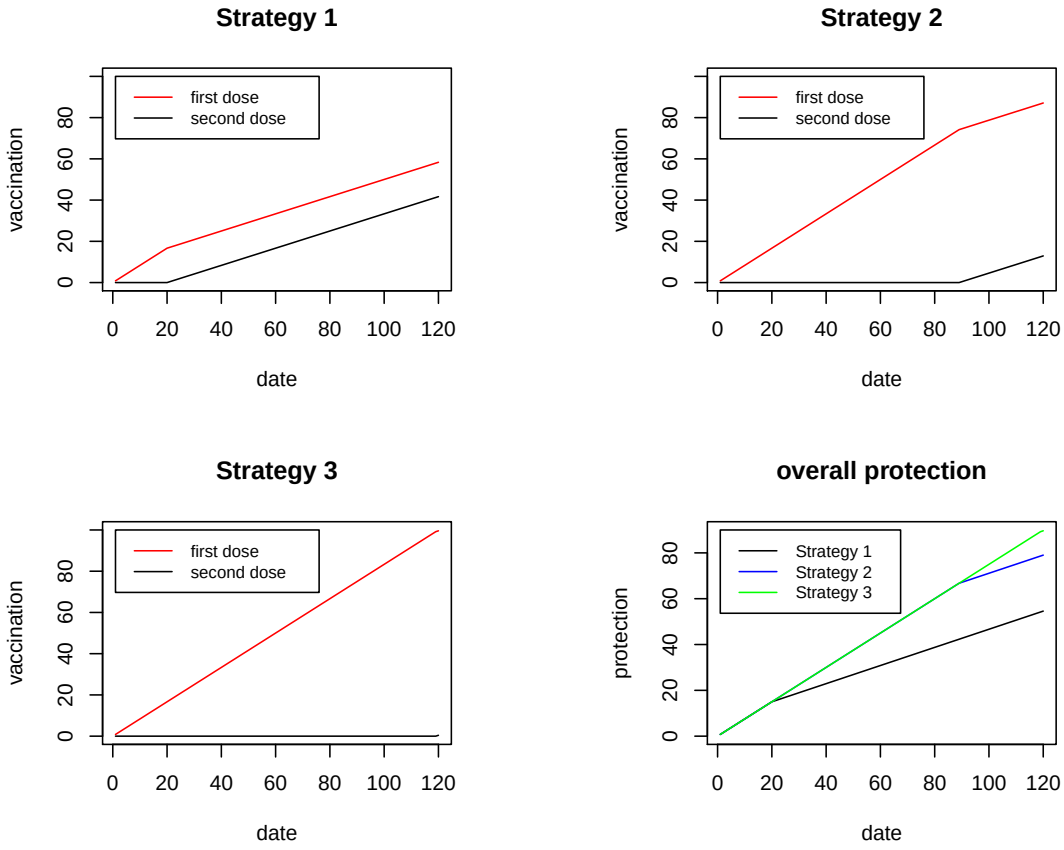
Table 1: Vaccine allocations and

Case 1 (1st dose VE: 90%, 2nd dose VE: 95%)			Case 2 (1st dose VE: 50%, 2nd dose VE: 95%)		
first dose	second dose	protection	first dose	second dose	protection
70%	0%	63.0%	70%	0%	35.0%
60%	10%	54.5%	60%	10%	34.5%
50%	20%	46.0%	50%	20%	34.0%
40%	30%	37.5%	40%	30%	33.5%
35%	35%	33.3%	35%	35%	33.25%

We compute the average protection levels among the population given different allocations of the first and second doses in Table 1. In both cases, allocating all the vaccine stocks to the first dose is the dominant strategy. Delaying the second dose is obviously much more effective when the first dose gives stronger protection as shown in Case 1. The allocation strategy does not matter if the one dose efficacy is as low as 42.5%. This simple calculation illustrates why the longer interval between doses can be beneficial under supply constraints if the underlying assumptions hold. Of course, there might be many other possibilities. For instance, the efficacy of one dose before the second could wane in a short period of time. It is also possible that the interval between the first and second doses also affects the overall efficacy level after the final dose. Voysey *et al.* (2021) showed that the longer interval ($\geq$ 12 weeks) between doses of the AstraZeneca vaccine provided a greater efficacy than the shorter interval ($<$ 6 weeks). A recent study in the UK (Payne *et al.* (2021)) found that longer dosing intervals (6-14 weeks) resulted in stronger immune responses than the standard regimen (3-4 weeks) for the Pfizer-BioNTech vaccine. They also reported that robust protection maintained 3 weeks after the first

[2] Polack *et al.* (2020) reported that the vaccine efficacy of the Pfizer-BioNTech vaccine between the first and second doses is 52.4%. However, they used data collected during the first two weeks after the first dose in their calculation. Skowronski and De Serres (2021) reanalyzed it using data submitted to the Food and Drug Administration (FDA) and found that the first dose efficacy is 92.6% from two weeks after the first dose and before the second dose. This is similar to the one dose efficacy of the Moderna vaccine (92.1%).

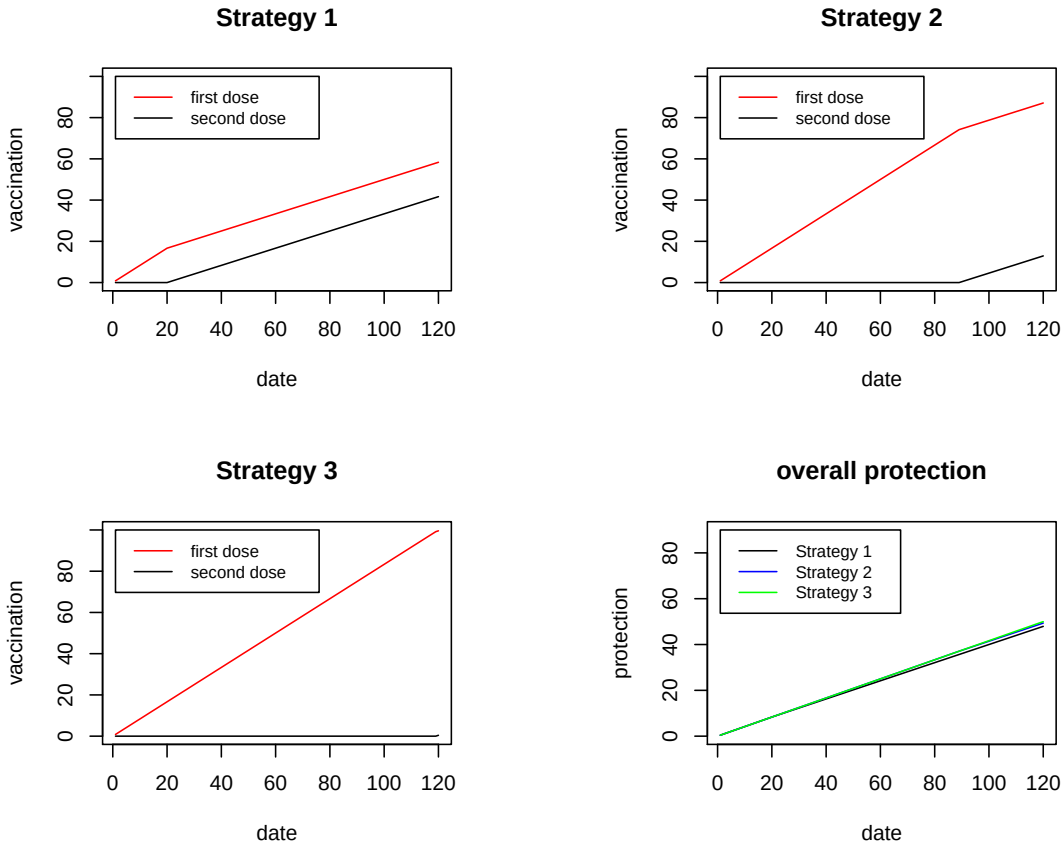
Figure 1: Vaccination strategies and overall protection over time - Case 1



dose. Another possibility is that one dose vaccine could provide stronger protection for people previously infected. Angyal *et al.* (2021) reported that previously infected healthcare workers in the UK showed strong immune responses after only one dose that are equivalent to responses of people receiving two doses with no past history. Similar findings are shown in two recent studies, Stamatatos *et al.* (2021) and Samanovic *et al.* (2021). In the latter study, the authors find that the second dose did not offer any additional antibody responses for individuals with prior exposure. This means that single dose vaccination can give full protection to a significant part of the population for countries with a large number of cumulative cases.

We also consider another thought experiment in which a country secures 100 doses per hundred and will be inoculating the vaccine stocks over 120 days. On top of the limited supply of vaccines, health care capacity is another constraint that limits the number of daily doses administered. We assume that the country's daily medical capacity allows to deliver 100/120 doses per hundred into its people's arms. Three vaccination strategies on the dosing interval are considered. In Strategy 1, the dosing interval is standard 3 weeks so the country delivers first doses from day 1 and starts to inoculate the second doses on day 21. From this time, the stocks

Figure 2: Vaccination strategies and overall protection over time - Case 2



are equally allocated to the first and second doses. In strategy 2 and 3, the dosing intervals are 3 months (90 days) and 4 months (120 days) respectively. We compute the overall protection levels under these strategies for Case 1 and Case 2 described in Table 1. As shown in Figures 1-2, longer dosing intervals help achieve higher protection levels in the given time period. It is obvious that Strategy 3 gives the best results in both cases followed by Strategy 2. The gaps between strategies shrink as the difference between the first and second dose vaccine efficacy increases.

In sum, there is scientific evidence in the medical literature from which one can expect the extending the dosing interval idea may work in practice. Allocating the available vaccine stocks to the first doses could help maximize the level of protection in the population given the limited supply. Furthermore, there might be healthcare capacity constraints. Focusing on the first doses by extending the interval between doses could also help reach a higher level of protection more quickly. Extending the dosing interval is particularly more effective when the first dose vaccine efficacy is not too much lower than the second dose efficacy. This could be the case in low income countries where a significant part of the population is previously infected. However, it

is still uncertain whether this strategy actually works in the real world setting. The previous studies rely on small scale experiments or simulations. Therefore, it is important to investigate the performances of different vaccination strategies using observable population level data across countries employing different vaccination strategies.

3 Empirical Analysis

3.1 Data

Our empirical analysis mainly relies on the country level epidemiological data from *Our World in Data* which is a collaborative project between the University of Oxford and *Global Change Data Lab*. The world-wide country level database on many aspects of the COVID-19 pandemic is in its GitHub repository (`https://github.com/owid/covid-19-data/tree/master/public/data`). We use the daily counts of new cases, total cumulative cases, new tests, total cumulative tests, vaccinated people with at least one dose per hundred, fully vaccinated people per hundred, total vaccine doses administered per hundred. For government policy responses, we employ Containment and Health Index developed by the Oxford COVID-19 Government Response Tracker (OxCGRT).[3] There are some missing values in this data set. We impute the missing values using linear interpolation for week days. If values in the weekends are missing, we take the previous value to impute the missing values. We also use the country level data from Google COVID-19 Community Mobility Reports to take people's behavioral responses into account. This data shows movement trends over time in each country across different categories of places compared to the baseline period (Jan 3 – Feb 6, 2020) before the pandemic. Following Karaivanov *et al.* (2021), we construct a mobility index by calculating the arithmetic average of three mobility ('retail', 'grocery and pharmacy', and 'workplace').

We use the period from June 1, 2020 to July 8, 2021 for our analysis. The first wave of the pandemic was almost over across most leading vaccination countries around the start date chosen. At the beginning of the pandemic, many countries did not have enough testing-tracing infrastructures so data would have missed a significant amount of infection cases. After the first wave, most countries well equipped with testing-tracing facilities as one can see from the substantially increased number of daily new tests. This period includes the up-to-date evolution of the pandemic and the wide spread of the Delta variant first identified in India is captured in some countries such as the UK and Israel.

We estimate time-series and panel data models to investigate the effects of vaccination on health outcomes controlling for policy and behavioral factors. In our time-series analysis, we

[3]This index is built upon OxCGRT's Stringency Index which is a composite measure based on nine policy response indicators including school closures, workplace closures, public event bans, restrictions on gatherings, public transit closure, public information campaigns, stay at home order, domestic and international travel bans rescaled to a value from 0 to 100 (100 = strictest). Containment and Health Index further in includes testing policy, contact tracing, face coverings, and vaccine availability. If policies vary at the sub-national level, the index is shown as the response level of the strictest sub-region.

use a sample of leading vaccination countries. We select eight nations, four of which (Canada, Israel, the US, and the UK) have used vaccine developed in the US and Europe and the others (Chile, Uruguay, UAE, and Bahrain) have heavily been reliant on vaccines produced by China.[4] These countries achieved highest vaccination rates in the world and relevant data are well kept in a daily frequency. Then we employ a larger panel of high income countries which includes OECD and EU members, Bahrain and Uruguay to further investigate the impact of vaccination exploiting both time-series and cross country variations.

We draw the trends in variables of primary interest (new confirmed cases per million, vaccination progress, Containment and Health Index, and the mobility index) in Figure 3 for eight selected leading countries we use in our time-series analysis. Among those countries mainly using mRNA-based vaccines, only Canada and the UK extended the dosing interval up to 12-16 weeks. The other two countries recommended the standard regimen (3-4 weeks, the US allowed up to a 6 week interval in an exceptional circumstance). As these countries adopted different vaccination strategies, the effectiveness of mass vaccination could vary across countries. As displayed in the upper four panels (Canada, Israel, the US, and the UK), the daily new cases per million (smoothed by a 7-day moving average) decreased as the vaccination program progressed. The government policy index responded to the spike of new cases. All the four countries eased restrictions as vaccination progressed and the case number declined. The mobility index showed the opposite trend to the case number as it dropped in line with the surge in new cases and recovered up as the case number decreased. It is not clear whether people's behavior responded to government restrictions or case numbers. Mass vaccination obviously leads to lower new infections but at the same time government restrictions are eased and people's mobility and interactions increase. Therefore, the estimated effects of vaccination on new infections are likely to be attenuated if policy and behavioral factors are not taken into account.

Different trends were observed in the lower four panels (Chile, Uruguay, UAE, and Bahrain). These countries have heavily relied on vaccines from China. These countries experienced the surge of new cases while mass vaccination continued through the period at a steady pace in both doses. Declines in the growth of new cases were seen only after very high vaccination rates were achieved as well as stronger restrictions were implemented. These trends cast doubts on the effectiveness of Chinese vaccines. Mobility and policy indexes responded to new cases similarly to the way in the other countries in upper four panels. It may suggest that countries relying on vaccines from China have to employ a different dosing strategy.

[4]Canada, Israel and the US rely on mRNA-based vaccines (Pfizer-BioNTech and Moderna) to inoculate most of the population (all for Israel). The UK has used both mRNA-based vaccines and the Astrazeneca-Oxford vaccine. Chile, Uruguay, UAE and Bahrain have vaccinated a significant part of the population with vaccines from China. According to Our World in Data, As of July 8, 2021, Chile administered 76.3% of its total doses with Chinese vaccines (17.72 million doses of Sinovac and 0.47 million doses of CanSino out of total 23.93 million doses) and Uruguay's share of Sinovac is 73.6% (3.12 million doses of Sinovac out of total 4.24 million doses). UAE and Bahrain also inoculated a majority of the population using the Sinopharm vaccine, yet the exact numbers are not publicly available.

Figure 3: Trends in new cases, vaccination, policy and mobility indexes

Note: UAE does not publicly report daily numbers of first and second doses administered until early July, 2021.

3.2 Time series analysis

We select eight leading countries in mass vaccination (Canada, Israel, the US, the UK, Chile, Uruguay, UAE, and Bahrain) and analyze the evolution of COVID-19 transmission using a standard time-series econometric framework. We estimate ARIMA models with exogenous variables (ARIMAX) to estimate the effect of first and second doses on new infections. The outcome variable is log of daily new cases. The number of people vaccinated per hundred (at least one dose given) and the number of people fully vaccinated per hundred are included exogenous variables that are of primary interest. To control for test intensity and the weekend effect, log of the number of new tests and a weekend dummy are also included.[5] Government policies and people's behavioral changes in line with policies and the evolution of the pandemic are also taken into account by including OxCGRT Containment and Health Index and the mobility index from Google Community Mobility Reports.

As vaccination and other policy and behavioral responses do not immediately affect the infections, it is important to choose appropriate lags for exogenous variables in the ARIMAX models. For first and second vaccine doses, we choose 21-day and 7-day lags respectively. These lags are chosen based on scientific evidence from clinical trials and real world outcomes. The first dose of approved vaccines begins to provide substantial protection against infection after 2-3 weeks and at least 14 days are required to see protection starts (see National Advisory Committee on Immunization (2021) for a detailed survey and Hunter and Brainard (2021) for evidence from Israel on the Pfizer-BioNTech vaccine where the estimated vaccine effectiveness reached its peak at day 21 after the first dose). 7 days after the second dose, the vaccine efficacy further enhances as shown in Polack *et al.* (2020) and clinical trials. Medical studies such as Hall *et al.* (2021) also used 21-day and 7-day thresholds for the first and second dose respectively to evaluate the vaccine effectiveness. 14-day lags are chosen for the government policy index and the mobility index as the same lags are used in Chernozhukov *et al.* (2021) and Karaivanov *et al.* (2021) after careful investigations.

The order (p, d, q) of the ARIMAX model is selected by R's `forecast` package (Hyndman *et al.* (2020)) in which the command `auto.arima` chooses the optimal order based on various criteria while ensuring that the chosen model numerically well-behaves. The outcome variable for each country becomes stationary after the first difference so the order d is set at 1. Note that all the exogenous variables are also first differenced in the estimation procedure. The econometric model we estimate is

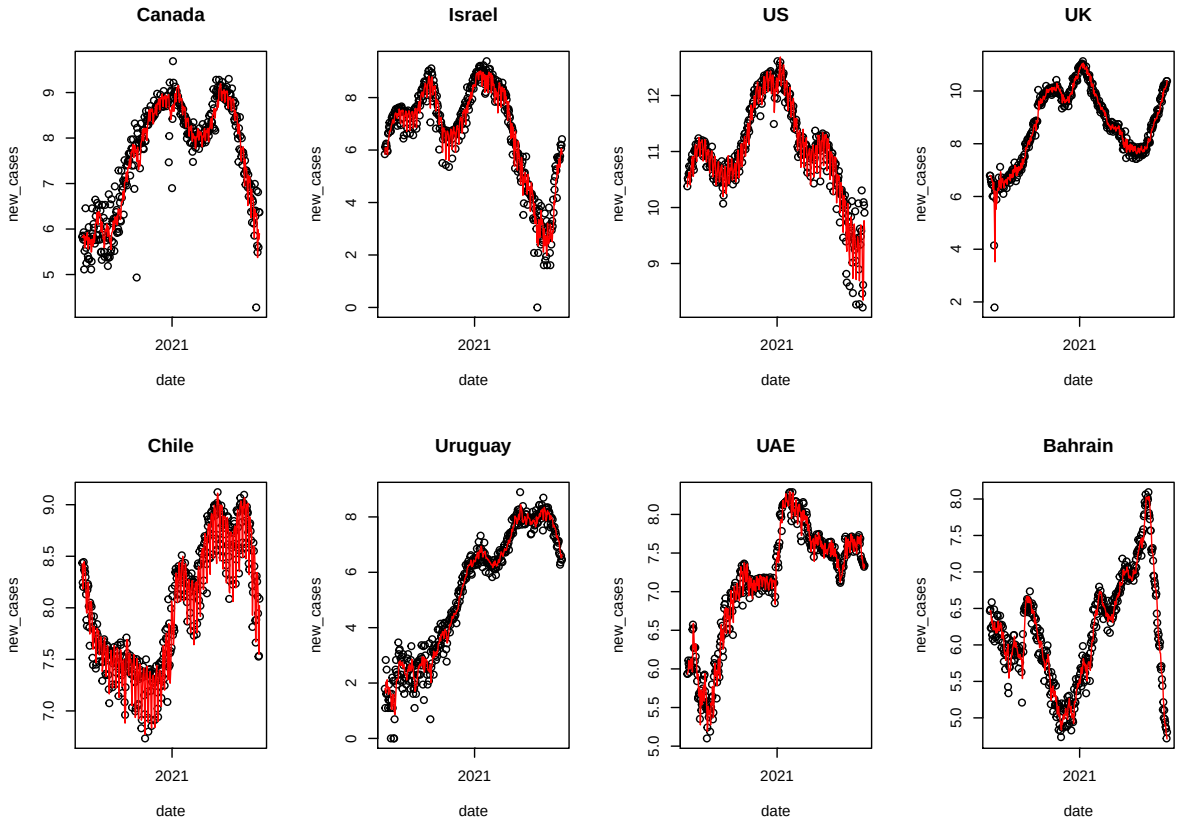
$$\Delta \log Y_t = c + \beta_1 \Delta V1_{t-21} + \beta_2 \Delta V2_{t-7} + \beta_3 \Delta \log T_t + wkd_t + \Delta P_{t-14} + \Delta M_{t-14} + n_t, \quad (1)$$

$$n_t = \sum_{i=1}^{p} \phi_i n_{t-i} + \varepsilon_t - \sum_{i=1}^{q} \theta_i \varepsilon_{t-i}, \quad (2)$$

where Y_t is daily new cases, $V1_t$ is population vaccinated with at least one dose per hundred, $V2_t$ is population fully vaccinated per hundred, T_t is log daily new tests, wkd_t is a weekend dummy,

[5] For Israel, UAE and Bahrain, the weekend dummy takes 1 if the days are either Friday or Saturday. For the other countries, the dummy variable equals 1 when the days are either Saturday or Sunday.

Figure 4: Daily new cases and fitted values



Note: The dots are logs of the numbers of daily new cases. The red solid lines are fitted values by selected ARIMAX models.

P_t is OxCGRT Containment and Health Index, and M_t is the mobility index. There certainly is day-to-day noise in the data but the selected ARIMAX models fit this daily fluctuation very well as shown in Figure 4. Note that Israel, the US, Chile and Uruguay exhibit very strong correlation between $V1_t$ and $V2_t$. The correlation coefficients are over 0.99 which means the estimates are likely suffer from the multicollinearity problem. To avoid this issue, we also estimate models with the number of total dose administered per hundred instead of first and second dose roll-outs for these countries. UAE does not provide daily vaccination progress so the same treatment is applied as well. The resulting regression residuals are all mean-zero stationary processes.

The estimation results are displayed in Table 2-3. For the countries that mainly vaccinate their populations with widely approved vaccines developed in the US and Europe, the progress in vaccination is negatively associated with the growth of new cases. It is noticeable that the share of people vaccinated with at least one dose has particularly large negative effects on the spread of COVID-19 for Canada and the UK. A 1% increase of the share of vaccinated people with at least one dose leads to around 6.2% and 8.6% reductions in the daily growth of new cases respectively. The two countries adopted longer dosing intervals between two doses. In both countries, the

Table 2: ARIMA(p, d, q) model estimation results

	Canada	Israel	US	UK
(p, d, q)	$(2, 1, 3)$	$(5, 1, 3)$	$(3, 1, 3)$	$(2, 1, 1)$
weekend	-0.104^{***}	-0.135^{***}	0.007	-0.101^{***}
	(0.031)	(0.044)	(0.009)	(0.037)
new_tests	0.060	0.557^{***}	0.826^{***}	0.0004
	(0.048)	(0.057)	(0.057)	(0.061)
first_dose	-0.062^{***}	-0.041	-0.018	-0.086^{***}
	(0.018)	(0.043)	(0.041)	(0.032)
second_dose	-0.011	-0.006	-0.020	0.040
	(0.020)	(0.045)	(0.046)	(0.033)
policy	-0.031^{**}	-0.006	0.014^{*}	0.004
	(0.014)	(0.005)	(0.007)	(0.013)
mobility	0.004	0.005	0.008	0.018
	(0.007)	(0.008)	(0.007)	(0.011)

Note: Standard errors are in parentheses. *p<0.1; **p<0.05; ***p<0.01

effect of the share of fully vaccinated people is not significant. The results are indicative of the success of their delaying strategy. For Israel and the US where the standard dosing schedule is followed, insignificant negative association between first dose vaccination progress and new infections is found. Second dose progress is also insignificant. However, the alternative models with total dose per hundred give significant negative coefficients on total dose administered for both countries. In Israel, one more dose administered per hundred leads to a 3.9% reduction in new cases. In the US, one more dose administered per hundred leads to a 0.5% reduction in new infections. This may be due to the slower vaccine roll-out as vaccine hesitancy has prevailed and persisted in the US.

The weekend dummy is in general negatively associated with new infections, whereas the number of new tests is positively associated. The government policy index and the mobility index are not significant, though the signs of their coefficients are generally consistent with expected directions.

Table 3: ARIMA(p, d, q) model estimation results

	Chile	Uruguay	UAE	Bahrain
(p, d, q)	$(2, 1, 4)$	$(2, 1, 2)$	$(0, 1, 3)$	$(1, 1, 2)$
weekend	-0.074^{***}	-0.242^{***}	-0.014	-0.032^{**}
	(0.010)	(0.040)	(0.017)	(0.014)
new_tests	0.686^{***}	0.004	0.189^{***}	0.001
	(0.017)	(0.005)	(0.039)	(0.003)
first_dose	0.011	-0.020		-0.020
	(0.010)	(0.035)		(0.023)
second_dose	-0.008	-0.041		-0.012
	(0.010)	(0.040)		(0.010)
total_dose			-0.013^{**}	
			(0.006)	
policy	-0.007	0.012	0.011	0.009
	(0.004)	(0.010)	(0.007)	(0.007)
mobility	0.004^{*}	-0.003	-0.006	-0.011
	(0.002)	(0.011)	(0.013)	(0.012)

Note: Standard errors are in parentheses. *p<0.1; **p<0.05; ***p<0.01

On the contrary, the results are mixed for the countries relying on vaccines from China. The effects of vaccination progress are in general negative but not significant when both $V1$ and $V2$ are included. This may be due to highly correlated trends in first and second dose roll-outs. Significant negative effects are found in Uruguay and UAE when the total dose administered per hundred is included instead of $V1$ and $V2$. One dose per hundred increase leads to 3.2% and 1.3% reductions in Uruguay and UAE respectively. These countries already vaccinated a significant part of the population (as of July 8, 2021, the shares of fully vaccinated people are UAE 65%, Chile 58.8%, Uruguay 54.7% Bahrain 59.6%). These results are in line with the evidence from clinical trials that these vaccines have a lower vaccine efficacy than mRNA-based

counterparts and the AstraZeneca-Oxford vaccine.[6]

Our results from time-series analysis suggest that extending the interval between first and second doses can be an effective strategy for the vaccines developed in the US and Europe. Larger negative effects of vaccination progress are found in the countries adopting this strategy. It is not clear whether this strategy works for vaccines from China. As shown in the clinical trials, these vaccines have a lower vaccine efficacy even with two doses than a single dose of mRNA-based vaccines. Therefore, it is likely not a more effective strategy so countries relying on these vaccines should be focusing on fully vaccinating the population.

We so far only exploit variations in vaccination progress over time. The purpose of estimating time-series models is to obtain some descriptive evidence how the choice of the dosing interval and types of vaccines matter to contain the spread of COVID-19. To investigate causal relationships between vaccination and new infections, we will further exploit cross-country variations in vaccination, policies and mobility using a large country panel.

3.3 Panel Data Analysis

We use OECD and EU member countries to construct our country panel, adding Bahrain and Uruguay in order to examine the effect of vaccines from China. Countries that do not publish daily COVID-19 related statistics are excluded. In total, there are 37 countries in our data set.[7] We closely follow the estimation strategies used in Chernozhukov *et al.* (2021) and Karaivanov *et al.* (2021). Let C_{it} denote the cumulative number of confirmed cases in country i at time t. We define ΔC_{it} as the 7-day new COVID-19 cases reported at time t:

$$\Delta C_{it} := C_{it} - C_{i,t-7}, \tag{3}$$

where Δ denotes the difference operator over a week between t and $t-7$. Our dependent variable

$$Y_{it}^{C} = \Delta \log(\Delta C_{it}) = \log(\Delta C_{it}) - \log(\Delta C_{i,t-7}) \tag{4}$$

approximates the weekly growth rates in new cases in country i from $t-7$ to t. Similarly, we denote $\Delta \log(\Delta T_{it})$ as the 7-day growth rates in new tests with the cumulative number of tests, T_{it}.

To analyze the impact of first and second dose vaccination, government policy responses, and people's behavioral changes on Y_{it}^{C}, we estimate

$$\begin{aligned} Y_{it}^{C} &= \alpha_{0i} + \alpha_{V1} V1_{i,t-21} + \alpha_{V2} V2_{i,t-7} + \alpha_{P} P_{i,t-14} + \alpha_{M} M_{i,t-14} \\ &\quad + \alpha_{C1} \Delta \log(\Delta C_{i,t-14}) + \alpha_{C2} \log(\Delta C_{i,t-14}) + \alpha_{T} \Delta \log(\Delta T_{it}) + \varepsilon_{it}^{C}, \end{aligned} \tag{5}$$

[6]World Health Organization (WHO) approved the Sinovac vaccine for emergency use and stated that the vaccine efficacy of this vaccine is 51% for symptomatic infection.

[7]Included countries are Australia, Austria, Belgium, Bulgaria, Bahrain, Canada, Switzerland, Chile, Colombia, Germany, Denmark, Spain, Estonia, Finland, France, the UK, Greece, Croatia, Hungary, Israel, Italy, Japan, South Korea, Lithuania, Luxembourg, Latvia, Mexico, Malta, Norway, New Zealand, Poland, Portugal, Romania, Slovenia, Turkey Uruguay, and the US.

where $V1_{it}$ is the number of people vaccinated with at least one dose per hundred, $V2_{it}$ is the number of fully vaccinated people per hundred, P_{it} and M_{it} are policy and behavioral variables. We use the same lag specifications for the exogenous variables as in our time series analysis. For deaths growth as the outcome, $Y_{it}^D = \Delta \log(\Delta D_{it})$, we use the lags 14 days behind those in the case equation:

$$\begin{aligned} Y_{it}^D &= \beta_{0i} + \beta_{V1} V1_{i,t-35} + \beta_{V2} V2_{i,t-21} + \beta_P P_{i,t-28} + \beta_M M_{i,t-28} \\ &\quad + \beta_{D1} \Delta \log(\Delta D_{i,t-28}) + \beta_{D2} \log(\Delta D_{i,t-28}) + \varepsilon_{it}^D, \end{aligned} \tag{6}$$

following Karaivanov *et al.* (2021).

Our regression equations are motivated by a variant of the SIRD model introduced in Chernozhukov *et al.* (2021) where new infections are only partially detected via testing. Let S, I, R and D denote the numbers of susceptible, infected, recovered, and deceased individuals in a given state. Each of these variables is a function of time. We modify the model by adding vaccination factors, $V1$ and $V2$. We assume that vaccinated individuals obtain immunity against infection at the rates δ_1 and δ_2 from the first and second doses, with which they exit the susceptible class and enter the recovered class. The laws of motion for these variables are specified as

$$\begin{aligned} \dot{S}(t) &= -\left(\delta_1 \dot{V1}(t-21) + (\delta_2 - \delta_1)\dot{V2}(t-7)\right) - \frac{S(t)}{N}\beta(t) I(t) \\ \dot{I}(t) &= \frac{S(t)}{N}\beta(t) I(t) - \gamma I(t), \\ \dot{R}(t) &= (1-\kappa)\gamma I(t) + \left(\delta_1 \dot{V1}(t-21) + (\delta_2 - \delta_1)\dot{V2}(t-7)\right), \\ \dot{D}(t) &= \kappa\gamma I(t), \end{aligned}$$

where N is the population, $\beta(t)$ is the rate of infection spread between $S_{t-\ell}$ and $I_{t-\ell}$, γ is the rate of recovery or death, and κ is the probability of death conditional on infection. The total number of confirmed cases, C_t, evolves as

$$\dot{C}(t) = \tau(t) I(t) \left(= \frac{\tau(t)}{\kappa\gamma}\dot{D}(t)\right),$$

where $\tau_j(t)$ is the rate that infections are detected. Note that we only observed $C(t)$ and $D(t)$, but not $I(t)$. The unobserved $I(t)$ can be eliminated in two ways:

$$\frac{\ddot{C}(t)}{\dot{C}(t)} = \frac{S(t)}{N}\beta(t) - \gamma + \frac{\dot{\tau}(t)}{\tau(t)}, \quad \frac{\ddot{D}(t)}{\dot{D}(t)} = \frac{S(t)}{N}\beta(t) - \gamma.$$

We note that the rate of infection, $\beta(t)$, can be affected by individual behavior and observed policies through social distancing and lockdown. We specify $\frac{S(t)}{N}\beta(t)$ as a linear function of vaccinations, policy, behavioral, information, and confounders other than testing.

We estimate our regression equations with country fixed effects to account for country-specific heterogeneity. We do not include week or month fixed effects as each country experienced heterogeneous evolution of the pandemic. Including country-specific time fixed effects results in

Table 4: The direct effect of behavior, policy, and vaccinations on confirmed cases

	Dependent variable: $\Delta \log \Delta C_t$			
	(1)	(2)	(3)	(4)
$\Delta \log \Delta C_{t-14}$	0.1102***	0.1056**	0.0901**	0.0908**
	(0.0395)	(0.0394)	(0.0350)	(0.0343)
$\log \Delta C_{t-14}$	-0.0374***	-0.0403***	-0.1496***	-0.1509***
	(0.0077)	(0.0077)	(0.0214)	(0.0214)
$V_{1,t-21}$	-0.0074***	-0.0077***	-0.0173***	-0.0185***
	(0.0021)	(0.0022)	(0.0043)	(0.0041)
$V_{2,t-7}$	0.0029	0.0024	0.0038	0.0066
	(0.0025)	(0.0029)	(0.0057)	(0.0064)
$V_{1,t-21}^{CHN}$		0.0149***		0.0108
		(0.0033)		(0.0087)
$V_{2,t-7}^{CHN}$		-0.0138***		-0.0180**
		(0.0042)		(0.0074)
P_{t-14}	-0.0020	-0.0019	-0.0027*	-0.0027*
	(0.0012)	(0.0013)	(0.0015)	(0.0015)
M_{t-14}	0.0052***	0.0053***	0.0101***	0.0098***
	(0.0012)	(0.0012)	(0.0014)	(0.0013)
$\Delta \log \Delta T_t$	0.5094***	0.5064***	0.4090***	0.4079***
	(0.1775)	(0.1767)	(0.1499)	(0.1496)
Country fixed effects	yes	yes	yes	yes
Country specific trend in days	no	no	quadratic	quadratic
R^2	0.2838	0.2868	0.3987	0.3999
Adjusted R^2	0.2834	0.2864	0.3953	0.3964
Number of countries	37	37	37	37
Obs. per country	382	382	382	382

Note: Standard errors in parentheses are clustered at the country level.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 5: The direct effect of behavior, policy, and vaccinations on deaths

	Dependent variable: $\Delta \log \Delta D_t$			
	(1)	(2)	(3)	(4)
$\Delta \log \Delta D_{t-28}$	0.0584**	0.0560*	0.0574**	0.0567**
	(0.0281)	(0.0280)	(0.0258)	(0.0259)
$\log \Delta D_{t-28}$	-0.0429***	-0.0479***	-0.1308***	-0.1308***
	(0.0096)	(0.0085)	(0.0112)	(0.0112)
$V_{1,t-35}$	-0.0096***	-0.0093***	-0.0125***	-0.0132***
	(0.0021)	(0.0023)	(0.0040)	(0.0041)
$V_{2,t-21}$	0.0036	0.0014	0.0040	0.0061
	(0.0029)	(0.0033)	(0.0043)	(0.0046)
$V^{CHN}_{1,t-35}$		0.0169***		0.0045
		(0.0034)		(0.0076)
$V^{CHN}_{2,t-21}$		-0.0116**		-0.0097
		(0.0050)		(0.0059)
P_{t-28}	-0.0008	-0.0005	-0.0013	-0.0013
	(0.0014)	(0.0015)	(0.0013)	(0.0013)
M_{t-28}	0.0057***	0.0057***	0.0077***	0.0075***
	(0.0016)	(0.0015)	(0.0016)	(0.0015)
Country fixed effects	yes	yes	yes	yes
Country specific trend in days	no	no	quadratic	quadratic
R^2	0.0966	0.1016	0.1747	0.1749
Adjusted R^2	0.0962	0.1010	0.1698	0.1699
Number of countries	37	37	37	37
Obs. per country	368	368	368	368

Note: Standard errors in parentheses are clustered at the country level.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

too many parameters to estimate, which lead to imprecise estimates. Instead, country-specific time trends are included to control for heterogeneous trends across countries. We consider quadratic time trends as a baseline specification. Alternative specifications (linear and cubic time trends) are also considered and our main findings hold under those specifications as shown in Appendix A. To examine the potentially distinct effects of vaccines from China, we add a Chinese vaccine dummy for Chile, Uruguay, Turkey and Bahrain.[8] The results are displayed in Tables 4-5 for new infections and deaths respectively. It is notable that first dose vaccination progress is significantly negatively associated with the weekly growth rates of new infections and deaths at the 99% confidence level across all the specifications considered. With no time trends, the estimates suggest that a 1% increase in the share of vaccinated people with at least one dose leads to around 0.77% reduction in the weekly case growth rate and around 0.93% reduction in the weekly death growth rate. When quadratic time trends are included, the magnitudes of first does vaccination estimates expand to 1.85% and 1.32% for new cases and deaths respectively and still highly significant. Second dose vaccination progress is not significantly different from 0 for both health outcomes. On the contrary, first dose progress in countries relying on Chinese vaccines is not effective for reducing both case and death counts. Only full vaccination progress leads to significant but smaller reductions in new cases and deaths but this effect disappears for deaths when quadratic time trends are controlled for. These findings are in line with those found in our time-series analysis.

The signs and magnitudes of the other coefficient estimates are in general very consistent across the specifications. It is obvious to see that the weekly growth rate of new tests is positively related to the growth of new cases. Government policies are negatively associated with weekly case growth rate, whereas the mobility index is positively associated with both cases and deaths. Note that government policy and mobility indexes are insignificant in our time series analysis for each country. These factors are now significant when time trends are taken into account because we further exploit the cross-country variations in government policies and people's behavioral changes. Our results mean that less stringent policy measures and more mobile people can be translated into a higher $\beta(t)$ in the SIRD model, which results in more cases and deaths.

We also examine how the evolution of pandemic, policies and vaccination affect people's mobility which is related to social distancing behaviors by estimating the following equation:

$$\begin{aligned} M_{it} &= \gamma_{0i} + \gamma_M M_{i,t-7} + \gamma_{dC}\Delta \log \Delta C_{it} + \gamma_C \log \Delta C_{it} + \gamma_{d1}\Delta V1_{it} + \gamma_{d2}\Delta V2_{it} \\ &\quad + \gamma_1 V1_{i,t-7} + \gamma_2 V2_{i,t-7} + \gamma_{dP}\Delta P_{it} + \gamma_P P_{i,t-7} + \varepsilon_{it}^{Mob}. \end{aligned} \tag{7}$$

This regression equation includes the weekly case growth rate and the number of weekly new infections as information variables. We estimate the regression coefficients using many different specifications, all of which include country fixed effects. Time trends are omitted as they are in

[8] Turkey stared its mass vaccination program using the Sinovac vaccine from China. According to Bridge Beijing (https://bridgebeijing.com/), Turkey has received 31.4 million doses of the Sinovac vaccine as of Sep 6, 2021. Turkey shifted to the Pfizer-BioNTech vaccine as the delivery of the Sinovac doses kept delayed but until Jul 8, 2021, the Sinovac vaccine accounted for more than a half of total inoculated vaccine doses.

Table 6: The direct effect of behavior, policy, and vaccinations on mobility

	Dependent variable: M_t			
	(1)	(2)	(3)	(4)
M_{t-7}	0.7635***	0.7637***	0.7469***	0.7472***
	(0.0220)	(0.0219)	(0.0239)	(0.0239)
$\Delta \log \Delta C_t$	0.4354*	0.4702*		
	(0.2520)	(0.2560)		
$\log \Delta C_t$	-0.7026***	-0.6950***		
	(0.0849)	(0.0924)		
$\Delta \log \Delta D_t$			-0.0742	-0.0624
			(0.1715)	(0.1717)
$\log \Delta D_t$			-0.8039***	-0.7976***
			(0.1150)	(0.1211)
ΔV_{1t}	0.5839***	0.6642***	0.5260***	0.5937***
	(0.1260)	(0.1623)	(0.1266)	(0.1636)
ΔV_{2t}	0.2641*	0.3941**	0.3033**	0.4396**
	(0.1316)	(0.1636)	(0.1439)	(0.1865)
$V_{1,t-7}$	0.0494	0.0314	0.0377	0.0204
	(0.0324)	(0.0372)	(0.0318)	(0.0373)
$V_{2,t-7}$	-0.0084	0.0032	0.0120	0.0220
	(0.0349)	(0.0379)	(0.0315)	(0.0346)
ΔV_{1t}^{CHN}		-0.3956*		-0.3474
		(0.2144)		(0.2233)
ΔV_{2t}^{CHN}		-0.4834*		-0.5110*
		(0.2568)		(0.2762)
$V_{1,t-7}^{CHN}$		0.0693		0.0736
		(0.0676)		(0.0641)
$V_{2,t-7}^{CHN}$		-0.0380		-0.0414
		(0.0742)		(0.0652)
ΔP_t	-0.3450***	-0.3464***	-0.3583***	-0.3590***
	(0.0449)	(0.0448)	(0.0428)	(0.0428)
P_{t-7}	-0.1120***	-0.1141***	-0.1028***	-0.1049***
	(0.0173)	(0.0175)	(0.0174)	(0.0175)
Country fixed effects	yes	yes	yes	yes
Time effects	no	no	no	no
R^2	0.8363	0.8367	0.8366	0.8369
Adjusted R^2	0.8362	0.8366	0.8365	0.8368
Number of countries	37	37	37	37
Obs. per country	396	396	396	396

Note: Standard errors in parentheses are clustered at the country level.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

general insignificant (Results with country specific linear time trends are provided in Appendix A). In an alternative specification, we replace the weekly case number and growth rate with the weekly death counts and growth rates. Table 6 displays the estimation results. Most explanatory variables are highly significant across all the specifications. The values of R-squared are close to 0.84 for all the specifications. Our results imply that vaccination and government policies have large effects on people's behaviors. Weekly progresses in first dose and second dose vaccination lead to large observed increase in people's mobility. When the weekly case counts, weekly case growth rates, and the Chinese vaccine dummy are included, a 1% weekly growths in first dose and second dose vaccination increase the mobility index by 0.66 and 0.39 respectively. These results are consistent with findings in Andersson *et al.* (forthcoming). Using Swedish survey data collected before vaccination launched (Dec 10-13, 2020), they show that providing vaccine information, such as the safety, effectiveness, and availability, reduces peoples' voluntary social distancing. On the other hand, more stringent government responses lead to a substantial reduction in people's mobility. Information also matters as people's mobility is negatively associated with both weekly growths and counts of new infections and deaths. The magnitudes of estimates for the weekly growth and counts of deaths are larger than those for new cases. This indicates that people responded more sensitively to new death counts than new case numbers, which conforms to Chernozhukov *et al.* (2021). Interestingly, no significant increases in mobility due to vaccination are observed in countries relying on vaccines from China. This may be related to the perceived credibility of the effectiveness of those vaccines.

The magnitudes of vaccination and policy effects are not very sensitive whether or not we include cases or deaths as information variables and across different specifications. As we show in Tables 4-5, people's mobility in the past is significantly positively associated with new infections and deaths. Therefore, there is an indirect effect of vaccination, which offsets the direct effect of vaccination on the transmission of COVID-19 by inducing people to be more mobile. Many leading countries have loosened public health measures amid high vaccination rates. Our findings imply that this could be a risky move as loosened restrictions and vaccination progress collectively pushes mobility up. Public health measures are still a key to containing the spread of the virus by restraining people's mobility and social interactions.

4 Robustness checks

4.1 Variants of Concerns

Each country suffers from different variants of concerns some of which are known to be more easily transmitted and more fatal. We try to control for this by using country fixed effects and country specific time trends. With or without time trends, our estimates remain with the same signs across different model specifications. In the period of our analysis, a number of countries such as the UK and Israel experienced another wave due to the Delta variant. When we exclude the period the new wave, the estimates still remain very similar. As the Delta variant

is becoming the most dominant variant in many countries, there may be a structural break in the evolution of the pandemic. The period after the rise of the Delta variant is an avenue of future research. As far as a single dose of approved vaccines is still highly effective against the variant (although somewhat weaker than against the original strain), the policy implications drawn from our findings can be valid. The evidence on single dose effectiveness of approve vaccines against symptomatic infection is mixed in the recent literature. Lopez Bernal *et al.* (2021) report that one dose effectiveness against the Delta variant is much lower for Pfizer-BioNtech (35.6%) and AstraZeneca-Oxford vaccines (30%) than the effectiveness with two doses (Pfizer-BioNtech: 88%, AstraZeneca-Oxford: 67%) using data from England. On the contrary, Nasreen *et al.* (2021) find much higher vaccine effectiveness with one dose against the Delta variant (Pfizer-BioNtech: 56%, Moderna: 72%, AstraZeneca-Oxford: 67%) using Canadian data.

One reason why the single dose effectiveness differs in the two countries would be the numbers of cumulative cases. The total case number in the UK is much higher than that in Canada. As researchers of US CDC suggest in Reese *et al.* (2021), there is a significant of proportion of actual infections that was undetected.[9] Therefore, a much larger portion of unvaccinated population in the UK is likely to have prior exposure than Canada. People who have been infected developed natural protection against the virus so comparing the vaccinated to a more immune control group may have resulted in the lower single dose vaccine effectiveness in the UK. For unvaccinated individuals with no previous infection, it may be still the case that one dose vaccination provides substantial protection against the Delta variant. Furthermore, vaccine effectiveness against severe illness (hospitalization or death) caused by the Delta variant is shown to be much higher than for symptomatic infection after partial vaccination. Nasreen *et al.* (2021) estimate that vaccine effectiveness against severe outcomes after single dose inoculation of Pfizer-BioNTech, Moderna, and AstraZeneca-Oxford vaccines was 78%, 96%, and 88% respectively. A technical report by Public Health England (Stowe *et al.* (2021)) also strongly agrees with the Canadian results on vaccine effectiveness against hospitalization, which was 94% for the Pfizer-BioNTech vaccine and 71% for the AstraZeneca-Oxford vaccine only after dose 1. This implies that maximizing the number of at least partially vaccinated people is an effective strategy to prevent worse health outcomes, which are of primary policy interest.

4.2 Alternative lags

We conduct sensitivity analysis with different lag specifications for vaccination centered around the baseline lags of 21 and 7 days for first dose and second dose progress respectively. In the alternative specifications, we use the baseline lags $\pm\, d$ ($d = 1, 2, 3$), for both vaccination variables. The results are provided in Figures 5-6. All the estimates across the alternative lag specifications are consistent with our baseline findings. The magnitudes of estimates slightly vary with lags and the coefficient estimates of first dose progress always remain highly significant. The effect of the share of vaccinated people with at least one dose becomes slightly larger when the lag

[9] Reese *et al.* (2021) estimate that only 1 of every 7.1 non-hospitalized illness might have been detected.

employed is longer. Full vaccination progress is insignificant with all the alternative lags. The effects of vaccines from China are not sensitive to the lag specifications.

4.3 Alternative periods

We also estimate our regression coefficients for alternative initial and end dates. Firstly, we change the initial date from June 1 to July 1, 2020 so that the first month in the full period is omitted. During the omitted period, the cases numbers were stable in many countries. Secondly, we exclude the data after May 31, 2021 from the full period. In the omitted period, some countries experienced a surge in new cases due to the spread of the Delta variant. The results are reported in Table 7. In the first sub-period (July 1, 2020 - July 8, 2021), the coefficients estimates remain very similar to Table 4. The magnitude of the effect of first dose progress shrinks in the second sub-period (June 1, 2020 - May 31, 2021) but it is still negative and significant. It would be naturally the case because most countries in our sample did not achieve high vaccination rates to effectively contain the transmission until May 31, 2021.

4.4 Data frequency

A few countries (Costa Rica, Cyprus, Iceland, and the Netherlands) release key epidemiological variables in a weekly frequency. We re-estimate our regression coefficients by aggregating the daily level data to the weekly level to include these countries. In total 41 countries are included in our weekly country panel where Turkey is also considered as a country relying on Chinese vaccines. The results are almost identical to our findings in the daily frequency estimation in terms of the magnitudes and significance of coefficient estimates. We provide the results in Appendix B.

5 Counterfactual vaccine allocations

We use our estimates in Tables 4-5 to evaluate counterfactuals where the actual vaccine allocations between first and second doses are replaced by alternative hypothetical allocations. Saad-Roy *et al.* (2021) consider an immuno-epidemiological model with a continuous spectrum for interdose period between two vaccines, and find that delaying second vaccine doses is beneficial in the short term. In line with them, to investigate the effect of the spacing between doses, we assume that the total amount of available vaccines does not change:

$$V1_{it} + V2_{it} = V1^*_{it} + V2^*_{it},$$

where $V1^*_{it}$ and $V2^*_{it}$ are sequences of counterfactual first and second dose vaccination for country i. As the interdose period increases, spreading of first doses is faster.

We focus on Canada and the US for our counterfactual experiments as both countries have mainly relied on the mRNA-based vaccines but have used very different dosing intervals. When it comes to the US, we extend the dosing interval to 8 weeks resulting faster growth of first dose

Figure 5: Alternative lags for vaccination variables (with no time trends)

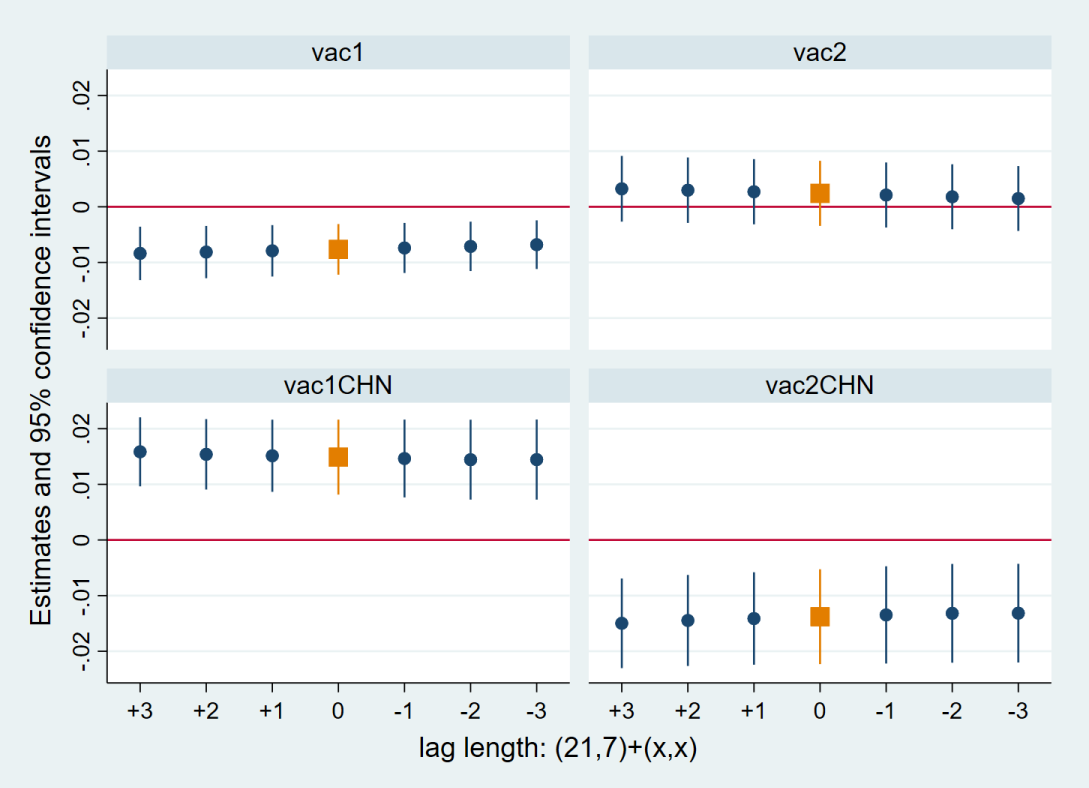


Figure 6: Alternative lags for vaccination variables (with cubic time trends)

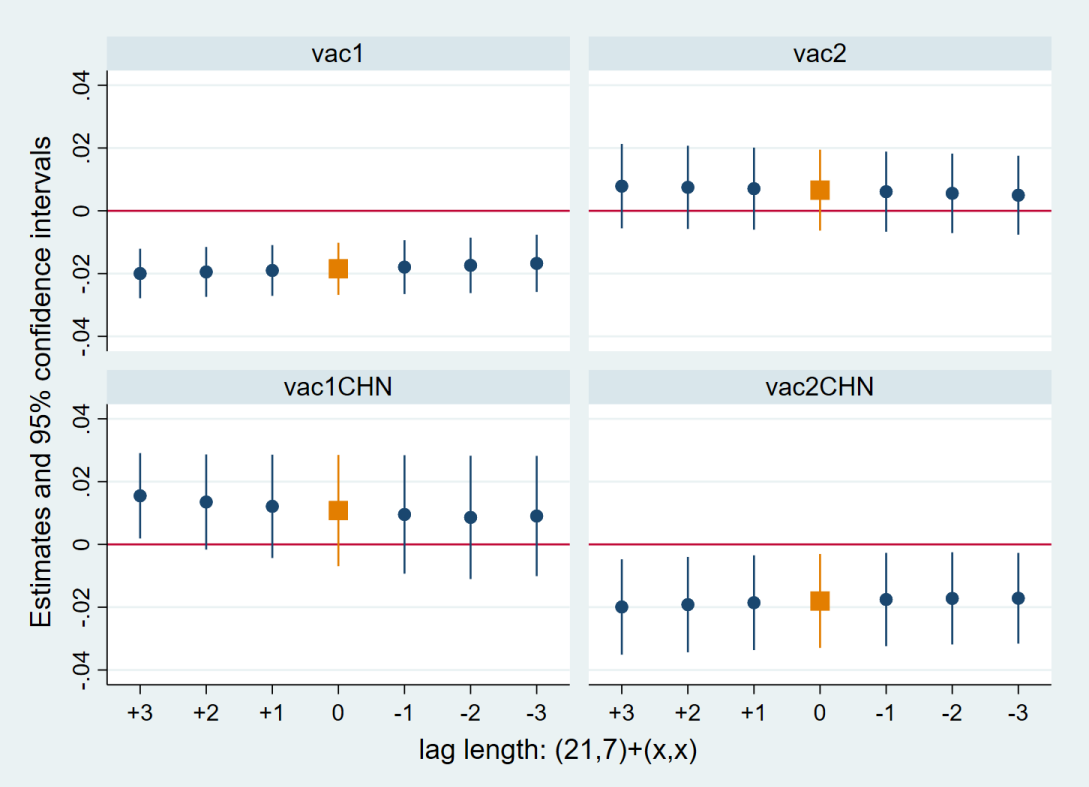


Table 7: Early and late sub-periods

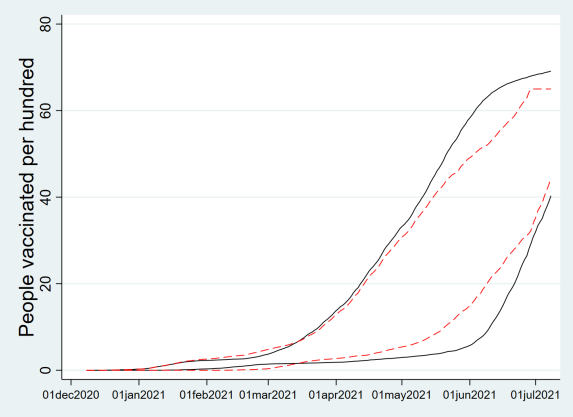
	Dependent variable: $\Delta \log \Delta C_t$			
	July 1, 2020 - July 8, 2021		June 1, 2020 - May 31, 2021	
$\Delta \log \Delta C_{t-14}$	0.0950***	0.0939***	0.0927**	0.0918**
	(0.0318)	(0.0318)	(0.0379)	(0.0376)
$\log \Delta C_{t-14}$	-0.1412***	-0.1412***	-0.1672***	-0.1665***
	(0.0204)	(0.0208)	(0.0210)	(0.0213)
$V_{1,t-21}$	-0.0164***	-0.0185***	-0.0132***	-0.0139***
	(0.0042)	(0.0041)	(0.0043)	(0.0049)
$V_{2,t-7}$	0.0035	0.0058	0.0006	0.0006
	(0.0055)	(0.0059)	(0.0038)	(0.0053)
$V^{CHN}_{1,t-21}$		0.0203***		0.0059
		(0.0055)		(0.0083)
$V^{CHN}_{2,t-7}$		-0.0199***		-0.0029
		(0.0067)		(0.0063)
P_{t-14}	-0.0031**	-0.0030**	-0.0027	-0.0027
	(0.0014)	(0.0015)	(0.0019)	(0.0019)
M_{t-14}	0.0106***	0.0106***	0.0104***	0.0105***
	(0.0012)	(0.0012)	(0.0012)	(0.0012)
$\Delta \log \Delta T_t$	0.3942**	0.3939**	0.3569**	0.3569**
	(0.1467)	(0.1467)	(0.1377)	(0.1376)
Country fixed effects	yes	yes	yes	yes
Quadratic time trends	yes	yes	yes	yes
R^2	0.4054	0.4067	0.3950	0.3951
Adjusted R^2	0.4018	0.4032	0.3911	0.3911
Number of countries	37	37	37	37
Obs. per country	373	373	344	344

Note: Standard errors in parentheses are clustered at the country level.

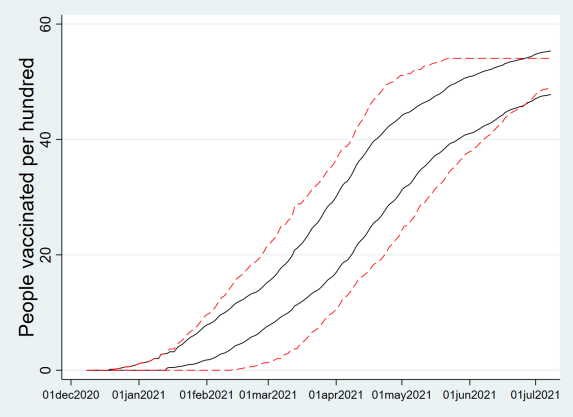
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Figure 7: Hypothetical vaccination rates (8 week dosing interval)

(a) Canada



(b) US



Note: Black solid lines are actual vaccination rates, the share of people vaccinated and the share of people fully vaccinated per hundred. Red dotted lines are hypothetical vaccination rates we consider in our counterfactual experiments.

vaccination. For Canada, we reduce the interval between two doses to 8 weeks. This means that first dose progress starts bending earlier and full vaccination progress grows more quickly than the actual data. Following the vaccination rates for two countries, we set the maximum rate of first dose vaccination to 65% for Canada and 55% for the US. The hypothetical sequences of vaccination rates are shown in Figure 7.

We compute the counterfactual outcomes using Equations (5)-(7) for new cases, deaths and mobility. We assume that government policies and all other variables remain fixed at their observed values in the data. As recent vaccination rates, case counts and growth affect people's behavior, we compute the counterfactual case growth and mobility iteratively conditional on the lagged values of counterfactual outcomes and the hypothetical sequences of vaccination allocations. Therefore, the information effects of counterfactual case and death counts and the indirect effects of vaccination via mobility are taken into account in such calculations. The 90% confidence bands are computed using simulations.

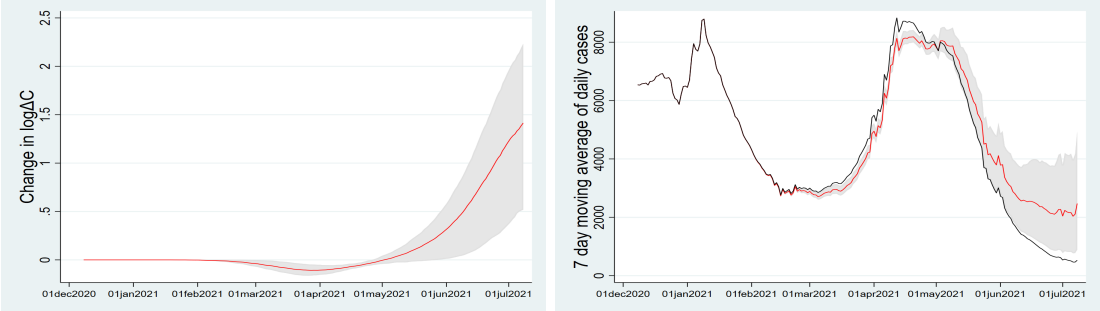
To compute counterfactual outcomes, Equations (7) and (5) are rewritten in terms of $\log \Delta C_{i,t}$:

$$\begin{aligned}
M_{i,t-14} =& \gamma_{0i} + \gamma_M M_{i,t-21} + (\gamma_{dC} + \gamma_C) \log \Delta C_{i,t-14} - \gamma_{dC} \log \Delta C_{i,t-21} \\
&+ \gamma_{d1} V1_{i,t-14} + \gamma_{d2} V2_{i,t-14} + (\gamma_1 - \gamma_{d1}) V1_{i,t-21} + (\gamma_2 - \gamma_{d2}) V2_{i,t-21} \\
&+ \gamma_{dP} P_{i,t-14} + (\gamma_P - \gamma_{dP}) P_{i,t-21} + \varepsilon^{Mob}_{i,t-14}, \\
\log \Delta C_{i,t} =& \log \Delta C_{i,t-7} + \alpha_{0i} + (\alpha_{C1} + \alpha_{C2}) \log (\Delta C_{i,t-14}) - \alpha_{C1} \log (\Delta C_{i,t-21}) \\
&+ \alpha_{V1} V1_{i,t-21} + \alpha_{V2} V2_{i,t-7} + \alpha_P P_{i,t-14} + \alpha_M M_{i,t-14} + \alpha_T \Delta \log (\Delta T_{it}) + \varepsilon^C_{it},
\end{aligned}$$

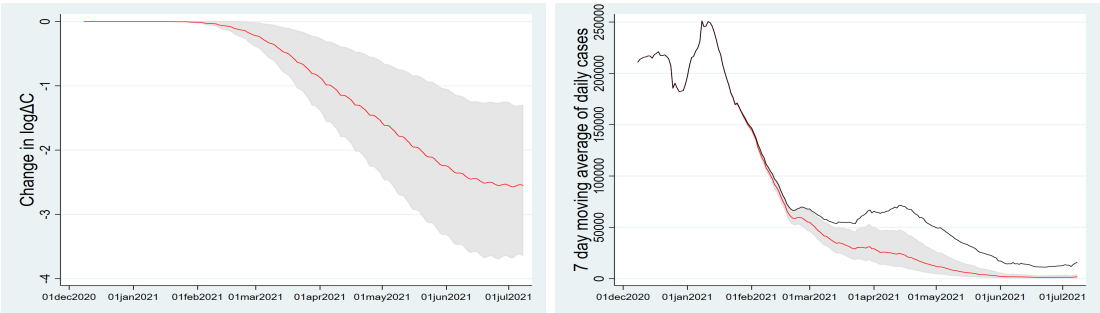
We use these two equations to iteratively compute counterfactual outcomes, $\{M^*_{i,t}\}$ and $\{\log \Delta C^*_{i,t}\}$, given $\{V^*_{1t}, V^*_{2t}\}$ and $\{P_{i,t}, \varepsilon^{Mob}_{i,t}\}$. We draw the parameters, $\tilde{\alpha}_j$, in Equations (5) and (6) from

Figure 8: Counterfactual case counts

(a) Canada



(b) US



Note: In the left panels, red solid lines are changes in log of weekly case counts due to altered vaccine schedules. In the right panels, black solid lines are actual case numbers and red solid lines are counterfactual counts. Shaded areas are 90% confidence bands.

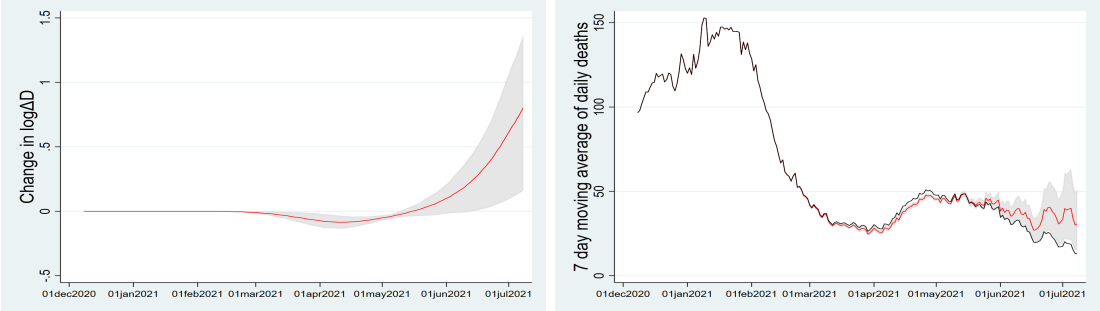
their asymptotic distribution and compute the associated residuals, $\tilde{\varepsilon}_j^C$, while the parameters for country specific time trends, country fixed effects in (5) and all parameters in (7) remain fixed. We then compute the counterfactual outcomes with $\left(\tilde{\alpha}_j, \tilde{\varepsilon}_j^C\right)$ for $j = 1, \ldots, 200$. The point estimate of each counterfactual outcome is the mean across 200 replications. We plot the 90% point-wise confidence bands by taking 5th and 95th percentiles across the replications at each t.

As one can expect from our estimates, converting second doses administered for the partially vaccinated people to first doses for unvaccinated individuals leads to substantially lower numbers of new cases and deaths. Likewise, reducing the interval between doses results in higher counts for both health outcomes. The lower or higher counts and growth rates of cases and deaths moderate the relative departures from the actual series directly and indirectly via mobility. We provide changes in weekly case counts due to altered vaccination progress and the counterfactual 7-day moving average daily case numbers in Figure 8.

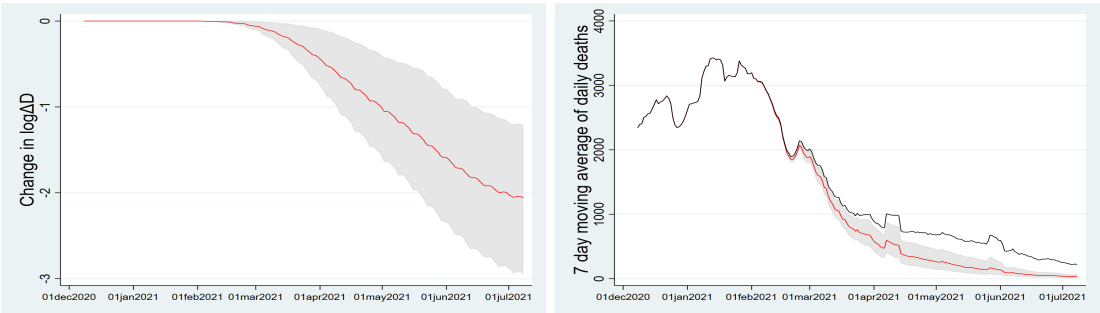
For Canada, the case counts substantially increase compared to their actual counterparts under the hypothetical vaccination schedules. The counterfactual outcomes are significantly different from the actual outcomes. The daily case counts decrease by 274 on average between

Figure 9: Counterfactual death counts

(a) Canada



(b) US



Note: In the left panels, red solid lines are changes in log of weekly case counts due to altered vaccine schedules. In the right panels, black solid lines are actual case numbers and red solid lines are counterfactual counts. Shaded areas are 90% confidence bands.

Feb 1 and Apr 30, 2021 as the first dose progress is slightly faster in the hypothetical vaccination schedule in the earlier period. The case numbers increase on average by 1,014 between May 1 and Jul 8, 2021 as the counterfactual first dose progress goes below the actual progress. On the contrary, the counterfactual outcomes become significantly lower than the actual values for the US as the first dose progress is much faster in the hypothetical scenarios. Between Feb 1 and Jul 8, 2021, the estimated reductions in the daily case numbers are 21,587. In terms of cumulative cases, those are translated into a 7% increase for Canada and a 43% reduction for the US between Feb 1 and July 8, 2021.

Similar patterns are observed in the counterfactual death counts as shown in Figure 9. For Canada, the daily death counts initially decrease on average by 1.4 between Feb 1 and Apr 30, 2021 and subsequently increase on average by 6.2 between May 1 and Jul 8, 2021. The average reductions in daily death numbers are 271 for the US from Feb 1 to Jul 8, 2021. In terms of cumulative death counts, those are translated into a 4.6% increase for Canada and a 25.9% reduction for the US between Feb 1 and July 8, 2021.

In alternative hypothetical scenarios, we adjust the dosing interval to 6 weeks and 12 weeks. The results are provided in Appendix C. For the US, the gaps between the counterfactuals and

the observed outcomes widen as the dosing interval becomes longer. When it comes to Canada, the 6 week dosing regimen results in worse health outcomes than the 8 weeks interval case. Under the 12 week dosing regimen, the hypothetical vaccination rates closely follow the actual rates but the hypothetical first dose progress is slightly faster in the earlier vaccination stage as Canada delayed the second dose in March 2021. Hence reductions in cases and deaths are observed when the 12 week dosing interval is imposed from the beginning.

The counterfactual outcomes are calculated under the assumption that government policies remain the same to their actual values observed in data. As government policies were eased according to the recent decline in new cases, it would be also the case in the counterfactual situations where the case numbers still drop along with vaccination progress. If we adjust the government policy index according to the relative changes in case and death counts, the gaps between the counterfactual outcomes and the actual outcomes will shrink.

6 Concluding Remarks

We evaluate the impact of vaccination progress and types of vaccines used on the spread of COVID-19 in leading countries. We exploit variations in vaccination rates over time and across countries using standard time-series and panel data models. We find significant negative association between vaccination progress and the transmission of COVID-19. The key factor is the share of vaccinated people with at least one dose which leads to significant reductions in new infections and deaths. Second dose progress offered no further reductions at least in the short-run. For vaccines from China, we find weaker effects on new cases and deaths only after full vaccination. Vaccination progress increases people's mobility by which it indirectly leads to higher growth rates of new infections and deaths. Our counterfactual experiments show that extending the interval between two vaccine doses can substantially reduce new cases and deaths.

Our findings support the idea of delaying the second dose adopted in Canada and the UK. As many wealthy countries announced that they will use the remaining vaccine orders to administer booster shots (the third dose), the supply of mRNA based vaccines will be likely to be limited for middle and low income countries. Given the constraints, a more efficient allocation strategy for available vaccine stocks would be to maximize the number of at least partially vaccinated people. However, this does not apply to vaccines from China so countries relying on those vaccines may need to administer both shots to provide protection against infection to the population. Another policy implication is that the indirect effects of vaccination offsets the direct effects on health outcomes via increased mobility. Many countries eased public health restrictions in line with the decline in new infections. Lower case numbers, vaccination progress and eased restrictions lead collectively to greater mobility. Hence maintaining policy restrictions helps contain the virus by reducing mobility and potential interactions between people. We do not focus on each public health measure and only include a composite index of overall stringency of government responses in our analysis. As coefficient estimates on this index remain negative and significant across all the specification considered, our results further support the previous studies on the

effectiveness of other policy interventions.

As the Delta variant has emerged, countries with high vaccination rates has experienced the surge in new infections. Vaccine effectiveness of approved vaccines against the new variant is substantially lower than against the original strain. However, it is also shown that those vaccines are still highly effective against severe illness even with only one dose. This implies that delaying the second dose can be an effective strategy to prevent worse heath outcomes, hospitalization and death, amid the rise of the Delta variant. Severe illness caused by the virus is a primary policy concern because it leads to a great burden on the healthcare system. It may not be possible to take the whittle down case counts to zero by vaccination but widely provided protection offered by vaccines can make the disease more manageable.

We conclude that vaccination has been indeed a very powerful weapon to battle the pandemic. However, it does not mean that other policy interventions can be quickly phased out as vaccination rates reach to a high enough level. Containment measures are still valuable tools to supplement the vaccination efforts. We only have focus on the impact of vaccination on epidemiological outcomes. Some extensions can be considered in future research. A relevant and important question is how to address vaccine hesitancy that has been a major barrier to progress in mass vaccination. Examining causes of vaccine hesitancy and policy efforts such as vaccine passports and monetary incentives to tackle it down would provide useful guidance on how to increase vaccine uptakes. Another interesting research avenue is the impact of vaccination along with eased restrictions on economic activities such as retail sales, employment and economic growth as recently studied in Dave *et al.* (2021).

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A Panel Data Regression with alternative time controls

Table 8: The direct effect of behavior, policy, and vaccinations on confirmed cases

	Dependent variable: $\Delta \log \Delta C_t$			
	(1)	(2)	(3)	(4)
$\Delta \log \Delta C_{t-14}$	0.1022***	0.1022***	0.0735**	0.0656*
	(0.0373)	(0.0372)	(0.0346)	(0.0354)
$\log \Delta C_{t-14}$	-0.0744***	-0.0831***	-0.1628***	-0.1622***
	(0.0136)	(0.0132)	(0.0208)	(0.0214)
$V_{1,t-21}$	-0.0176***	-0.0189***	-0.0176***	-0.0227***
	(0.0036)	(0.0041)	(0.0046)	(0.0042)
$V_{2,t-7}$	0.0066	0.0046	0.0047	0.0025
	(0.0041)	(0.0051)	(0.0065)	(0.0058)
$V^{CHN}_{1,t-21}$		0.0179***		0.0377***
		(0.0059)		(0.0081)
$V^{CHN}_{2,t-7}$		-0.0100*		0.0024
		(0.0059)		(0.0063)
P_{t-14}	-0.0035*	-0.0037*	-0.0057**	-0.0060**
	(0.0021)	(0.0021)	(0.0022)	(0.0023)
M_{t-14}	0.0058***	0.0065***	0.0098***	0.0100***
	(0.0016)	(0.0015)	(0.0013)	(0.0013)
$\Delta \log \Delta T_t$	0.4860***	0.4804***	0.3882**	0.3847**
	(0.1712)	(0.1696)	(0.1442)	(0.1427)
Country fixed effects	yes	yes	yes	yes
Country specific trend in days	linear	linear	cubic	cubic
R^2	0.3219	0.3266	0.4285	0.4346
Adjusted R^2	0.3197	0.3244	0.4237	0.4298
Number of countries	37	37	37	37
Obs. per country	382	382	382	382

Note: Standard errors in parentheses are clustered at the country level.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 9: The direct effect of behavior, policy, and vaccinations on deaths

	Dependent variable: $\Delta \log \Delta D_t$			
	(1)	(2)	(3)	(4)
$\Delta \log \Delta D_{t-28}$	0.0656**	0.0681**	0.0520*	0.0506*
	(0.0293)	(0.0289)	(0.0262)	(0.0262)
$\log \Delta D_{t-28}$	-0.0817***	-0.0942***	-0.1263***	-0.1249***
	(0.0121)	(0.0121)	(0.0127)	(0.0127)
$V_{1,t-35}$	-0.0202***	-0.0206***	-0.0112**	-0.0133***
	(0.0040)	(0.0047)	(0.0043)	(0.0041)
$V_{2,t-21}$	0.0075	0.0027	0.0083	0.0081
	(0.0053)	(0.0069)	(0.0050)	(0.0054)
$V^{CHN}_{1,t-35}$		0.0155**		0.0139**
		(0.0074)		(0.0060)
$V^{CHN}_{2,t-21}$		-0.0017		-0.0016
		(0.0083)		(0.0064)
P_{t-28}	-0.0035*	-0.0037*	-0.0038**	-0.0039**
	(0.0019)	(0.0019)	(0.0018)	(0.0018)
M_{t-28}	0.0053***	0.0059***	0.0087***	0.0088***
	(0.0019)	(0.0017)	(0.0014)	(0.0014)
Country fixed effects	yes	yes	yes	yes
Country specific trend in days	linear	linear	cubic	cubic
R^2	0.1271	0.1324	0.1860	0.1864
Adjusted R^2	0.1244	0.1295	0.1789	0.1792
Number of countries	37	37	37	37
Obs. per country	368	368	368	368

Note: Standard errors in parentheses are clustered at the country level.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 10: The direct effect of behavior, policy, and vaccinations on mobility

	Dependent variable: M_t			
	(1)	(2)	(3)	(4)
M_{t-7}	0.7065***	0.7034***	0.6735***	0.6721***
	(0.0230)	(0.0234)	(0.0242)	(0.0243)
$\Delta \log \Delta C_t$	0.7572***	0.7607***		
	(0.2356)	(0.2389)		
$\log \Delta C_t$	-1.0037***	-0.9634***		
	(0.1176)	(0.1190)		
$\Delta \log \Delta D_t$			0.2439*	0.2339*
			(0.1361)	(0.1333)
$\log \Delta D_t$			-1.1954***	-1.1445***
			(0.1565)	(0.1588)
ΔV_{1t}	0.4922***	0.6020***	0.4196***	0.4985***
	(0.1103)	(0.1472)	(0.1150)	(0.1548)
ΔV_{2t}	0.1511	0.2597	0.1710	0.2787
	(0.1291)	(0.1579)	(0.1365)	(0.1798)
$V_{1,t-7}$	0.0619*	0.0549	0.0650**	0.0590
	(0.0356)	(0.0397)	(0.0306)	(0.0353)
$V_{2,t-7}$	-0.0244	-0.0130	-0.0023	0.0071
	(0.0382)	(0.0450)	(0.0302)	(0.0345)
ΔV_{1t}^{CHN}		-0.4470**		-0.3085*
		(0.1658)		(0.1761)
ΔV_{2t}^{CHN}		-0.3209		-0.3235
		(0.2853)		(0.3159)
$V_{1,t-7}^{CHN}$		-0.0517		-0.0405
		(0.0965)		(0.0937)
$V_{2,t-7}^{CHN}$		0.0493		0.0364
		(0.0759)		(0.0654)
ΔP_t	-0.3474***	-0.3491***	-0.3576***	-0.3584***
	(0.0452)	(0.0449)	(0.0432)	(0.0430)
P_{t-7}	-0.1744***	-0.1765***	-0.1546***	-0.1572***
	(0.0203)	(0.0199)	(0.0187)	(0.0185)
Country fixed effects	yes	yes	yes	yes
Country specific trend in days	linear	linear	linear	linear
R^2	0.8432	0.8438	0.8443	0.8447
Adjusted R^2	0.8427	0.8433	0.8438	0.8442
Number of countries	37	37	37	37
Obs. per country	396	396	396	396

Note: Standard errors in parentheses are clustered at the country level.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

B Panel Data Regression with weekly data

Table 11: The direct effect of behavior, policy, and vaccinations on confirmed cases

	Dependent variable: $\Delta \log \Delta C_t$			
	(1)	(2)	(3)	(4)
$\Delta \log \Delta C_{t-14}$	0.0787	0.0732	0.0522	0.0515
	(0.0517)	(0.0518)	(0.0469)	(0.0467)
$\log \Delta C_{t-14}$	-0.0329***	-0.0365***	-0.1399***	-0.1403***
	(0.0076)	(0.0073)	(0.0224)	(0.0226)
$V_{1,t-21}$	-0.0077***	-0.0078***	-0.0166***	-0.0180***
	(0.0020)	(0.0021)	(0.0044)	(0.0043)
$V_{2,t-7}$	0.0025	0.0015	0.0011	0.0032
	(0.0023)	(0.0027)	(0.0057)	(0.0062)
$V^{CHN}_{1,t-21}$		0.0164***		0.0152**
		(0.0032)		(0.0073)
$V^{CHN}_{2,t-7}$		-0.0145***		-0.0171**
		(0.0042)		(0.0072)
P_{t-14}	-0.0024*	-0.0022*	-0.0034**	-0.0033**
	(0.0012)	(0.0013)	(0.0015)	(0.0015)
M_{t-14}	0.0054***	0.0055***	0.0108***	0.0108***
	(0.0012)	(0.0012)	(0.0015)	(0.0015)
$\Delta \log \Delta T_t$	0.5589***	0.5543***	0.4391***	0.4387***
	(0.1434)	(0.1426)	(0.1244)	(0.1243)
Country fixed effects	yes	yes	yes	yes
Country specific trend in weeks	no	no	quadratic	quadratic
R^2	0.2837	0.2879	0.3980	0.3987
Adjusted R^2	0.2813	0.2848	0.3726	0.3728
Number of countries	41	41	41	41
Obs. per country	54	54	54	54

Note: Standard errors in parentheses are clustered at the country level.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 12: The direct effect of behavior, policy, and vaccinations on deaths

	Dependent variable: $\Delta \log \Delta D_t$			
	(1)	(2)	(3)	(4)
$\Delta \log \Delta D_{t-28}$	0.0636***	0.0611***	0.0639***	0.0633***
	(0.0223)	(0.0224)	(0.0227)	(0.0228)
$\log \Delta D_{t-28}$	-0.0448***	-0.0492***	-0.1317***	-0.1319***
	(0.0107)	(0.0100)	(0.0121)	(0.0122)
$V_{1,t-35}$	-0.0097***	-0.0094***	-0.0123***	-0.0130***
	(0.0022)	(0.0023)	(0.0038)	(0.0039)
$V_{2,t-21}$	0.0039	0.0018	0.0044	0.0068
	(0.0030)	(0.0032)	(0.0042)	(0.0044)
$V^{CHN}_{1,t-35}$		0.0172***		0.0035
		(0.0038)		(0.0069)
$V^{CHN}_{2,t-21}$		-0.0121**		-0.0098*
		(0.0055)		(0.0055)
P_{t-28}	-0.0010	-0.0007	-0.0016	-0.0016
	(0.0014)	(0.0015)	(0.0013)	(0.0013)
M_{t-28}	0.0056***	0.0055***	0.0083***	0.0081***
	(0.0016)	(0.0016)	(0.0017)	(0.0016)
Country fixed effects	yes	yes	yes	yes
Country specific trend in weeks	no	no	quadratic	quadratic
R^2	0.1017	0.1063	0.1852	0.1855
Adjusted R^2	0.0990	0.1028	0.1500	0.1494
Number of countries	41	41	41	41
Obs. per country	52	52	52	52

Note: Standard errors in parentheses are clustered at the country level.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 13: The direct effect of behavior, policy, and vaccinations on mobility

	Dependent variable: M_t			
	(1)	(2)	(3)	(4)
M_{t-7}	0.7547***	0.7547***	0.7402***	0.7405***
	(0.0248)	(0.0249)	(0.0272)	(0.0272)
$\Delta \log \Delta C_t$	0.2696	0.2993		
	(0.2639)	(0.2663)		
$\log \Delta C_t$	-0.7097***	-0.6992***		
	(0.0909)	(0.0976)		
$\Delta \log \Delta D_t$			-0.1759	-0.1645
			(0.2216)	(0.2211)
$\log \Delta D_t$			-0.7710***	-0.7585***
			(0.1279)	(0.1334)
ΔV_{1t}	0.5894***	0.6601***	0.5188***	0.5778***
	(0.1216)	(0.1504)	(0.1223)	(0.1521)
ΔV_{2t}	0.2504*	0.3451**	0.2876**	0.3860**
	(0.1277)	(0.1528)	(0.1388)	(0.1725)
$V_{1,t-7}$	0.0531	0.0390	0.0424	0.0292
	(0.0327)	(0.0371)	(0.0316)	(0.0364)
$V_{2,t-7}$	-0.0133	-0.0032	0.0072	0.0163
	(0.0361)	(0.0396)	(0.0320)	(0.0355)
ΔV_{1t}^{CHN}		-0.3402		-0.2865
		(0.2269)		(0.2347)
ΔV_{2t}^{CHN}		-0.3465		-0.3598
		(0.2477)		(0.2670)
$V_{1,t-7}^{CHN}$		0.0410		0.0395
		(0.0645)		(0.0597)
$V_{2,t-7}^{CHN}$		-0.0176		-0.0180
		(0.0731)		(0.0625)
ΔP_t	-0.2323***	-0.2320***	-0.2559***	-0.2547***
	(0.0505)	(0.0507)	(0.0485)	(0.0489)
P_{t-7}	-0.1182***	-0.1204***	-0.1096***	-0.1120***
	(0.0179)	(0.0182)	(0.0183)	(0.0186)
Country fixed effects	yes	yes	yes	yes
Time effects	no	no	no	no
R^2	0.8232	0.8235	0.8232	0.8234
Adjusted R^2	0.8225	0.8225	0.8225	0.8224
Number of countries	41	41	41	41
Obs. per country	56	56	56	56

Note: Standard errors in parentheses are clustered at the country level.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

C Additional counterfactuals

Figure 10: Canada (Left: 6 weeks, Right: 12 weeks)

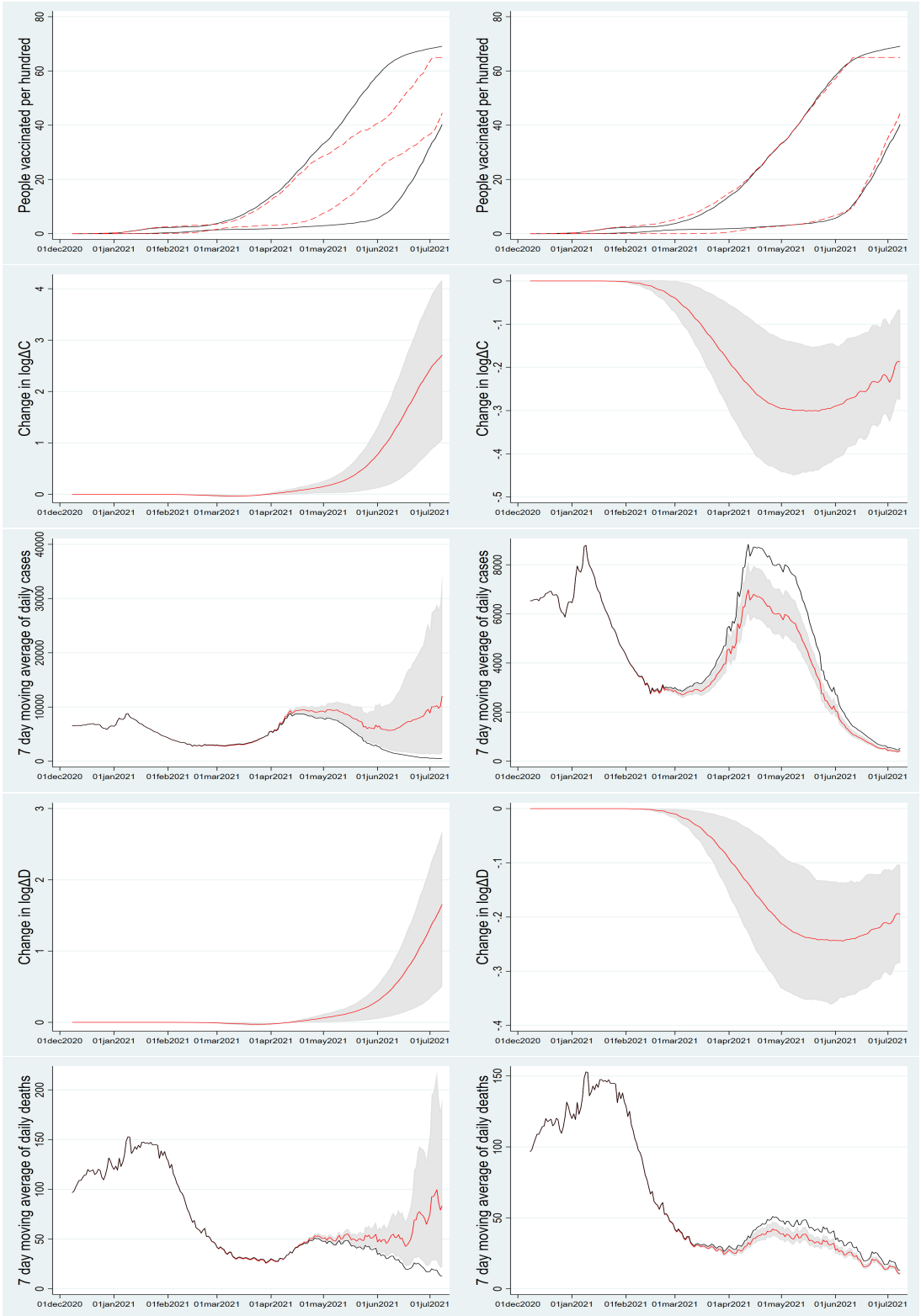

Figure 11: US (Left: 6 weeks, Right: 12 weeks)