How quickly can we get back to the pub?

An investigation into the impacts of the N501Y variant, population immunity and vaccine distribution strategies on COVID-19 spread.

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Abstract

COVID-19 has caused unprecedented damage to public health and the global economy. Effective vaccines offer hope that the pandemic can be controlled quickly, however, the best method of vaccine distribution in light of the new N501Y variant of COVID-19 remains unclear. Here, we update DELVE's Test, Track and Isolate (TTI) Simulation [1] to accommodate: 1) POLYMOD's [2] high fidelity contacts database, 2) Contact immunity via vaccination, and 3) The N501Y variant of COVID-19. We use our updated model to compare the UK Government's existing vaccination strategy that prioritises the elderly with novel strategies prioritising different age groups to see which yields the lowest R and mortality rates. Then, we assess how the different age groups affect these rates using relative First-Order Sobol indices.

We find that the existing distribution strategy provides the lowest mortality rate, but to reduce the R rate and the number of deaths (a combination of mortality and R rates), prioritising vaccinations of 31-50 year olds is the most effective strategy. This finding was corroborated by the sensitivity analysis which showed that 31-50 year olds have the largest impact on the R rate, whilst 51-70 year olds have the largest effect on mortality rate. In addition, we investigated changes to the R and mortality rates based on a range of attack rates, vaccine efficacies, and population immunity proportions. We find that current restrictions (S5) are not sufficient to keep the R rate below one for the new variant; that the R rate is largely unaffected by vaccine efficacy; and that at least 25% of the population must be immune for the R rate to remain below one with restrictions and 75% without restrictions.

1 Introduction

COVID-19, caused initially by SARS-CoV-2, has led to loss of life, pressure on healthcare systems and damage to the global economy. To contain the spread of the disease, the R rate - the average number of people infected by a positive COVID-19 case - must be below one. To reduce the R rate, a number of interventions are required, including: national lockdown [3, 4], local restriction tiers, and a Test and Trace system [5]. More recently, vaccines from AstraZeneca, Pfizer and Moderna were approved offering hope of a resolution to the pandemic [6]. This development raises questions about how best to roll out the vaccines in combination with other restrictions to minimise the R rate whilst allowing society maximum freedom.

Throughout the pandemic, the UK Government relied upon scientific advice to determine the impact of government policies. Part of the scientific advice arose from simulations run by a Royal Society Team, DELVE [7]. They produced a simulation based on contact data from the BBC Pandemic dataset [8] to simulate the R rate given different Test Trace and Isolate (TTI) policies [9]. Whilst useful to assess different TTI policies, the current version of the simulation does not allow the user to assess the effect of vaccination on disease propagation, nor does it accommodate the new variant of COVID-19 (N501Y).

1.1 New Variant (N501Y)

In October 2020, a new variant of the SARS-CoV-2 virus was detected in England [10]. The new variant N501Y (B.1.1.7.) has become highly prevalent in the South-East and London accounting for around 60 percent of COVID-19 cases in these areas [11]. It is spreading faster and caused an increase in the R rate of between 0.4 and 0.7 during the November lockdown [12]. It seems likely that N501Y will affect the spread further, and therefore, a simulation to determine its impact on the R rate, and what level of government restrictions are required would be valuable.

1.2 Vaccination

As of January 2021, three COVID-19 vaccines have been approved in the UK [13]. The approved vaccines are being administered in two doses with a recommended gap of three weeks between each injection [14]. The first dose offers from between 64 and 85% protection while the second dose increases this to between 70 and 95% efficacy [15] [16].

Millions of people in the UK have now been vaccinated [17]. The focus has moved from development of the vaccines to effective distribution - especially considering the higher infectiousness of the new variant. The UK Government policy thus far consists of two phases. In the first phase, they intend to reduce the mortality rate of COVID-19 and reduce the pressure on the NHS, by giving the vaccine to the most at-risk groups [18]. This consists of mostly older people and those with pre-existing conditions. In this report, we simulate the impact of various distribution strategies on the R rate and the average mortality rate.

1.3 DELVE TTI Simulator

The DELVE TTI Simulator [1] models individual-level transmission of COVID-19. It was developed to assess the spread of COVID-19 (with and without TTI) under possible tiers of government restriction. By varying the stringency of the restrictions, the R rate can be compared.

It simulates transmission from a COVID-positive individual to contacts in their household, work, school or elsewhere. This contact data comes from the BBC Pandemic dataset, and likelihood of transmission to a contact in a particular setting is defined by a set of Secondary Attack Rates (SAR) [19]. The simulation first generates a number of primary cases, with a certain probability that each is under 18. Then, for each primary case, the BBC Pandemic data is sampled to find their contacts. Based on the SAR for each setting, we sample to identify infected contacts. These infections are used to find a base R rate - the number of people infected by one primary case. TTI eliminates some of these secondary cases through the primary case testing positive and isolating. This is used to find an effective R rate.

Whilst the simulation works well to find the R rates, it has a number of simplifications:

- Primary cases are not categorised by demographics beyond over 18 and under 18;
- Contacts are not categorised by demographics;
- Previous secondary contacts do not affect future primary cases;
- Mortality rates are not considered; and
- Immunity of contacts is not considered.

1.4 Project Aims

In this project, we tackle three questions that DELVE did not consider, these are:

1. How does the infectiousness of the new variant affect the R rates and mortality rate? What stringency of government restrictions would be required to keep the R rates below one?
2. How does population immunity impact the R rates and mortality rate? What proportion of the population must be immune (either by vaccination or having contracted the disease) to ensure the R rates below one?
3. How do differing vaccination distribution strategies affect the R rates and mortality rate? Can we design a distribution strategy that has a lower mortality and disease spread than the government's existing plan?

2 Related Work

Shortly after the COVID-19 outbreak in Wuhan, reports confirming that the virus would become a severe pandemic were released [20]. This led to massive concern worldwide, pushing nations to research everything from virus composition to possible strategies to eliminate the spread. Research relevant to this project falls into one of four categories: 1) Epidemiological modelling, 2) N501Y effects, 3) Population immunity and 4) Vaccination.

Epidemiological modelling: For our research, we used the DELVE TTI simulator as a base and modified it to include N501Y, population immunity, and vaccination distribution strategies. A similar simulator is the COVID-19 Open-source Infection Dynamics (COVOID) which models COVID-19 and other infectious diseases using deterministic compartmental models [21]. COVOID enables simulation of the virus with demographic-specific contacts, social distancing, and government interventions. It does not, however, accommodate levels of population immunity in its analysis. A Danish COVID-19 simulator, Corona-land, models COVID-19 spread and the effect of containment measures [22]. It is an exploration and learning tool and not intended as a professional tool to assist with decision making. The simulator does not consider vaccine strategies or any demographic-level contacts.

N501Y effects: In this research, we analyse the effect N501Y has on the R rates and mortality rate. N501Y's increased SAR has been reported widely, notably in [23, 24, 25] which focus on the composition of the new variant compared to other strains of COVID-19. Volz et al. [23] look at the fast growth of the R rate of N501Y, while SAGE's paper [26] (the UK Government's Science Advisory Group) focuses on mitigating the effects of the new variant N501Y by introducing stricter lockdowns. This paper states that the new variant's R rate could be 39% higher than existing variants and that the SAR is upto 71% higher. To the best of our knowledge, nobody is yet to research the affect of N501Y on the mortality rate in the UK.

Population immunity: The key concept of herd immunity and the part it plays in containing the pandemic is discussed in [27, 28]. These reports, however, do not consider the effects of N501Y. Furthermore, herd immunity and vaccination strategies are analysed in [29] where the authors use a mathematical model to model COVID-19 spread given various levels of population immunity. To contain the virus, nations are acquiring and distributing vaccines to achieve sufficient herd immunity.

Vaccination: The UK's Department of Health & Social Care released a detailed paper covering their vaccination strategies on the 11th of January 2021 [30]. In the paper they state that the priority groups are 1) residents in care homes, 2) people over 80 years and front-line health and social care workers, 3) people over 75 years old, and 4) people over 70 years old and clinically extremely vulnerable individuals. These groups are prioritised with the aim of reducing the COVID-19 mortality rate and the protection of health and social care workers. The paper does not provide quantitative justification for this distribution strategy.

Moghadas et al. analyse the impact of vaccination on COVID-19 spread in the United States [31]. They simulate the transmission of COVID-19 using US demographic and contact data. In the paper they prioritise healthcare workers and high-risk individuals for vaccination. Given a vaccine efficacy of 90%, 40% population vaccine coverage, 10% pre-existing population immunity they predict an effective R rate of 1.5. They suggest that vaccinations could lead to a reduction in infections numbers of 77% and deaths of 85%.

Other papers focus on the logistical challenges of COVID-19 vaccine distribution, considering cold storage, syringes, needles and required staff [32]. Asgary et al. simulate the most efficient way to vaccinate people in a mass drive-through vaccination clinic [33]. Meanwhile, Persad et al. focus on prioritising groups for vaccination ethically [34].

3 Methodology

To answer the questions posed in 1.4, we augmented the DELVE TTI Simulator to include: a new, high-fidelity contact dataset (3.1), contact propagation (3.2), the new variant N501Y (3.3), vaccination distribution (3.4), and mortality rate simulation (3.5). In this section, we will discuss each of these amendments to the simulator in turn. All of our code is available on our GitHub repository [35].

3.1 Contact Dataset

The original simulation does not consider the differing demographics of contacts for a given primary case. Therefore, we needed to introduce a more granular social contact database. The first idea was to semi-automatically label clusters of people in the BBC Pandemic database. We attempted to do this using K-means clustering, but Figure 1 shows that clusters were not well defined and separating the participants of the BBC Pandemic contact database into demographic groups based on numbers of contacts would have been challenging.

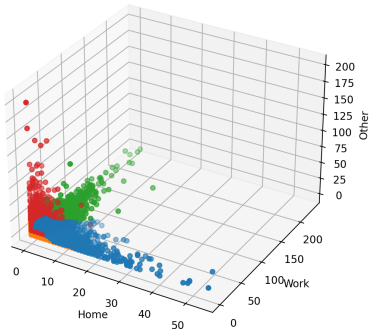


Figure 1: Clusters found using K-means clustering (k=5) on over 18 contacts

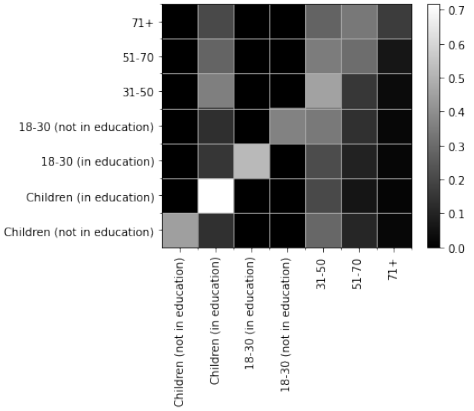


Figure 2: Heatmap of contacts between various groups. Value of (x, y) denotes the probability of x having a contact with group y.

We instead used the POLYMOD database [2] which was constructed as part of a European Commission funded project to study the movement of infectious diseases in 2008. They had 7,290 participants, who recorded the characteristics of their 97,904 contacts. Importantly, the dataset tells us the age of both the participant and their contacts. We split both sides of the contact into specific demographic groups reported in Table 1.

Demographic Group	Number of participants
Children not attending school	953
Children attending school	1637
18-30 year olds still in education	309
18-30 year olds not in education	732
31-50 year olds	1696
51-70 year olds	1516
70+ year olds	216

Table 1: Table of participants in POLYMOD study

We pre-processed the POLYMOD data into a format similar to the BBC Pandemic dataset. We produced a CSV file for each of the demographic groups that denoted the number of contacts they had with each other group in three different settings: (1) Home, (2) Work / School, (3) Other. Figure 2 shows how the contacts are significantly more likely between people of the same demographic but shows two main demographics as having the most contacts across all groups: children in education and 30-50s.

When a primary case is generated, it is assigned a demographic group randomly. The probability with which this is assigned is found by weighting by the historic COVID-19 cases proportions according to the Office for National Statistics (ONS) figures [36].

3.2 Contact Propagation

The next step is adding a propagation of contacts between primary cases. We do this by modifying the contact generation (`generate_contacts` in `contacts.py`) function. Because of the work in 3.1, when sampling from a row of the dataset for a given primary case, we know the demographic

group of secondary contacts. We return this as a probability distribution. This can be used as the input probability distribution for a new primary case's demographic group. For each simulation run, we generate 1000 independent primary cases before recursing on each 20 times. The R rates and mortality rates are averaged over all simulations.

3.3 N501Y

In order to address question 1 in section 1.4, we analyse the new variant N501Y and its effect on the R rates and mortality rate. We modified the SAR for work, home, and others in the existing Delve TTI model's contacts config. The contacts model of the TTI follows the model of Kucharski et al. [19] for contacts generation. We simulate the new variant by increasing the SAR for each contact category. As mentioned in 2, N501Y increases the SAR of COVID-19 by up to 71%. Given the uncertainty in this estimate, we analyse its effect by increasing the SAR from 0-100%.

3.4 Vaccination

To answer question 3 posed in section 1.4 we amend the Delve TTI model to accommodate three vaccine-related parameters: 1) Distribution strategies, 2) Efficacy i.e. the probability of a vaccine recipient being immune, and 3) Dosing i.e. the change to 2) based on a single-dose or double-dose vaccination regime. To assess the varying effect of changes to these parameters on disease spread and mortality, we hold some other distribution parameters constant, namely the future date when the simulation runs and the number of vaccinations expected to have been distributed by said date. We define the simulation date to be the end of Q1 2021 (31/03/2021), and the number of doses administered by that time to be 20 million. This follows from an expected roll-out of two million doses per week for 12 weeks with an allowance for distribution ramp-up [37]. We believe an assessment of vaccine strategies at this time provides a non-trivial solution as vaccine rates beyond 50% of the population begin to eradicate the virus regardless of distribution strategy [38].

3.4.1 Vaccine Factor

Distribution strategies are summarised by a `vaccine_factor` added to `generate_contacts`. The `vaccine_factor` is the probability that a contact with the primary case has immunity to COVID-19 via vaccination:

$$vaccine\_factor = \mathbb{P}(V|D, a) \times e \tag{1}$$

where $\mathbb{P}(V)$ is the probability of being vaccinated, D is the vaccine distribution strategy represented as the probability of a person in each demographic group having received a vaccine by end of Q1 2021, and e is the efficacy of the vaccine. In this section, we will describe how both the vaccine efficacy e and distribution strategies D are defined in our model.

The vaccine efficacy is defined as a weighted sum of the expected number of AstraZeneca, Pfizer and Moderna doses available for distribution in Q1 2021 and their associated efficacies in the single-dose and double-dose regimes. The doses and efficacies of each vaccine are reported in Table 2, with figures taken from stage 3 trials reports in [15] [16] and [39]. Our single-dose weighted average efficacy is 68.3% and our double-dose weighted average efficacy is 75.8%.

In our analysis we look at a five vaccine distribution strategies:

1. Existing government approach (elderly prioritised), as per [40];
2. Young people prioritised (including children);
3. Young people prioritised (excluding children);
4. Prioritising 30-50s
5. Equal allocation.

Strategies 2), 3) and 4) are used to understand whether vaccinating younger people with more contacts than the elderly will slow the spread of the disease quicker than the existing approach. Children have been included for analysis, but we appreciate that they are unlikely to receive the vaccine before it has been tested on them in regulatory trials.

Vaccine	Doses (million)	Share (%)	Single-dose efficacy (%)	Double-dose efficacy (%)
Pfizer	10	19.2	82	95.0
Moderna	2	3.8	≈85 [42]	95.2
Astrazeneca	40	76.9	64	70.0

Weighted single-dose efficacy (%)	68.3
Weighted double-dose efficacy(%)	75.8

Table 2: Vaccine efficacies and their weighted average efficacy based on number of doses available to the UK Government by the end of Q1 2021. The weighted average is reported for both single and double-dose regimes

		Single-dose Distribution Strategies				
Demographic Group	**Group Population (millions)**	**Gov**	**Young People (inc. children)**	**Young People (excl. children)**	**31-50s**	**Equal**
Children attending school	14.3/?	0	1	0	0.0271	0.3
Children not attending school	14.3/?	0	1	0	0.0271	0.3
18-30 year olds still in education	2.4	0.109	0.533	1	0.0271	0.3
18-30 year olds not in education	8.3	0.159	0.533	1	0.0271	0.3
31-50 year olds	18.7	0.409	0	0.5	1	0.3
51-70 year olds	15.3	0.226	0	0	0.0271	0.3
70+ year olds	7.8	1	0	0	0.0271	0.3

Table 3: Probabilities of each demographic group receiving a vaccine by the end of Q1 2021 for each our 5 distribution strategies, under the single-dose regime. The probabilities are calculated based on an assumed 20 million vaccine doses available for distribution.

		Double-dose Distribution Strategies				
Demographic Group	**Group Population (millions)**	**Gov**	**Young People (inc. children)**	**Young People (excl. children)**	**31-50s**	**Equal**
Children attending school	14.3/?	0	0.67	0	0	0.15
Children not attending school	14.3/?	0	0.67	0	0	0.15
18-30 year olds still in education	2.4	0	0	0.93	0	0.15
18-30 year olds not in education	8.3	0.05	0	0.93	0	0.15
31-50 year olds	18.7	0.05	0	0	0.535	0.15
51-70 year olds	15.3	0.05	0	0	0	0.15
70+ year olds	7.8	1	**0**	0	0	0.15

Table 4: Probabilities of each demographic group receiving a vaccine by the end of Q1 2021 for each our 5 distribution strategies, under the double-dose regime. The probabilities are calculated based on an assumed 20 million vaccine doses available for distribution.

The strategies are stored as a vector with each element representing the probability of a contact from each of our demographic groups (3.1) having received a vaccine by the end of Q1 2021. For the existing government approach, this probability was obtained by finding the number of people in each demographic group from the ONS figures [41] and calculating the number of people who will receive the vaccine by March 2021 based on their prioritisation approach. The probability of receiving a vaccine differs depending on whether we choose to administer double-doses or single-doses, as such we make calculate distribution proportions in both cases. Table 3 reports the distribution proportions for the single-dose regime and Table 4 reports the same for the double dose regime.

The vaccine factor is passed into the `generate_contacts` function such that every contact is assigned a probability of having immunity based on the probability they have received a vaccine (conditioned on their age and on the dosing regime) and the probability the vaccine is effective (conditioned on the efficacy of the vaccine and on the dosing regime).

3.5 Mortality Rate

We define the mortality rate as the probability of any contact to a COVID-19 positive individual dying. To find this, we first define the mortality rates for each demographic group. This uses empirical mortality rates from New York, Italy and China from the start of the pandemic [43]. This was before doctors had understood how best to treat the illness and reduce the mortality rate. Thus, any changes in mortality rate will be exacerbated.

The mortality rate per run of the simulation is defined as follows:

$$mortality\_factor = (1 - vaccine\_factor) \circ mortality\_rate\_per\_demographic\_group \quad (2)$$

$$mortality\_rate = \begin{bmatrix} mortality\_factor \cdot age\_dist\_for\_home\_contacts \\ mortality\_factor \cdot age\_dist\_for\_work\_contacts \\ mortality\_factor \cdot age\_dist\_for\_other\_contacts \end{bmatrix} \cdot \begin{bmatrix} \frac{n\_of\_pos\_cases\_home}{n\_of\_total\_contacts} \\ \frac{n\_of\_pos\_cases\_work}{n\_of\_total\_contacts} \\ \frac{n\_of\_pos\_cases\_other}{n\_of\_total\_contacts} \end{bmatrix} \quad (3)$$

The mortality rate is averaged over all runs of the simulation. It is important to note that the number of deaths would be impacted by both the number of cases and this mortality rate. A drop in either of these would reduce the number of deaths.

4 Evaluation

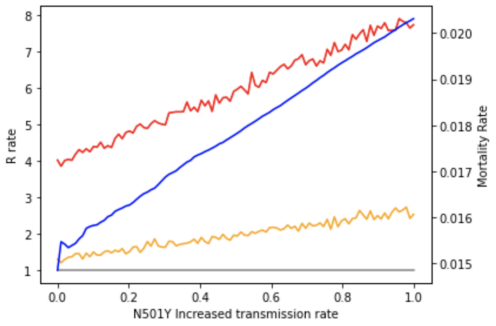
4.1 N501Y

To evaluate the consequences of the increased transmission of N501Y, we look at the base R rate, the effective R rate, and the mortality rate. Figure 3a shows the impact of increasing the SAR. For an increase of 40%, the base R rate increases by approximately 45% and the effective R increases by 33%. For an increase in the SAR of 70%, the base R rate increases by 82% and the effective R increases by 49%. As we would expect, the mortality rate grows when the base R rate grows.

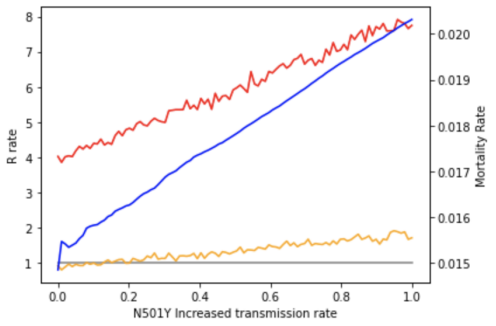
To stop the rapid spread of the virus, the R-rate needs to be below one - represented by a grey line in Figure 3. Figure 3a shows the effective R rate is greater than one for all increases in virus transmission at stringency level S3. As such, the UK government must introduce stricter approaches than S3, which they did by announcing the third UK national lockdown at the beginning of January 2021 [44].

Figure 3b shows the impact of N501Y increased transmission on the effective R rate when stringency level S5 is considered, which is comparable to national lockdown. Neither the base R rate nor the mortality rate is affected by the TTI strategies, therefore we can only see a change in the effective R rate. The effective R rate starts below one, but it exceeds one when the SAR increases more than approximately 24%. This indicates greater restrictions would likely be required to prevent the rapid spread of N501Y.

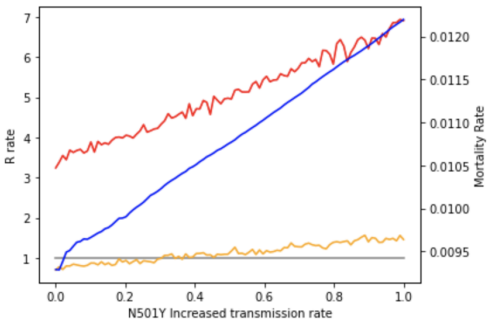
By amending the simulation to add both stringency level S5 and the 30% of the population vaccinated, the effective R rate does not exceed one until the increased SAR reaches approximately 64%, as



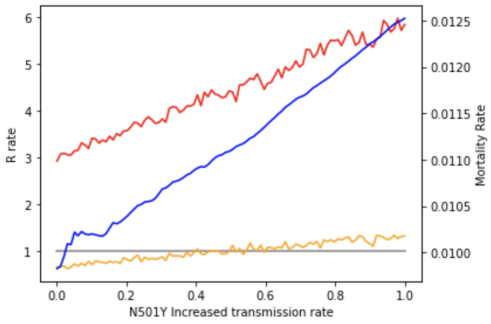
(a) Stringency level S3



(b) Stringency level S5



(c) Stringency level S5 and the government's vaccination strategy



(d) Stringency level S5 and the most effective vaccination strategy

Figure 3: Impact on the effective reproduction number, the base reproduction number, and the death rate when the virus becomes more infectious with various stringency levels and vaccination strategies. Red: base R, orange: effective R, blue: average mortality rate.

shown in Figure 3d. This indicates that we can hopefully contain the spread by combining an extreme lockdown and rapid vaccination roll-outs.

4.2 Population Immunity

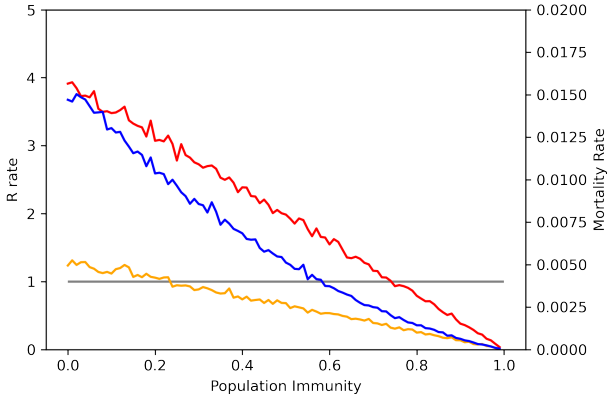


Figure 4: Effect of population immunity proportion on base R rate (red), effective R rate (orange) and mortality rate (blue). For each population immunity increment the model simulates 1000 primary cases with associated contacts.

In Q2 2020, there was much debate around how best to achieve so-called *herd immunity* - the proportion of the population that must be immune to COVID-19 to materially stop its spread. Such immunity can be achieved either by vaccination or by contracting the disease and developing antibodies. Strategies for optimising the former are found in section 4.3.2, but the latter helps slow community transmission too and is worth investigating. Dan et al. [45] suggest that those who have

contracted COVID-19 are immune for 8-months post infection, and as of December 2020 the ONS estimate population immunity is around 8.7% [46]. This existing societal immunity offers hope that fewer vaccine doses will be required to slow disease spread. Here, we investigate the the required proportion of population immunity needed to lower both R rates below one.

Figure 4 illustrates the results of the simulation. We are interested in the population immunity percentage for which both the effective and base R rates drop below one as this tells us when disease spread will begin to decay with and without restrictions. Figure 4 suggests that the effective R rate (with a stringency level of S3) does not drop below one until approximately 25% of the population are immune, and the base R rate does not drop below one until approximately 75% of the population are immune. The latter suggests restrictions will be required well past the end of Q1 2021 - the date of our simulation - where we estimate a maximum of 30% of the population could receive immunity via vaccination. As expected the mortality rate decreases approximately linearly from $\approx$1.75% to 0 as population immunity increases.

4.3 Vaccination

4.3.1 Vaccine Efficacy

There is uncertainty in the true efficacy of the vaccine given the phase 3 trials were conducted on a limited number of participants. To assess how differing vaccine efficacies affect the R number and average mortality we ran simulations with vaccine efficacy varying in the range 20-100% in 1% increments. For these simulations we follow the existing government vaccination strategy and assume a single-dose vaccination regime. Figure 5 illustrates the result of the simulation.

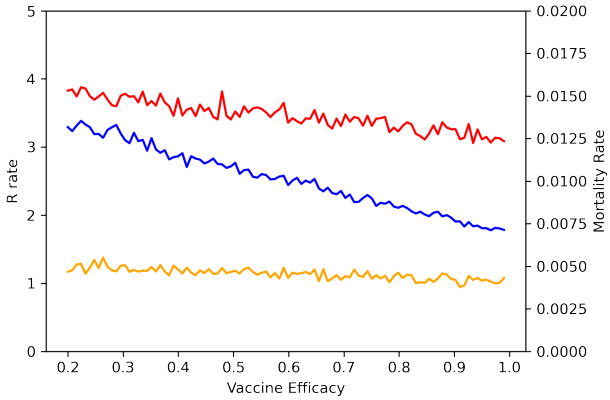


Figure 5: Effect of vaccine efficacy on base R rate (red), effective R rate (orange) and mortality rate (blue). For each vaccine efficacy increment the model simulates 1000 primary cases with associated contacts. The simulation follows the government's existing distribution strategy where the elderly are prioritised and assumes 20 million doses are distributed.

Both the base and expected R rates are not significantly affected by changes to the vaccine efficacy. When compared with Figure 4 which shows the R rate decreasing consistently with increased population immunity, these findings suggest that reductions in R rate are more sensitive to the absolute number of vaccinations rather than the efficacy of any individual vaccine. The mortality rate does indeed drop with increased efficacy as would be expected, but it does not reach zero as approximately 70% of the population are yet to be vaccinated at the time of simulation.

4.3.2 Distribution Strategy

We compare the different distribution strategies discussed in 3.4.1. The results are shown in Table 5 and Figure 6. Firstly, we can address the government decision to reduce number of doses per person (in a twelve week period) from two to one. This change is positive. The R rates (p=0.0002) and mortality rates (p=0.01) are reduced by a statistically significant margin.[1]

[1]Statistical testing is done with a paired t test with an alpha value of 0.05. The null hypothesis is that the two systems are the same.

n. of doses pp	Strategy	Base R rate (before TTI)	Effective R rate (after TTI)	Mortality Rate of contacts (%)
N/A	None (baseline)	4.04	1.44	1.63
2	Government	3.77	1.31	1.15
	Young (including children)	3.15	1.09	1.40
	Young (excluding children)	4.04	1.44	1.37
	Equal	3.45	1.24	1.22
	Prioritising 30-50s	3.36	1.07	1.17
1	Government	3.3	1.08	0.94
	Young (including children)	2.73	0.95	1.30
	Young (excluding children)	3.44	1.14	1.27
	Equal	3.17	1.02	1.02
	Prioritising 30-50s	2.94	0.94	0.95

Table 5: Results from various vaccine distribution strategies

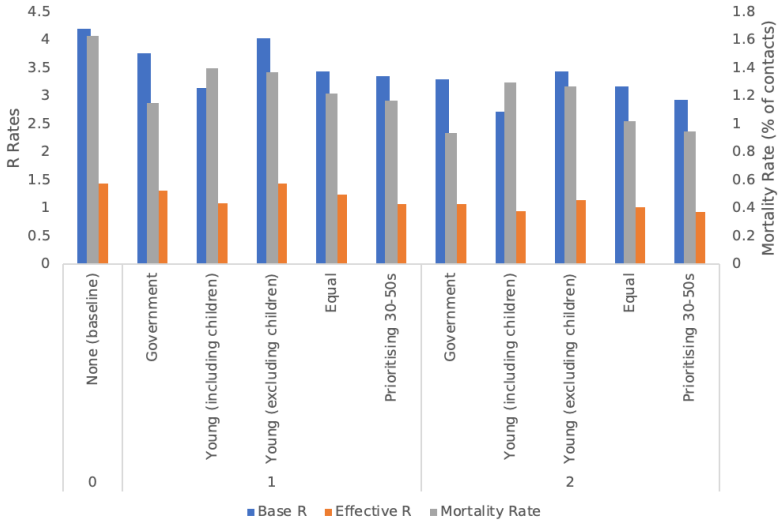


Figure 6: Bar Chart of R rates and Mortality Rate of different vaccine distributions

Looking at where vaccination doses are distributed, we first note that the government's strategy is effective at its aim. It has the lowest mortality rate for both one dose and two doses. However, this comes with a significant impact to the R rates. Since the actual number of deaths is a combination of both R rate and mortality rate, it appears likely that the government's strategy could lead to more deaths than other strategies. Amongst the lowest R rates come from the 'young including children' strategy, since they have the most contacts. This however, assumes that the infectiousness of COVID-19 is the same across all age groups. This is not true as children appear to be much worse vectors than other demographics, due to low susceptibility [47]. This is slightly reversed with the new variant [12]. Therefore, while the positive impact of the 'young including children' strategy appears overstated now, these figures might be true for the situation by March which will likely be dominated by the new variant. The lowest R rates come with a significant hit to mortality rate, with it performing 13% worse for 2 doses and 26% worse than the government's strategy. However, it performs significantly better than the method excluding children since children have more mobility across demographic groups.

The 'prioritising 30-50s' strategy appears to draw a good compromise between reduced mortality rate and reduced R rate. It has an R rate which is the same (no statistically significant difference) as the 'young including children' method with the same mortality rate as the government's strategy. This would likely lead to a lower number of deaths than the government strategy. 30-50s seem to have the most cross demographic contacts, therefore can spread cases to each group where it can widely spread inside that group. Hence, this investigation seems to suggest that an effective strategy should use one dose per person, whilst giving a large proportion of vaccines to 30-50 year olds.

To further investigate the impact of each group being vaccinated, we conducted a global sensitivity analysis looking at each groups' vaccination proportion's relative first order Sobol indices for base R (no TTI), effective R (with TTI) and mortality rate. These were found using Monte-Carlo simulation with Emukit running for 10,000 iterations. The results are in Figure 7. This shows how 31-50 year olds are amongst the most important for all of the rates. We can observe that TTI (higher importance for effective R rate than base R) has less of an effect on working young people and that they should perhaps be vaccinated before people in education. 50-70 year olds are the most important for mortality rate, but less important for R rates, whilst the opposite is true for children in education. This implies that an effective strategy to tackle the R rate and the mortality rate would be to give the majority of the vaccine doses available to those between 31 and 50, with other doses given to those above the age of 50.

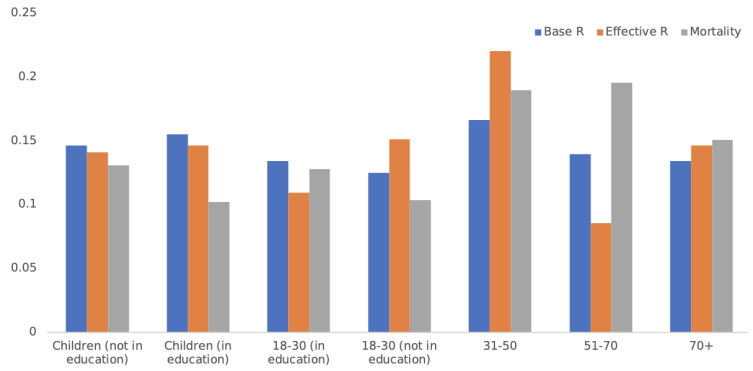


Figure 7: Relative First-Order Sobol indices for base R, effective R and mortality rate for vaccine distribution to different age groups

5 Future Work

Firstly, we should increase the flexibility of the simulation, allowing some currently fixed variables to change. The first of these is the number of vaccines distributed. Whilst we have chosen 20 million, as the number that the government are aiming for by March, there is much uncertainty in the true number of vaccines that will be distributed by then [48]. Another variable is the date of simulation; it would be useful to see the changing R rate as the date changes and we get closer to (or beyond March) and a progressively larger proportion of the population is vaccinated.

Additionally, it would be useful to increase the specificity of the demographic groups for the contacts database, especially splitting the 31-50, 51-70 and 70+ groups. This is because the contacts and mortality vary significantly within these groups. Therefore, it would be useful to consider the impact and importance of vaccinating sub-parts of these groups. In addition to this, it would be useful to extend the demographic groups to infectiousness. John et al. [49] have shown that the transmissibility of COVID-19 has varied significantly across demographics and our model currently does not consider this. In particular, we don't model the increased susceptibility and transmissibility of N501Y in children. Therefore, introducing different SARs for demographic groups would be important.

Currently, the mortality rate does not consider the impact of TTI, instead looking only at contacts who have the potential to be infected without TTI. It would be an important extension to consider how TTI impacts the mortality rate in different situations - since the likelihood of TTI having an effect is not constant across age demographics. It could also be interesting to introduce relative economic output as another measure of the impact of COVID. We would expect 30-50s to dominate in the importance for this group as well but this would be useful to validate.

Finally, as can be seen from 2, a lot of the theory and data that is used for the simulation comes from investigations into other similar illnesses. Hence, we could consider using this simulation for the spread of other illnesses with varied transmission mechanisms.

6 Conclusion

To conclude we'll provide answers to each of the questions posed in 1.4. The higher infectiousness of the new variant (N501Y) leads to a significant increase in the R rate and therefore an exponential increase in number of cases. With current estimates of the increased SAR of between 40 and 70%, we expect an increase in R rate of between 45% and 82%. The mortality rate would be expected to increase by between 17% and 28%. In order to control the new variant, a stringency level of higher than S5 would be required.

The level of population immunity required to reduce the base R rate below one was found to be 75%, and for the effective R rate to drop below one it was found to be 25%. In this report we estimate 20 million vaccine doses will be administered by the end of Q1 2021 which provides 30% of the UK population a 68.3% chance of immunity - as per Table 2. Adding current estimates of existing population immunity for those having recovered from COVID-19 (8.7%) [46], it is unlikely that more than 29% of the population will have immunity by Q2 2021. Restrictions will therefore need to be maintained beyond March if we want the effective R rate to remain below one.

When considering vaccination, we find that using a single dose offers a statistically significant improvement to both R rates and mortality rates. In order to reduce the mortality rate, the current government strategy is the most effective, but to reduce the number of deaths (a combination of R rate and mortality rate), prioritising 31-50 year olds is the most impactful strategy. It is also the best method for reducing the R rate since they have the most contacts across demographic groups. This was verified through the use of sensitivity analysis, comparing the first-order Sobol indices for each group's vaccination proportions. Hence, the simulation shows in order to best reduce the R rate, we should give most doses to 31-50 year olds (tackling most cross-group transmission), with the rest being equally spread across demographic groups in order to reduce in-group transmission. To reduce mortality, we should instead give the remaining doses to those more susceptible to dying from COVID, notably those between 51 and 70 and above 70.

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