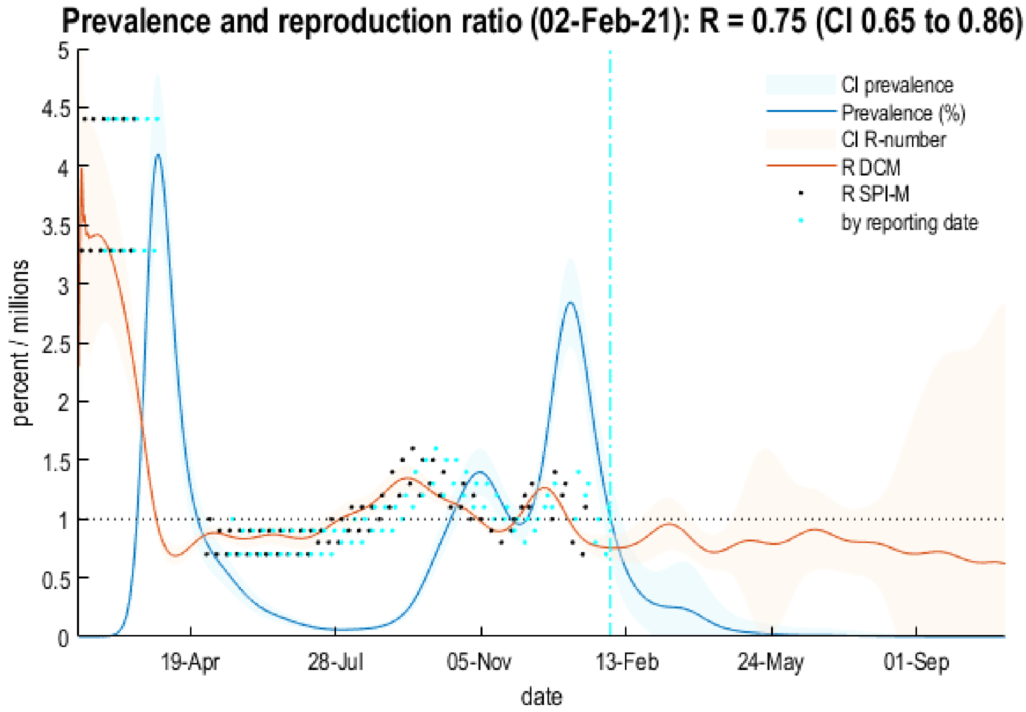
Long-term forecasting of the COVID-19 epidemic

Dynamic Causal Modelling, UCL, UK

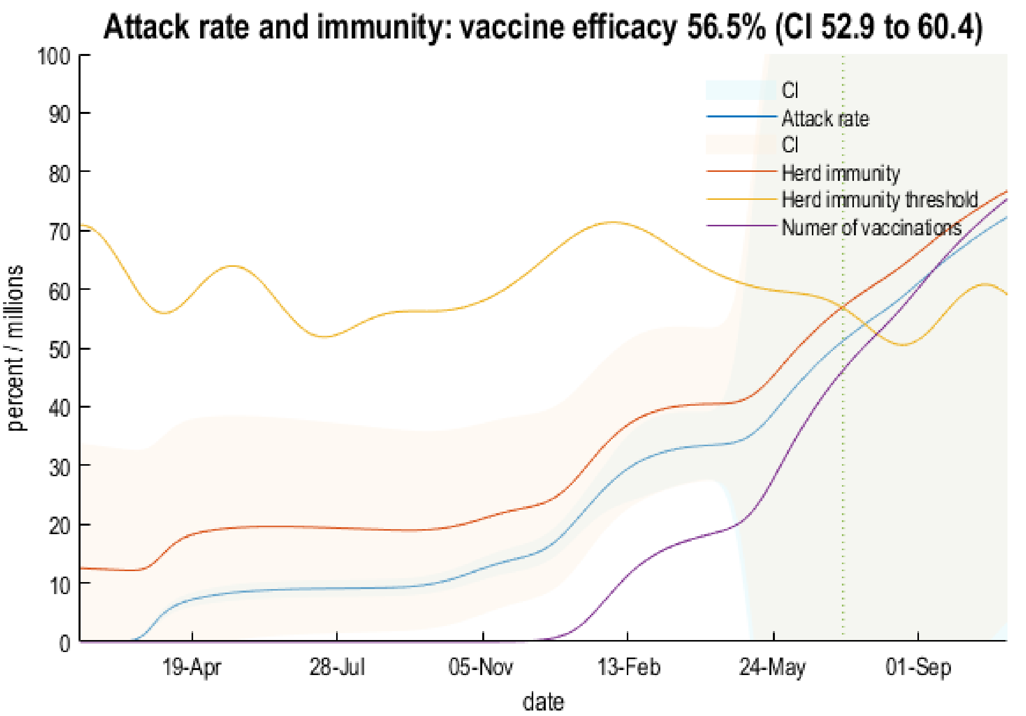
- **The reproduction ratio is currently estimated to be 0.75 (credible interval from 0.65 to .86) on 2 February 2021.**
- **The current best estimate of the efficacy of vaccination stands at 56.5% (credible interval from 52.9 to 60.4%).**
- The long-term forecast suggests that **herd immunity will be reached in mid July**. No further peaks in the prevalence of infection are forecast by dynamic causal modelling. The reproduction ratio is currently at a minimum and will increase towards one over the next few weeks.

The graphics report long-term forecasts based upon a dynamic causal model (DCM) of viral transmission and mitigated responses. This particular (age-stratified) model is equipped with a vaccination state that affords sterilising immunity (i.e., precludes transmission and clinical susceptibility). Immune efficacy is modelled with a certain probability of moving to an effectively vaccinated state following vaccination. For example, an efficacy of 52% means that you have a 52% chance of being immune from infection, following vaccination.

The resulting DCM can then generate various data that quantify the progression of the epidemic, including **the number of reported vaccinations**. These data are then used to estimate the model parameters controlling contact rates, transmission risk and periods of infectiousness using standard variational procedures. Crucially, these variables are themselves time-dependent and depend upon mitigating responses, modelled as the prevalence-dependent probability of moving from low to high contact rate locations. The data that underwrites these estimates includes daily positive tests, reported deaths within 28 days of a positive PCR test, certified deaths disaggregated by age and place of death, hospital admissions, contact rate proxies such as car use and Google mobility data and so on).



Prevalence and reproduction ratio (02-Feb-21): R = 0.75 (CI 0.65 to 0.86)
CI prevalence
Prevalence (%)
CI R-number
R DCM
R SPI-M
by reporting date
percent / millions
date
19-Apr
28-Jul
05-Nov
13-Feb
24-May
01-Sep



Attack rate and immunity: vaccine efficacy 56.5% (CI 52.9 to 60.4)
CI
Attack rate
CI
Herd immunity
Herd immunity threshold
Numer of vaccinations
percent / millions
date
19-Apr
28-Jul
05-Nov
13-Feb
24-May
01-Sep

The upper panel provides a forecast of the next few months of (i) the **prevalence of infection** and (ii) the reproduction ratio or **R-number** (blue and orange lines, respectively) with their accompanying confidence intervals (shaded areas). The long-term forecasts are based upon the parameters estimated from the data up until the reporting date (the vertical line). These data include GOV.UK estimates of the R-number, which are shown for comparison with the DCM estimates. The black dots correspond to the GOV.UK (SPI-M consensus) estimates moved backwards in time by 16 days from their date of reporting (cyan dots).

The lower panel shows long-term forecasts of **attack rate, herd immunity** and the number of vaccinations. In addition, an estimate of the **herd immunity threshold** is provided (yellow line). The vertical line illustrates the time at which herd immunity reaches the herd immunity threshold (here, in mid-July). Based upon the changes in testing, death rate and other data, one can estimate the efficacy of vaccination. The attack rate corresponds to the number of people who have been infected since the onset of the outbreak (blue line). This can be supplemented with a relatively small proportion of the population that have an estimated pre-existing immunity (e.g., mucosal immunity or cross immunoreactivity with other SARS viruses), shown in red. The combination can be read as the herd or population immunity.

The herd immunity threshold is based upon the effective reproduction ratio under pre-pandemic contact rates. The reproduction ratio corresponds to the product of the contact rate, transmission risk and mean infectious period. Note that the herd immunity threshold fluctuates. This reflects the fact that transmission risk changes with time. In this model, transmission risk is modelled as a seasonal fluctuation multiplied by a smooth function of time (parameterised with a discrete cosine set over two years). A fluctuating transmission risk accommodates changes in transmissibility (e.g., due to viral evolution) that is contextualised with seasonal variations in transmission (e.g., due to changes in temperature, humidity, socialising outdoors and the propensity for aerosol transmission).

The current estimates of the herd immunity threshold show that it has risen substantially since last July and is predicted to fall again during the spring. Clearly, there is a substantial amount of uncertainty about these long-term forecasts - as indicated by the wide credible intervals in both panels. Part of this uncertainty reflects uncertainty about the age-specific rollout of vaccinations, which are not constrained by empirical vaccination rates for younger age groups at the time of writing.

This dynamic causal model includes age-stratification into three groups (below the age of 25, between 25 and 65 and over 65 years of age). The contact rates within and between the three groups (for high and low contact rate locations) are estimated from the data, under mildly informative lognormal shrinkage priors. Please see the following technical report for further technical details.
