DISCUSSION PAPER SERIES

5049-1612964360

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PUBLIC ECONOMICS

CEPR

ISSN 0265-8003

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Discussion Paper 5049-1612964360
Published N/A
Submitted 10 February 2021

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www.cepr.org

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Abstract

This paper models the current pandemic to analyze vaccination strategies in a setting with three age groups that differ with respect to their fatality rates. The model also accounts for heterogeneity in the transmission rates between and within these age groups. We compare the outcomes in terms of the total number of deceased, the total number of infected, the peak infection rate and the economic consequences. We find that fatalities are almost always minimized by first vaccinating the elderly, except when vaccination is slow and the general transmission rate is relatively low. In this case deaths are minimized by first vaccinating the middle-aged as this group is responsible for substantial spreading of the virus to the elderly. With regard to the other outcome variables it is always best to vaccinate the middle-aged group first. A trade-off may therefore emerge between reducing fatalities on the one hand and lowering the number of infected as well as maximizing the economic gains from vaccinations on the other hand.

JEL Classification: N/A

Keywords: Vaccines, SIR-model, COVID-19

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Whom to Vaccinate First - Some Important Trade-offs *

Rikard Forslid† **Mathias Herzing**‡

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Abstract

This paper models the current pandemic to analyze vaccination strategies in a setting with three age groups that differ with respect to their fatality rates. The model also accounts for heterogeneity in the transmission rates between and within these age groups. We compare the outcomes in terms of the total number of deceased, the total number of infected, the peak infection rate and the economic consequences. We find that fatalities are almost always minimized by first vaccinating the elderly, except when vaccination is slow and the general transmission rate is relatively low. In this case deaths are minimized by first vaccinating the middle-aged as this group is responsible for substantial spreading of the virus to the elderly. With regard to the other outcome variables it is always best to vaccinate the middle-aged group first. A trade-off may therefore emerge between reducing fatalities on the one hand and lowering the number of infected as well as maximizing the economic gains from vaccinations on the other hand.

JEL Classification: D42, D62, H10, I18, L10

Keywords :Pandemics, Vaccination, SIR-model, COVID-19

*Herzing is grateful for financial support from the Jan Wallander and Tom Hedelius Research Foundation. Forslid is grateful for financial support from the Jan Wallander and Tom Hedelius Research Foundation and from the Swedish Research Council.

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1 Introduction

The rapid development of vaccines against COVID-19 and the quick ramping up of production facilities has been unprecedented. However, vaccines also need to be distributed and administered to susceptible individuals. This is an important logistic challenge and also raises the question of whom to vaccinate first.[1] With the exception of front-line health care workers, most countries start with the older and most fragile part of the population. However, there is also the alternative strategy to first vaccinate a younger part of the population, which is primarily responsible for spreading the virus, in order to quickly reduce the number of infected. This reduction in the transmission of the infection could in principle result in fewer deaths in the long run also among the elderly.

This paper employs a SIR-model to examine the consequences of different vaccination strategies.[2] The focus is on outcomes in terms of the total number of deceased, the total number of infected, the peak infection rate, as well as economic consequences. In our model the population is divided into three groups. The first group consists of young individuals (below 20 years of age) that are very unlikely to die from the infection. The second group comprises working-age adults (20-59 years old) that have a slightly higher risk of dying. The third group consists of the elderly (60 years and older) who face a considerably higher fatality rate when being infected.

The transmission rates between and within these groups is an important factor for the spread of the infection. We will base our transmission rates on estimates from Wallinga et al. (2006), which use age-specific Dutch data on face-to-face conversations as a proxy for exposure to infectious respiratory-spread agents. Two important features stand out from this data. First, intra-group transmission rates are higher than transmission rates between age groups. Second, transmissions rates between middle-aged adults and the older group are considerably higher than between young individuals and the older group.[3]

We analyze six different vaccination strategies, under which the three population groups are vaccinated in sequence; since there are three groups there are six permutations. We have also considered alternative strategies, e.g. all groups being vaccinated simultaneously at rates in proportion to their share of the total population; none of these strategies generates an optimal outcomes in terms of any of the outcome measures that we focus upon.

To assess the implications of different vaccination strategies we will focus on the following outcome measures:

[1] See e.g Luyten et al. (2020) and Roope et al. (2020).

[2] This type of epidemiological model was introduced by Kermack and McKendrick (1927).

[3] An aspect not considered here is that transmission rates also differ among professions. Occupation-based infection risks are estimated by e.g. Babus et al. (2020).

(i) *The share of the population that will have deceased on day* 730 *after vaccinations have started.* Reducing the number of fatalities is obviously an important objective. The number of days is chosen to be equivalent to two years duration to make it possible to assess the impact also of low vaccination rates; in two years time the pandemic will have subsided even in the absence of a vaccine.

(ii) *The share of the population that will have been infected two years after vaccinations have started.* Keeping the total number of infected individuals low is also important; many surviving infected individuals have been ill for a long time and some suffer long-term consequences.

(iii) *The peak of the share of infectious individuals.* From a public health perspective it is desirable to keep the maximum number of infected persons low. In many countries the number of treated people has increased dramatically during the last weeks of 2020. It is therefore of interest to analyze which vaccination strategy dampens the peak infection rate most.

(iv) *Economic gains from vaccinations one year after their start.* We limit our analysis of economic consequences to one year, because these are almost entirely influenced by the number of ill, which after one year will be neglible even in the absence of a vaccine.

Key parameters in our analysis are the efficacy of the vaccine (the share of vaccinated persons that become immune)[4], the vaccination rate and the general transmission rate, which to varying degrees are policy parameters. The efficacy of the vaccine can be varied in a few discrete steps by the choice among existing vaccines against Covid-19. The vaccination rate can be increased by purchasing more doses and improving the implementation of a vaccine program. The general transmission rate can be influenced by the restrictions that a government imposes on the population.

We assume in our base case a vaccine efficacy of 0.9 in line with the reported levels of some of the vaccines against Covid-19 that have been developed so far. The recovery rate is assumed to be the same across the age groups and equal 0.2. However, as mentioned above, we allow for heterogeneity with respect to transmission rates within and between groups as well as age specific fatality rates.. In our base case we assume a general transmission rate of 0.25, such that the infection reproduction number is given by $R_0 = 1.25$, which is roughly in line with current estimated levels for Sweden. To check the sensitivity of our results we consider the effects of changes in the efficacy rate as well as the transmission rates.

Our main results can be summarized as follows. First, the strategy of vaccinating the elderly first minimizes the fatality rates for most parameter value configurations. However, it is possible

[4]Hodgson et al. (2020) thoroughly discuss the definition of efficacy in relation to potential Covid-19 vaccines. As they point out, "many different endpoints are used in vaccine research to define efficacy depending on the pathogen, consequences of infection, and transmission dynamics." Furthermore, "outcomes might include reduction in infection (i.e., assessing sterilising immunity), severity of resultant clinical disease (i.e., assessing disease-modifying immunity), or duration of infectivity." Here we use the share of vaccinated persons that become immune for vaccine efficacy.

that vaccinating the middle-aged group first minimizes the fatality rate when the vaccination rate is low and the general transmission rate takes on values around 0.25, in particular at lower efficacy rates. Vaccinating the youngest group first always yields the highest number of deaths. Which group gets vaccinated secondly is less important, but the strategy of vaccinating the middle-aged group after the oldest group leads to the lowest fatality rates in the standard case with relatively high vaccination rates.

Second, the total number of infected persons (after two years) and the peak share of infectees are always minimized by first vaccinating the middle-aged. Since this age group is an important transmitter of the virus to all other age groups, this is the fastest way of eradicating the disease. Finally, the economic gains from vaccination are highest when the middle-aged group, which contributes most economically, gets vaccinated first. We also find that there are substantial economic gains from speeding up the vaccination campaign. For instance, we obtain a low benchmark for the gains from a campaign where the vaccination rate is doubled, such that it takes 168 rather than 325 days to vaccinate the entire susceptible population, of 0.28 billion USD (2.34 billion SEK) in the case of Sweden.

Hence, if the main policy objective is to reduce fatalities the elderly should be vaccinated first, followed by the middle-aged group. In contrast, when the aim is to minimize the total number of infected people or the peak share of infectees or to maximize economic output, the middle-aged group should be vaccinated first, while vaccinating the elderly first would yield the worst outcomes. We thus obtain a trade-off between minimizing fatalities and the other three outcome variables when it comes to the order of vaccination. Vaccinating the oldest group first implies less deaths, in particular at higher vaccination rates, but it comes at the cost of a higher share of the population becoming infected and therefore also a smaller economic gain from vaccinations. The negative consequence of not vaccinating the middle-aged group first are largest at intermediated vaccination rates.

There are a couple of highly related recent papers. Matrajt et al. (2020) analyze the optimal use of vaccine in an epidemiological model calibrated to U.S. demographics with 16 age groups that have different levels of susceptibility. Their main analysis assumes that vaccination has been carried out at the beginning of the simulations. The central result here is that deaths are minimized when vaccinating older people first, if the efficacy of a vaccine is between 10 and 50 per cent, but that it is optimal to switch to vaccinating younger persons first when the efficacy of the vaccine is above 60 per cent and there is enough vaccine to cover roughly half of the population. They also model a vaccination campaign where the entire population is vaccinated in 25, 50 or 101 weeks. Here they find that deaths are minimized by first vaccinating the elderly at low vaccination rates, but that vaccinating both old and young people is optimal at high vaccination rates. Although these results resemble ours, we find that it is optimal to start with the middle-aged group when vaccination is slow and the infection reproduction number is close to one (such that deaths are not minimized by starting with the oldest group

first). This different result is likely to be due to the fact that we are using a full matrix of estimated social interactions between age groups, whereby we account for there being relatively little transmission between the youngest and the oldest, most fragile age groups.

Moore et al. (2020) analyze the optimal sequence of Covid 19 vaccination in the UK in terms of deaths and quality adjusted life years. They divide the population into five age groups and use a social contact matrix between the groups based on UK data. They find that it is always optimal to target older age groups first. Three types of vaccine are analyzed: a vaccine that reduces susceptibility, one that reduces the probability of becoming symptomatic, and one that protects against symptoms becoming severe. The bulk of their analysis is based on the assumption that the vaccine can be instantaneously administered, but they also simulate a case where the speed of vaccine deployment is varied. In contrast to Matrajt et al. (2020) and the present study they find that the optimal ordering of age groups is unaffected by the speed of vaccine deployment.

Bartsch et al. (2020) calibrate a model of the spread of SARS-CoV-2 in the U.S. to identify the vaccine efficacy thresholds, above which vaccination could extinguish an ongoing wave of the pandemic across a range of possible scenarios. Contrary to our paper they do not analyze a vaccination campaign or consider a population divided into age groups with different mortality and transmission rates.

Vellodi and Weiss (2020) analyze optimal vaccination in a model without infection dynamics where individuals are randomly matched. Agents differ in exposure vulnerability and they may voluntary chose to self-isolate. They find that it is optimal to first vaccinate individuals with an intermediate risk of severe illness.

Our paper is also related to a recent publication by Britton et al. (2020) where population heterogeneity is accounted for to assess herd immunity. The analysis focuses on four cases, where the population is either homogeneous, or is categorized by age cohorts but not by activity levels, or is categorized by different activity levels but not by age, or is categorized both by age and activity levels. Here, we introduce vaccination in a modified version of the case with age cohorts (using three age groups).

2 The Model

We employ a modified SIR-model, where there are three groups of individuals (A, B and C) with different characteristics. In each group $X \in \{A, B, C\}$ there are six categories of individuals: susceptible persons (S_X) who have never been exposed to the virus; infectious persons (I_X); recovered persons (R_X) who are no longer infectious and have developed resistance to the virus; deceased persons (D_X); vaccinated persons who are immune (V_X^{im}); and vaccinated persons who are still susceptible (V_X^s).

The dynamics in a SIR-model depend on the recovery rate and the transmission rate. We use a uniform recovery rate γ across all groups. Assuming that infectees are, on average, sick for five days, implies that $\gamma = 0.2$.

In standard pandemic models the transmission rate β is homogenous across the entire population, i.e. the rate at which a susceptible individual becomes infected by infectious individuals is βI, where I is the total number (or share) of infectious persons. Here, we instead assume that the rate of transmission varies across different segments of the population, which has been analyzed e.g. in Britton et al. (2020). We employ a simple modification of this approach. Groups A, B and C correspond to age cohorts consisting of young persons (below 20 years of age), middle-aged persons (20 to 59 years of age) and old persons (above 60 years of age), respectively. The shares of these three groups are 0.25, 0.5 and 0.25, roughly corresponding to Swedish population data.

To assess the evolution of the pandemic it is crucial to capture differences in social contact patterns within the population. Unfortunately there is a lack of detailed data on interactions between different age groups. A notable exception is the study by Wallinga et al. (2006), which uses age-specific Dutch data on face-to-face conversations as a proxy for exposure to infectious respiratory-spread agents. They obtain normalized age-specific contact rates for six cohorts (1-5, 6-12, 13-19, 20-39, 40-59 and 60-). We use the same data, but reduce the number of cohorts to three (1-19, 20-59 and 60-), to obtain the following transmission rates β_{XY} between an infected individual in group Y and a susceptible person in group X, given a general transmission rate of $\beta = 0.25$ across the entire population.[5]

β_{XY}	1-19 (A)	20-59 (B)	60- (C)
1-19 (A)	0.5184	0.1907	0.0690
20-59 (B)	0.1907	0.3371	0.1510
60- (C)	0.0690	0.1510	0.2945

The values for the general transmission rate and the recovery rate imply that the reproduction rate is 1.25, which is roughly in line with the estimated levels for Sweden by the Public Health Agency of Sweden.[6] This relatively low reproduction number is a result of the restrictions

[5] More specifically, we use the normalized age-specific contact rates (after correction for reciprocity) of Appendix Table 2 in Wallinga et al. (2006) to calculate the total number of reported weekly contacts for every age group (1-5, 6-12, 13-19, 20-39, 40-59, 60-). Next, we use these numbers to calculate the total number of reported weekly contacts for our cohorts (1-19, 20-59, 60-), which we then, following Diekmann et al. (1990), transform into a next-generation transmission matrix that is adjusted so that its largest eigenvalue equals $R_0 = 1.25$, implying a general transmission rate of $\beta = 0.25$ among the entire population given that $\gamma = 0.2$.

[6] The reproduction number for Covid 19 for Sweden has hovered between 1 and 1.5 since September 2020 acording to estimates by the Public Health Agency of Sweden that publish the current reproduction number on their home page: https://www.folkhalsomyndigheten.se/smittskydd-beredskap/utbrott/aktuella-utbrott/covid-19/statistik-och-analyser/analys-och-prognoser/

on public life that have been implemented.

Data on deaths due to Covid-19 clearly reveal a fatality rate that increases sharply with age. A meta-analysis by Levin et al. (2020) provides estimates of infection fatality rates (i.e. the likelihood of dying from Covid-19 among those infected by the virus) for different cohorts. On the basis of these estimates and Swedish population data for 2019, provided by Statistics Sweden, we obtain the following probabilities of dying per day of being infected: $\delta_A = 0.00000396017$, $\delta_B = 0.000268962$ and $\delta_C = 0.010573046$.

A vaccination program is introduced, such that susceptible persons are vaccinated at rate u. The vaccination rate is u_A, u_B and $u_C = u - u_A - u_B$ for groups A, B and C, respectively; while u is assumed to be constant over time (as long as there are still susceptible persons in the population), u_A, u_B and u_C change over time in accordance with the chosen vaccination strategy. For example, vaccination strategy ABC implies that $u_A = u$ and $u_B = u_C = 0$ until $S_A = 0$ (i.e. until all susceptible group A individuals have been vaccinated), whereafter $u_B = u$ and $u_A = u_C = 0$ until $S_B = 0$, followed by $u_C = u$ and $u_A = u_B = 0$ until $S_C = 0$ and the vaccination campaign ends.

Given a vaccination rate u_X of susceptibles in group X and a vaccine efficacy $e \in (0, 1]$ the number of immune vaccinated individuals increases by eu_X and the number of vaccinated individuals that remain susceptible increases by $(1-e)u_X$ in group X per day.[7] For each group X the dynamics of the pandemic can be described as follows:

$$
\begin{aligned}
\dot{S_X} &= -(\beta_{XA}I_A + \beta_{XB}I_B + \beta_{XC}I_C)S_X - u_X, \\
\dot{I_X} &= (\beta_{XA}I_A + \beta_{XB}I_B + \beta_{XC}I_C)S_X + (\beta_{XA}I_A + \beta_{XB}I_B + \beta_{XC}I_C)V_X^s - \gamma I_X - \delta_X I_X, \\
\dot{R_X} &= \gamma I_X, \\
\dot{D_X} &= \delta_X I_X, \\
\dot{V_X^{im}} &= eu_X, \\
\dot{V_X^s} &= (1-e)u_X - (\beta_{XA}I_A + \beta_{XB}I_B + \beta_{XC}I_C)V_X^s.
\end{aligned}
$$

For simplicity it will be assumed that S_A, I_A, R_A, D_A, V_A^{im}, V_A^s, S_B, I_B, R_B, D_B, V_B^{im}, V_B^s, S_C, I_C, R_C, D_C, V_C^{im} and V_C^s represent shares of the population, i.e. $S_A(t) + I_A(t) + R_A(t) + D_A(t) + V_A^{im}(t) + V_A^s(t) + S_B(t) + I_B(t) + R_B(t) + D_B(t) + V_B^{im}(t) + V_B^s(t) + S_C(t) + I_C(t) + R_C(t) + D_C(t) + V_C^{im}(t) + V_C^s(t) = 1$ at any point in time t, where day 1 is the first day that people start being vaccinated. We assume that at day 0, the number of deceased individuals is zero, i.e. $D_A(0) = D_B(0) = D_C(0) = 0$; in terms of how vaccination strategies affect outcomes the number of those who have already died from Covid-19 is of no importance. Rather, our focus is on how many more fatalities there will be under different vaccination schemes.

[7] We thus assume that immunity lasts for the time interval analyzed here.

As mentioned above, it is difficult to assess exactly how many have already been infected, as there have been many asymptomatic cases or cases with very light symptoms, where it was never established whether these were due to the Corona virus or not. In our calibration we assume that an equal share of 0.1 in all groups belong to the category of recovered people, implying that $R_A(0) = 0.025$, $R_B(0) = 0.05$ and $R_C(0) = 0.025$. Data on new infections per day suggest that by the end of December 2020 (when the first doses of vaccine were administered in Sweden and many other countries) about 0.3 per cent of the Swedish population was infectious. However, although testing capacity has increased considerably, there might still be many undiscovered Covid-19 cases. We therefore assume that a share of 0.005 in all groups are infected on day 0, i.e. $I_A(0) = 0.00125$, $I_B(0) = 0.0025$ and $I_C(0) = 0.00125$. Hence, the share of susceptibles is 0.895 in all groups, such that $S_A(0) = 0.22375$, $S_B(0) = 0.4475$ and $S_C(0) = 0.22375$.

While we allow for the possibility of vaccinated persons not being immune (whenever the efficacy of the vaccine is below one), we do not account for recovered persons becoming infected again. In light of reports of people having become infected more than once, this may be a strong assumption. However, the number of persons having been infected by the Covid-19 virus twice is still very low, suggesting that recovery provides immunity at least in the short run. A vaccination program is likely to lead to the pandemic having run its course in the not-too-distant future, such that the number of those reinfected will probably still be very low. Currently lack of data makes it hard to make a meaningful assessment of the reinfection rate.

To evaluate the implications of different vaccination strategies we will focus on the following measures:

(i) The share of the population that will have deceased two years after vaccinations have started.

(ii) The share of the population that will have been infected two years after vaccinations have started.

(iii) The peak of the share of infectious individuals.

(iv) Economic gains from vaccinations one year after their start, measured as the percentage gain in output in relation to one year's output in the absence of a vaccine.

Productivity has been normalized such that non-infectious (and non-deceased) group B individuals have a productivity of 1 per day in the presence of the current pandemic. While many infectees only suffer light symptoms and may still be able to work from home we make the simplifying assumption that productivity is zero for all infectious persons. For non-infected (and non-deceased) individuals it is assumed that productivity is 0 per group A individual and day, while it is 0.1 per group C individual and day. Hence, no young person contributes to output, while old people make a contribution roughly corresponding to the number of 60-64 year olds in relation to the number of group B individuals.

Normalized total output at any day t is given by

$$Y(t) = S_B(t) + R_B(t) + V_B^{im}(t) + V_B^s(t) + 0.1\left[S_C(t) + R_C(t) + V_C^{im}(t) + V_C^s(t)\right].$$

To assess the economic consequences of the pandemic, $Y = \sum_{t=1}^{365} Y(t)$ will be measured.[8] As a benchmark we use the outcome in the absence of a vaccine, such that we are able to calculate the economic gain during one year in relation to the vaccination rate.

3 Simulations

We simulate the outcomes for six different vaccination strategies (ABC, ACB, BAC, BCA, CAB, and CBA), according to which susceptible individuals in the three age groups are vaccinated in sequence, for vaccination rates between 0 and 0.01.[9] The upper bound would imply that the entire population would be vaccinated in less than one hundred days, which would be hard to implement in most countries. In our simulations we assume a general transmission rate of $\beta = 0.25$ and a vaccine efficacy of $e = 0.9$. The sensitivity of our results with regard to changes in these parameter values is examined in section 4.

3.1 Fatalities

The total number of fatalities decreases sharply in the vaccination rate, from 1294 deaths per million in the absence of a vaccination program to 215-382 fatalities per million for $u = 0.01$, as shown in Figure 1. Hence, rapidly creating vaccination capacities is crucial to keep the number of deceased as low as possible.

[8] The economic outcomes in year 2 after the start of vaccinations are hardly affected by the vaccination rate. We therefore restrict our analysis to the effects during the first year after the start of the vaccination campaign.

[9] We have also simulated alternative strategies, such as all groups being vaccinated simultaneously at rates in proportion to their share of the total population have. None of these strategies have generated optimal outcomes in terms of any of the outcome measures that we focus upon.

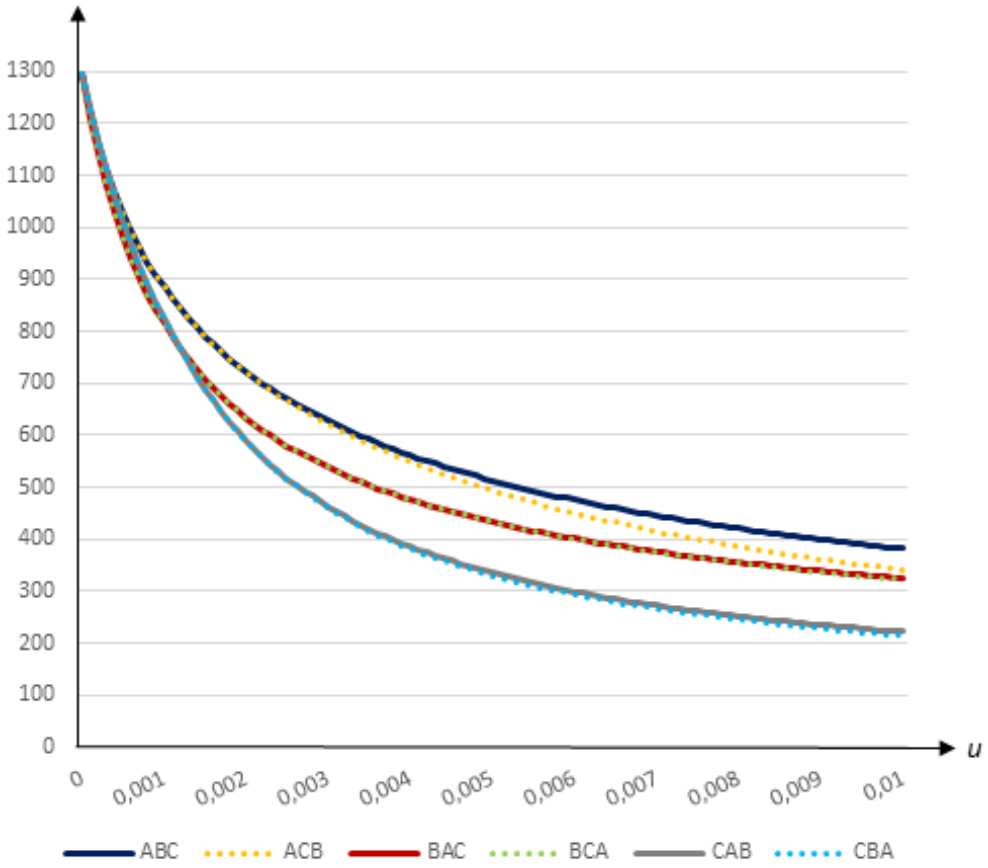

Figure 1. The number of deceased (per million) in relation to the vaccination rate when $\beta = 0.25$ and $e = 0.9$.

Our simulations also reveal significant differences between the strategies under consideration. Figure 1 shows that vaccinating group A (the young) first leads to most fatalities. However, which strategy minimizes fatalities crucially depends on the vaccination rate. To illustrate this, Figure 2 zooms in on vaccination rates below 0.002.

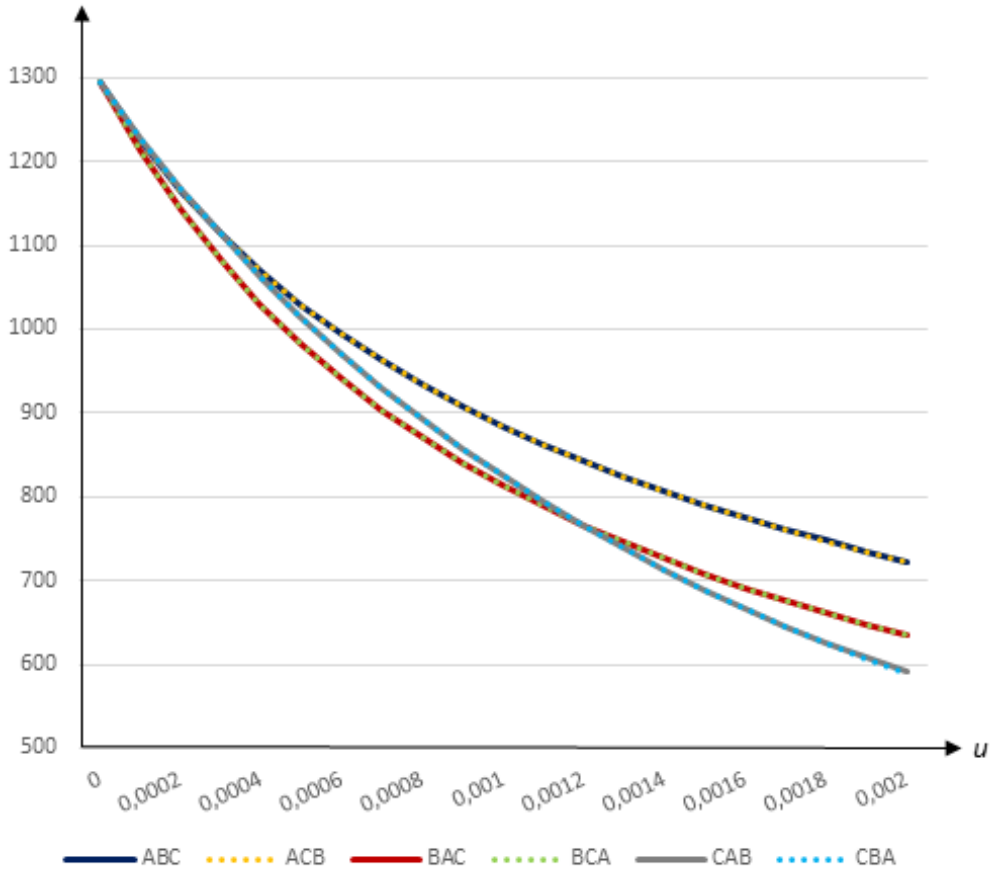

Figure 2. The number of deceased (per million) in relation to the vaccination rate when $\beta = 0.25$ and $e = 0.9$

Figure 2 shows that first vaccinating the elderly (group C) leads to the lowest total number of deaths for sufficiently high vaccination rates. In contrast, fatalities are minimized by first vaccinating group B (the middle-aged) for vaccination rates below 0.00117 (implying that it would take 699 days to cover the entire susceptible population under strategies BAC and BCA). When vaccination proceeds slowly it is more important to dampen the spread of the virus to protect the elderly. Under these conditions the total number of deaths are minimized by first vaccinating the middle aged group, which is crucial for the transmission of the virus across age groups.

Figure 2 also reveals that it is of little importance which group gets vaccinated secondly when the vaccination rate is low. However, at higher vaccination rates there are differences in outcomes depending on which group gets vaccinated secondly, as shown by Figure 3, which illustrates outcomes for vaccination rates above 0.005. In particular, there is a substantial and increasing difference in outcomes between strategies ABC and ACB, but there is also a non-neglible difference between strategies CAB and CBA. Vaccinating group C first and group B

secondly is the optimal strategy if the objective is to minimize fatalities at all vaccination rates above 0.00117.(i.e. for vaccination campaigns of less than 673 days duration under strategy CBA).

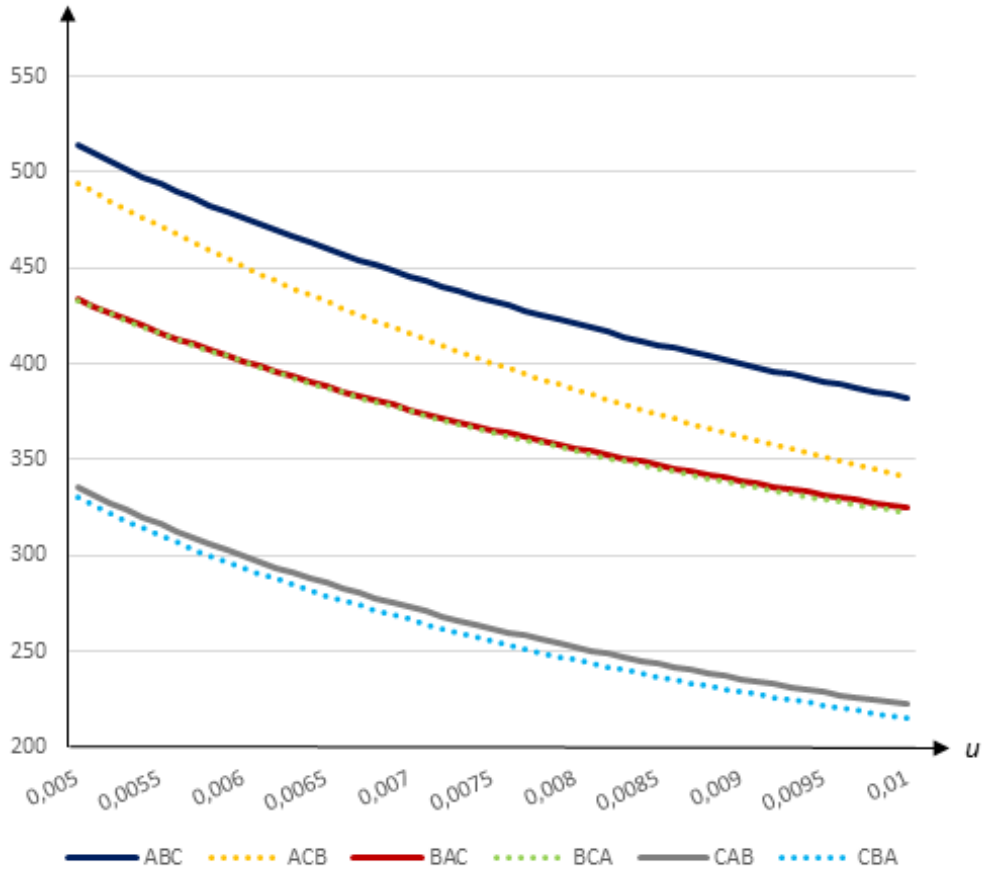

Figure 3. The number of deceased (per million) in relation to the vaccination rate when $\beta = 0.25$ and $e = 0.9$

3.2 Total number of infected

The share of the population that will have been infected by the virus decreases substantially in the vaccination rate, from 23.9 per cent for $u = 0$ to 12.9-14.2 per cent for $u = 0.01$, as shown by Figure 4.

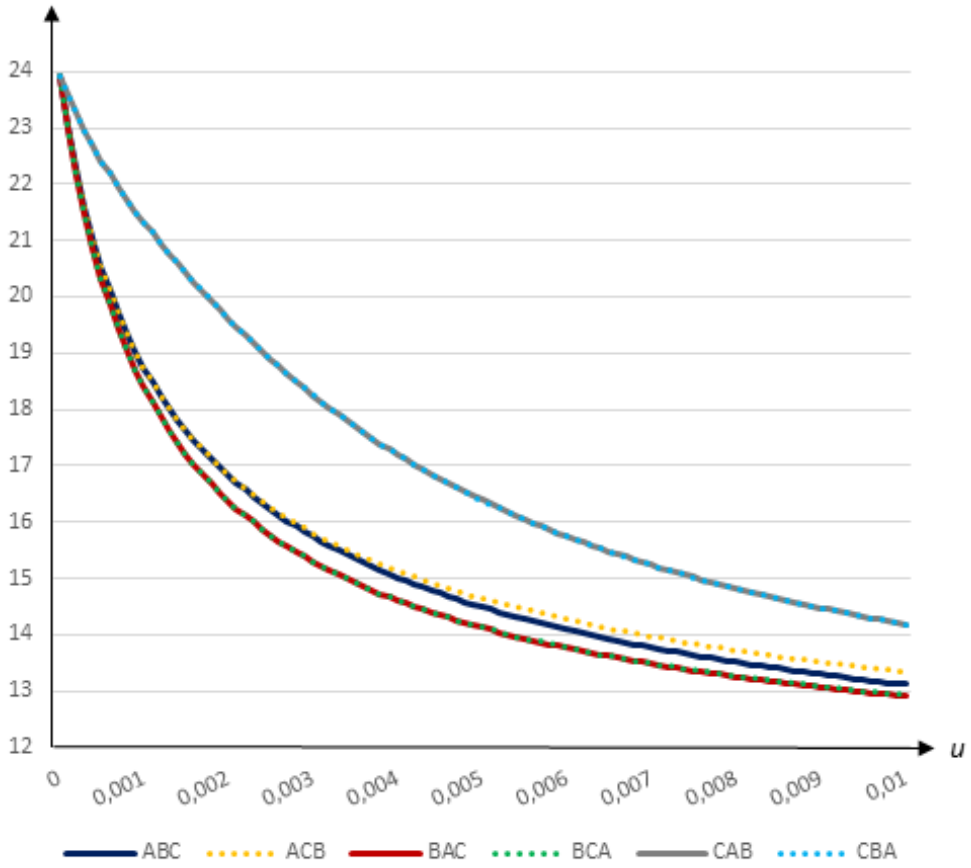

Figure 4. The total share of infected people (per cent of population) in relation to the vaccination rate when $\beta = 0.25$ and $e = 0.9$

It turns out that vaccinating group C first clearly yields the highest total number of infected people, while vaccinating group B first leads to the lowest total number of infected persons at all vaccination rates. This is due to group B having high rates of transmission to all groups. The difference between vaccinating group B first and vaccinating group C first is largest at intermediate vaccination rates. For example, given a vaccination rate of 0.0025 (such that it would take 325-337 days to vaccinate the entire population), 18.9 per cent of the population will have been infected under strategy CBA, whereas 15.8 per cent of the population will have been infected under strategy BAC. Figure 4 also shows that what matters for the total share of infected people is which group gets vaccinated first, while it is of little importance which group gets vaccinated secondly.

3.3 The peak share of infectees

Given that the vaccination program is implemented in the midst of the pandemic (the total share of infected people is 0.5 per cent on day 0) and the transmission rates are relatively low

due to the imposed restrictions, the peak rate of infection does not increase dramatically even in the absence of vaccinations. The day when the infection rate peaks occurs relatively early (on day 38 for $u = 0$ and in less than a week for $u = 0.01$). Nevertheless, there are differences in the peak infection rate with respect to which strategy is chosen, as shown in Figure 5.

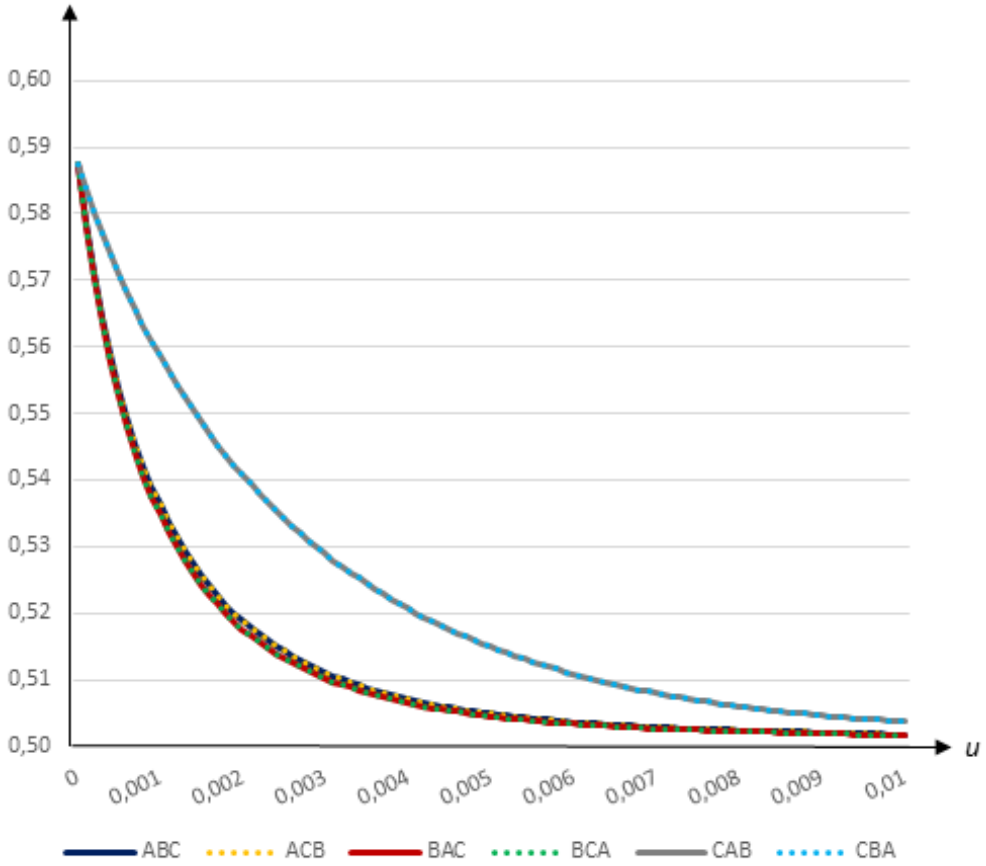

Figure 5. The peak share of infected people (per cent of population) in relation to the vaccination rate when $\beta = 0.25$ and $e = 0.9$

The peak share of infectees decreases in the vaccination rate, from 0.587 per cent for $u = 0$ to 0.502-0.504 per cent for $u = 0.01$. Vaccinating group B first yields the best outcome, but the difference to vaccinating group A first is very small. In contrast, vaccinating group C first leads to a somewhat higher peak infection rate, especially at intermediate vaccination rates, but the difference compared to when group B gets vaccinated first is never higher than 0.0245 per cent, which implies a difference of about 2500 cases in Sweden (population 10.4 million in 2020).[10]

[10] As will be demonstrated in section 4.2, higher transmission rates increase this difference substantially.

3.4 Economic gains from vaccination

Economic gains increase in the vaccination rate, and they reach 0.16-0.20 per cent of GDP for $u = 0.01$, as shown in Figure 6.

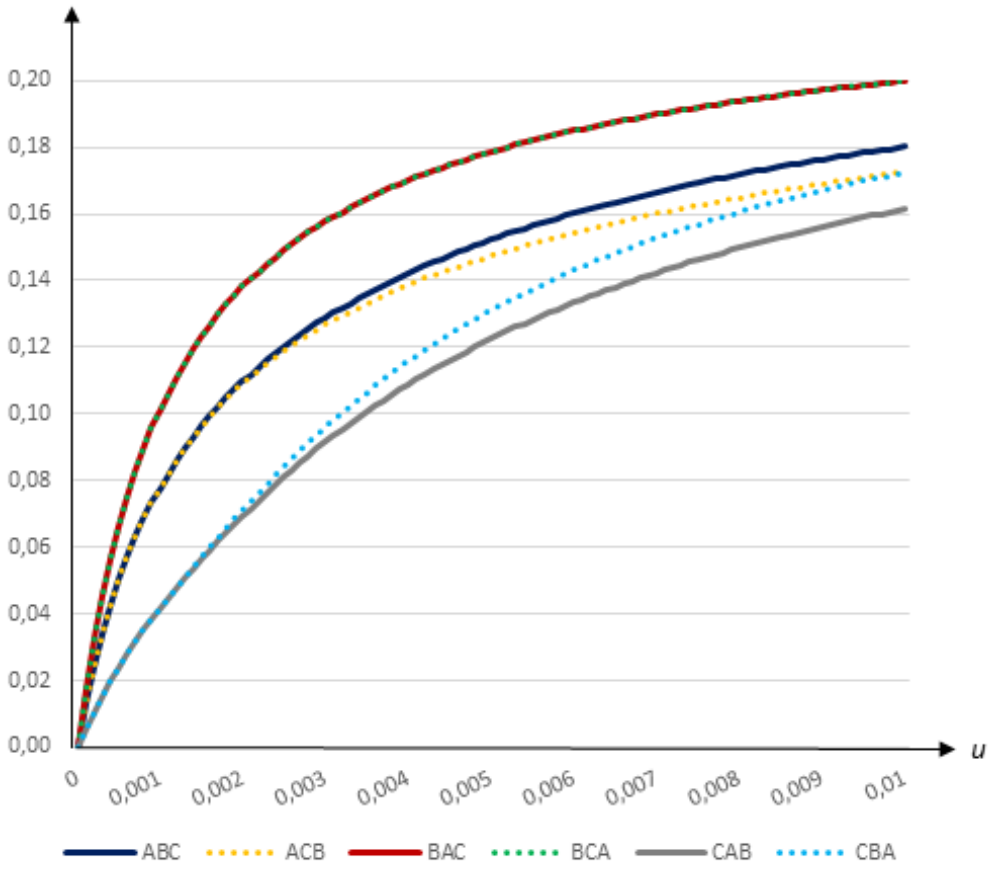

Figure 6. The economic gain from vaccinations (per cent) in relation to the vaccination rate when $\beta = 0.25$ and $e = 0.9$

Our estimates of economic gains are probably close to a lower bound since neither economic multipliers nor the cost of health care for those infected are taken into account, although we also do not consider the costs of administrating vaccinations. Nevertheless, our simulations suggest that there are substantial economic gains from increasing the vaccination rate. For instance, an acceleration of the vaccination rate from $u = 0.0025$ (lasting 325 days to cover the entire susceptible population) to $u = 0.005$ (lasting 168 days) under the fatality-minimizing strategy CBA would lead to a gain of roughly 0.28 billion USD (2.34 billion SEK) for Sweden.[11] Moreover, this increase in the vaccination rate would lead to a decrease in fatalities of 186 per million (1932 fewer deaths in Sweden) and a decrease of 2.51 per cent in the total share of

[11] Sweden had a GDP of about 5000 billion SEK or 600 billion USD in 2020.

infected people (261 040 fewer cases in Sweden), while also slightly reducing the peak infection rate.

With respect to the economic outcomes, vaccinating group B first yields the highest gains and implementing strategy CAB leads to the smallest gains from vaccinations. Especially at intermediate vaccination rates the differences in economic outcomes between the strategies are considerable. For example, given a vaccination rate of $u = 0.0025$, the economic gain generated by switching from the fatality-minimizing strategy CBA to vaccinating group B first is about 0.39 billion USD (3.25 billion SEK) for Sweden. In addition, such a switch would imply a reduction in the total share of infected people of 3.13 per cent (about 325 000 more cases in Sweden); however, it would also lead to an increase in fatalities by 64 per million (668 cases in Sweden) as more old persons would become exposed to the virus.

3.5 Summary

The simulations where $\beta = 0.25$ and $e = 0.9$ provide clear-cut results. What matters most to outcomes is which group gets vaccinated first, while it is much less important which group gets vaccinated next.

If the main policy objective is to reduce fatalities, it is optimal to start vaccinating group C, followed by group B, for sufficiently high vaccination rates (such that it takes less than 700 days to cover the entire susceptible population). However, at lower vaccination rates it is optimal to start vaccinating the middle-aged (group B) first in order to minimize the total number of deaths. When the aim is to minimize the total number of infected people or the peak share of infectees or to maximize economic output, group B should be vaccinated first, while vaccinating group C would yield the worst outcomes, at all vaccination rates.

If capacities for swift vaccinations of the population are limited it is thus unambiguously optimal to start vaccinating group B first. In contrast, we obtain a trade-off between minimizing fatalities and the other three outcome variables at higher vaccination rates. Vaccinating group C implies less deaths, but it comes at the cost of a higher share of the population becoming infected and therefore also a smaller economic gain from vaccinations. The negative consequences of vaccinating group C rather than group B first are largest at intermediate vaccination rates.

4 Sensitivity analysis

In what follows we examine how sensitive the above results are to changes in the parameter values for the efficacy of the vaccine and the general transmission rate.

4.1 Vaccine efficacy

Naturally, a higher efficacy of the vaccine is associated with a lower fatality rate, a lower total number of infected people and a lower peak share of infectees, as well as larger economic gains from vaccinations for all strategies under consideration. For example, when $\beta = 0.25$ and $u = 0.0025$ (such that it would take 321-332 days to vaccinate all susceptible persons) the fatality rate is 728-800 per million people for $e = 0.5$, which decreases to 476-648 per million people for $e = 1$. The total share of infected persons is 17.4-20.2 per cent for $e = 0.5$, which is reduced to 15.5-18.6 per cent for $e = 1$. The peak share of infectees is 0.53-0.55 per cent of GDP for $e = 0.5$, which decreases to 0.51-0.53 per cent for $e = 1$. Finally, the economic gain is 0.06-0.12 per cent for $e = 0.5$, which increases to 0.09-0.15 per cent for $e = 1$. Although we obtain improvements with respect to all our four measures by increasing the efficacy, the reduction in the peak infection rate is only marginal, which is due to the fact that vaccinations are initiated at a time with relatively low transmission rates.

In terms of the ranking of strategies the general pattern is qualitatively similar for different efficacy levels. In particular, fatalities are minimized by strategy CBA for sufficiently high vaccination rates and by vaccinating group B first at low vaccination rates, while the total number of infectees and the peak share of infectees are minimized and economic output is maximized by vaccinating group B first. The threshold value for u, below which first vaccinating the middle-aged (group B) minimizes fatalities, decreases in the efficacy rate; it is 0.002475 (such that it would take 336 days to vaccinate the entire susceptible population under strategies BAC and BCA) when $e = 0.5$ and 0.00105 (such that it would take more than two years to vaccinate all susceptible persons under all vaccination strategies) when $e = 1$. Hence, the effect of a lower vaccine efficacy resembles the effect of a lower vaccination rate.

Numerical simulations confirm that an increase in vaccine efficacy has a similar impact as a higher vaccination rate on outcomes. For example, doubling the vaccination rate to $u = 0.005$ when $e = 0.5$ implies a fatality rate of 519-620 per million people, a total share of infected persons of 15.5-17.7 per cent, a peak infection rate of 0.51-0.53 per cent and economic gains of 0.10-0.15 per cent. By comparing these numbers to the ones above for $e = 1$ and $u = 0.0025$ we thus find that improvements in terms of our outcome measures are similar, but slightly stronger, when the vaccination rate rather than the vaccine efficacy is increased.

4.2 Transmission rates

If the transmission rates increase uniformly, this will obviously lead to more fatalities, a higher total share of infected persons and a higher peak number of infectees at all vaccination rates for all strategies. Not surprisingly, the economic gain from vaccinations also increases as transmission rates increase. We obtain qualitatively similar results regarding which strategies are best in terms of our outcome measures, with one important exception. For general transmission rates

below 0.205 and above 0.271, it is optimal to implement strategy CBA to minimize fatalities at all vaccination rates.

The gains from increasing the vaccination rate in terms of the four outcome measures become more pronounced for higher transmission rates. In what follows we present simulation results when $\beta = 0.3$ (implying a R_0-value of 1.5) and $e = 0.9$. Figure 7 illustrates how the fatality rate decreases from 3383 per million for $u = 0$ to 357-826 per million for $u = 0.01$. Clearly higher rates of transmission make increasing vaccination capacities more urgent to avoid a high number of deaths. As noted above, group C should be vaccinated first at all vaccination rates when the virus spreads quickly to reduce the number of deaths among the elderly.

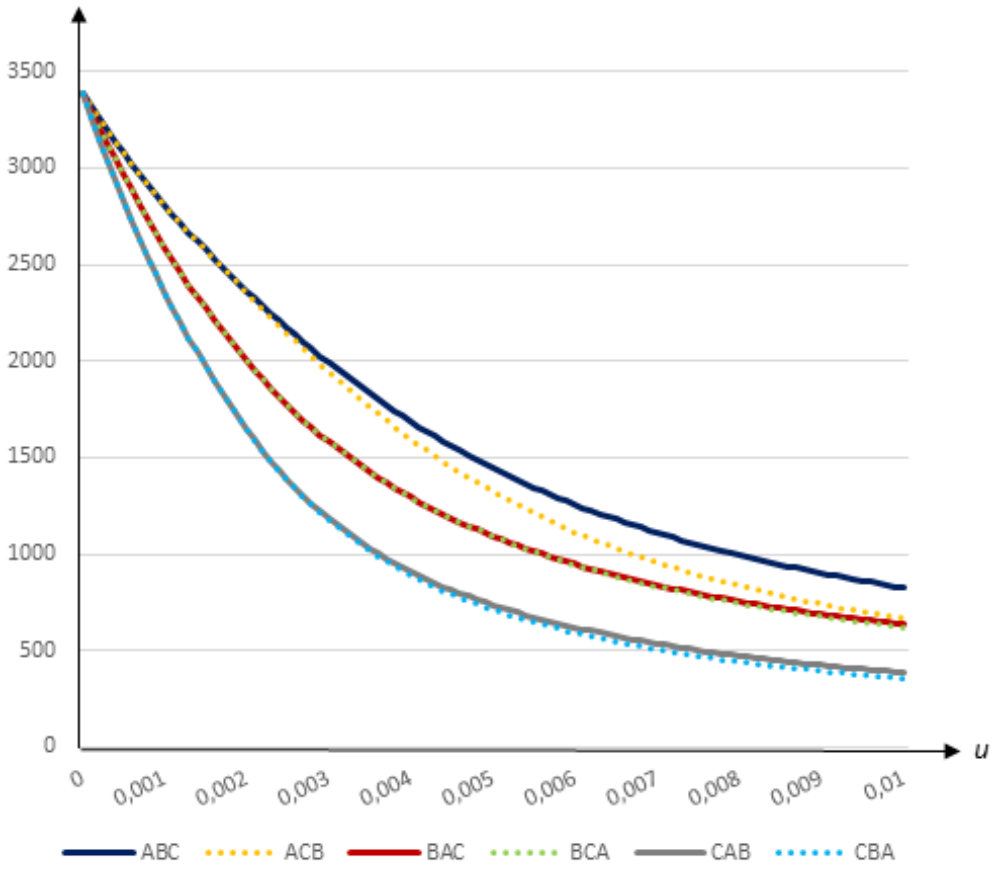

Figure 7. The number of deceased (per million) in relation to the vaccination rate when $\beta = 0.3$ and $e = 0.9$.

The total share of infected persons decreases substantially in the vaccination rate, from 44.6 per cent for $u = 0$ to 15.5-19.8 per cent for $u = 0.01$, as shown by Figure 8. Also in terms of the total number of infected people increases in the vaccination rate lead to substantially better

outcomes. The difference between vaccinating group B rather than group C first becomes larger when the virus spreads more quickly, in particular at intermediate vaccination rates.

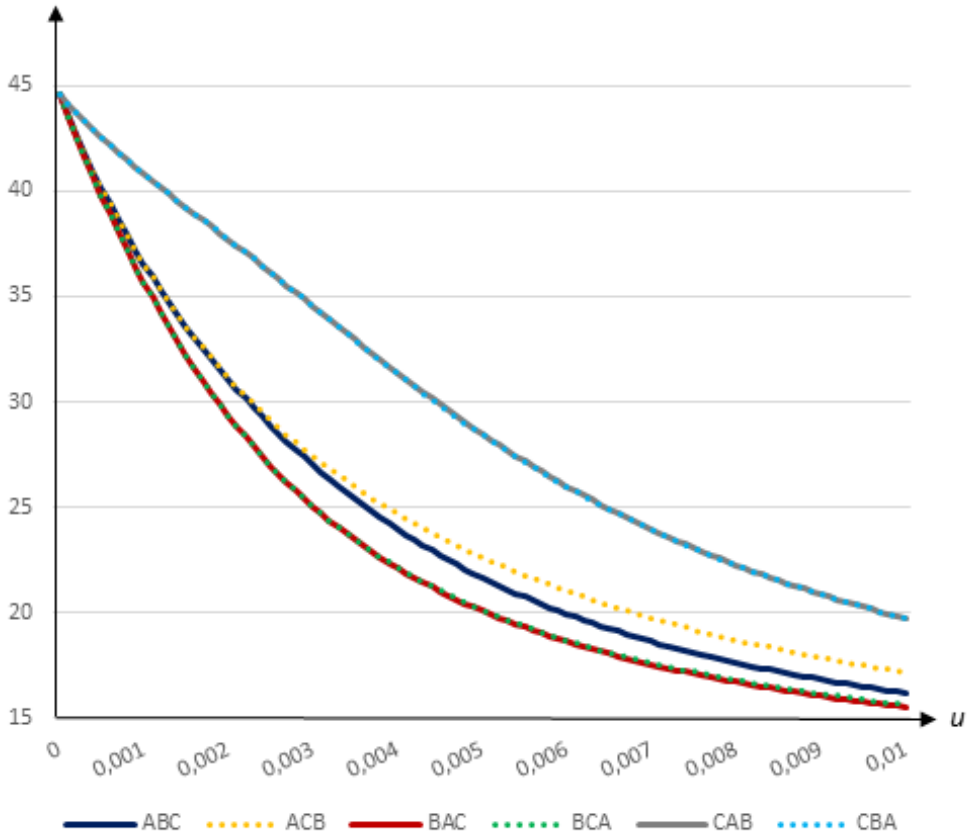

Figure 8. The total share of infected people (per cent of population) in relation to the vaccination rate when $\beta = 0.3$ and $e = 0.9$

The impact of an increasing vaccination rate on the peak infection rate becomes much stronger when the general transmission rate increases. Figure 9 shows how the peak share of infected people decreases from 2.49 per cent for $u = 0$ to 0.74-1.12 per cent for $u = 0.01$. It also clearly demonstrates that vaccinating group B rather than group C first yields substantially better outcomes, especially at intermediate vaccination rates, which is a crucial factor to account for to avoid the health care system becoming overwhelmed in case the virus spreads quickly.

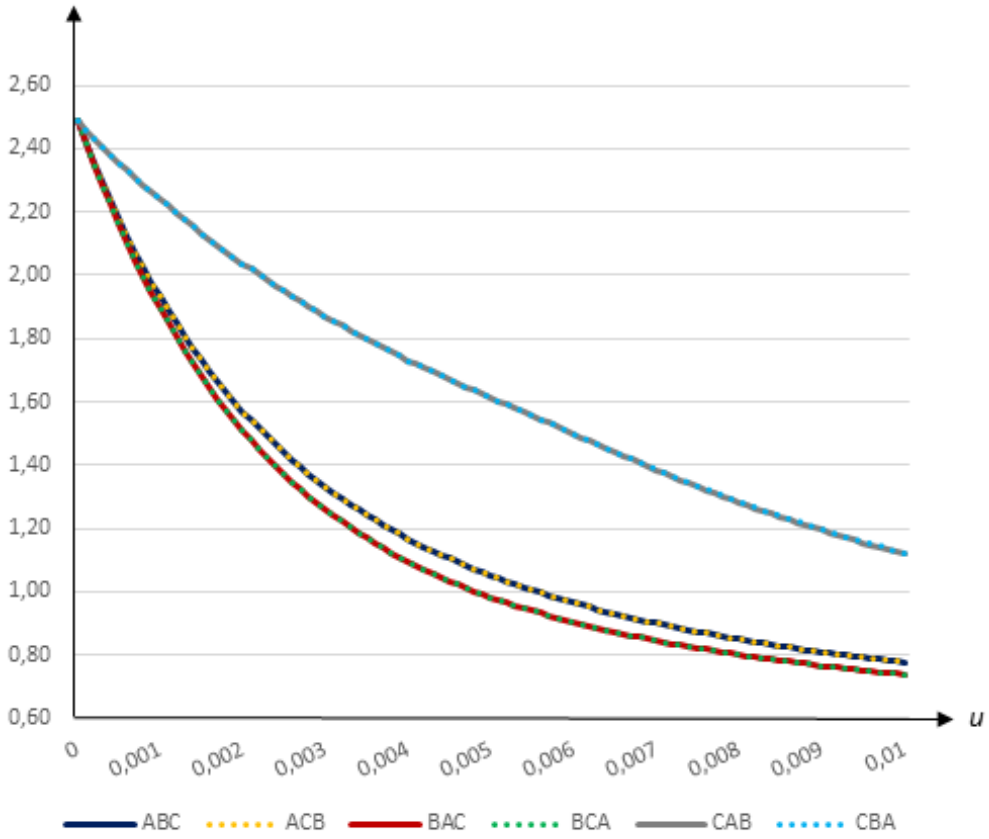

Figure 9. The peak share of infected people (per cent of population) in relation to the vaccination rate when $\beta = 0.3$ and $e = 0.9$

Economic gains increase in the vaccination rate, and they reach 0.41-0.53 % for $u = 0.01$, as shown in Figure 10. The results in section 3.4 are confirmed. Vaccinating the middle-aged first yield the best economic outcomes, particularly at intermediate vaccination rates.

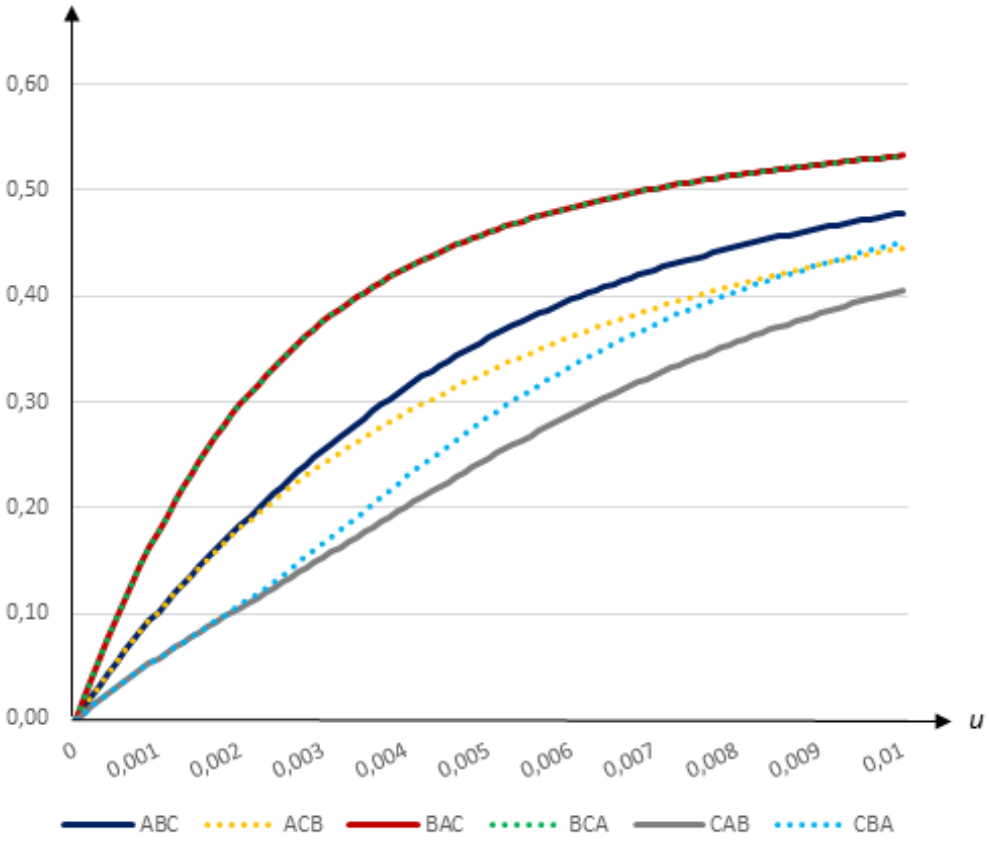

Figure 10. The economic gain from vaccinations (per cent) in relation to the vaccination rate when $\beta = 0.3$ and $e = 0.9$

To summarize, although the general pattern becomes more pronounced, it remains qualitatively the same for higher transmission rates. Fatalities are substantially lower when group C gets vaccinated first, while vaccinating group B first leads to considerably lower total and peak shares of infectees, as well as higher economic gains from vaccinations. Thus, the trade-off between these two alternative approaches becomes more apparent.

For example, given a vaccination rate of $u = 0.0025$ (implying that it would take 256 days to cover all susceptible persons) and an efficacy of $e = 0.9$, the fatality-minimizing strategy CBA leads to 1382 deaths per million, 36.1 per cent of the population becoming infected, a peak infection rate of 1.95 per cent and economic gains of 0.14 per cent, while implementing strategy BAC (which would last for 293 days) would lead to 1771 deaths per million, 27.0 per cent of the population becoming infected, a peak infection rate of 1.37 per cent and economic gains of 0.34 per cent. In the Swedish case, choosing strategy CBA rather than strategy BAC would imply 4042 fewer deaths, but almost one million more infected persons, a peak number

of infected people about 60 000 higher and foregone economic gains of 1.23 billion dollars (10.2 billion SEK).

The gains from accelerating the administration of vaccines are more substantial at higher transmission rates. By doubling the vaccination rate to $u = 0.005$ (such that it would take 144 days to vaccinate all susceptible persons) when implementing strategy CBA, fatalities would be reduced by 700 per million, the total share of infected persons would decrease by 7.7 per cent, the peak infection rate would fall by 0.34 per cent and economic gains would be 0.15 per cent higher. In the Swedish case this would imply almost 700 fewer deaths, about 800 000 fewer infected persons, a peak number of infected about 35 000 lower and economic gains of 0.9 billion USD (7.47 billion SEK).

5 Conclusions

We analyze a vaccine campaign against Covid 19 in a stylized model with three age groups that are roughly calibrated to Swedish demographic data. The age groups differ with respect to their fatality rates. Crucially, we also account for heterogeneity in contact patterns within and between age groups, such that the transmission parameters are specific to each pair of age groups.

A vaccine campaign can either prioritize the most fragile part of the population to protect them from the infection or aim at quickly eradicating the infection, in which case age groups with high transmission rates should be vaccinated first. We show that fatalities are almost always minimized by first vaccinating the elderly, followed by the middle-aged group. However, for some combinations of low vaccination rates and low transmission rates (e.g. due to restrictions) deaths are minimized by first vaccinating the middle-aged group; the lower is the efficacy of the vaccine, the wider is the range of vaccinations rates, for which this is true. This is due to a strong decrease in the spread of the infection, as the middle-aged have high transmission rates within their own group as well as to the other age groups. A policy implication for countries where vaccinations cannot progress at a high rate and the vaccine efficacy is not so high might therefore be to impose further restrictions in order to protect the elderly and to start vaccinating the working-age population first. Thereby deaths would be minimized, while at the same time the spreading of the disease would be countered most efficiently.

In terms of other outcome measures such as the total number and the peak number of infected persons it is always best to start vaccinating the middle-aged group first, because this groups is driving the infection through its many social contacts with the other age groups. Vaccinating the young first is never optimal. This group has a very low fatality rate, and the fact that intra-group transmission rates are high is of less importance, because the transmission rate to other groups, in particular the elderly, is relatively low.

When it comes to the economic gains from vaccinations it is always best to start vaccinating the middle-aged group first as this group has the highest productivity. We also demonstrate that there are substantial economic gains, in addition to the health benefits, from a speedy vaccination campaign. In our model we obtain a low benchmark for the gains from doubling the vaccination rate, such that covering the entire susceptible population would take 168 rather than 325 days, of 0.28 billion USD (2.34 billion SEK) in the case of Sweden.

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