Durham University Business School

Department of Economics

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Parantap Basu & Clive Bell

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Hesitancy and Free Riding in a Pandemic:
Findings from COVID-19 in the EU

Parantap Basu (First author) Clive Bell (Second author)

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Department Economics
Durham University Business School
Mill Hill Lane
Durham DH1 3LB, UK
Tel: +44 (0)191 3345200
https://www.durham.ac.uk/business/about/departments/economics/

Abstract

We develop a two-period model of the evolution of COVID-19. Individuals make choices about vaccination and social distancing. A subgroup of non-believers always rejects vaccination. We analyse two variants of the model: (i) freely chosen social distancing and (ii) an enforced minimum distancing rule. The model yields two notable results across multiple subgame-perfect equilibria. First, the zero-transmission threshold (ZTT) cannot be achieved in period 2 if it is not achieved in period 1. Second, a mixed-strategy equilibrium may arise in which some individuals who are open to vaccination still refuse it. Using EU infection and vaccination data, we calibrate the model innovatively through reverse engineering. This allows us to estimate the expected costs of infection and vaccination (including side effects), the size of the non-believer subgroup, and the strength of the minimum distancing rule. The estimates vary substantially across EU countries and across the two model variants. While the first variant fails to find any non-believers in 13 countries, the second indicates that non-believers were ubiquitous. Our framework also has applications beyond the COVID-19 pandemic.

1 Introduction

The COVID-19 pandemic has profoundly shaken the world. However, several important and unresolved issues remain, among which vaccine hesitancy is particularly prominent. Despite intense efforts to implement vaccination programs, substantial shares of the populations declined to be vaccinated. As of December 15, 2021, refusal rates across 15 OECD countries ranged from 7% to 25%. In the United Kingdom, official sources (UK ONS, 2021) identified concerns about anticipated side effects as the primary reason for hesitancy. However, Graeber et al. (2022) present evidence from Germany indicating that, even in the absence of such effects, only about 70% of the population would opt for vaccination. Based on a Hong Kong study, Zhang et al. (2022) identified four reasons for vaccine hesitancy: (i) "not feeling in good health", (ii) "worrying about side effects", (iii) "feeling no need", (iv) "lack of recommendation from doctors". Daral and Shashidhara (2022) use data from a facebook survey to ascertain the reasons for vaccine hesitancy in India. They include: insufficient knowledge, doubts about the efficacy of vaccines, concerns about side effects, the desire to wait and watch, an anti-vaccination attitude based on misinformation, and scientifically unfounded beliefs. Farhar et al. (2022) attribute resistance primarily to misinformation and beliefs about conspiracy. Yet, regardless of how the effects of vaccination are assessed, individuals' decisions appear to be driven largely by their perceptions of the associated costs and benefits. The costs comprise the certain burden of the treatment itself and the expected costs of side effects, and the benefits stem from the anticipated level of immunity conferred.

There is a substantial literature on acceptance rates. Solis Arce et al. (2021) report individuals' declared attitudes from studies conducted in 15 countries, of which the Russian Federation and the U.S. were the only developed countries. The authors highlight the declared rates of 30.4% and 64.6%, respectively, in those two countries, in contrast to an average of 80% in the rest. Attitudes aside, according to Our World in Data (2022), the actual full vaccination rates for Russia and the U.S. stood at

51.1% and 67.0%, respectively.[1] Conversely, whereas the declared rate of 66.5% in Pakistan was the lowest among the other 13 countries, the actual rate was 55.7%. Whether this disparity was due to deficiencies in Pakistan's healthcare system or the respondents' failure to follow through with their intentions remains an open question. Other contributions that address reported vaccine hesitancy include Tran (2021) and Vu (2021) for the U.S., and Unterschultz et al. (2021) for Canada. Vu estimates specifications with measures of hesitancy and actual vaccination rates as the regressand, using county-level data (as of September 21, 2021, when the national rate was 57%). What is termed 'rugged individualism' turns out to be a statistically significant obstacle to vaccination in all specifications.

The other way of preventing infection is to practise social distancing. Here there is another strand of literature wherein strategic elements play a significant role. Theoretical studies of endogenous social distancing include Eichenbaum et al. (2020), Getachew (2020), Toxvaerd (2020) and Farboodi et al. (2021). Ng (2021) develops a model of mask-wearing in an environment wherein agents engage in free riding by not wearing a mask. Talamas and Vohra (2020) construct a network model in which agents strategically choose their partners, and conclude that a partially effective vaccine can be detrimental because it increases the chances of risky interactions. Empirical evidence of endogenous social distancing in China is presented by Chudik et al. (2020). Basu, Bell, and Edwards (2022) also explore the issue of free riding in social distancing in England. Based on the empirical facts documented in the paper, they develop a stylized two-period model to demonstrate why the poor socially distance less than the rich and respond less to more stringent policies.

Despite these studies of vaccination and social distancing decisions, the exploration of strategic interactions between them remains relatively neglected in the COVID literature. This motivates an analysis of such behaviour in the face of the outbreak of an

[1] The rates for other, selected OECD. countries are: France, 78.3%; Italy, 80.5%; Japan, 81.0%; South Korea, 86.1%; Spain, 85.5%.

epidemic. In our two-period model, a vaccine becomes available at the start of period 2. Individuals infected in period 1, as well as those vaccinated at the beginning of period 2, are immune to symptomatic infection and do not, therefore, practise social distancing in period 2, although they may still transmit the virus. In both periods, social distancing reduces the probability of infection. The population is risk-neutral but heterogeneous in its attitudes towards distancing and vaccination. One group, termed non-believers, rejects vaccination under all circumstances and distancing unless compelled to do otherwise. The other group acts rationally on the available evidence. Although its members are identical in terms of preferences, costs, and expectation formation, and therefore make identical decisions about distancing in period 1, infections render them heterogeneous ex post at the start of period 2.

Our model possesses a number of subgame-perfect equilibria. First, it admits the (unlikely) possibility that the pandemic ends in period 1: endogenous social distancing alone can eliminate transmission, provided that the share of the population infected in period 1 exceeds the zero-transmission threshold (ZTT, defined in Section 2). Second, we show that if the ZTT is not reached in period 1, then voluntary vaccination and social distancing together will not eliminate transmission in period 2 because of strategic free-riding incentives. If agents believe that everyone else will be vaccinated, each has an incentive to deviate unless the expected cost of vaccination is zero. This triggers widespread rejection of vaccination, thereby prolonging the pandemic. Third, there is a more plausible mixed-strategy equilibrium in which not all susceptible members of the rational group choose to be vaccinated. This equilibrium can arise when the expected costs of social distancing and vaccination are exactly balanced. Individuals are then indifferent between two 'pure' alternatives: choosing vaccination and rejecting social distancing, or rejecting vaccination and choosing the level of distancing.

We study two variants of the model. In the first, individuals freely choose their levels of social distancing. In the second, the authorities enforce a minimum level. The two variants are structurally distinct and cannot be nested within a single framework through a flexible distancing constraint. We therefore analyse them separately.

We next take the model to the data. Our two-period framework runs from the initial outbreak in early 2020 to early 2023, by which time the epidemic had largely subsided. Inspection of the data supports the hypothesis that vaccination rates across EU member states during the COVID-19 pandemic were outcomes of a mixed-strategy equilibrium. In the first variant, we use the data on infection rates and vaccine uptake to recover structurally the expected costs of infection and vaccination as well as the numbers of non-believers in the member states. In the second variant, we proceed in the same way to obtain a measure of the stringency of minimum distancing policies and the associated estimates of the expected costs of vaccination. This approach allows us to recover otherwise unobservable beliefs about the expected costs of infection and vaccination and a measure of regulatory stringency. We find that these attributes varied widely across EU countries, with the caveat that infections in the second period could be under-reported in some countries. To our knowledge, this reverse-engineering procedure is novel in the pandemic literature.

Our analysis extends beyond the COVID-19 pandemic. Vaccine hesitancy reflects both the behavioural foundations of individual decision making under uncertainty, including perceived risks and biased beliefs, and strategic interaction among individuals. Similar trade off between preventive measures and comparable incentives to free ride are likely to arise in future pandemics. Our framework shows how the timing of vaccine availability, the presence of alternative protective behaviours, and heterogeneous beliefs jointly shape aggregate outcomes. It provides policymakers with desirable insights into these connections when they formulate measures to address vaccine hesitancy in current public health crises and those yet to come.

The paper is organized as follows. Section 2 describes the setting and the model's structure. The argument of Section 3, which deals with the first variant, proceeds by backward induction: period 2 in Section 3.1 and period 1 in Section 3.2. The same procedure is applied to the second variant in Section 4. Section 5 treats the specific functional forms for the empirical analysis of Section 6. The main findings are drawn together in Section 7.

2 The Model

The model builds on Basu et al. (2022). At the start of period 1, there is an outbreak of disease in a population lacking any immunity. Infection is never fatal.[2] In each period, individuals choose safety measures, which include social distancing and the wearing of masks, taking the choices of other individuals as given. Hereinafter, these various measures are called 'social distancing'. A vaccine will become available at the start of period 2, but its side effects remain uncertain.

The population consists of a continuum of risk-neutral individuals represented by $[0, 1]$, each endowed with ω units of a composite good in both periods. There is a group of non-believers, $S_0 = \{j : j \in [0, n_0)\}$, who reject vaccination unconditionally and, unless compelled to do otherwise, any other defensive measures against infection. All others, comprising the set $S^r = \{j : j \in [n_0, 1]\}$, are assumed to make individually rational decisions. Individual i's private cost of social distancing in the measure x_{it} is given by the increasing, strictly convex, twice-differentiable function c, where $c(0) = c'(0) = 0$.

Infection inflicts suffering and costs, with clinical outcomes that range from few or no symptoms to a stay in an ICU. Vaccinated individuals are assumed to acquire full immunity, as do those infected in period 1.[3,4] All individuals have access to free testing

[2] Deaths in the first period necessarily result in fewer individuals in the second. In fact, the Covid-19 case mortality rate is low, which is not to downplay the tragedies of individual deaths.

[3] Block's assessment (2021) of the evidence is that the immunity conferred by infection is not inferior to vaccination.

[4] Survivors of certain infectious diseases enjoy full, lifetime immunity: prime examples are measles and smallpox. Zero transmission following an initial outbreak can then occur if the population does

at the end of period 1, which offers those in S^r a decisive incentive to establish their immune status when deciding about vaccination. Denote the set of all such seropositive individuals by S_1, and their share of the population by n_1, which the authorities report at the end of period 1.[5]

The decisions and their timing are as follows. At the start of period 1, each member of S^r forms beliefs about others' distancing decisions in period 1 and the number who will get a jab in period 2. Each individual then chooses some measure of distancing. At the end of period 1, all of them learn their immune status. At the start of period 2, all individuals make decisions about vaccination and distancing.

Two variants are analysed. In Section 3, individuals choose social distancing completely freely in both periods. In period 2, those members of S^r infected in period 1 (confirmed by free testing) reject both a jab and distancing. In the light of n_1, those who were not infected choose between vaccination and risking infection without it, but with suitable distancing. The latter individuals have sharp priors concerning the fraction $n_2^e \in [0, 1 - n_0 - n_1]$ who decide to get a jab.[6] Since they are identical *ex ante*, their priors are identical. Let all of them expect n_2^e with probability 1, where $n_2^e = n_2$ in equilibrium. Vaccinated individuals comprise the set S_2. The members of the fully susceptible, unvaccinated group, S_3, make up the remainder, if any: $n_3 \in [0, n_s - n_2]$, where $n_s = 1 - n_0 - n_1$. Index all individuals at the start of period 2 as follows: if $j \in S_1$, then $j \in (n_s, 1]$; if $j \in S_2$, then $j \in (n_s - n_2, n_s]$; if $j \in S_3$, then $j \in [n_0, n_s - n_2]$. The distancing profile is $\{x_{j2}\}_{j=0}^{j=1}$, and the aggregate social distance is $X_2 = \int_0^1 x_{j2} dj$, where $x_{2j} = 0 \; \forall j \in S_0 \cup S_1 \cup S_2$.

The second variant is analysed in Section 4. The authorities enforce some positive minimum level of distancing on all unvaccinated individuals in each period, so that

not encounter infectious outsiders.

[5]Individuals who get infected in period 1 can still be infectious in period 2. The delta and omicron variants may well have this property.

[6]For a vigorous argument that rational actors must have sharp priors, see Elga (2010).

members of S_1 must still get a jab if they wish to dispense with distancing in period 2. The aggregate social distance is $X_2 = \int_0^1 x_{j2} dj$, where $x_{2j} = 0$ only for vaccinated individuals.

Comparing the aggregates X_t, it should be noted that in the first variant, non-believers pose a particularly strong hazard for members of S^r in period 1, and in period 2, they join forces with the members of S_1 and S_2. In both periods, the susceptible members of S^r take correspondingly stronger defensive measures when non-distancing individuals are more numerous. In the second variant, enforcement of the minimum reduces this hazard.

The fact that infection and vaccination confer immunity, and so alter individuals' decisions and the course of the disease in the population must also be taken into account. Here, there is a key distinction between the herd immunity threshold (HIT) and the zero transmission threshold (ZTT). At the HIT, the basic reproduction number satisfies $R_0 = 1$, but transmission need not stop immediately; for infections can decline gradually before ceasing altogether, a phenomenon often termed overshooting (Fine et al., 2011). At the ZTT, in contrast, transmission stops completely and the remaining susceptible population is no longer at risk.[7] We use the ZTT, since it yields an important simplification. If the HIT is reached in period 1, this does not rule out the possibility that susceptible individuals will get infected in period 2. If, however, the ZTT is reached in period 1, then not only will there be no infections in period 2, but there will also be wholesale rejection of vaccination. If the ZTT is less than 1 and actually attained, then there will be some susceptible individuals at the start of period 2, and their wholesale rejection of vaccination can arise in equilibrium as a consequence of all individuals' behaviour in period 1.

[7] For the ancestral variant, Garcia-a-Garcia et al. (2022) estimate the HIT to lie between 28.1 and 67.1 per cent; for the Delta variant that emerged in 2021, the corresponding range is 75.1 to 88.8 per cent. With the subsequent Omicron variant, the corresponding ZTT may exceed unity. By way of comparison, the HIT for measles is approximately 95 per cent.

3 Zero Transmission: Attained or Not

Let the fraction of non-believers infected in period 1 be λ. If $\lambda n_0 + n_1 \geq \underline{n}$ (< 1), where $\underline{n}$ denotes the ZTT value, then distancing decisions in period 1 will yield zero transmission throughout period 2. Those in S^r who escaped infection in period 1 need have no fears and so decline vaccination. With no risk of infection, no one distances in period 2. It then remains only to establish under what conditions ZTT is attained from distancing decisions in period 1, a task taken up in Section 3.2.

3.1 Period 2

Suppose, on the contrary, that $\underline{n}$ is not thus attained. All individuals who escaped infection in period 1 are fully susceptible and those in S^r must decide whether to get a jab at once. These individuals have beliefs about the full costs of infection and vaccination in the form of a prior distribution of the variates Ξ_2 and Ξ_v, respectively; but being risk-neutral, the only features of this distribution that matter for their decisions are the expected values $\bar{\xi}_2 = \mathbb{E}(\Xi_2)$ and $\bar{\xi}_v = \mathbb{E}(\Xi_v)$.

If i decides in favour of vaccination, she obtains $\omega - \bar{\xi}_v$. If she declines, she must decide on distancing given the distancing decisions of the others in S_3. Let the probability of infection take the form

$$p_{i2} = f(x_{i2}) \cdot g(X_2, n_z) \text{ if } n_z \equiv \underline{n} - (\lambda n_0 + n_1 + n_2) > 0; \text{ otherwise, } p_{i2} = 0,\ i \in S_3, \quad (1)$$

where f is a decreasing, strictly convex and thrice-differentiable function, $f(0) = 1$ and $\lim_{x_{it} \to \infty} f = 0$. Let g be decreasing in X_2, increasing in n_z, positive if $n_z > 0$ and continuously differentiable, with $g(0, n_z) = 1$ if $n_z > 0$. Thus, if no one is immune and no one distances, then all get infected. Given any $X_2 > 0$, i can lower her chances of infection by distancing more, but with diminishing returns. She obtains the payoff $\omega - p_{i2}\bar{\xi}_2 - c(x_{i2})$.

If i conjectures that $\underline{n}$ will be reached through vaccinations alone, so that she would face no risk of infection, then she will refuse both distancing and, if $\bar{\xi}_v > 0$, vaccination, and so obtain ω. Since all those in S^r not infected in period 1 are identical, all will think this way and behave likewise. This wholesale rejection of vaccination goes with $X_2 = 0$, which implies that transmission will indeed continue in period 2, thus contradicting the conjecture that $\underline{n}$ will be reached through voluntary vaccinations alone.

There remains the possibility that $\underline{n}$ is reached through a combination of vaccinations and infections in the course of period 2. Suppose i in S_3 conjectures that the aggregate distancing chosen by others in that group is such that $\underline{n}$ is reached. Then i will neither engage in distancing, thus sparing herself its attendant costs, nor get vaccinated as the equally costly alternative. Once more, therefore, all i in S_3 will deviate and $\underline{n}$ will not be attained, thus establishing the following proposition.

Proposition 1 *If distancing decisions in period 1 do not yield zero transmission by the start of period 2 and the expected cost of vaccination is positive, then that state cannot arise as a Nash equilibrium in period 2.*

The proposition yields a signal result, which reveals that free riding among the group S^r can also hinder vaccination of the whole population. Suppose i in S_3 conjectures that all other members of that group will get vaccinated: that is, $n_2^e = 1 - n_0 - n_1$, each individual having no measure. If $\lambda n_0 + (1 - n_0) \geq \underline{n}$, then the ZTT will be attained, and i will reject vaccination. This contradiction establishes

Corollary 1 *Vaccination of all susceptible members of the group S^r is not a Nash equilibrium if $1 - (1 - \lambda)n_0 \geq \underline{n}$.*

If $1 - (1 - \lambda)n_0 < \underline{n}$, then i's conjecture $n_2^e = 1 - n_0 - n_1$ also implies $X_2 = 0$. Given the assumption $g(0, n_z) = 1$, i will minimize $f(x_{i2})\bar{\xi}_2 + c(x_{i2})$ if she declines vaccination. This problem has a unique, positive solution, denoted by $x_{i2}(X_2 = 0)$. She will therefore reject vaccination if and only if $f(x_{i2}(X_2 = 0))\bar{\xi}_2 + c(x_{i2}(X_2 = 0)) < \bar{\xi}_v$; and if this condition holds, then all other susceptible members of S^r will do likewise.

There are other possible outcomes. Suppose that, in equilibrium, some susceptible individuals choose vaccination, but without $\underline{n}$ being reached, i.e., $n_2 \in (0, \underline{n} - \lambda n_0 - n_1)$. Suppose i conjectures as much and declines vaccination. The assumptions on the functions f, g and c imply that her optimal choice, x_{i2}^0, is positive and unique for any given X_2, n_z and $\bar{\xi}_2 > 0$. Her first-order condition (f.o.c.) is

$$f'(x_{i2}) \cdot g(X_2, n_z)\bar{\xi}_2 + c'(x_{i2}) = 0. \tag{2}$$

In a symmetric allocation, $x_{j2} = x_{i2}^0 \ \forall i, j \in S_3$ and $X_2 = n_3 x_{j2} = (1 - n_0 - n_1 - n_2^e)x_{j2}$.[8] In equilibrium, therefore,

$$f'(x_{i2}^0) \cdot g(n_3 x_{i2}^0, n_z)\bar{\xi}_2 + c'(x_{i2}^0) = 0. \tag{3}$$

Denote the equilibrium value by $x_2^0(n_1, n_2^e, n_z, \bar{\xi}_2)$. The expected payoff is

$$y_2^*(3) = \omega - p_2(x_2^0)\bar{\xi}_2 - c(x_2^0) = \omega - [c(x_2^0) - f(x_2^0)c'(x_2^0)/f'(x_2^0)] \quad \forall j \in S_3,^{9}$$

These individuals compare it with the alternative of vaccination, which yields $\omega - \bar{\xi}_v$.

Given that only some of the susceptible members of S^r choose vaccination, it follows that $\bar{\xi}_2, \bar{\xi}_v$ and n_2^e must be such that all susceptible members of S^r are indifferent between vaccination and distancing. Then $n_2^e \in (0, \underline{n} - \lambda n_0 - n_1)$ must be such that

$$c(x_2^0) - f(x_2^0)c'(x_2^0)/f'(x_2^0) = \bar{\xi}_v, \tag{4}$$

which involves the interplay of vaccination and distancing decisions.[10] For this outcome to be an equilibrium, all individuals in S^r who escaped infection in period 1 must not

[8] We invoke the law of large numbers, although we have a continuum of agents. We make this appeal throughout our analysis. The resulting approximation error is of second-order importance when the number of agents in a countable set is close to infinity (Judd, 1985).

[9] The RHS can be written in a form with elasticities: $\omega - c(x_2^0)\left(1 + \frac{\eta_x^c(x_2^0)}{\eta_x^f(x_2^0)}\right)$, where $\eta_x^c(x_2^0) = c'(x_2^0)x_2^0/c(x_2^0)$ and $\eta_x^f(x_2^0) = f'(x_0^2)x_2^0 f(x_2^0)$ are the respective elasticities of private cost and private benefit, in the form of a reduction in the probability of suffering a symptomatic infection, with respect to social distancing.

[10] As n_2^e increases, $x_2^0(n_1, n_2^e, \bar{\xi}_2)$ will decrease steadily (see Appendix 1), so that if $\bar{\xi}_2$ is not too large, there is an $n_2^e \in (0, \underline{n} - n_1)$ such that $x_2^0(n_1, n_2^e, \bar{\xi}_2)$ also satisfies (4).

only conjecture $n_2^e \in (0, \underline{n} - \lambda n_0 - n_1)$, but also choose to get vaccinated with probability $n_2^e/(1 - \lambda n_0 - n_1)$ given that conjecture. The said equilibrium then involves mixed strategies. It should be noted, however, that the LHS of (4) is positive, increasing in x_{i2}^0 and independent of $\bar{\xi}_v$. Hence, there can be no such equilibrium if $\bar{\xi}_v$ is sufficiently close to 0, as intuition suggests. For further results and the possibility of wholesale rejection of vaccination, see Appendix 1.

3.2 Period 1

Some infections always occur in period 1, all individuals being susceptible at the outset. In view of proposition 1, the first question to be addressed is whether distancing decisions in period 1 yield zero transmission throughout period 2, and thus make vaccination and distancing in that period superfluous. If the ZTT is not attained, then there are three general possibilities (see proposition 4 in Appendix 1): (i) some members of S^r who escaped infection in period 1 choose vaccination, (ii) all reject vaccination, and (iii) there is no subgame perfect Nash equilibrium.

3.2.1 ZTT attained

Distancing decisions must be made at the start of the period and, by hypothesis, the ZTT will be reached by its close. If all $i \in S^r$ expect this outcome when making their distancing decisions in period 1, they know that they will obtain ω for sure in period 2, so that the structure reduces to a one-shot game wherein these individuals minimise expected costs in period 1. Since the whole population is susceptible, (1) specialises to

$$p_{i1} = f(x_{i1})g(X_1, \underline{n}),\ i \in S^r. \tag{5}$$

Let $\bar{\xi}_1$ denote the expected value of the costs of infection in period 1. The f.o.c. is

$$f'(x_{i1})g(X_1, \underline{n})\bar{\xi}_1 + c'(x_{i1}) = 0.$$

Assuming a symmetric equilibrium, let $x_{i1} = x_1^*(Z)\,\forall i$, where Z is an index denoting that decisions are made given the conjecture that the ZTT is attained and $x_1^*(Z)$ satisfies

$$f'(x_1^*(Z))g[(1-n_0)x_1^*(Z), \underline{n}]\bar{\xi}_1 + c'(x_1^*(Z)) = 0. \tag{6}$$

Note that $x_1^*(Z)$ is independent of $\bar{\xi}_2$ and $\bar{\xi}_v$, and is increasing in $\bar{\xi}_1$:

$$\frac{dx_1^*(Z)}{d\bar{\xi}_1} = \frac{-f'g}{(f'' + (1-n_0)f'g_X)\bar{\xi}_1 + c''} > 0.$$

In any symmetric allocation, the law of large numbers yields, from (5),

$$n_1^*(Z) = f(x_1^*(Z)) \cdot g[(1-n_0)x_1^*(Z), \underline{n}](1-n_0). \tag{7}$$

Some non-believers also get infected in period 1: the resulting fraction is

$$\lambda^*(Z) = f(0)g[(1-n_0)x_1^*(Z), \underline{n}]. \tag{8}$$

The total number infected is $\lambda^*(Z)n_0 + n_1^*(Z))$, which is decreasing in $\bar{\xi}_1$:

$$\frac{d(\lambda^*(Z)n_0 + n_1^*(Z))}{dx_1^*} = (1-n_0)\{g_X[n_0 f(0) + (1-n_0)f(x_1^*(Z))] + f'g\} < 0.$$

By assumption, $f' < 0$ and $g_X < 0$, so that the total number infected is decreasing in $\bar{\xi}_1$, and for some sufficiently large value thereof, the ZTT will not be attained. This argument therefore establishes

Proposition 2 *If $\bar{\xi}_1$ is sufficiently small such that $\lambda^*(Z)n_0 + n_1^*(Z) \geq \underline{n}$, then there is a subgame perfect Nash equilibrium wherein $x_{i1} = x_1^*(Z)\,\forall i \in S^r$ and the outbreak ends by the close of period 1.*

3.2.2 ZTT not attained

In any symmetric allocation, $X_1 = (1-n_0)x_{i1}\ \forall i$. Hence, from (5), if $\bar{\xi}_1$ is such that the ZTT is not attained, then $X_1 > X_1(Z)$. For $f' < 0$ and $g_{X_1} < 0$ imply that $dp_1/dX_1 < 0$, and if the ZTT is not attained, then there must be fewer infections than

$n_1^*(Z)$ in period 1. (The index Z is dropped from all variables when the ZTT is not attained.) Suppose, to begin with, that all those in S^r who escaped infection in period 1 are indifferent between vaccination and distancing. Then all obtain the payoff $\omega - \bar{\xi}_v$ in period 2. With this conjecture, all individuals in S^r obtain, evaluated *ex ante* in period 1, the expected payoff $\omega - (1 - p_1(x_1^*))\bar{\xi}_v$ in the symmetric equilibrium in period 2.[11] These individuals obtain the expected payoff

$$\omega - p_1(x_1^*)\bar{\xi}_1 - c(x_1^*) = \omega - f(x_1^*) \cdot g[(1 - n_0)x_1^*, \underline{n}]\bar{\xi}_1 - c(x_1^*) \tag{9}$$

in period 1, where $x_1^* > x_1^*(Z)$ in virtue of $X_1 > X_1(Z)$. That is to say, if the ZTT is not attained, then $\bar{\xi}_1$ is sufficiently large such that aggregate distancing is greater than any level it takes when the ZTT is attained. The corresponding values of n_1^* and λ^* are given by (7) and (8), with x_1^* replacing $x_1^*(Z)$, so that n_1^* and λ^* are smaller than their counterparts $n_1^*(Z)$ and $\lambda^*(Z)$, this being a consequence of $\bar{\xi}_1$ taking a value sufficiently large to prevent the ZTT from being reached. Note that the expected cost of vaccination *ex ante* is net of the probability of getting infected in period 1, infection making vaccination unnecessary.

The individual preference function V_i, evaluated ex ante at the start of period 1, comprises the payoff in period 1, which is given by (9), and the discounted payoff in period 2, which is $\beta[\omega - (1 - p_{i1}(x_{i1}, x_1^*))\bar{\xi}_v]$. Note that the expected cost of vaccination nets out the probability of being infected in period 1 because people who were infected in period 1 will refuse vaccination. Therefore, with symmetric choices of all other members of S^r,

$$V_i = (1 + \beta)\omega - p_{i1}(x_{i1}, x_1^*)(\bar{\xi}_1 - \beta\bar{\xi}_v) - c(x_{i1}) - \beta\bar{\xi}_v \ \forall i \in S^r,$$

where β (≤ 1) is the discount factor. The associated f.o.c. is

$$f'(x_{i1})g[(1 - n_0)x_1^*, \underline{n}](\bar{\xi}_1 - \beta\bar{\xi}_v) + c'(x_{i1}) = 0, \tag{10}$$

[11] It is assumed that the expectation $\mathbb{E}(\Xi_v)$ is not revised between the two periods.

so that $x_{i1}^0 > 0$ if, and only if, $\bar{\xi}_1 - \beta\bar{\xi}_v > 0$. The evidence is strongly in favour of $\bar{\xi}_1 > \beta\bar{\xi}_v$, which ensures that $x_{i1}^0 > 0$. Yet beliefs to the contrary cannot be ruled out a priori. This possibility is treated in Appendix 1.

Mixed strategy, subgame perfect equilibria are of particular interest. When the ZTT is not attained, they can exist when $\lambda^* n_0 + n_1^* < \underline{n}$. If $\bar{\xi}_1 - \beta\bar{\xi}_v$ is close to 0, then so too is x_1^*, so that $\lambda^* n_0 + n_1^* \geq \underline{n}$ – and hence attaining the ZTT in period 1 – is more likely to hold under the conjecture that there is a mixed strategy equilibrium in period 2. If, however, $\bar{\xi}_1 - \beta\bar{\xi}_v$ is sufficiently large, then $\lambda^* n_0 + n_1 * < \underline{n}$ is almost assured, and a mixed strategy equilibrium becomes possible.

The following proposition sets out the conditions under which there is a mixed strategy Nash equilibrium in period 2 and an associated subgame perfect Nash equilibrium. Note that, from (5), $\lambda^* = f(0)g[(1-n_0)x_1^*, \underline{n}]$ and $n_1^* = f(x_1^*)g[(1-n_0)x_1^*, \underline{n}](1-n_0)$, and that (10) holds with $x_{i1} = x_1^*$.

Proposition 3 *If the ZTT is not attained and there exist x_1^* such that*
(i) $f'(x_1^*)g[(1-n_0)x_1^*, \underline{n}](\bar{\xi}_1 - \beta\bar{\xi}_v) + c'(x_1^*) = 0$ and
(ii) $[f(0)n_0 + f(x_1^*)(1-n_0)]g[(1-n_0)x_1^*, \underline{n}](1-n_0) < \underline{n}$,
and
(iii) $n_2^e \in (0, \underline{n} - \lambda^* n_0 - n_1^*)$ that satisfies condition (3) when $x_{j2} = x_2^*(\bar{\xi}_v)$ and the indifference condition (4),
then the allocation $(x_1^*, n_1^*, \lambda^*, x_2^*(\bar{\xi}_v), n_2^e)$ is a subgame perfect Nash equilibrium, wherein all susceptible individuals in S^r at the start of period 2 choose vaccination with probability $n_2^e/(\underline{n} - \lambda^* n_0 - n_1^*)$ and transmission continues throughout period 2.

Proof: see Appendix 1, which also addresses the question of uniqueness.

Condition (i) is identical in form to (6), except for the intrusion of $\beta\bar{\xi}_v$. If the ZTT is not attained, condition (i) implies that, in keeping with intuition, x_1^* is increasing in $\bar{\xi}_1$ and decreasing in $\bar{\xi}_v$; for distancing more in period 1 lowers the chances of infection in that period, but increases the chances of entering the next without immunity, and thus having to face the vaccination decision. If $\bar{\xi}_v$ increases, then so will n_1^* and λ^*, for (7) holds and x_1^* decreases. There are, indeed, limits on $\bar{\xi}_v$ if there is to be a mixed strategy equilibrium, as we now demonstrate.

First, if the expected cost of vaccination is sufficiently high, then all susceptible individuals will refuse it; for (9) and (10) will not hold and $n_2^e = n_2^* = 0$. In particular, if $p_1(x_1^*)\bar{\xi}_1 < \beta\bar{\xi}_v$, then the expected cost of suffering a bout of the illness in period 1 is less than than the expected cost of preventing it in period 2, which ensures refusal.

Secondly, suppose $\bar{\xi}_v$ is close to 0. In a symmetric equilibrium in period 2,

$$f'(x_2^*)g[(1-n_0-n_1^*)x_2^*, n_z]\bar{\xi}_2 + c'(x_2^*) = 0,$$

from which it follows that x_2^* is not arbitrarily close to 0 $\forall\bar{\xi}_v > 0$. By hypothesis, the members of S_3 are indifferent between vaccination and distancing, that is,

$$f(x_2^*)g[(1-n_0-n_1^*)x_2^*, n_z]\bar{\xi}_2 + c(x_2^*) = \bar{\xi}_v;$$

but this cannot hold if $\bar{\xi}_v$ is sufficiently close to 0, thus implying $n_2^e = 1 - n_0 - n_1^*$. Hence, by Corollary 1, there is then no subgame perfect equilibrium.

To sum up, the foregoing argument establishes what outcomes can arise under what conditions. First, when $\bar{\xi}_v > 0$, the ZTT is attained in period 1 if and only if $\lambda^*(Z)n_0 + n_1^*(Z) > \underline{n}$, which can hold only if $\bar{\xi}_1$ is sufficiently small. Secondly, if the ZTT is not attained in period 1, then there are three possibilities: (i) a mixed strategy, subgame perfect Nash equilibrium wherein some, but not all, susceptible members of S^r choose vaccination; (ii) a wholesale rejection of vaccination; and (iii) no subgame perfect Nash equilibrium, which arises when the expected costs of vaccination are sufficiently small.

4 Minimum Distancing Enforced

Thus far, individuals have chosen their levels of social distancing perfectly freely. Yet a defining regulatory feature of the COVID-19 pandemic was the enforcement of minimum distancing rules, particularly during the later phases of the pandemic. For example, in many EU countries, a vaccination certificate was required to participate in public gatherings. This raises the question of whether such regulatory features can be captured by imposing a uniform, lower limit on social distancing. A key complication is that governments ignored the fact that individuals infected in period 1 acquired a level of immunity comparable to that provided by vaccination. No such certificates were issued to grant them access to restaurants or similar venues: proof of vaccination remained a strict requirement. It is therefore important to emphasize that certain of the minimum distancing rules effectively applied only to unvaccinated individuals. Consequently, Variant A, which assumes unconstrained social distancing, is not a special case of the framework that follows—denoted as Variant B—as will become clear.

Suppose the minimum level $\underline{x}_t$ is enforced on all and sundry, with one exception, namely, those choosing vaccination, who are treated more lightly. For simplicity, let those vaccinated have leave to choose $x_{i2} = 0$, so that all will. Non-believers must comply with $\underline{x}_t$. The members of S^r fall into two groups: those infected in period 1, S_1, and those who escaped, numbering n_1 and $1 - n_0 - n_1$, respectively. The former, who are immune to symptomatic infection in period 2, will accept or reject vaccination according as $c(\underline{x}_2) \gtrless \bar{\xi}_v$, for c is an increasing function and $x_{i2} \geq \underline{x}_2$. They will be indifferent if and only if $c(\underline{x}_2) = \bar{\xi}_v$, a condition that will hold only by the merest fluke, both quantities concerned being exogenous; its occurrence is ignored. If they accept, then so, too, will all members of the second group; for if the latter decline vaccination, they will face the expected cost $p_{i2}\xi_2 + c(x_{i2})$, which exceeds $\bar{\xi}_v$. Hence, a necessary and sufficient condition that all members of S^r get vaccinated is $c(\underline{x}_2) > \bar{\xi}_v$.

If, on the contrary, $c(\underline{x}_2) < \bar{\xi}_v$, then all members of S_1 will decline vaccination. Those members of the second group who choose vaccination will obtain $\omega - \bar{\xi}_v$; those who decline still enjoy the option of distancing more strongly than $\underline{x}_2$. Suppose i declines and that she conjectures that all others will accept, so that $X_2 = (n_0 + n_1)\underline{x}_2$ and her f.o.c. is the pair of complementary inequalities

$$f'(x_{i2})g[(n_0 + n_1)\underline{x}_2, n_z]\bar{\xi}_2 + c'(x_{i2}) \geq 0, \ \underline{x}_2 \leq x_{i2}, \ \text{compl.} \tag{11}$$

Let $x_{i2}^0(\underline{x}_2, n_1)$ satisfy (11), where it should be noted that $x_{i2}^0(\underline{x}_2, n_1)$ may exceed $\underline{x}_2$. If

$$f[x_{i2}^0(\underline{x}_2, n_1)]g[(n_0 + n_1)\underline{x}_2, n_z]\bar{\xi}_2 + c(x_{i2}^0(\underline{x}_2, n_1)) > \bar{\xi}_v, \tag{12}$$

then she, too, will choose vaccination. Hence, given the n_0 non-believers, the outcome n_1 in period 1, and the conditions $c(\underline{x}_2) < \bar{\xi}_v$ and (12), there is a Nash equilibrium in period 2 wherein all non-believers comply with $\underline{x}_2$, all members of S_1 decline vaccination, and all those in S^r who escaped infection get a jab.

If, however, (12) is violated, then i will deviate by declining vaccination, and since she has no measure, others will do likewise, thus introducing the possibility of a mixed strategy equilibrium, wherein some, but not all, members of the second group of S^r reject vaccination in favour of distancing at least $\underline{x}_2$. Suppose i conjectures that $n_2 \in (0, 1 - n_0 - n_1)$ will choose vaccination and that all those who decline also choose $\underline{x}_2$. Then $X_2 = (1 - n_2)\underline{x}_2$ and (11) becomes

$$f'(x_{i2})g[(1 - n_2)\underline{x}_2, n_z]\bar{\xi}_2 + c'(x_{i2}) \geq 0, \ \underline{x}_2 \leq x_{i2}, \ \text{compl.}. \tag{13}$$

Let $x_{i2}^0(\underline{x}_2, n_2)$ satisfy this condition. The assumptions on f, g and c imply that $x_{i2}^0(\underline{x}_2, n_2) = \underline{x}_2$ for all sufficiently large values of $\underline{x}_2$. In what follows, it is assumed that the minimum $\underline{x}_2$ is so stringent that it binds for i and hence, in equilibrium, for all unvaccinated individuals. If

$$f(\underline{x}_2)g[(1 - n_2)\underline{x}_2, n_z]\bar{\xi}_2 + c(\underline{x}_2) = \bar{\xi}_v, \tag{14}$$

then members of the second group will be indifferent between vaccination and distancing at least $\underline{x}_2$. If there is indeed an $n_2 \in (0, 1 - n_0 - n_1)$ satisfying (14), then there is a Nash equilibrium wherein some, but not all, members of the second group choose vaccination. If, however, (14) is violated for $n_2 = 0$, then all will reject vaccination. Although g is decreasing in X_2, (14) will hold for some sufficiently large value of $\bar{\xi}_2$, even when n_2 is close to 0, all the other magnitudes being fixed independently of $\bar{\xi}_2$.

Comparing the aggregate $X_2 = (1 - n_2)\underline{x}_2$ with its counterpart in (2), namely, $X_2 = (1 - n_0 - n_1 - n_2^e)x_{i2}^0$, it is seen that imposing $\underline{x}_2$ on non-believers and those members of S^r who got infected in period 1 and refuse vaccination in period 2 confers a substantial benefit on those in the second group of S^r. For the restriction makes their environment less hazardous, and if they are indifferent between vaccination and distancing, then they will not resort to the stronger defensive measures yielding x_{i2}^0. Under the foregoing assumptions, therefore, the freely chosen distancing by susceptible members of the second group in period 2 in variant A will exceed the enforced minimum $\underline{x}_2$ in B, quite possibly by a substantial margin. This result, at first sight rather counter-intuitive, will arise in Sections 6.2 and 6.3.

Turning to period 1, under a sufficiently stringent minimum, all will comply with it exactly, so that $X_1 = \underline{x}_1$ and $f(\underline{x}_1)g(\underline{x}_1, \underline{n})$ get infected. Assuming, plausibly, that the ZTT is not attained under $\underline{x}_1$, the members of S_1 number $n_1(\underline{x}_1) = (1-n_0)f(\underline{x}_1)g(\underline{x}_1, \underline{n})$, thus determining the value of n_1 for decisions in period 2. This is strikingly simple in comparison with Section 3.2, which involves the apparatus of backward induction. Imposing $\underline{x}_1$ on non-believers implies that the freely chosen x_1^* in variant A exceeds $\underline{x}_1$.

To sum up, suppose there are some non-believers, so that vaccination in the population is incomplete. If the minimum distance measures are sufficiently stringent, then the following subgame perfect equilibria can arise for particular constellations of parameter values:

(i) all members of S^r choose vaccination if and only if $c(\underline{x}_2) > \bar{\xi}_v$;

(ii) vaccination is rejected by all if $c(\underline{x}_2) < \bar{\xi}_v$ and condition (14) is violated for $n_2 = 0$;

(iii) if $c(\underline{x}_2) < \bar{\xi}_v$ and condition (12) holds, then all susceptible members of S^r choose vaccination, but no one else;

(iv) if $c(\underline{x}_2) < \bar{\xi}_v$ and (14) holds when a certain positive fraction of all susceptible members of S^r choose vaccination, then there is a mixed strategy equilibrium wherein these are the only individuals who so choose.

Since wholesale rejection is not actually observed, type (ii) is ruled out. Type (i) seems a rather remote, ideal outcome in practice, but it is a logical possibility. Type (iii) cannot be distinguished from type (iv) when only the population vaccination rate is known. It should be noted that whether the inequality $c(\underline{x}_2) > \bar{\xi}_v$ or its converse holds plays a decisive role in separating (i) from (iii) and (iv), a fact employed in Section 6.3.

5 Functional Forms for Calibration

Let the probability that individual i is infected in period 1 be given by

$$p_{i1} = \left[(x_{i1} + 1)(aX_1 + 1)\right]^{-1}, \tag{15}$$

where a is a positive constant representing how strongly aggregate distancing influences individuals' risks. The corresponding probability in period 2 is

$$p_{i2} = q\left[(x_{i2} + 1)(aX_2 + 1)\right]^{-1} \text{ if } q > 0; \text{ otherwise, } p_{i2} = 0, \tag{16}$$

where $q = 1 - \gamma(\lambda n_0 + n_1 + n_2)/\underline{n}$. Those infected in period 1 and those vaccinated at the start of period 2 number altogether $\lambda n_0 + n_1 + n_2$, with no overlap. By assumption, they are safe from symptomatic infection in period 2. The parameter γ reflects how any intervening mutation of the virus affects the general propagation of the disease in period 2 given that number. If γ is maximal, at the value 1, then there is no such effect. The ZTT will have been attained just after the start of period 2 if, and only if, $\gamma(\lambda n_0 + n_1 + n_2) \geq \underline{n}$. Let the distancing cost function be $c(x) = x^2/2$.

The argument proceeds according to the summary closing Section 3.2. To illustrate, the closed-form expressions for period 1 are derived in the following subsection. The

Table 1: Regimes and key variables in equilibrium

ZTT attained in period 1	$x_1^*(Z), n_1^*(Z)$
ZTT not attained in period 1, wholesale rejection in 2	$x_1^*(R), n_1^*(R), x_2^*(R), n_2^* = 0$
ZTT not attained in period 1, mixed strategy equilibrium in 2	$x_1^*, n_1^*, x_2^*(\bar{\xi}_v), n_2^*(\bar{\xi}_v)$

derivation of those for period 2 is consigned to Appendix 2, being both similar in nature and involving nothing in principle beyond Section 3.2.2.

The regimes and the associated key variables in equilibrium are summarised in Table 1. It is seen from (21) below that if $a \geq 1$, then large values of $\bar{\xi}_1 - \beta\bar{\xi}_v$ are compatible with modest values of x_1^*, and from (30) in Appendix 2, that the same holds for x_2^* ($= x_2^*(\bar{\xi}_v)$) in relation to $\bar{\xi}_2$. The scope for mixed strategy equilibria is then large, as confirmed empirically in Section 6. It is also seen from a comparison of (29) and (30) that if $\bar{\xi}_v$ is small, say about 1, then $q\bar{\xi}_2 \approxeq 1$ will involve $x_2(\bar{\xi}_v) < x_2^*$, thus ruling out a subgame perfect equilibrium. That is to say, $\bar{\xi}_v$ must be sufficiently large to ensure the existence of such an equilibrium; where Covid-19 is concerned, that condition appears to be satisfied.

5.1 Period 1: ZTT or no

If $i \in S^r$ conjectures that the ZTT will be attained in period 1, then she expects to obtain ω for sure in period 2, so that V_i reduces to $(1+\beta)\omega - p_{i1}\bar{\xi}_1 - c(x_{i1})$. The associated f.o.c. is

$$\frac{\bar{\xi}_1}{(x_{i1}(Z)+1)^2(aX_1(Z)+1)} - x_{i1}(Z) = 0.$$

In the corresponding symmetric equilibrium, $X_1(Z) = (1-n_0)x_1^*(Z)$, where $x_1^*(Z)$ satisfies

$$x_1^*(Z)(x_1^*(Z)+1)^2(a(1-n_0)x_1^*(Z)+1) = \bar{\xi}_1. \tag{17}$$

It is seen that $x_1^*(Z)$ is unique, positive, increasing in $\bar{\xi}_1$ and decreasing in a; it is small when $\bar{\xi}_1$ is small, and is largely independent of n_0 when a is small. By the law of large numbers,

$$n_1^*(Z) = \frac{1 - n_0}{(x_1^*(Z) + 1)[a(1 - n_0)x_1^*(Z) + 1]}; \tag{18}$$

and, since non-believers do not practise distancing in variant A,

$$\lambda^*(Z) = 1/[a(1 - n_0)x_1^*(Z) + 1]. \tag{19}$$

From (18) and (19), the number infected is

$$\lambda^*(Z)n_0 + n_1^*(Z) = \frac{n_0 x_1^*(Z) + 1}{(x_1^*(Z) + 1)[a(1 - n_0)x_1^*(Z) + 1]}. \tag{20}$$

If the structural parameters are such that $\lambda^*(Z)n_0 + n_1^*(Z) \geq \underline{n}$, then agents' expectation that the ZTT will be reached in the first period will be self-fulfilling, in keeping with proposition 2.

If, on the other hand, $\lambda^*(Z)n_0 + n_1^*(Z) < \underline{n}$, suppose $i \in S^r$ conjectures that some of those who did not get infected in period 1 will choose vaccination. In such a symmetric equilibrium in period 1, (17) becomes

$$x_1^*(x_1^* + 1)^2[a(1 - n_0)x_1^* + 1] = \bar{\xi}_1 - \beta\bar{\xi}_v, \tag{21}$$

which has a unique positive solution, and n_1^* and λ^* are given by (18) and (19), respectively, with x_1^* replacing $x_1^*(Z)$. The form of (21) is identical to (17), where the latter holds if and only if the ZTT is attained. The intrusion of $\beta\bar{\xi}_v (> 0)$ in (21) is accompanied by a different value of $\bar{\xi}_1$, one sufficiently large so as to rule out attaining the ZTT. That $x_1^* > x_1^*(Z)$ for any such pair of values has been proved in Section 3.2.2. Intuitively, greater distancing in aggregate is the only means of prevention in aggregate in period 1, and higher values of $\bar{\xi}_1$ induce more distancing.

6 An Empirical Application to the EU

Any empirical application of the foregoing framework imposes two immediate requirements. First, vaccines must be available in such quantities that all those who want to get vaccinated can actually get a jab. Secondly, the number of confirmed cases of infection must be independent of the extent of testing. These requirements restrict consideration to advanced countries. The EU pursued a programme of providing vaccines in common, and has common standards of reporting requirements. For these reasons, we deal only with its member states.

Even within the EU, the course of Covid infections and vaccinations varied across countries at similar levels of development. This prompts the question of whether these varying trajectories resulted from variations in the expected costs of infection and vaccination, and in the size of the group of non-believers. These variables are not observed, but if the model is correct, then certain of their values can be inferred from available data on infections and vaccinations. The measures adopted to contain the epidemic also varied, as did the stringency with which they were enforced.

6.1 The course of infections and vaccinations

A further requirement is to squeeze the continuous trajectories of the data into the corset of the two-period model. Setting the outbreak at 01.01.2020 is uncontroversial: period 1 starts on that date. The numbers of confirmed cases of infection up to 18.02.2024 are reported in https://www.worldometers.info/coronavirus/, a widely-used source.

The numbers are quite small up to 01.07.2021 (see Table 2); they roughly doubled in the following six months, whereupon the omicron wave broke. That wave accounted for the overwhelming share of all infections over the whole course of the pandemic. It had ebbed away by the close of 2022, and all relevant variables were quite close to their long-term values by the spring of 2023. It is assumed, therefore, that the story ends on 31.12.2022, making both periods 18 months long when period 1 ends on 30.06.2021 (see below).[12] With period 2 thus defined, the cumulative infection rates for each period,

[12] A later cut-off date is admissible, but arguably not much later than 31.03.2023 if the two periods

denoted by I_1 and I_2, respectively, can be calculated. It is seen from Tables 2 and 3 that I_2 is much larger than I_1 however period 2 be plausibly defined.

An important caveat concerning these data is in order: the intensity of testing varied enormously within the EU (see Table 2). The citizens of Austria, Cyprus, Denmark, Greece and Spain were each tested, on average, 10 to 30 times, the French, Italians and Portuguese were thus subjected to a comparatively modest four or five, and their counterparts in the other countries at most thrice. Since more testing surely leads to more confirmed cases, though surely not *pari passu*, the infection data – and hence any results derived from them – must be regarded with some reservations.

The European Surveillance System (TESSy) reported vaccination data up to 05.10.2023. It defines the primary course of vaccination as comprising the primary dose and the accompanying booster. (The second booster, which was rolled out in the autumn of 2021, is called the 'first booster'.) Vaccination began on a limited scale early in 2021, and roll-outs accelerated in the first half. The model demands a date sufficiently early in 2021 to rule out extensive vaccination. Inspection of the various graphs suggests 01.07.2021, 18 months after the outbreak. The cumulative vaccination rates (denoted by N_v) on 01.07.2021 were at most 60% of their levels on 01.01.2022 (see Table 2), where the latter levels were quite close to their long-term levels in 2023. There are two further points. First, those vaccinated in June 2021 were not fully immune in July, so that 01.07.2021 is on the conservative side in this regard. Secondly, the supplementary booster in the late months of 2021 was rolled out on a much more limited scale. By the end of 2021, it typically covered about one half of those who had had their primary course. It is arguable, therefore, that if period 2 started on 01.07.2021 and vaccination (in the model) is supposed to have occurred early on in that period, then the cumulative vaccination rate on 01.01.2022 corresponds to n_2 in the model. The starting date for period 2 is taken to be 01.07.2021.

are to be of roughly equal length.

Table 2: Covid-19 in the EU: infections, vaccinations, mortality and testing

Country	Pop.[a]	Number of infections (Mi.)[b]				N_v [c]		Deaths	Tests[d]
	(Mi.)	01.07.21	01.01.22	01.01.23	18.02.24	01.07.21	01.01.22	per Mi.	p.c.
Austria	9.18	0.64	1.27	5.71	6.08	0.386	0.714	2,486	23.12
Belgium	11.88	1.08	2.13	4.69	4.86	0.367	0.765	2,946	3.17
Bulgaria	6.44	0.42	0.75	1.29	1.34	0.125	0.281	5,661	1.58
Croatia	3.87	0.36	0.72	1.26	1.31	0.307	0.542	4,604	1.34
Cyprus	1.36	0.08	0.17	0.63	0.68	0.429	0.699	1,116	32.23
Czechia	10.88	1.69	2.52	4.58	4.60	0.331	0.627	4,053	2.11
Denmark	5.98	0.29	0.81	3.17	3.18	0.343	0.786	1,511	11.62
Estonia	1.37	0.13	0.24	0.61	0.63	0.348	0.616	2,270	2.74
Finland	5.64	0.10	0.29	1.45	1.52	0.211	0.751	2,153	1.63
France	68.52	5.78	10.19	39.33	40.14	0.336	0.744	2,556	4.17
Germany	83.51	3.74	7.20	37.37	38.83	0.392	0.718	2,182	1.46
Greece	10.39	0.44	1.29	5.63	6.10	0.377	0.677	3,671	9.43
Hungary	9.56	0.81	1.26	2.19	2.23	0.510	0.614	5,106	1.18
Ireland	5.38	0.27	0.77	1.69	1.73	0.399	0.777	1,891	2.64
Italy	58.99	4.29	6.38	25.21	26.73	0.340	0.756	3,261	4.46
Latvia	1.86	0.14	0.28	0.97	0.98	0.304	0.671	3,632	2.96
Lithuania	2.89	0.28	0.53	1.29	1.40	0.387	0.663	3,718	3.24
Luxembourg	0.68	0.07	0.10	0.37	0.39	0.385	0.687	1,918	6.79
Malta	0.57	0.03	0.05	0.12	0.12	0.667	0.820	1,993	2.45
Netherlands	17.99	1.69	3.15	8.57	8.64	0.340	0.663	1,336	1.51
Poland	36.55	2.88	4.12	6.37	6.66	0.370	0.558	3,196	1.01
Portugal	10.70	0.87	1.42	5.55	5.64	0.369	0.836	2,774	4.51
Romania	19.07	1.08	1.81	3.31	3.53	0.238	0.406	3,622	0.89
Slovakia	5.42	0.39	0.84	1.86	1.88	0.315	0.492	3,887	1.35
Slovenia	2.13	0.26	0.47	1.31	1.36	0.327	0.549	3,417	1.35
Spain	48.81	3.82	6.48	13.69	13.91	0.405	0.752	2,606	10.08
Sweden	10.57	1.09	1.34	2.68	2.75	0.324	0.686	2,682	1.48

[a] https://data.worldbank.org/indicator/SP.POP.TOTL

[b] https://www.worldometers.info/coronavirus/ (accessed 25.07.2025).

[c] https://vaccinetracker.ecdc.europa.eu/public/extensions/covid-19/vaccine-tracker.html#uptake-tab.

[d] https://en.wikipedia.org/wiki/Template:COVID-19_testing_by_country

6.2 Variant A: freely chosen social distancing

The underlying assumption is that countries share the same structural parameters namely, $a, \beta, \underline{n}$ and γ, whose values we fix at the following levels: $a = 1$, so that individual and aggregate distancing have equal weights in determining an individual's risk; $\beta = 0.95$, a conventional value of the discount factor for a period of 18 months; $\underline{n} = 0.95$ (see footnote 4); and $\gamma = 0.5$.[13] For the sake of minimizing the state space, let $\bar{\xi}_2 = \bar{\xi}_1$. Countries differ only in the perceptions of the expected costs of infection, $\bar{\xi}_1$, vaccination, $\bar{\xi}_v$, and the number of non-believers, n_0. Armed with the three cross-country empirical magnitudes I_1, I_2 and N_v (see Table 3), we back out the estimates of $(\bar{\xi}_1, \bar{\xi}_2, \bar{\xi}_v, n_0)$ for each country. This is the essence of our reverse engineering methodology.

Table 2 presents the salient facts of the Covid-19 experience of the member states. Inspection yields three immediate conclusions. First, the ZTT was not attained in any of the countries during the whole period 01.01.2020 to 31.12.2022, since there were trickles of cases after the latter date. Secondly, there was no instance of a wholesale rejection of vaccination. Thirdly, the non-believers could be quite numerous; for although, by definition, n_0 cannot exceed $1 - N_v$, this upper bound is well clear of 0 for all member states, the smallest values being Portugal and Malta, at 0.164 and 0.180, respectively.

There is also a clear indication that not all members of the group S^r who escaped infection in period 1 chose to get vaccinated in period 2. In all countries, the sum $I_1 + N_v$ falls well short of 1, and non-believers, who do not practise distancing in this regime, must make up a disproportionately large share of I_1, implying that the susceptible fraction of S^r at the start of period 2 would be close to $1 - n_0$, since I_1 is quite small, Czechia having the highest value at 0.155. In this connection, the necessary condition

[13] Using data for England, Allen et al. (2023) estimate that the adjusted risk ratio of transmission for the omicron variant was 1.48 to 2.13 times that of the delta variant it displaced. Recalling that $\gamma = 1$ corresponds to no mutation, choosing 2 from the interval [1.48, 2.13] yields $\gamma = 0.5$.

Table 3: Estimates: expected costs of infection and vaccination, n_0 and distancing

Country	I_1	I_2	N_v	$\bar{\xi}_1$	$\bar{\xi}_v$	n_0	x_1^*	x_2^*
Austria	0.070	0.552	0.714	1519.6	124.8	0.258	5.78	8.80
Belgium	0.091	0.304	0.765	98.0	14.1	0	2.32	2.75
Bulgaria	0.065	0.135	0.281	248.3	20.6	0.034	3.19	3.38
Croatia	0.093	0.223	0.542	92.0	12.2	0	2.28	2.54
Cyprus	0.059	0.404	0.699	1957.2	124.8	0.234	6.23	8.79
Czechia	0.155	0.266	0.627	31.3	6.4	0	1.54	1.75
Denmark	0.048	0.482	0.786	2064.7	141.2	0.179	6.17	9.37
Estonia	0.095	0.350	0.616	387.2	37.6	0.210	3.81	4.69
Finland	0.018	0.239	0.751	2851.8	99.2	0	6.51	8.70
France	0.084	0.490	0.744	475.1	51.6	0.194	4.01	5.54
Germany	0.045	0.403	0.718	4714.3	223.3	0.233	7.94	11.87
Greece	0.042	0.500	0.677	13994.6	534.2	0.303	11.95	18.54
Hungary	0.085	0.144	0.614	111.4	14.1	0	2.43	2.75
Ireland	0.050	0.264	0.777	339.3	30.2	0	3.47	4.16
Italy	0.073	0.355	0.756	159.1	18.9	0	2.73	3.23
Latvia	0.075	0.446	0.671	1278.3	97.6	0.266	5.52	7.74
Lithuania	0.097	0.349	0.663	194.7	23.2	0.132	2.99	3.61
Luxembourg	0.103	0.441	0.687	289.5	34.5	0.207	3.46	4.47
Malta	0.053	0.158	0.820	302.0	29.4	0	3.34	4.11
Netherlands	0.094	0.382	0.663	340.3	35.8	0.194	3.63	4.57
Poland	0.079	0.095	0.558	129.5	15.1	0	2.56	2.85
Portugal	0.081	0.437	0.836	184.8	24.6	0.060	2.88	3.73
Romania	0.057	0.117	0.406	254.4	21.1	0	3.19	3.43
Slovakia	0.070	0.277	0.492	166.3	17.2	0	2.78	3.05
Slovenia	0.122	0.493	0.549	748.9	72.1	0.385	4.89	6.61
Spain	0.078	0.202	0.752	134.6	17.0	0	2.58	3.04
Sweden	0.103	0.150	0.686	74.8	11.4	0	2.11	2.44

Authors' calculations.

$n_2(\bar{\xi}_v) \in (0, \underline{n} - \lambda^* n_0 - n_1^*)$ in proposition 3 becomes $N_v \in (0, \underline{n} - I_1)$, which indeed holds in all cases. It follows that the course of events in these countries can be interpreted as reflecting a mixed strategy, subgame perfect equilibrium, with the observed outcomes I_1, I_2 and N_v.

Since the ZTT is ruled out, it is possible to reduce the system of equations in Section 5 to three equations in x_1^*, x_2^* and n_0 (see Appendix 2), which are solved numerically using matlab. The solution then yields the values of the three fundamental parameters, but with an important qualification: the triple (ξ_1, ξ_v, n_0) must be non-negative, with n_0 at most 1. The requirement that there be at least zero non-believers turns out to be binding in 13 of the 27 countries; left free, the estimated values of n_0 are negative. The pair (ξ_1, ξ_v) was then obtained by fixing n_0 at 0 and dropping the equation in I_2. In view of the reservations about I_2 that follow, this choice is the most defensible, but it makes comparisons across the two groups rather problematic, especially where x_2^* is concerned. This problem will arise again in Section 6.3.

What is distinctive about the 13 countries in question? Whatever be their underlying characteristics, the finding that they are free of non-believers stems largely from their infection rates, especially I_2. Under freely chosen distancing, non-believers are not only much more likely to get infected, but also much more likely to infect others, even if they manage to avoid testing. All else being equal, the more numerous they are, the higher will be the total infection rate, $I_1 + I_2$. For the 14 countries with $n_0 > 0$, $I_1 + I_2$ ranged from a mere 0.200 in Bulgaria, but then with a jump to 0.445 in Estonia and Lithuania, 0.448 in Germany and then up to 0.622 in Austria. For the 13 with $n_0 = 0$, $I_1 + I_2$ ranged from 0.174 in Poland and Romania to 0.428 in Italy. Apart from the outlier Bulgaria, the ranges of the two groups do not overlap. Where the statistic $I_1 + I_2$ is concerned, therefore, the entire EU zone can be separated into two distinct groups.

So much for one salient feature of the general pattern. Turning to the group with some non-believers, n_0 is quite small in Bulgaria and Portugal, but then ranges from 0.132 in Lithuania to 0.385 in Slovenia. The coefficients of correlation between n_0 and I_1, I_2 and N_v are not large: $\rho(n_0, I_1) = 0.283, \rho(n_0, I_2) = 0.211, \rho(n_0, N_v) = -0.365$, but all are in keeping with intuition. The associated coefficients for the measures of distancing, which are jointly estimated with n_0, are similar: $\rho(n_0, x_1^*) = 0.230, \rho(n_0, x_2^*) = 0.235$. The values of the expected costs $\bar{\xi}_1$ and $\bar{\xi}_v$ correspond to units of distancing through the cost function $c(x) = x^2/2$. Thus, Slovenia's values of 748.9 and 72.1 are equivalent to 38.7 and 12.0 units of distancing, respectively. It is clear that $\bar{\xi}_1$ and $\bar{\xi}_v$ are not ordered very closely in line with n_0. Although $\bar{\xi}_1$ for Portugal is the lowest value, at 184.8, with Lithuania close by, at 194.7, $\bar{\xi}_1$ for Greece is the highest, at almost two orders of magnitude greater, whereas Slovenia's falls in the middle of the rest. Reassuringly, $\bar{\xi}_1$ is about an order of magnitude greater than $\bar{\xi}_v$ for all members of the group, which is consistent with high rates of vaccination, even with n_0 positive.

The relation between infection rates and the splitting of the EU countries into the two groups discussed above calls into question certain items of the data. Consider, for example, the Iberian neighbours Portugal and Spain, intimately tied by geography, history and culture. Their values of I_1 scarcely differ, yet Portugal's I_2, at 0.437, is more than double Spain's, at 0.202, which implies that the omicron wave hammered the former, relatively speaking. Squaring this 'observed' outcome with Portugal's higher vaccination rate, at 0.836 the highest in the EU, with Spain's, at 0.752, is a tall order. Now consider their population death rates, with Covid-19 as cause or co-morbidity, which are reliable statistics. These were almost identical, at 2,774 and 2,606 per million, respectively. They imply that Portugal's case-specific mortality rate was about 40% lower than Spain's, which begins to beggar belief. There are grounds, therefore, to suspect that infections in Spain were substantially under-reported. Comparisons of other close neighbours in the EU, for example, Belgium and France, Denmark and Sweden, and Slovenia and Croatia, arouse the same suspicion about Belgium, Sweden and Croatia. This has important consequences for the estimated value of n_0. It follows at once from (32) in Appendix 2, that n_0 and I_2 move together. It could well be, therefore, that the finding of an absence of non-believers in 13 members of the EU is an artefact of the data on infections in period 2. This finding is subjected to independent scrutiny in variant B.

6.3 Variant B: minimum distancing enforced

This variant offers an alternative way of interpreting the data in Table 2. In particular, it admits the distinct possibility that the minimum distancing rules varied and were enforced with varying degrees of strictness across the EU. In contrast to variant A, the equation involving I_2 is employed for all 27 countries.

The chief task, then, is to estimate the minima $\underline{x}_1$ and $\underline{x}_2$, which, by assumption, apply only to the unvaccinated, whatever be their seropositive status. Recall from Section 4 that $\underline{x}_1$ and $\underline{x}_2$ must be sufficiently large for both to bind and so yield equilibria of types (iii) and (iv). As noted in Section 6.2, n_0 cannot exceed $1 - N_v$. As shown below, however, its lower bound in variant B, which holds when all members of S^r who got infected in period 1 decline vaccination, cannot be deduced from the available data. The condition that n_0 be at least zero can then be ignored in the estimation procedure, and all the I_2 data are taken and used at face value. As a by-product, we can infer the ranges of the perceived costs $\bar{\xi}_v$ associated with the minima.

Given $a = 1$, (15) yields $\underline{x}_1$: $I_1 = 1/(\underline{x}_1 + 1)^2$. A comparison of X_1 with that in variant A reveals that $\underline{x}_1 < x_1^*$; for I_1 is fixed and non-believers must comply with $\underline{x}_1$ in variant B, whereas they will not distance at all in variant A and so induce members of S^r to take correspondingly stronger defensive measures. This result confirms the importance of who is subject to enforcement and under what circumstances.

According to Section 4, there are two possible qualitative outcomes in period 2, whose occurrence is determined by whether the inequality $c(\underline{x}_2) > \bar{\xi}_v$ or its converse holds. Each yields a value of $\underline{x}_2$ and an associated value of $\bar{\xi}_v$. The resulting pair of values defines a range whose upper end arises if and only if only non-believers reject vaccination, i.e., $N_v = 1 - n_0$. Otherwise, the value of $\underline{x}_2$ cannot be inferred from the data for I_2 and N_v without knowing n_0.

In the first outcome, all members of S^r will choose vaccination if and only if $c(\underline{x}_2) > \bar{\xi}_v$, where $\underline{x}_2$ and $\bar{\xi}_v$ are exogenous. In that event, $n_0 = 1 - N_v$ is obtained directly. The data in Table 2 then imply that, in contrast to the finding yielded by variant A, there were non-believers everywhere in the EU.

To pursue this further, recall from (16) that $q = 1 - \gamma(I_1 n_0 + N_v)/\underline{n}$. Given the assumption that those infected in period 1 or vaccinated in period 2 can still experience asymptomatic infection in period 2, we have, from (16),

$$I_2 = (1 - \gamma(I_1 n_0 + N_v)/\underline{n}) \left[\frac{1 - n_0}{(n_0 \underline{x}_2 + 1)} + \frac{n_0}{[(\underline{x}_2 + 1)(n_0 \underline{x}_2 + 1)]} \right], \; n_0 = 1 - N_v, \quad (22)$$

which pins down $\underline{x}_2$ given $n_0 = 1 - N_v$. The numerators in brackets are the sizes of the groups of S^r and non-believers, and the denominators reflect the fact that the former, all vaccinated, do not practise distancing, whereas the latter are compelled to choose $\underline{x}_2$. Although it is improbable that only non-believers rejected vaccination in the EU, analysing this logically possible outcome does yield a useful finding. Since this outcome occurs if and only if $c(\underline{x}_2) > \bar{\xi}_v$, the resulting value of $\underline{x}_2$ implies that the value of $\bar{\xi}_v$ is less than $\underline{x}_2^2/2$. In the following, the said value of $\underline{x}_2$ is denoted by $\underline{x}_2^u$.

Turning to the converse case $c(\underline{x}_2) < \bar{\xi}_v$, this implies that no members of S^r who got infected in period 1 choose vaccination; for although, in contrast to variant A, they are compelled to distance, the cost of distancing $\underline{x}_2$ is less than the expected cost of vaccination. It follows that $N_v > 0$ implies that at least some, and just possibly all, of those in S^r who escaped infection in period 1 chose vaccination. In this second outcome, q shifts from $1 - \gamma(I_1 + (1 - I_1)N_v)/\underline{n}$ to $1 - \gamma(I_1 + N_v)/\underline{n}$, and

$$I_2 = (1 - \gamma(I_1 + N_v)/\underline{n}) \left[\frac{N_v}{(1 - N_v)\underline{x}_2 + 1} + \frac{1 - N_v}{(\underline{x}_2 + 1)[(1 - N_v)\underline{x}_2 + 1]} \right]. \quad (23)$$

In terms of the observed N_v, the expression in brackets is identical to that in (22), but the associated value of the multiplicand q is smaller. Hence, the associated value of $\underline{x}_2$

in (23), denoted by $\underline{x}_2^\ell$, is less than the corresponding $\underline{x}_2^u$ in (22). In this outcome, N_v is smaller than $1-n_0$, but the fraction of susceptible members of S^r who chose vaccination and n_0 cannot be deduced from the available information. This is in contrast to the alternative, extreme outcome, which yields the upper bound on n_0. What can be said is that, in virtue of (14), in this second, more plausible outcome, the value of $\bar{\xi}_v$ is at least $(\underline{x}_2^\ell)^2/2$. In variant B, therefore, the interval $[(\underline{x}_2^\ell)^2/2, (x_2^u)^2/2]$ encloses the true value, where it is seen from Table 4 that the estimated intervals are all small. The reason for this is that the I_1 are small and $\gamma = 0.5$, so that the multiplicands q in (22) and (23) differ little.

It is important to emphasise that the distancing variable x, whether freely chosen or otherwise, is a synthetic measure of a whole array of actions and the rules governing them, not just two meters and wearing a mask. Table 4 reports what levels of these synthetic measures must have been enforced in order to be consistent with the data on infections and vaccinations. The estimated lower bounds do not rule out the possibility that the associated, but unrecoverable, values of n_0 are zero; equivalently, that all those who rejected vaccination were rational individuals comparing the expected costs of vaccination with the sure costs of distancing. Yet, although logically possible, this hypothesis seems rather far-fetched. For whereas the pairwise differences between $\underline{x}_2^u$ and $\underline{x}_2^\ell$ are all small, the values of the normalised quantity $1 - N_v$ are not close to 0. The smallest is that for Portugal, at 0.164, and variant A yields $n_0 = 0.06$. Among the group of 13, Malta (hardly a typical member state) has the smallest value, at 0.180, followed by Ireland, at 0.223.

Since the values of I_1 are all quite close to 0, the value for Finland especially so, those of $\underline{x}_1$ are fairly similar in size, but well away from 0, Finland's value being the largest, i.e., the most stringent. Turning to period 2, I_2 exceeds I_1 for all countries, and for most, by a substantial margin; the exceptions are Bulgaria, Hungary, Malta, Poland, Romania, Spain and Sweden. This implies, *cet. par.*, $\underline{x}_1 > \underline{x}_2^\ell$, and this indeed holds, except for Czechia, Hungary, Ireland, Malta, Poland, Romania, Spain and Sweden, for

Table 4: Estimates: enforced minimum distancing

Country	$\underline{x}_1$	$\underline{x}_2^\ell$	$\underline{x}_2^u$	$\bar{\xi}_v^\ell$	$\bar{\xi}_v^u$
Austria	2.78	0.11	0.20	0.01	0.02
Belgium	2.31	2.19	2.56	2.40	3.28
Bulgaria	2.92	2.64	2.67	3.48	3.56
Croatia	2.28	0.25	0.30	0.03	0.05
Cyprus	3.12	0.91	1.02	0.41	0.52
Czechia	1.54	1.82	2.12	1.66	2.25
Denmark	3.56	0.42	0.54	0.09	0.15
Estonia	2.24	1.11	1.24	0.62	0.76
Finland	6.45	3.39	4.08	5.75	8.32
France	2.45	0.31	0.47	0.05	0.11
Germany	3.71	0.98	1.07	0.48	0.57
Greece	3.87	0.40	0.45	0.08	0.10
Hungary	2.43	5.11	5.41	13.06	14.63
Ireland	3.47	3.60	3.87	6.48	7.49
Italy	2.70	1.46	1.69	1.07	1.43
Latvia	2.65	0.59	0.70	0.17	0.25
Lithuania	2.21	1.19	1.37	0.71	0.94
Luxembourg	2.11	0.56	0.71	0.16	0.25
Malta	3.34	10.33	10.98	53.35	60.28
Netherlands	2.26	0.94	1.09	0.44	0.59
Poland	2.55	7.40	7.71	27.38	29.72
Portugal	2.51	0.65	0.99	0.21	0.49
Romania	3.18	4.02	4.09	8.08	8.36
Slovakia	2.78	1.51	1.57	1.14	1.23
Slovenia	1.86	0.35	0.43	0.06	0.92
Spain	2.58	4.89	5.35	11.96	14.31
Sweden	2.11	5.89	6.43	17.35	20.67

Authors' calculations.

ℓ: some members of S^r choose vaccination.

u: all choose vaccination ($n_0 = 1 - N_v$).

all of which $n_0 = 0$ must be imposed when estimating variant A. The values of $\underline{x}_2^\ell$ vary greatly, ranging from 0.11 for Austria to 10.33 for Malta, an outlier in various ways; but the intra-country differences in the pairs $[\underline{x}_2^\ell, \underline{x}_2^u]$ are all quite small. In this connection, Austria had the largest value of I_2, with Denmark, France, Greece and Slovenia not far behind at almost 0.5. The associated values of $\underline{x}_2^\ell$ are therefore quite close to 0, whereas the corresponding values of x_2^* in variant A are an order of magnitude larger. At the other extreme, Bulgaria, Hungary, Malta, Poland, Romania and Sweden had quite low infection rates in period 2, and the associated values of $\underline{x}_2^\ell$ are correspondingly large.

Now, $\underline{x}_1$ and I_1 must move in opposite directions, in the specific form (15). The natural interpretation here is that the authorities that enforced more stringent distancing accomplished lower infection rates. The connection between I_2 and the two bounds for $\underline{x}_2$ is more involved; for the bounds relate to N_v, and hence I_2, in different ways through differences in the vaccination rate. If $\underline{x}_2$ is sufficiently large, then all members of S^r will choose vaccination. The least such value is $\underline{x}_2^u$, and it need not be large if the expected cost of vaccination is small. Indeed, it can be smaller than $\underline{x}_1$, as in 18 countries. At the other extreme, if the distancing rules are sufficiently weak, those members of S^r who suffered infection in period 1 will decline vaccination in period 2. This puts a lower bound on $\underline{x}_2$, since $N_v > 0$; but the difference between the two bounds is indeed quite small for all 27 countries. The upper bound is effectively independent of $\underline{x}_1$, which is the main influence on I_1. Although I_1 somewhat influences the lower bound, the factors governing both bounds in period 2, chiefly the vaccination rate, are much stronger in play. The values of $\underline{x}_2$ are correspondingly more heterogeneous than those of $\underline{x}_1$: $\text{var}(\underline{x}_1) = 1.6$, $\text{var}(\underline{x}_2^\ell) = 7.5$ and $\text{var}(\underline{x}_2^u) = 8.3$; though it should be noted that the values of I_1 are considerably smaller than those of I_2.

While comparing Tables 3 and 4 two features are noteworthy. First, in majority of cases, voluntary distancing exceeds the corresponding regulatory benchmarks. Specifically, x_1^* exceeds $\underline{x}_1$ in 19 out of the 27 countries, while in period 2 the equilibrium level x_2^* exceeds the average of $\underline{x}_2^l$ and $\underline{x}_2^h$ in 20 countries. Strikingly, both inequalities hold jointly in 17 countries. These findings provide strong quantitative support for the theoretical prediction that, when individuals internalise infection risks in an environment with heterogeneous behaviour (including non believers), they tend to choose higher levels of social distancing than those implied by uniform minimum regulations. The result is particularly pronounced in period 2, consistent with the model's emphasis on strategic interactions and the reduced hazard environment under enforcement, which lowers the required minimum but does not eliminate incentives for stricter voluntary distancing.

7 Conclusions

This paper deals with a two-period setting in which individuals, acting separately, make decisions about social distancing and vaccination, where the latter carries the risk of side effects and both affect the prevalence of symptomatic infection. In one variant, these decisions are wholly voluntary. In the second, the authorities enforce a minimum level of distancing on all unvaccinated individuals.

There exist various subgame perfect equilibria. If individual immunity is perfect and the zero transmission threshold is less than 1, then zero transmission in the second period can arise from distancing decisions in the first. If it does not thus arise, it can never do so as a result of vaccination at the start of the second if the expected cost of vaccination is positive. There can be a mixed strategy equilibrium, wherein some of those who escaped infection in the first period choose vaccination in the second, or even a wholesale rejection of vaccination, depending on the expected costs of infection and vaccination. These outcomes among rational agents also hold in the presence of a sufficiently small group of Covid deniers, who reject both distancing and vaccination.

Applying the model to the Covid-19 pandemic in the EU yields the qualitative finding that its course can be interpreted as a mixed strategy outcome in all countries, the ZTT being attained nowhere in the four-year interval from 2020 to 2023. The corresponding estimates of the expected costs of infection and vaccination varied greatly across the member states, with the former about an order of magnitude greater than the latter. According to the first variant, there was a group of non-believers in 14 members, ranging from 6 to 39 per cent of their respective populations; but the analysis also indicates a distinct possibility of under-reporting of infections in some of the rest, thereby potentially masking such groups in their midst. When the data are applied to the second variant, they yield strong indications that there were non-believers everywhere in the EU.

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Appendix 1: Proofs

Distancing decisions

Denote the partial derivatives of g by g_{X_2} and g_{n_z}, respectively. Differentiating (3) totally, rearranging and noting that n_1 is fixed in period 2, we obtain

$$\frac{dx_2^0}{dn_2^e} = \frac{f'(x_2^0)[g_{X_2} \cdot x_2^0 + g_{n_z}]}{f''(x_2^0)g + c''(x_2^0)/\bar{\xi}_2 + n_3 g_{X_2} f'(x_2^0)},$$

where the assumptions on f, c and g include $f' < 0, f'' > 0, c'' > 0, g_{X_2} < 0$ and $g_{n_z} > 0$. Thus, the denominator is positive, so that x_2^0 is continuous in n_2^e, increasing in n_2^e if $g_{X_2} \cdot x_2^0 + g_{n_z}$ is negative, and decreasing if the latter is positive. ■

Claim: If only some of the susceptible members of S^r choose vaccination, then given c and f, distancing in period 2 in equilibrium depends only on $\bar{\xi}_v$.

By assumption, $c(0) = c'(0) = 0$, $c(x_2)$ increases without bound as x_2 increases, and $-f/f' > 0$. Hence, for any $\bar{\xi}_v > 0$, there exists an $x_2 > 0$ such that

$$c(x_2) - [f(x_2)c'(x_2)]/f'(x_2) = \bar{\xi}_v.$$

Denote that value by $x_2^*(\xi_v)$, which is increasing in $\bar{\xi}_v$ and independent of $\bar{\xi}_2$, as well as of $\underline{n}, n_1$ and n_2^e for all $n_2^e \in (0, \underline{n} - n_1)$, the latter being arguments only of g. Since (4) holds, $x_2^*(\bar{\xi}_2) = x_2^0(n_1, n_2^e, \bar{\xi}_2)$ and $c(x_2^*(\bar{\xi}_2)) + p_2(x_2^*(\bar{\xi}_2))\bar{\xi}_2 = \bar{\xi}_v$. ■

Let $x_2^*(\bar{\xi}_2)$ satisfy (4) without reference to (3). In equilibrium, $x_2^*(\bar{\xi}_v) = x_2^0(n_1, n_2^e, \bar{\xi}_2)$. As $\bar{\xi}_v$ varies, then so, too, does the equilibrium pair $(n_2^e, x_2^*(\bar{\xi}_v))$, with $n_2^e > 0$ provided $\bar{\xi}_v$ is not so large that condition (24) below holds, as is now demonstrated.

Vaccination: expected costs and acceptance

It is also possible that all individuals in S^r who escaped infection in period 1 reject vaccination, thus avoiding the expected cost $\bar{\xi}_v$, and expect all others to do likewise. If

$$\left\{c(x_2^0) - f(x_2^0)c'(x_2^0)/f'(x_2^0)\right\}_{x_2^0(n_1, n_2^e = 0, n_z, \bar{\xi}_2)} < \bar{\xi}_v, \tag{24}$$

that expectation is indeed fulfilled under rational choices of distancing, and there is a wholesale rejection of vaccination. The derivative of the expression in braces is $(f/f'^2)(-f'c'' + c'f'') > 0$. Hence, if x_2^0 is decreasing in n_2^e, then the LHS is decreasing therein, attaining a maximum when $n_2^e = 0$, so that (24) holds $\forall n_2^e \in [0, \underline{n} - \lambda n_0 - n_1)$.

Suppose the threshold is not attained and that ξ_v is close to zero, so that condition (24) does not hold. Then considerations of continuity suggest that there exists a subgame perfect Nash equilibrium wherein $n_1 < \underline{n}$ and $n_1 + n_2$ is smaller than, but close to, $\underline{n}$. In such an equilibrium, all individuals know that if they get infected in period 1, they will obtain ω for sure in period 2, whereas if they escape, they will obtain the expected pay off $\omega - \bar{\xi}_v$. If $\bar{\xi}_v$ is sufficiently large, however, condition (24) will hold. This indicates that as the expected cost $\bar{\xi}_v$ increases steadily from zero, it will induce the level of voluntary vaccinations to fall steadily, eventually to zero, with accompanying adjustments to the level of distancing in period 2.

The foregoing results are summarised as

Proposition 4 *Suppose the ZTT is not reached in period 1.*
(i) If condition (24) holds, then universal rejection of vaccination is a Nash equilibrium. If $g_{X_2} \cdot x_2^0 + g_{n_z} > 0$, then it is the only Nash equilibrium.
(ii) If the converse of condition (24) holds, $\bar{\xi}_v$ is sufficiently small and $g_{X_2} \cdot x_2^0 + g_{n_z} > 0$, then there is a mixed strategy Nash equilibrium wherein the share of those in S^r and susceptible at the start of period 2 who choose vaccination is $n_2^e/(1 - \lambda n_0 - n_1)$, where $n_2^e \in (0, \underline{n} - \lambda n_0 - n_1)$ is such that x_2^0 satisfies (4).

Proof of proposition 3

In view of

$$V_i = (1+\beta)\omega - (p_{i1}\xi_1 + c(x_{i1})) - \beta(1 - p_{i1}(x_{i1}))\xi_v,$$

let $x_{i1}^0(x_1^*)$ minimize the (convex) function $f(x_{i1}) \cdot g(x_1^*, 0, 1)(\xi_1 - \beta\xi_v) + c(x_{i1})$. Then $x_{i1}^0(x_1^*)$ satisfies

$$f'(x_{i1})g(x_1^*, 0, 1)(\xi_1 - \beta\xi_v) + c'(x_{i1}) \leq 0,\ x_{i1} \geq 0. \tag{25}$$

It is seen that $x_{i1}^0(x_1^*)$ is unique and positive, and that it depends only on the difference $\xi_1 - \beta\xi_v$. Individual i will deviate from the hypothesized symmetric equilibrium in period 1 if, and only if,

$$p_{i1}^0(x_1^*)(\xi_1 - \beta\xi_v) + c(x_{i1}^0(x_1^*)) < p_1^*(\xi_1 - \beta\xi_v) + c(x_1^*). \tag{26}$$

Observing that, in the limit, condition (26) is violated when the strict equality

$$p_{i1}^0(x_1^*)(\xi_1 - \beta\xi_v) + c(x_{i1}^0(x_1^*)) = p_1^*(\xi_1 - \beta\xi_v) + c(x_1^*),$$

holds, i.e., no deviation, we have established the conditions in part (i). ■

Remark. If $\xi_1 \leq \beta\xi_v$, i will choose $x_{i1} = 0$, as will everyone else, so that $n_1 = 1$, contradicting the conjecture $n_2^e \in (0, \underline{n})$. This obvious result is an instance of a violation of part (i) of proposition 3.

Concerning the uniqueness of (symmetric) equilibrium, condition (25) becomes

$$f'(x_1^*)g(x_1^*, 0, 1)(\xi_1 - \beta\xi_v) + c'(x_1^*) = 0.$$

This equation has a unique positive solution, and hence the pair $(x_1^*, n_1(x_1^*))$ is unique. If $n_1(x_1^*) < \underline{n}$, the solution is admissible. Turning to $x_2^*(\xi_v)$, this is always unique. Given that value, n_2 is unique if the function g is monotonically decreasing in n_2, whereby g is positive when $n_2 = 0$ and g vanishes when $n_1 + n_2 = \underline{n}$.

It should be noted that given the conjecture of a mixed strategy equilibrium in period 2, the distancing decision in period 1 becomes independent of all other outcomes in period 2. Suppose n_2^e is very close to 0, so that the mixed strategy equilibrium is very close to the boundary of the set of such equilibria. Let $\bar{\xi}_2$ increase a little, but $\bar{\xi}_v$ remain constant. Then (3) will cease to hold if g_{X_2}, evaluated at $X_2 = (1 - n_0 - n_1^*)x_2^0$ is sufficiently large; for $x_2^0 = x_2(\bar{\xi}_v)$, a constant, within the said boundary. It follows that condition (iii) of proposition 3 is no longer satisfied. The alternative possibilities of wholesale rejection of vaccination and of no equilibrium at all remain.

Appendix 2: Calibration and empirical application

Period 2

If the ZTT is not attained in period 1, then there are three possibilities: wholesale rejection of vaccination, a mixed strategy equilibrium, and no subgame perfect equilibrium.

Wholesale rejection of vaccination

Suppose $i \in S^r$ was not infected in period 1. If she declines vaccination, she will take a chance by distancing, in which case her f.o.c. is

$$\frac{q\bar{\xi}_2}{(x_{i2}+1)^2(aX_2+1)} - x_{i2} = 0, \; i \in S_3.$$

If she conjectures that all other members of S_3 will do likewise ($n_2^e = 0$), then in a symmetric equilibrium, $X_2 = n_3 x_2^*$, where $n_3 = 1 - n_0 - n_1^*$ and x_2^* satisfies

$$x_2^*(x_2^*+1)^2(an_3x_2^*+1) = q\bar{\xi}_2, \tag{27}$$

which has a unique positive solution for all $q > 0$. Denoting this solution by $x_2^*(R)$, it is seen that $x_2^*(R)$ is increasing in $\bar{\xi}_2$. Given the specific functional forms, it is shown in Appendix 1 that if the expected cast of infection and the cost of optimal social distancing in period 2 is less than the expected cost of vaccination, i.e., if

$$\xi_R \equiv x_2^*(R)(3x_2^*(R)/2+1) < \bar{\xi}_v, \tag{28}$$

then wholesale rejection of vaccination is a Nash equilibrium in period 2; (28) will hold if $\bar{\xi}_v$ is sufficiently large. In this symmetric equilibrium, $n_2^e = n_2 = 0$ is a self-fulfilling expectation.

Turning to period 1, replacing $\bar{\xi}_1 - \beta\bar{\xi}_v$ in (21) with $\bar{\xi}_1 - \beta\xi_R$ and solving for $x_1^*(R)$ yields $n_1^*(R)$ and $\lambda_1^*(R)$. The associated subgame perfect Nash equilibrium is $(x_1^*(R), n_1^*(R), \lambda^*(R), x_2^*(R), n_2 = 0)$. If condition (28) does not hold, then there is no such equilibrium.

A mixed strategy equilibrium

Suppose i declines vaccination, but now conjectures that some susceptible members of S^r will do otherwise. If there is such a mixed strategy equilibrium in period 2, then $\bar{\xi}_2$ and $\bar{\xi}_v$ must be such that the expected cost of infection plus the cost of social distancing just balance the expected cost of vaccination:

$$p_{i2}(x_2^*)\bar{\xi}_2 + c(x_2^*) = \bar{\xi}_v,\ n_2^e \in (0, 1 - \lambda n_0 - n_1^*).$$

Hence, from (16) and (30),

$$x_2^*(3x_2^*/2 + 1) = \bar{\xi}_v,$$

which has the unique positive solution

$$x_2^*(\bar{\xi}_v) = [-1 + (6\bar{\xi}_v + 1)^{1/2}]/3, \tag{29}$$

so that $x_2^*(\bar{\xi}_v)$ is increasing, quite strongly concave in $\bar{\xi}_v$ and independent of n_2^e. Substituting $x_2^*(\bar{\xi}_v)$ into the f.o.c. for optimal social distancing at date 2, namely,

$$x_2^*(x_2^* + 1)^2[a(1 - n_0 - n_1^* - n_2)x_2^* + 1] = q\bar{\xi}_2 = [1 - \gamma(\lambda^* n_0 + n_1^* + n_2)]\bar{\xi}_2, \tag{30}$$

and recalling from (21) that n_1^* and λ^* depend on $\bar{\xi}_1 - \bar{\xi}_v$, yields $n_2 = n_2(\bar{\xi}_1, \bar{\xi}_2, \bar{\xi}_v)$, the number of susceptible individuals in S^r choosing vaccination. Let $A = x_2^*(x_2^* + 1)^2/\bar{\xi}_2$. Then, from (27), given $\bar{\xi}_1$ and $\bar{\xi}_2$,

$$n_2(\bar{\xi}_v; \bar{\xi}_1, \bar{\xi}_2) = \frac{A[a(1 - n_0 - n_1^*)x_2^*(\bar{\xi}_v) + 1] - (1 - \gamma(\lambda^* n_0 + n_1^*)/\underline{n})}{Aax_2^*(\bar{\xi}_v) - \gamma/\underline{n}}.$$

If $n_2(\bar{\xi}_v) \in (0, \underline{n} - \lambda^* n_0 - n_1^*)$, then $(x_2^*(\bar{\xi}_v), n_2(\bar{\xi}_v))$ is a Nash equilibrium wherein the ZTT will not be reached in period 2, and $(x_1^*, n_1^*, \lambda^*, x_2^*(\bar{\xi}_v), n_2(\bar{\xi}_v))$ is a subgame perfect Nash equilibrium. Otherwise, there is no such equilibrium.

Solving for $\mathbf{x_1^*, x_2^*, n_0}$ and other values

The ZTT is not attained, so that the index Z is dropped. Substituting $I_1 = \lambda^* n_0 + n_1^*$ in (20) yields

$$I_1 = \frac{1 + n_0 x_1}{(x_1 + 1)[a(1 - n_0)x_1 + 1]}.$$

Since I_1 is quite small, this equation is almost certain to have one positive root for any given $n_0 \in [0, 1)$, where $n_0 \geq 0$ if and only if $x_1 \geq (1/\sqrt{I_1}) - 1$, which puts a lower bound on $\bar{\xi}_1$. Let $\Delta = \bar{\xi}_1 - \beta\bar{\xi}_v$, so that (21) is written

$$\Delta = x_1^*(x_1^* + 1)^2(a(1 - n_0)x_1^* + 1).$$

In period 2, we have the indifference condition (29), which can be expressed as

$$x_2^*(3x_2^*/2 + 1) = \bar{\xi}_v,$$

and the f.o.c. (30) written in the form (by assumption $\bar{\xi}_2 = \bar{\xi}_1$)

$$q\bar{\xi}_1 = q(\Delta - \beta\bar{\xi}_v) = x_2^*(x_2^* + 1)^2(a(1 - n_0 - n_1^* - N_v)x_2^* + 1). \tag{31}$$

where n_1^* is given by (18) and $q = 1 - \gamma(I_1 + N_v)/\underline{n}$. Substituting for $\bar{\xi}_v$, (31) becomes the second equation in x_1^*, x_2^* and n_0.

If $n_2^e = 0$, distancing yields the expected cost $p_2^*(x_2^*(R))\bar{\xi}_2 + c(x_2^*(R))$. Using (27), this reduces to $x_2^*(R)(3x_2^*(R)/2 + 1)$, and if this expression is smaller than $\bar{\xi}_v$, then vaccination will be rejected.

The final step is to use I_2, for which analytical expressions are needed. Consider the $\lambda^* n_0 + n_1^* + n_2^*$ individuals who could get infected in period 2 and so test positive. Since they practise no distancing, for these individuals (16) specialises to

$$p_{i2} = q[a(1 - n_0 - n_1^* - n_2^*)x_2^0 + 1)]^{-1} \text{ if } q > 0; \quad \text{otherwise, } p_{i2} = 0.$$

Hence, the law of large numbers yields the number of infections:

$$n_{r2} = q \cdot \frac{\lambda^* n_0 + n_1^* + n_2^*}{a(1 - n_0 - n_1^* - n_2^*)x_2^0 + 1} \text{ if } q > 0; \text{ otherwise, } n_{r2} = 0.$$

To these must be added the total number of infections among those fully susceptible in period 2:

$$n_{s2} = q \cdot \frac{(1 - \lambda^*)n_0}{a(1 - n_0 - n_1^* - n_2^*)x_2^0 + 1} + p_{i2}(x_2^0)[1 - n_0 - n_1^* - n_2^*]$$
$$\text{if } q > 0; \text{otherwise, } n_{s2} = 0.$$

The first term on the RHS is the number of infections among the non-believers who escaped infection in period 1. The second term is the corresponding number among those in S^r who escaped infection in period 1 and declined vaccination in period 2. The probability $p_{i2}(x_2^0)$ is calculated from (16), where $x_{i2} = x_2^0$.

The total number of infections in period 2 is therefore $n_{r2} + n_{s2}$, which is observed empirically as I_2. We have, after some manipulation,

$$I_2 = q \cdot \frac{(n_0 + n_1^* + N_v)x_2^* + 1}{[a(1 - n_0 - n_1^* - N_v)x_2^* + 1](x_2^* + 1)}, \tag{32}$$

which is the third equation. Solving for x_1^*, x_2^*, n_0, and then substituting the values of x_1^* and n_0 in (18), (19) and (21), we obtain n_1^*, λ^* and Δ. Substituting x_2^* in (31), we obtain $\bar{\xi}_1$ $(= \bar{\xi}_2)$, as well as $\bar{\xi}_v$.

If the solution involves $n_0 < 0$, then the first two equations are solved for $\bar{\xi}_1$ and $\bar{\xi}_v$, with n_0 fixed at 0. The reason for this choice is the particular doubt concerning the values of I_2 for the countries in question.