

Reducing COVID-19 Cases and Deaths by Applying Blockchain in Vaccination Rollout Management

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Abstract—Goal: Because a fast vaccination rollout against coronavirus disease 2019 (COVID-19) is critical to restore daily life and avoid virus mutations, it is tempting to have a relaxed vaccination-administration management system. However, a rigorous management system can support the enforcement of preventive measures, and in turn, reduce incidence and deaths. Here, we model a trustable and reliable management system based on blockchain for vaccine distribution by extending the Susceptible-Exposed-Infected-Recovery (SEIR) model. The model includes prevention measures such as mask-wearing, social distancing, vaccination rate, and vaccination efficiency. It also considers negative social behavior, such as violations of social distance and attempts of using illegitimate vaccination proofs. By evaluating the model, we show that the proposed system can reduce up to 2.5 million cases and half a million deaths in the most demanding scenarios.

Index Terms—Blockchain, COVID-19, SARS-CoV-2, SEIR model, vaccination model, vaccination passport.

Impact Statement—The use of blockchain technology on the system managing vaccination distribution enables a reliable exercise of infection prevention measures and a reduction of COVID-19 incidence and the number of deaths during and after vaccination rollout.

I. INTRODUCTION

WITH the ongoing coronavirus disease 2019 (COVID-19) pandemic, the world has been waiting for vaccines against the disease to counter its negative health and economic impacts that have affected everyone. COVID-19 is caused by the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), which is highly contagious and has been fatal for millions of people [1]–[5]. COVID-19 is transmitted through droplets of nasal secretion and saliva that are expelled when a person

Manuscript received May 13, 2021; revised June 10, 2021 and June 23, 2021; accepted June 24, 2021. Date of publication June 30, 2021; date of current version August 20, 2021. (Corresponding author: Roberto Cessa-Rojas.)

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Digital Object Identifier 10.1109/OJEMB.2021.3093774

coughs, heavily breaths, talks, or even normally breathes. Detection of saliva is difficult as multiple of its components may need to be detected. Therefore, face-covering is considered a pivotal prevention measure as it provides a high degree of protection to both the wearer and the surrounding people. However, it is not 100% protective. Therefore, there is hope that vaccinations will mitigate or even stop the spreading of this disease [6].

Recently, the rollout of COVID-19 vaccines, while exercising social distancing and wearing face masks, is giving hope to the global population of restoring normal life. As more of the world population is now getting vaccinated, the management of the rollout and verification of vaccination records require not only accurate bookkeeping but also ubiquitous and secure access while maintaining user privacy. Accurate and accessible vaccination records are critical to provide an effective vaccination rollout and to support the execution of preventive measures, such as social distancing [2], [7].

COVID-19 vaccines from different manufacturers are being administered to the world population [8]–[10] aiming to vaccinate people rapidly and thus to leverage restoring normalcy, minimize health and economic damage, and reduce virus mutation opportunity [11]. The speedy distribution has to be carefully managed to avoid suboptimal benefits. However, the desirable synchronization and coordination of electronic vaccination records may be difficult to achieve in such a large vaccine distribution as it requires compatibility and administrative agreements among vaccination sites and upper administrators. Furthermore, the lack of secure processes to record vaccination events may make it difficult to enforce prevention measures at the rollout time and in the future. Vaccine verification could help to quickly restore daily social activities and traveling, as it may allow us to identify the susceptible and the potential source of infection. This verification requires reliable vaccination records that are secure, private, and accessible.

Blockchain has been proposed as a technology that can satisfy the security and reliability of vaccination records [12]–[16]. Beyond the technological advantages, a management system leveraged by blockchain may encourage people to get vaccinated and ultimately reduce the number of COVID-19 cases and deaths. In such approach, electronic immunization records are tied to verifiable blockchain transactions. Despite many recent proposals of blockchain-based vaccination certification

approaches to store verifiable vaccination records, their impact on limiting or stopping the incidence of COVID-19 is still unknown.

To address this issue, we model the incidence and vaccination rollout by extending two Susceptible-Exposed-Infected-Recovered (SEIR) models. The SEIR-Vaccination (SEIR-V) model includes a vaccinated compartment using a conventional vaccination rollout campaign, and the SEIR-Vaccination-Blockchain (SEIR-VB) model uses blockchain to perform vaccination verification. With SEIR-VB, a policy of social distancing can be encouraged by enabling vaccination verification as a passport to activities that may require reduced social distancing. This paper shows that blockchain not only facilitates the management of vaccinations but also decreases the incidence of COVID-19 cases and deaths as compared to a system without blockchain.

II. MATERIALS AND METHODS

Developed as a secure ledger in digital cryptocurrencies [17], blockchain is an immutable distributed ledger technology that records verifiable transactional data [18]. Its immutability feature makes it applicable to a variety of healthcare systems [19]–[21]. A blockchain ledger consists of a cryptographically secured chain of chronologically ordered blocks of transactions. This ledger is distributed across multiple peers to ensure data availability and resiliency against failures and attacks [22].

Bansal *et al.* [14] proposed to use blockchain as a repository of test results and vaccination records as verifiable immunization certificates. Hasan *et al.* [16] proposed a blockchain-based solution to securely store digital medical passports with immunity certificates for COVID-19. Eisenstadt *et al.* [15] developed a prototype of a decentralized blockchain-based mobile application to store portable COVID-19 vaccination certificates. Such certificates may be used to verify the susceptibility of a person to contract COVID-19 and of being a source of infection.

Blockchain can also be used as a decentralized tracking information system. For example, Marbouh *et al.* [23] proposed a blockchain that leverages smart contracts to transparently and reliably consolidate statistical data on COVID-19 incidence. Nguyen *et al.* [24] presented a conceptual architecture that combines blockchain and artificial intelligence to monitor and track the COVID-19 outbreak in real-time.

Blockchain can find its main application in detecting events that actually occurred, such as a vaccination, vaccine production, or social distancing neglects. Tseng *et al.* [25] and Yong *et al.* [26] proposed a blockchain system to verify the legitimacy of drugs and vaccines, respectively. Blockchain has been also proposed to monitor the efficacy of administered vaccines and dosages and to detect possible secondary effects [24]. However, these works have not addressed the question that justifies its adoption during the COVID-19 vaccination rollout, as how helpful blockchain would be in such a campaign by preventing cases and deaths. We address this question in this paper through the following models.

A. Extended SEIR Models

The SEIR model is used to evaluate the spreading of an infectious disease over time [27]. It categorizes individuals

of a population into different compartments. The susceptible compartment is the group of individuals without immunity to the infection. The exposed compartment is the group of individuals who have been in close contact with infected individuals, and the recovered compartment is the group of the individuals who have recovered from the disease and developed immunity.

The prevention measures that reduce the number of COVID-19 cases considered in the extended SEIR models are mask wearing and social distancing. Vaccination against COVID-19 is a measure considered in the model to reduce cases and to convert a susceptible individual into an immune individual. This conversion depends on the vaccine efficacy, the vaccination rate, and the time for individuals to develop immunity. The willingness of individuals to get vaccinated also affects the immunity rate. Particularly, the models consider symptomatic and asymptomatic COVID-19 infections. The models also consider individuals' behaviors that affect the efficacy of these measures, such as neglecting social distancing and falsely claiming wellness and vaccination.

Both SEIR-V and SEIR-VB models are described by (1) to (7), which determine the daily number of individuals in the respective compartments. The daily rate of change in the number of susceptible individuals, given by (1), is the sum of unvaccinated individuals that get exposed to both symptomatic and asymptomatic infected individuals, based on the contagious rate (β); the susceptible individuals that get vaccinated based on both the vaccination rate (v_r), and the likelihood of vaccine willingness (l_v); and the vaccinated individuals that remain susceptible based on the vaccine efficacy (v_e). The contagious rate β is defined as the ratio between the basic reproduction number (R_0), which is defined by the average number of secondary cases that an infected individual infects, and the infection period [28].

Table I describes the variables used in the models. S_k and I_k represent the susceptible and infected individuals in the SEIR-V ($k=w$) and SEIR-VB ($k=b$) models, respectively (8). The daily number of exposed individuals, given in (2), accounts for the newly exposed individuals; the exposed and unvaccinated individuals who may start to develop symptoms after the incubation period ($1/\delta$ days); and the fraction of the total exposed individuals that are vaccinated and recover as determined by the vaccine efficacy. The daily number of infected individuals includes symptomatic and asymptomatic cases, and both having a similar viral load [29]. A case fatality rate (α) is defined as the ratio of the number of deaths to the total number of cases.

The daily number of infected symptomatic individuals in (3) accounts for the exposed and unvaccinated individuals who get COVID-19 symptoms with a probability of symptomatic infection p_{is} ; the cases that recover after the infection period of $1/\gamma$ days; the asymptomatic individuals that develop COVID-19 symptoms with probability p_{ip} after $1/\lambda$ days; and the critical cases that unfortunately become deaths after the critical infection period of $1/\rho$ days. The daily number of asymptomatic individuals in (4) accounts for the portion of exposed and unvaccinated individuals who become asymptomatic; the cases that develop infection; and the cases that remain asymptomatic and develop immunity with or without vaccination after $1/v_i$ days or $1/\mu$ days, respectively.

TABLE I

PARAMETERS USED IN THE EVALUATION OF CASES AND DEATHS OF THE SEIR-V AND SEIR-VB MODELS

Variable	Description	Default value
β	Contagious rate per day	
R_0	Basic reproduction number	2.5
δ	Incubation rate	1/5
γ	Recovery rate	1/9
ρ	Fatality rate	1/19
α	Case fatality rate	2/100
λ	Rate of asymptomatic to symptomatic infection	1/14
μ	Recovery rate of asymptomatic infection	1/14
p_m	Percentage of the population wearing mask	
m_e	Mask efficacy	80%
v_e	Vaccine efficacy	95%
v_r	Daily vaccination rate	5/1000
v_i	Immunity rate after vaccination	1/14
l_v	Likelihood of vaccine willingness	8/10
p_{is}	Probability of symptomatic infection	4/10
p_{ia}	Probability of asymptomatic infection	6/10
p_{ip}	Probability of asymptomatic to symptomatic infection	3/10
p_a	Probability of infected individuals aware of infection	6/10
p_{ci}	Probability of concealing infection by an infected individual aware of infection	3/10
p_{fv}	Probability of incomplete or false immunization claim	3/10
p_{sn}	Probability of unsafe socializing	9/10
p_{si}	Probability of disease transmission by an infected individual aware of infection	1/10

The daily number of recovered individuals, determined by (5), is the accumulated number of the recovered cases and the vaccinated individuals per day. A portion of the vaccinated individuals develop immunity. The portion is defined by the vaccine efficiency. The daily number of immune individuals in (6) is a function of both the recently vaccinated individuals and the vaccinated individuals that develop immunity. The daily number of deaths in (7) is the accumulated number of critical cases that result in deaths.

$$\frac{dS(t)}{dt} = -\frac{\beta S_k I_k (1 - l_v v_r)(I_s(t) + I_a(t))S(t)}{N} - l_v v_r S(t) + (1 - v_e)V(t) \quad (1)$$

$$\frac{dE(t)}{dt} = \frac{\beta S_k I_k (1 - l_v v_r)(I_s(t) + I_a(t))S(t)}{N} - \delta(1 - l_v v_r)E(t) - l_v v_r E(t) \quad (2)$$

$$\frac{dI_s(t)}{dt} = \delta p_{is}(1 - l_v v_r)E(t) - \gamma(1 - \alpha)I_s(t) + \lambda p_{ip}(1 - l_v v_r)I_a(t) - \rho \alpha I_s(t) \quad (3)$$

$$\frac{dI_a(t)}{dt} = \delta(1 - p_{is})(1 - l_v v_r)E(t) - l_v v_r I_a(t) - \lambda p_{ip}(1 - l_v v_r)I_a(t)$$

$$- \mu(1 - p_{ip})(1 - l_v v_r)I_a(t) \quad (4)$$

$$\frac{dR(t)}{dt} = \gamma(1 - \alpha)I_s(t) + \mu(1 - p_{ip})(1 - l_v v_r)I_a(t) + v_e v_i V(t) \quad (5)$$

$$\frac{dV(t)}{dt} = (l_v v_r)[S(t) + E(t) + I_a(t)] - (1 - v_e)V(t) - v_e v_i V(t) \quad (6)$$

$$\frac{dD(t)}{dt} = \rho \alpha I_s(t) \quad (7)$$

Where:

$$k = \begin{cases} w & \text{SEIR-V model.} \\ b & \text{SEIR-VB model.} \end{cases} \quad (8)$$

Then, the S_k and I_k for the SEIR-V and SEIR-VB models are:

$$S_w = (1 - p_m m_e)[p_{fv} + p_{sn}(1 - p_{fv})] \quad (9)$$

$$I_w = (1 - p_m m_e)\{(1 - p_a)[p_{fv} + p_{sn}(1 - p_{fv})] + p_a[p_{si}(1 - p_{ci}) + p_{ci}]\} \quad (10)$$

$$S_b = (1 - p_m m_e)[p_{sn}(1 - p_{fv})] \quad (11)$$

$$I_b = (1 - p_m m_e)\{(1 - p_a)[p_{sn}(1 - p_{fv})] + p_a[p_{si}(1 - p_{ci})]\} \quad (12)$$

The different compartments of the SEIR-V and SEIR-VB models follow the tree diagram shown in Fig. 1. False vaccination claims might occur with probability p_{fv} . Infected individuals are aware of infection with probability p_a and may conceal the infection with probability p_{ci} . The percentage of the mask-wearing population and the protection efficacy of mask wearing are denoted by p_m and m_e , respectively.

Individuals with an active immunization proof (i.e., a proof showing the period that immunization is active) are allowed to socialize and participate in regular activities. Individuals without the proof may be allowed to socialize with restrictions with probability p_{sn} . Table I lists the notations used in this paper. S_k and I_k for an immunization system without blockchain are denoted as S_w as in (9) and I_w as in (10), and for a system with blockchain, as S_b as in (11) and I_b as in (12), respectively. See the code of these models in [30].

III. RESULTS

The numerical evaluations of SEIR-V and SEIR-VB show the difference in the number of cases and deaths for a period of 120 days using parameters as reported in the literature (Table I also shows the default values). Both SEIR-V and SEIR-VB are applied to a population of 330 million individuals (e.g., USA population), as an example. As initial conditions, the population considers 2% infected cases [31], which includes symptomatic and asymptomatic cases, and the rest as susceptible. These models were developed during 2020 and 2021.

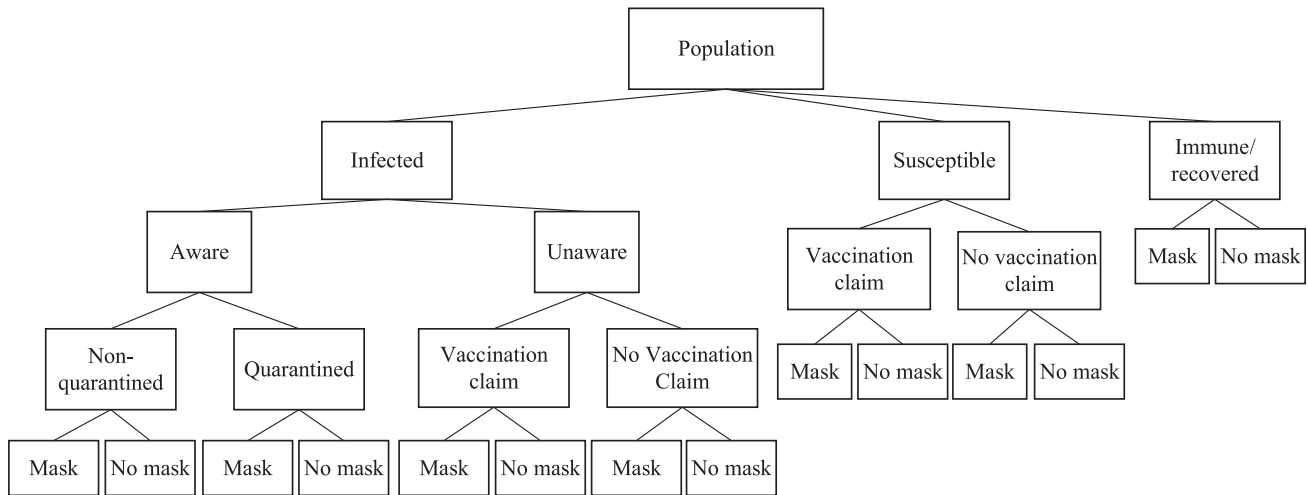


Fig. 1. Tree diagram of the factors that determine the highly susceptible, infected, and contagious individuals and the sequence of states of an individual used in the proposed SEIR extended models. The diagram shows the considered states in this paper.

The evaluation considers the following parameters: A reproduction number of 2.5 [32]; a case fatality rate of 2/100 [33]; an average infection, incubation, and critical infection periods of 9, 5, and 19 days, respectively [34]–[37]; a probability of infection awareness of 2/100 [38]; a vaccine efficacy of 95% [39], [40]; the start of the vaccination rollout on day 1; a daily vaccination rate of 5/1000 [41]; a vaccine willingness of 80% [42], [43]; and an immunity period of 14 days after vaccination [44], [45].

The models assume that individuals with a vaccination proof socialize without restrictions, while those without a proof may socialize with a 10% restriction. Immunity may be claimed arbitrarily by any individual. Infected individuals may conceal the infection with 3/10 probability [46], and neglect prevention rules. The probability of asymptomatic infection is set to 6/10, from which 3/10 may become symptomatic after 14 days [47]–[49]. Both the daily and total reduced number of cases and deaths are analyzed considering different percentages of the population that wear masks. The mask-wearing efficacy is set to 80% [50], [51]. Table I shows the default parameters used in the evaluation of the SEIR-V and SEIR-VB models.

A. Reduced Cases and Deaths by Blockchain

Fig. 2 shows the reduced number of cases and deaths by using the blockchain management system. Fig. 2(a) shows the reduced prevalence of COVID-19 cases through enforcing prevention measures, such as managing access to places that require a reduced social distancing by verification of vaccination certificates. Fig. 2(b) shows the reduced total number of deaths. The figures show that during the first 20 days of the vaccination rollout, the blockchain management system would decrease the number of cases by more than 2.5 million with 50% of the population wearing masks and about 500,000 cases with 90% of the population wearing masks. Fig. 2(b) shows that the blockchain system can reduce the number of deaths by about 46,000 with 50% of the population wearing masks and about 4,200 deaths with 90% of the population wearing masks.

B. Impact by People Behavior and Vaccine Features

We classify the variables into two groups: prevention measures that decrease the incidence, such as vaccination efficacy, vaccination rate, and social distancing, and negative social behavior that increases the incidence, such as infected individuals who are aware or unaware of their infections and unvaccinated individuals claiming being vaccinated, all ignoring social distancing.

Fig. 2(c) shows that the number of deaths decreases as individuals become aware of their infection and quarantine themselves. These results show that the adoption of blockchain could reduce more than 30,000 deaths for 70% of infection awareness with 50% of the population wearing masks. The difference in the number of deaths increases as the percentage of the wearing-mask population decreases because blockchain enables the detection of high-risk individuals as more individuals are exposed. The blockchain system may reduce about 3,000 deaths with 90% of the population wearing masks and 100% of infection awareness.

C. Impact of Individual's Behavior

Fig. 2(d) shows that the blockchain system may reduce about 27,000 deaths with 10% of the infected individuals concealing their infection and 50% of the population wearing masks. On the other hand, this system may decrease about 3,000 deaths with 90% of the population wearing masks. The blockchain system also shows benefits against false vaccination claims. Fig. 2(e) shows that the blockchain system may reduce about 70,000 deaths for a 90% false vaccination claim rate with 50% of the population wearing masks and about 6,700 deaths with 90% of the population wearing masks. Its smallest impact is a reduction of about 2,700 deaths for a 10% rate of false vaccination claims with 90% of the population wearing masks.

The blockchain management system also reduces the number of cases and deaths when individuals neglect social distancing. It reduces about 60,000 deaths when each individual practices unsafe social distancing with 50% of the population wearing

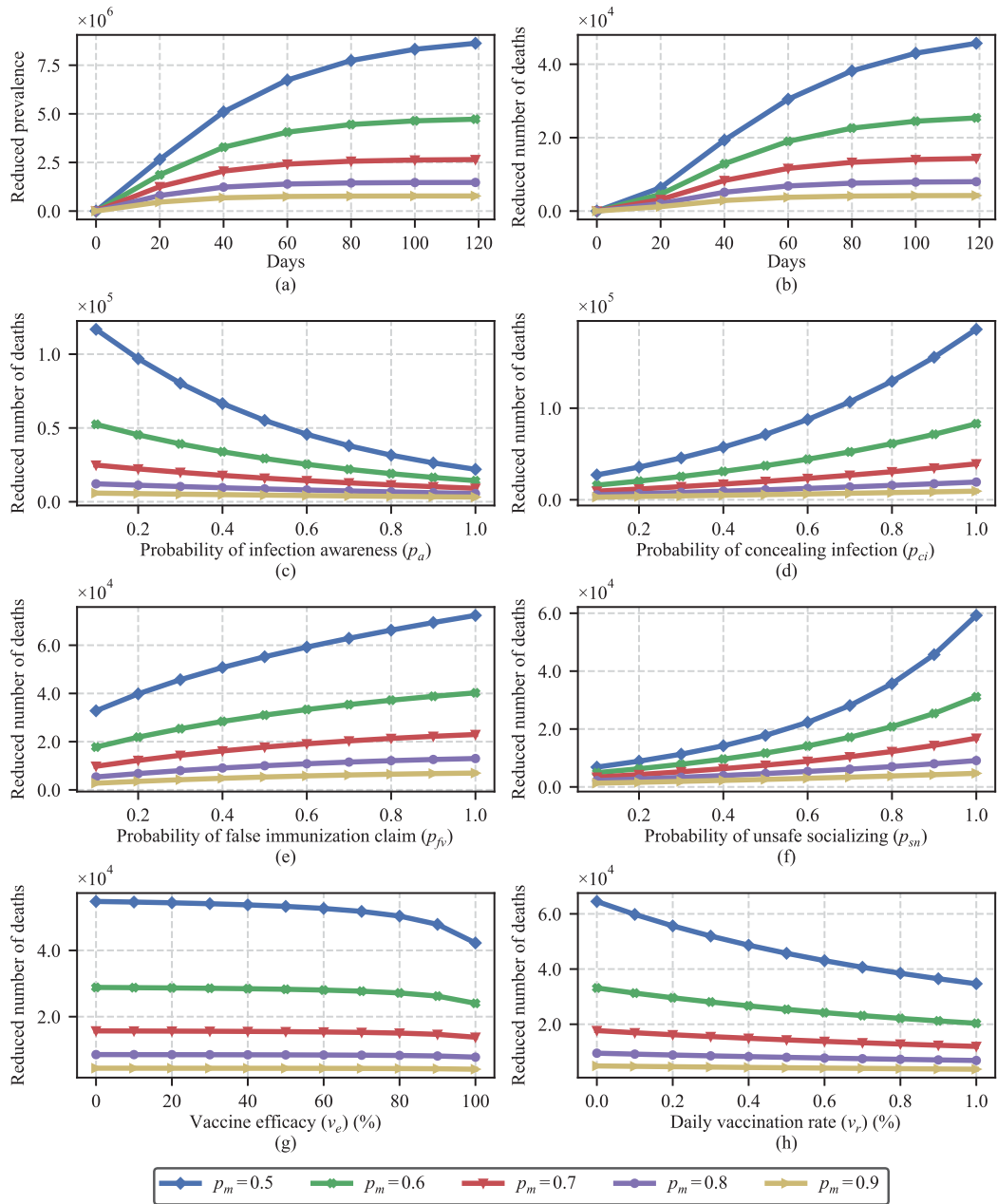


Fig. 2. Reduced (a) prevalence; (b) cumulative reduced number of deaths; and total reduced number of deaths using a blockchain-based immunization system for a period of 120 days, as a function of (c) probability of infection awareness; (d) probability of concealing infection; (e) probability of unsafe socializing; (f) vaccine efficacy; and (g) daily vaccination rates. Prevalence and number of deaths are more effectively reduced as conditions worsens. It is in such cases that blockchain is more impactful.

masks, as shown in Fig. 2(f). The smallest impact can be seen by a reduction of about 5,000 deaths with 90% of the population wearing masks.

D. Impact of Vaccine Features

Fig. 2(g) shows that a 100% effective vaccine alone would be insufficient to avoid as many deaths as the combination of vaccination, mask wearing, and social distancing would. The blockchain system combined with a 100% effective vaccine would reduce more than 40,000 deaths with 50% of the population wearing masks and about 4,000 deaths with 90% of

the population wearing masks. A lower efficacy vaccine may increase the number of deaths and that may increase the role importance of the blockchain system.

Fig. 2(h) shows that at a daily vaccination rate of 1% of the population, the blockchain system would reduce 3,700 and 35,000 deaths with 90 and 50% of the population wearing masks, respectively. Table II shows that the blockchain system can reduce the number of cases as the contagion level increases. For example, the proposed system may reduce 15 and 47 million cases under no social distancing but with 50% of the population wearing masks and a low vaccination rate of 0.1%, for virus reproduction numbers of 2.5 and 3.5, respectively. Also, the

TABLE II

CASES AND DEATHS FOR DIFFERENT VIRUS REPRODUCTION NUMBERS, PROBABILITY OF UNSAFE SOCIALIZING, AND VACCINATION RATES. CASES AND DEATHS CAN BE DECREASED BY USING BOTH BLOCKCHAIN AND PREVENTION MEASURES DESPITE LARGE REPRODUCTION NUMBERS

Basic Reproduction Number (R_0)	Probability of unsafe Socializing (p_{sn})	(Reduced number of cases, Reduced number of deaths) in thousands					
		Daily Vaccination Rate (v_r) (%)					
		Low (0.10)			High (0.50)		
		Percentage of the Population Wearing Masks (p_m) (%)					
		Low (10)	Medium (50)	High (90)	Low (10)	Medium (50)	High (90)
2.5	0.10	(4,549.04, 24.82)	(1,392.31, 7.68)	(258.99, 1.43)	(3,904.62, 21.15)	(1,256.25, 6.85)	(238.22, 1.30)
	0.50	(28,327.80, 142.88)	(3,851.26, 20.99)	(524.70, 2.90)	(19,614.47, 101.49)	(3,288.74, 17.81)	(478.83, 2.61)
	1.00	(204,776.90, 1,028.72)	(15,566.14, 80.30)	(963.47, 5.31)	(149,254.40, 742.90)	(11,295.44, 59.25)	(863.80, 4.71)
3.0	0.10	(6,245.50, 33.85)	(1,745.62, 9.61)	(313.37, 1.73)	(5,235.33, 28.26)	(1,565.76, 8.53)	(287.97, 1.57)
	0.50	(52,525.99, 256.35)	(5,330.80, 28.87)	(644.18, 3.56)	(34,066.27, 172.10)	(4,443.70, 23.97)	(586.27, 3.20)
	1.00	(243,863.00, 1,284.53)	(27,648.09, 138.31)	(1,221.79, 6.72)	(199,461.10, 1,029.78)	(18,734.58, 96.38)	(1,087.45, 5.92)
3.5	0.10	(8,431.48, 45.32)	(2,131.15, 11.72)	(368.64, 2.04)	(6,877.79, 36.96)	(1,899.43, 10.34)	(338.44, 1.85)
	0.50	(89,492.53, 428.90)	(7,247.59, 38.92)	(769.17, 4.24)	(56,559.08, 280.07)	(5,878.57, 31.57)	(698.05, 3.81)
	1.00	(255,965.10, 1,389.28)	(47,324.80, 230.20)	(1,508.76, 8.29)	(225,759.70, 1,197.98)	(30,368.07, 153.03)	(1,332.48, 7.25)

blockchain system could reduce 1.3 and 1.9 million cases for a high vaccination rate of 0.5%, with 50% of the population wearing masks, and individuals socializing with 90% restrictions with reproduction numbers of 2.5 and 3.5, respectively.

With the vaccination rollout, the number of individuals wearing masks may decrease but that could increase the number of cases and deaths. Table II shows that with a low daily vaccination rate of 0.1%, with 50% of the population wearing masks and no individuals keeping social distance, the system could reduce more than 80,000 deaths for a (virus) reproduction number of 2.5 and more than 230,000 deaths for a reproduction number of 3.5. On the other hand, at a daily vaccination rate of 0.5%, 90% of the population wearing masks, and individuals socializing with 90% restrictions, the system could still reduce 1,300 and 1,850 deaths for reproduction numbers of 2.5 and 3.5, respectively. Even though these numbers of deaths are small in comparison with the initial population, decreasing incidence and mortality is deemed significant.

IV. DISCUSSION

Modeling and forecasting the incidence of infectious diseases such a COVID-19 is challenging because of the dynamics of the many involved parameters [52]. The parameters used in our evaluations are time invariant. However, as more people become vaccinated, mask wearing rates may decrease and evaluations of such scenario would be needed.

Using blockchain to track vaccinated individuals would support the enforcing of prevention measures. These evaluations consider a uniform enforcement of preventive rules across the whole population in the SEIR-VB model, but non-uniformity

may be more realistic in a country and that may need to be considered. Enforcing the prevention measures in the world has been challenging. Therefore, the use of blockchain may face some resistance and a flexible approach may need to be developed. Also, the current rollout may target fast vaccination of the population to provide a fast health and economic relief. Such a case may include variable vaccination rates that may need to be analyzed in similar performance terms as done in this paper.

V. CONCLUSION

Blockchain provides a means to reliably record vaccinations and issues time-dependent certificates that can be used to enforce vaccination verification in a pandemic. We modeled and evaluated a vaccine distribution management system that reliably verifies whether an individual is vaccinated so that such individual can be allowed to participate in social activities of normal daily life, including reduced social distancing, traveling, or group gatherings.

The performance of the proposed blockchain system was evaluated by the reduced number of cases and deaths between the blockchain management system and a conventional system that uses no blockchain. The results indicate that the adoption of blockchain as an immunization control system could reduce the number of cases and deaths, as an important effect of performing preventive measures.

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