COVID 19 Epidemic Trajectory Modeling Results for Ethiopia

Wondimu Ayele[1], Latera Tesfaye[2], Abdulnasir Abagero[1], Girma Taye[1*], Biruk Abate[2], Tigist Habtamu[1], Solomon Kassahun[2], Ephrem Biruk[1], Mezgebu Yitayal[3], Shegaw Mulu[2], Alemnesh Murikuze[4]

Abstract

Background: An outbreak of "pneumonia of unknown etiology" later renamed as Novel Corona Virus (COVID 19) was first reported from Hubei Province, China on 31 December 2019. The cases have increased exponentially; the pandemic has reached all countries in the world with 81.2 million confirmed cases and over 1.8 million by December 28, 2020. Ethiopia reported its first case on March 13, 2020, and as of December 28, 2020, the country had 122864 confirmed COVID-19 cases and 1909 deaths. Being a new pandemic its epidemiologic trajectories across regions and populations remains unknown. Mathematical models are widely used to understand and predict the possible courses of an outbreak, given a set of underlying assumptions.

Objective: This study intends to model COVID 19 epidemic trajectory under different assumptions and to predict the likely timing of peak of the epidemic in Ethiopia.

Methods: Standard Susceptible Exposed, Infected and Recovery (SEIR) compartmental epidemiological deterministic model was employed to estimate and predict COVID 19 in progression in Ethiopia and Addis Ababa at different points of time. Exhaustive literature reviews were carried out to contextualize COVID 19 pandemic epidemiological. Efficacy and coverage of face mask and social distancing were considered in the best and worst situation to run the model and estimate the number of infections after sustained local transmissions.

Result. Without any intervention, the COVID 19 viruses spread will peak at 150 days from the first report, infecting 8.01million people given local/community transmission. As the compliance with face mask coverage increases by 25%, 50%, and 75%, the infection will be reduced by about 20%, 40%, and 60% respectively social distancing compliance by le 25% of the population alone will reduce above 60% of infections. Compliance of 40% face mask use and social distance combined effect will reduce 97% of the estimated number of cases.

Conclusion: This predication indicated that compliance with combination of non-pharmaceutical intervention such as use of face mask use with physical distance averted significant number of COVID infection. For a county like Ethiopia with poor health systems resilience, mitigating the pandemic at an early stage through strong preventive measures is necessary. [*Ethiop. J. Health Dev*. 2021; 35(SI-1):25-32]

Key word: COVID 19, Modelling, Non-Pharmaceutica intervention, Ethiopia

Background

An outbreak of "pneumonia of unknown etiology" later renamed as Novel Corona Virus (COVID 19) was first reported from Hubei Province, China on 31 December 2019(1). Later on, the viruses become a life-threatening pandemic and spread to all countries worldwide. The cases are increasing exponentially; within twelve months of the first case report, 81.2 million confirmed cases and over 1.8 million deaths have been reported globally (2). Of these, 2.7 million cases and 62903 deaths have been reported from 57 Africa countries (2). Ethiopia reported its first case on March 13, 2020, and as of December 2020, the country had 122864 confirmed COVID-19 cases and 1909 deaths (2).

Governments and stakeholders across the globe are striving to control the widespread transmission of COVID 19 infections. The absence of proven effective vaccines and treatment coupled with the limited knowledge on the epidemiological feature of the diseases has presented a major challenge for the containment of the virus. Implementing social distance, closure of the school and non-essential public services, use of disinfectant for public places, and practicing hand hygiene are globally accepted interventions for COVID19 (3).

Generating continuous evidence on COVID 19 epidemic trajectory is crucial for future planning and resource mapping as well as getting prepared for the expected overflow of patients if community transmission happens. Several mathematical modeling studies have been conducted to estimate important epidemiological parameters that help to understand the epidemiological trajectory of the viruses within different pandemic prevention and control scenarios in China and other countries since the onset of the epidemic (4-6).

So far, the epidemic pattern of COVID-19 is different in sub-Saharan Africa countries, showing slow progression despite the outbreak starting as early as in most of the highly affected European countries. This is happening despite countries in sub-Saharan Africa are having strong social interaction, communal lifestyle, weak surveillance system, limited screening capacity, and poor contact tracing (7).

Modeling of COVID 19 epidemic trajectory with different scenarios can be used for determining the current trend and future direction of the epidemic, which is necessary to comprehend the natural history of the pandemic in the local context.

According to World health organization, at least seven COVID 19 vaccines have been administered and as of February 2021 about 175.3million people have been vaccinated for the first doses (8). Mathematical models are useful to predict the course of the pandemic with a

[1]School of Public Health, College of health Sciences, Addis Ababa University, Addis Ababa, Ethiopia
[2]Ministry of Health, Addis Ababa, Ethiopia
[3]University of Gondar, Gondar, Ethiopia
[4]Ethiopian Public Health Institute (EPHI), Addis Ababa, Ethiopia

set of underlying assumptions to understand an epidemiological feature of the virus, given the limited capacity to carry out mass vaccination to achieve epidemiological threshold.

Modeling of the course of the pandemic through generated evidence on pattern of different non pharmaceutical intervention also helps to strengthen prevention and control measures of national COVID 19 task force response activities through galvanizing multi-sectoral collaboration and community engagement based on evidence. It's also important for resource mapping, allocation, and prioritization to effectively respond to the pandemic. Hence, this study was designed to model COVID 19 epidemic trajectory with different assumptions and provide predictions about the likely timing of the peak of the epidemic in Ethiopia and Addis Ababa.

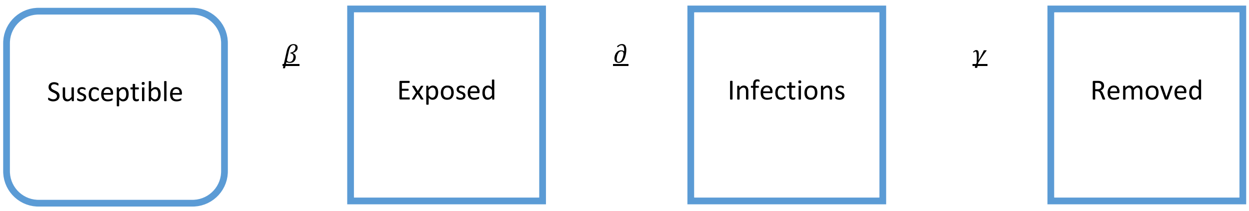
Methods

The standard Susceptible Exposed, Infected, and Recovery (SEIR) compartmental epidemiological model was employed to estimate the parameters and to predict COVID 19 in Ethiopia at different points of time. An exhaustive literature review was carried out to contextualize COVID 19 epidemiological parameters such as contact rate, incubation and latent periods, basic reproductive number, recovery rate, duration of illness, the dynamic of virus transmission, hospitalization, and ICU rate. The model investigates the transmission dynamics of COVID 19 for the nation with three scenarios.

SEIR epidemiological model was adopted and simulated with Python. The first model fitted was the basic SEIR without any intervention by the government; in the second scenario, we reduced the number of contacts by half, assuming the government recommended social distancing interventions would work. Then the model was run to show the potential effectiveness of the social distancing intervention to avert COVID 19 infections.

Parameter Estimation and Prediction Models

A recent population estimate from the Central Statistical Agency was used as a reference in the modeling exercise. This model divides the virus's transmission into four compartments in which individuals move from one class (or compartments) to the next (Figure 1): susceptible, exposed, infectious, and removed (i.e. individuals are assumed to recover or die and no longer infected). In our model, the removed compartments have only recovered; because the number of deaths was very few by the time this manuscript was written. This is also one of the major reasons for choosing the SEIR model in this work (9). The mathematical derivation using differential equations has been provided below to show the model formulations and derivations of the parameter, to facilitate the practical use of the model, and to facilitate understanding of the background theory for meaningful interpretation of parameters.



The model equation is given as:

$$\frac{dS}{dt} = -\frac{\beta si}{N} \ldots\ldots\ldots\ldots\ldots\ldots 1$$
$$\frac{dE}{dt} = \frac{\beta si}{N} - \partial \ldots\ldots\ldots\ldots 2$$
$$\frac{dI}{dt} = \partial E - \gamma I \ldots\ldots\ldots\ldots 3$$
$$\frac{dR}{dt} = \gamma I \ldots\ldots\ldots\ldots\ldots\ldots 4$$
$$\frac{dN(t)}{dt} = \frac{ds}{dt} + \frac{dE}{dt} + \frac{dI}{dt} + \frac{dR}{dt} \ldots\ldots\ldots\ldots 5$$
$$\boldsymbol{\lambda} = \frac{\boldsymbol{\beta} * (\mathbf{1} - \boldsymbol{\varepsilon} * \mathbf{c}) * (\mathbf{I})}{\mathbf{N}} \ldots\ldots\ldots\ldots\ldots\ldots \mathbf{6}$$

Where

- β, the probability of transmitting disease between a susceptible and an exposed individual
- Incubation rate σ, is the rate of latent individuals becoming infectious. Given the known
  the average duration of incubation Y, $\sigma = 1/Y$.
- Recovery rate $\gamma = 1/D$ is determined by the average duration of recovery D, of infection. After this period, they enter the removed phase.
- The average duration of infection is calculated by subtracting the average serial interval from the average incubation duration.
- **ε** efficacy of face mask towards break transmission of the viruses
- C is Face Mask Compliance or use of the face mask among susceptible population.
- **λ** is a force of infection among susceptible?

The susceptible people in equation [1], progressively change from exposed to the compartment due to presumed contact with infected individuals at a rate - the force of infection**λ**. Equation [2] shows people who have been exposed to the disease through contact would eventually join the infected group. But this process is not automatic and depends on the prevailing contact rate and incubation period. Equation [3] shows the transition of the infected population to recovery. Due to the few numbers of reported deaths so far, we have assumed death is minimal or tolerable; this is based on the exposed population and the inception period. This process is regulated based on the infectious period and recovery rate, which is indicated in the final stage in Equation [4]. Equation [5] indicates that the sum of individuals in the four compartments constitute the total population, assuming the whole population is susceptible to COVID 19. Selected parameter values were coded into machine learning in python with the stated assumptions. Then coefficients of the SEIR model (i.e., r α, β, and γ) were determined and projections of cases and other situations to future dates were carried out.

Model Assumption:

Several studies have estimated the parameters for the transmission of COVID-19, including basic reproduction number (R0), incubation period, infection rate, case fatality rate, and serial interval (11-18). Key epidemiological parameters were adopted from previous studies (table 1). The model fitted using three basic scenarios towards compliance to a non-pharmaceutical intervention of face mask use, social distancing/physical distance, and combined effect of social distancing and face mask. In the first scenarios, compliance of face mask use was assumed at 0%, 25%, 50%, 67%, 75%, and 85%. In the second scenario adherence to social distancing were assumed to be 0%, 10%, 25%, and 40%. In the three scenarios combined effect of social distancing and face mask compliance were assumed 0%, 10%, 25%, and 40%. In these scenarios the basic reproductive number was assumed to be 2.6, the effective transmission rate was computed from basic reproductive number (Ro) and incubation period, average contacts for case estimated to be 20 from previous study in Africa and considering empirical data COVID19 case and contract reports from Ethiopia (10). Moreover, insisted public health preventive measure to control spready of virus, i.e., ensuring adhere to the recommended non-pharmaceutical intervention such as social distancing, strict face mask use in public places, and closure of the school and non-essential gathering and reducing international traveling, early cases isolation, contact identification and contact follow-up including a port of entry screening and quarantine would be properly implemented. If these measures are properly implemented, there will be a considerable impact on the force of infection, basic reproductive number, and reduced contact rate. Moreover, the model assumed a fixed population with no in and out-migration. The face mask use efficacy is assumed to be 33% given a different type of mask used by the community (11). On other hand, strict social-distancing strategies (such as nation/city-wide lockdown) can reduce the effective transmission rate by 40% (11). Social-distancing effectiveness was measured in terms of efficacy and adherence/coverage levels (11).

Tables 1. Key baseline epidemiological parameter used for the modeling.

Assumption	Value (reference)
Average Incubation period	5.2 days (12-16)
Total population of Ethiopia in 2020(N):	100,820,000 C (17)
Basic reproductive number	2.6(18)
The average recovery period from infection:	18 days
The average number of contacts	20(18)
Probability of transmission	0.07&0 02 (machine computed)
Face mask	0%, 25%, 50%, 67%, 75% and 85% assumed
Social distancing	0%, 10%, 25% and 40% assumed
Social distance and face mask use	0%, 10%, 25% and 40% assumed
Efficacy face mask use	33% (11)
Efficacy of social distancing	10%, 25%, 40% (11)

The infectious state of the virus was assumed to follow one of the exponential family of distributions, thus Gamma distribution was fitted, and predictions performed at different time points.

Result

Outbreak trajectory in Ethiopia

To forecast the COVID 19 epidemic trajectory in Ethiopia and Addis Ababa, we used the actual number of COVID-19 cases, an average number of close contacts, population size and basic reproductive number, and other inputs as described in the methods section. Our model estimated the number of exposed, infected, and recovered individuals in the coming months given stochastic compliance to face mask use, social distancing, and a combination of both interventions. Following the first COVID-19 case report on the 13th of March 2020, the pandemic has steadily yet gradually increased in the first month. If there are no mandatory interventions by the government in response to the pandemic, the spread of COVID 19 viruses is expected to peak after 150 days nationally from the date of the first case report. At its peak, about 8.01 million of the population are expected to be infected through local/community transmission. The outbreak is expected to decline nearly after one year after an established local transmission. This worst-case scenario happens because of delayed government responses as was seen in most western countries. It is unlikely for Ethiopia that this scenario holds, as the government has initiated public health preventive interventions early on before community transmission has been established.

Effect of Face Mask Use and Social Distancing

The second scenario happens because of the early implementation of strict non-pharmaceutical public health interventions with law enforcement, which significantly reduces the basic reproductive number and an average number of the contact. This could avert a significant number of infected cases, as compared to the non-intervention scenario.

If compliance for mask use increases from baseline to 25%, the expected number of infections would be reduced by about 1.1 million to 1.7 million cases from the baseline, which is nearly 20%. Increasing face mask use alone from 0% to 50%, 0 to 67%, 0% to 75 and 0% to 85% will reduce the estimated number of cases by 40%, 53%, 60% and 68%, respectively. If half the coverage of face mask use is achieved, an estimated number of infections would be reduced from 8.01 million to 2.6 million nearly after one year of local transmission established. In this connection then, more than 5.4 million cases would be averted from the baseline. (Figure 1).

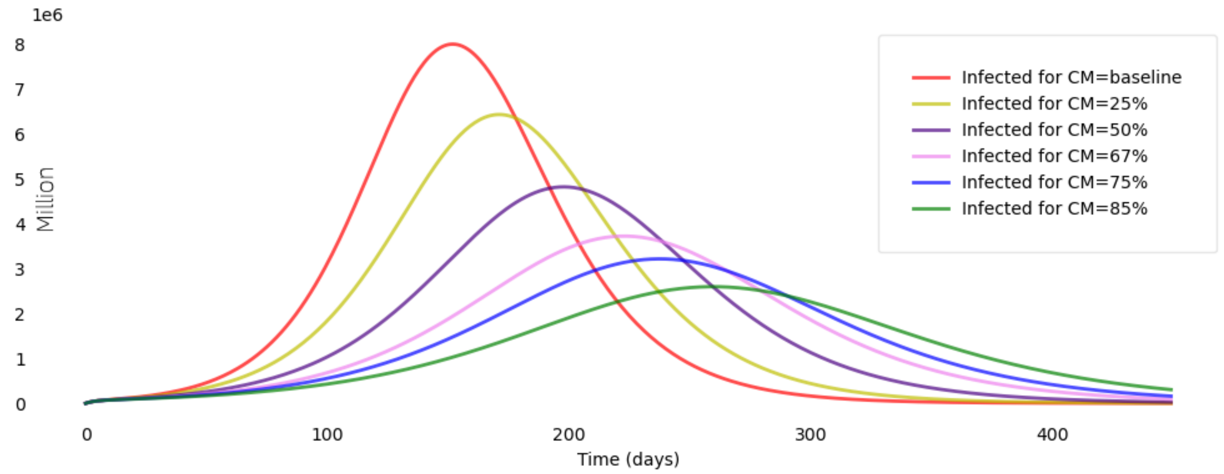


Figure 1***: The estimated number of COVID 19 cases with Face mask use***

Regarding compliance with social distancing, 25% adherence for recommended social distance in all settings would avert 60% of the estimated number of cases. implementing strict social-distancing strategies (such as nation/city-wide lockdown) that would reduce the effective transmission rate by 40%, which would reduce 91% of the estimated number of cases. If compliance for social distancing increases from 0% to 10%, 0% to 25%, and 0% to 40% coverage, the number of infections would reduce by 24%, 52%, and 78% respectively. If the country can achieve 40% social distancing, the number of cases expected to be peak with about 685,197 infected cases through local/community transmission (Figure 2)

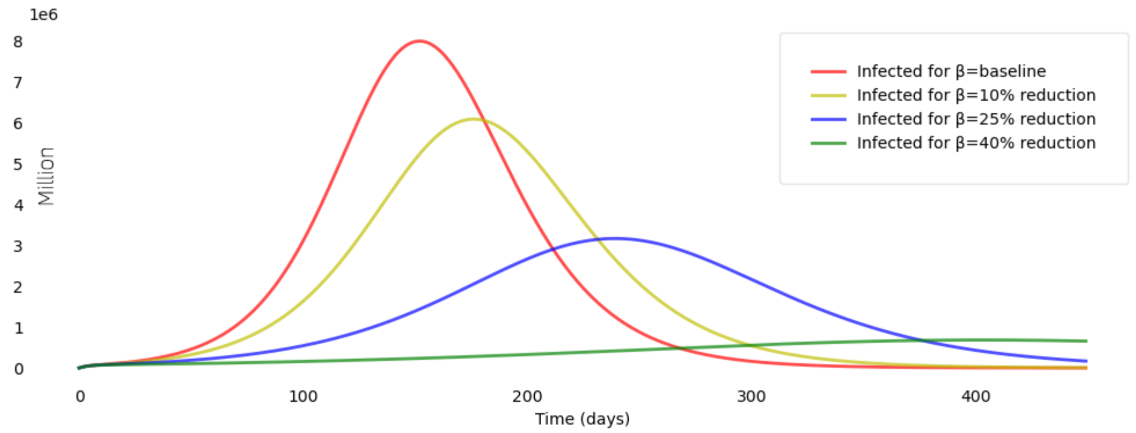


Figure 2: **The estimated number of COVID 19 cases with** social distancing

Combined Effect of Social Distancing and Face Mask Compliance.
Compliance with 10% social distancing and face mask use could avert more than 42% of the estimated number of cases in the worst cases scenario. Increasing the combined effect of social distancing and face mask use from 10% to 25% could reduce about three fourth of the excepted number of infections from the baseline. On the other hand, if the country achieves 40% of coverage compliance with social distancing and face mask use combined, expected number of infections would be 204 473 people after one year of local transmission established. This will be about a 97% reduction in the number cases from an anticipated number of cases in worst cases scenario (Figure 3).

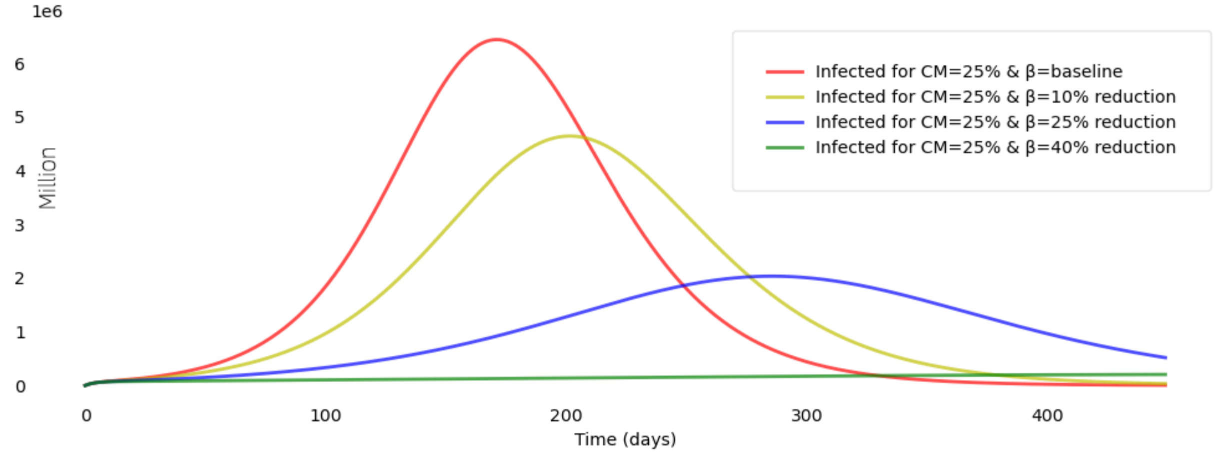


Figure 3: **The estimated number of COVID 19 cases with the combined effect of social distancing and face mask use in Ethiopia, 2020.**

Moreover, to understand the trade-off between face mask use and social distancing, different scenarios for mask and social distancing compliance were generated in one plot. This enabled us to identify scenarios that will lead to the same infection progression. As it is shown in Figure 4, facemask use of 75% with no social distancing leads to a similar infection trajectory as social distancing practice resulting in a 25% reduction in contact rate with no face mask use. One more example, facemask compliance of 25% with 10% reduction in contact rate leads to closely similar infection trajectory as facemask compliance of 50% with no social distancing.

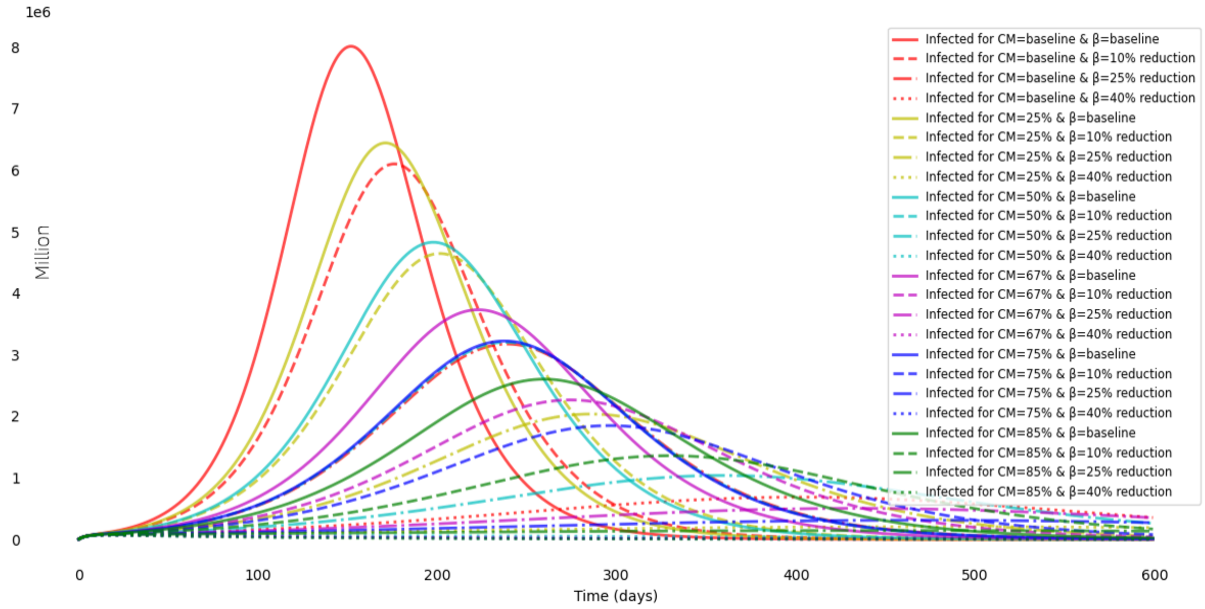


Figure 4: **The estimated number of COVID 19 cases with detailed coverage rate of combined effect of social distancing and face mask use in Ethiopia, 2020.**

Sensitivity Analysis
Variance based sensitivity analysis or SOBOL indices was deployed to map the degree to which output, in this case, the infected compartment (I), varies given a change in our inputs in this case basic reproductive number, transmission rate, facemask compliance, recovery and incubation period. We generated values for the following three indices:

1. First Order (S1) – The effect of a single variable on the output.
2. Second Order (S2) – Combined effect of variables on the output.
3. Total Order (ST) – The effect of a variable by itself and in combination with the others (Figure 5).

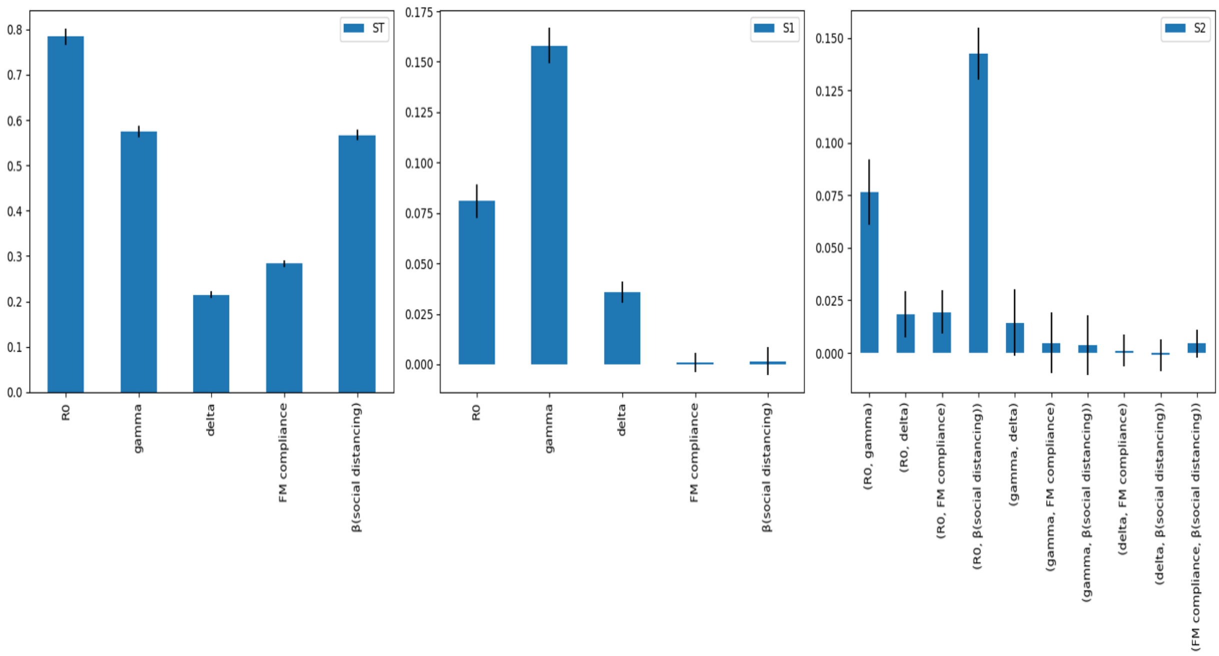


Figure 5: **Global sensitivity analysis result.**

Table 2 shows the total order indices for the input parameters. As is indicated in the table, the basic reproductive number has the highest impact on the infected compartment (I). This analysis assumes all five input parameters are independent of each other.

Table 2: **Total indices results for input values.**

Parameters	**Range**	**Baseline**	**Index Value**
Basic reproductive number (R_0)	[1 – 5]	2.6	0.78 (± 0.017)
Recovery period	[1/7 – 1/21]	1/14	0.57 (±0.012)
Incubation period	[1/2 – 1/14]	1/5.2	0.21(±0.006)
Face Mask compliance	[0 - 90] %	0% - No face mask use	0.28 (±0.007)
Social distancing	[0 - 50] %	0.0 – No social distancing	0.56(±0.011)

Discussion
We used the SEIR model to estimate COVID 19 peak time in Ethiopia with two scenarios. Parameters used in the model were abstracted from exhaustive literature reviews done beforehand. In Ethiopia, a COVID-19 case was reported on the 13th of March 2020 for the first time.

In the case of the first scenario, if we let the outbreak to go without intervention, close to one-third of the population in Ethiopia could be infected with COVID-19. It takes almost four months for the outbreak to the peak. This could also result in high demand for surge capacity for clinical care. This finding is consistent with the estimation from mathematical modeling for England and Wales, which indicated that CoVID-19 would peak around 4 months following the start of person-to-person transmission (20).

The epidemic trajectory finding indicated that the COVID-19 pandemic depends on compliance with existing public health interventions implemented by the country. The modeling finding indicated that if half of the population complies with non-pharmaceutical intervention, it could avert about 46% of infection and shift the peak time from four months to eleven months. The shifting of the peak time through delaying the epidemic peak could give time to build health system capacity to respond to the pandemic in addition to reducing the size of the epidemics. Increasing testing capacity, contact tracing, and isolation with strict public health measures have the potential to suppress transmission (21). Contact tracing and isolation without strong public health intervention cannot be able to control the epidemic (21). In limited capacity to achieve epidemiological threshold of vaccination, non-pharmaceutical intervention is an alternative cost-effective approach used to control rapid spread of the virus through community engagement on awareness of the disease and self-protection, social distancing, and mask use. This significantly averts transmission and reduces the burden at service delivery point (20). Non-pharmaceutical interventions provide an opportunity to use a scarce resource to manage critical patients and reduce mortality. Besides these, continuous modeling of the COVID 19 cases with the different assumption in the local context and using accurate data will provide evidence. Most of the predicted number of cases might be mild or asymptomatic and less than 20% of cases might become moderate or severe, which might not overwhelm the health facility (23). Number of cases depends on countries testing capacity given more than 90% of cases being asymptomatic (24-25)

The trajectory of the outbreak for an infectious disease like COVID-19 is not well clear and the spread of the outbreak is dependent on many factors such as social distancing measure, mass testing, mass awareness, and hospital preparedness. A lag time of case identification, line listing of cases such as date of symptom, and health facilities visit/testing will extend the peak time of infected cases in our projection. The strength of this model depends on the assumed key epidemiological parameter. Because the parameter we used to forecast epidemic trajectory came from a variety of nations, which may differ in our scenario, computing country-specific parameters will improve prediction accuracy.

We also assumed that COVID-19 epidemics are identical to those in China, while this may not be the case in Africa, which would be considered a drawback of this modeling approach. A national lockdown might not be productive and could cause serious economic damage, increase hunger and reduce the population resilience for handling the infection peak (26-27). However, strong social distancing, travel restriction and personal hygiene measures are important to reduce community transmissions. If no timely and adequate social distancing measures were put in place, the epidemic could have continued to grow exponentially, increasing hospitalizations and deaths.

As previously stated, this model was based on the first month of instances, with one, two, or three cases reported per day. This could have reduced the occurrence of infections, delaying the peak of infection dates. Unfortunately, the daily pattern of cases has changed considerably in recent months which completely change the model outcome both in terms of the predicted number of cases and the number of days required to hit the peak. But these initial models may provide insight about what is going on in the COVID-19 world and what the government should do to level off the inevitable economic and social problems in terms of resources such as hospital resource requirement, isolation center capacities, need for enforcement of regulations, strategy to generate money to support the economy, etc. Nevertheless, there is no perfect model that provides perfect size, since all models depend on model inputs that are not perfect neither. However, when refined with better quality data and appropriate assumptions, the model outcome will be closer to reality. The variation of predicated number of cases could be explained by limited testing capacity of the country that resulted in fewer cases. Today with increased daily number tested, the number of cases has also increasing. No testing capability was reflected in the model thus no way the model accounts for such occurrences. Therefore, with the changing situation of testing results, we have an impression that models should be fitted weekly to provide meaningful policy advice.

Conclusion and recommendation

This predication indicated that compliance with combination of non-pharmaceutical interventions such as use of face mask with physical distance could avert significant number of COVID-19 infection. It takes almost four months for the outbreak to the peak after local transmission. For a county like Ethiopia that has poor health systems resilience, mitigating the pandemic at an early stage through strong preventive measures is necessary. The government must enforce compliance with face mask use and social distancing measures to avert the grave consequences of the disease.

Acknowledgment

This work was supported by the Ministry of Health-Ethiopia through CBMP project.

Reference

1- World Health Organization(WHO), Novel Coronavirus (2019-nCoV) SITUATION REPORT 1, 21 JANUARY 2020, WHO https://www.who.int/docs/default-source/coronaviruse/situation-reports/20200121-sitrep-1-2019-ncov.pdf?sfvrsn=20a99c10_4. Accessed May 9, 2020

2- Worldometer, COVID-19 CORONAVIRUS PANDEMIC, Last updated: December 28, 2020, https://www.worldometers.info/coronavirus/. Accessed December 28, 2020

3- European Centre for Disease Prevention and Control Novel coronavirus disease 2019 (COVID-19) pandemic: increased transmission in the EU/EEA and the UK – situational report update, Stockholm, March 2020

4- Dalin Li, Jun Lv, Gregory Botwin, Jonathan Braun , Weihua Cao, Liming Li, Dermot P.B. McGovern. Estimating the scale of COVID-19 Epidemic in the United States: Simulations Based on Air Traffic directly from Wuhan, China. **doi:** https://doi.org/10.1101/2020.03.06.20031880

5- Li Q, Guan XH, Wu P et al (2020) Early transmission dynamics in Wuhan, China, of novel coronavirus-infected pneumonia. N Engl J Med. https://doi.org/10.1056/NEJMoa2001316.

6- Kucharski, A. J., Russell, T. W., Diamond, C., Liu, Y., Edmunds, J., Funk, S., Eggo, R. M., & Centre for Mathematical Modelling of Infectious Diseases COVID-19 working group (2020). Early dynamics of transmission and control of COVID-19: a mathematical modeling study. *The Lancet. Infectious diseases*, *20*(5), 553–558. https://doi.org/10.1016/S1473-3099(20)30144-4.

7- Africa center for strategic studies, Mapping Risk Factors for the Spread of COVID-19 in Africa https://africacenter.org/spotlight/mapping-risk-factors-spread-covid-19-africa/

8- World Health Organization, Coronavirus disease (COVID-19): Vaccines 28 October 2020: Available https://www.who.int/news-room/q-a-detail/coronavirus-disease-(covid-19) accessed February 2021.

9- Glynn JR, McLean E, Malava J, et al. Effect of Acute Illness on Contact Patterns, Malawi. *Emerging Infectious Diseases*. 2017;26(1):44-50. doi:10.3201/eid2601.181539.

10- He, S., Peng, Y. & Sun, K. SEIR modeling of the COVID-19 and its dynamics. Nonlinear Dyn 101, 1667–1680 (2020). https://doi.org/10.1007/s11071-020-05743.

11- Calistus N. Ngonghala, Enahoro Iboi, Steffen Eikenberry, Matthew Scotch, Chandini Raina et.al, Mathematical assessment of the impact of non-pharmaceutical interventions on curtailing the 2019 novel Coronavirus, Mathematical Biosciences, Volume 325, 2020,108364, ISSN 0025-5564, https://doi.org/10.1016/j.mbs.2020.108364.

12- Jomar F. Rabajante Insights from early mathematical models of 2019-nCoV acute respiratory disease (COVID19) dynamics. https://arxiv.org/ftp/arxiv/papers/2002/2002.05296.pdf

13- Backer, J. A., Klinkenberg, D., & Wallinga, J. (2020). Incubation period of 2019 novel coronavirus (2019-nCoV) infections among travellers from Wuhan, China, 20-28 January 2020. *Euro surveillance: bulletin Europeen sur les maladies transmissibles = European communicable disease bulletin*, *25*(5), 2000062. https://doi.org/10.2807/1560-7917.ES.2020.25.5.2000062

14- Linton, N. M., Kobayashi, T., Yang, Y., Hayashi, K., Akhmetzhanov, A. R., Jung, S. M., Yuan, B., Kinoshita, R., & Nishiura, H. (2020). Incubation Period and Other Epidemiological Characteristics of 2019 Novel Coronavirus Infections with Right Truncation: A Statistical Analysis of Publicly Available Case Data. *Journal of clinical medicine*, *9*(2), 538. https://doi.org/10.3390/jcm9020538

15- Li Q, Guan X, Wu P, et al. Early Transmission Dynamics in Wuhan, China, of Novel Coronavirus-Infected Pneumonia. *N Engl J Med*. 2020;382(13):1199-1207. doi:10.1056/NEJMoa2001316

16- Jonathan M Read, Jessica RE Bridgen, Derek AT Cummings, Antonia Ho, Chris P Jewell. Novel coronavirus 2019-nCoV: early estimation of epidemiological parameters and epidemic prediction: preprint server for health science. **doi:** https://doi.org/10.1101/2020.01.23.20018549

17- 13. Central Statistical Agency, Population Projections for Ethiopia 2007-2037, CSA, Ethiopia www.csa.gov.et › 368-population-projection-2007-2037pdf.

18- Glynn, J. R., McLean, E., Malava, J., Dube, A., Katundu, C., Crampin, A. C., & Geis, S. (2020). Effect of Acute Illness on Contact Patterns, Malawi, 2017. Emerging infectious diseases, 26(1), 44–50. https://doi.org/10.3201/eid2601.181539.

19- Liu, Y., Gayle, A. A., Wilder-Smith, A., & Rocklöv, J. (2020). The reproductive number of COVID-19 is higher compared to SARS coronavirus. *Journal of travel medicine*, *27*(2), taaa021. https://doi.org/10.1093/jtm/taaa021

20- Leon D, Ellen B-P Mick B, Matt K, A spatial model of CoVID-19 transmission in England and Wales: early spread and peak timing. medRxiv preprint doi: https://doi.org/10.1101/2020.02.12.20022566.

21- Hellewell J, Abbott S, Gimma A, Bosse NI, Jarvis CI, Russell TW, et al. Feasibility of controlling 2019-nCoV outbreaks by isolation of cases and contacts. medRxiv preprint [Internet]. Available from: https://www.medrxiv.org/content/10.1101/2020.02.08.20021162v1.

22- Lee VJ, Chiew CJ, Khong WX. Interrupting transmission of COVID-19: lessons from containment efforts in Singapore. Journal of Travel Medicine. 2020

23- Wu JT, Leung K, Bushman M, Kishore N, Niehus R, de Salazar PM, et al. Estimating clinical severity of COVID-19 from the transmission dynamics in Wuhan, China. Nature Medicine. 2020.

24- Nikolai LA, Meyer CG, Kremsner PG, Velavan TP. Asymptomatic SARS Coronavirus 2 infection: Invisible yet invincible. *Int J Infect Dis*. 2020; 100:112-116. doi: 10.1016/j.ijid.2020.08.076

25- Nega BA, Addissie D, Mamo G et al. Sero-prevalence of anti-SARS-CoV-2 Antibodies in Addis Ababa, Ethiopia. 2020 available https://www.biorxiv.org/content/10.1101/2020.10.13.337287v1.full.pdf. Accessed December 2020

26- Padhan R, Prabheesh KP. The economics of COVID-19 pandemic: A survey. *Econ Anal Policy*. 2021; 70:220-237. doi: 10.1016/j.eap.2021.02.012

27- Ogunleye, Olayinka O et al. "Response to the Novel Corona Virus (COVID-19) Pandemic Across Africa: Successes, Challenges, and Implications for the Future." *Frontiers in pharmacology* vol. 11 1205. 11 Sep. 2020, doi:10.3389/fphar.2020.01205