“Projecting the effects of non-pharmaceutical interventions and vaccination on COVID-19 control in Lusaka using a mathematical model”

By

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DECLARATION

I, **Mwamba Nsofwa,** do hereby declare that the contents of this dissertation are my original work and has not previously been presented for the award of a degree to this or any other university or institution.

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CERTIFICATE OF APPROVAL

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ABSTRACT

The COVID-19 epidemic in Zambia has had significant social and economic impact on the health sector and wellbeing of the population. Hence it is vital to investigate the effect of various Interventions that were implemented to control the spread of the pandemic. Non-pharmaceutical interventions (NPIs) were introduced to help contain the spread of COVID- 19 pandemic in the absence of pharmaceutical interventions. Since then, COVID-19 vaccines have been developed and are readily available globally.

Projecting the combined impact of vaccine uptake and NPIs in the control of the COVID 19 pandemic is crucial to support evidence-based policy making**.**

The Vensim Personal Learning Edition (PLE) simulation software was used to create a modified Susceptible-Exposed-Infectious-Recovered (SEIR) mathematical model to show the simultaneous effects of vaccination combined with NPIs such as social distance, hand hygiene and cough etiquette which we termed as behaviour change, and also vaccination with face masking only against COVID-19 in Lusaka. Behaviour change and face masking were simulated at different percentages compliance together with varying vaccine uptake levels of low, moderate and high. Twelve different scenarios for groups of people who practice behaviour change or combined (NPIs) with vaccination and twelve scenarios for face masking with vaccination were modelled.

Results from the simulation showed a reduction in the number of both cumulative cases and deaths from the interventions put in place as compared to scenarios without intervention. Furthermore, the basic reproduction number (R_0) which was initially set at 2.64 in the model and was reduced to 2.37 in the scenario set at 10% behaviour change with low vaccination rate and 2.34 in the scenario set at 10% behaviour change with high vaccination rate as well as 0.61 in the scenario set at 80% behaviour change with low vaccination rate and 0.55 in the scenario set at 80% behaviour change with high vaccination rate. In the masking with vaccination scenarios, reproduction number was reduced to 2.45 in the scenario set at 10% masking with low vaccination rate and 2.29 in the scenario set at 10% masking with high vaccination rate as well as 1.25 in the scenario set at 80% masking with low vaccination rate and 1.24 in the scenario set at 80% masking with high vaccination rate.

These findings highlight the importance of continued adherence to NPIs even when the population is being vaccinated, particularly under scenarios of lower vaccination rates which are influenced by vaccine efficacy, distribution and community hesitancy.

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DEDICATION

To God: for his ability working in me, I am eternally grateful. My family, friends and colleagues, I say thank you for your support and patience.

TABLE OF CONTENTS

DECLARATION ..... **i**

CERTIFICATE OF APPROVAL ..... **ii**

ABSTRACT ..... **iii**

AKNOWLEDGEMENT ..... **iv**

DEDICATION ..... **v**

TABLE OF CONTENTS ..... **vi**

LIST OF TABLES ..... **viii**

LIST OF FIGURES ..... **ix**

LIST OF ABBREVIATIONS AND ACRONYMS ..... **x**

CHAPTER ONE **1**

1.0 INTRODUCTION 1

1.1 Background 1

1.2 Problem statement 3

1.3 Study justification 4

1.4 Research questions 4

1.5 Objectives 4

1.5.1 Main Objective 4

1.5.2 Specific Objectives. **4**

CHAPTER TWO **5**

2.0 LITERATURE REVIEW 5

2.1 Aetiology of COVID-19 5

2.2 Epidemiology 6

2.3 Clinical signs 10

2.4 Reproduction number and Herd Immunity Threshold 11

2.5 Vaccination 13

2.6 Prevention and Control 14

CHAPTER THREE: **17**

3.0 MATERIALS AND METHODS 17

3.1 Study area 17

3.1 Ethical considerations 17

3.2 Study design 17

3.4 Model optimization and simulation 30

CHAPTER FOUR: **31**

4.0 RESULTS **31**

4.1 Results **31**

CHAPTER FIVE: **49**

5.0 DISCUSSION **49**

CHAPTER SIX: **52**

6.0 CONCLUSION AND RECOMMENDATIONS. 52

6.0 Conclusion 52

6.1 Recommendation 52

CHAPTER SEVEN **54**

7.0 REFERENCES 54

LIST OF TABLES

Table 1: Model Variables.. 20

Table 2: Parameters.. 21

Table 3: Ordinary Differential Equations 22

Table 4: Ordinary differential equations for Behaviour change 23

Table 5: Ordinary differential equations for Face Masking... 24

Table 6: Percentage reduction in the expected cumulative number of confirmed cases for......... 46

LIST OF FIGURES

Figure 1: The anatomy of a pandemic: from pathogen spillover at the wildlife–livestock–human nexus to human-to-human transmission within cities, between cities, and across countries (Wu et al, 2021) 9

Figure 2: Modes of Transmission of COVID-19 Inhuman population........ 10

Figure 3: Breaking the chain of COVID 19 Infection: Contributions of different NPIs 16

Figure 4: The Two-group model for the spread of COVID-19 in Lusaka province incorporating face masking and vaccination and/or vaccination and behaviour. The solid arrows represent flow between compartments, and the dotted arrows represent the additive contribution relationship to a compartment........ 19

Figure 5: Stock and flow diagram in Vensim for behaviour change 25

Figure 6: Stock and flow diagram in Vensim for masking with vaccination 26

Figure 7: Showing Model data fit to Lusaka COVID-19 data........ 31

Figure 8: Null cumulative cases and expected cumulative cases from each of the simulates........ 38

Figure 9: Null cumulative deaths and cumulative deaths from each of the simulates........ 45

Figure 10: Effect of behaviour change (BC) and Vaccination interventions on Ro........ 47

Figure 11: Effect of Masking and Vaccination intervention on Ro........ 48

LIST OF ABBREVIATIONS AND ACRONYMS

COVID -19	Coronavirus Disease-2019
CFR	Case Fatality Rate
CDC	Centers for Disease Control and Prevention
COVAX	COVID-19 Vaccine Global Access
ECDC	European Centre for Disease Prevention and Control
HIT	Herd Immunity Threshold
MOH	Ministry of Health
WHO	World Health Organization
NPIs	Non-Pharmaceutical Interventions
SARS-CoV-2	Severe Acute Respiratory Syndrome Coronavirus-2
ZNPHI	Zambia National Public Health Institute
ODEs	Ordinary Differential Equations
MERS	Middle East Respiratory Syndrome
SARS	Severe Acute Respiratory Syndrome
SEIR	Susceptible-Exposed-Infectious-Recovered
RNA	Ribonucleic Acid
VoC	Variants of Concern
ZSA	Zambia Statistics Agency

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background

Coronavirus Disease-2019, (COVID-19), was first reported in December 2019 in the Chinese city of Wuhan. Its cause was identified as a novel coronavirus which was later named severe acute respiratory syndrome coronavirus-2(SARS-CoV-2) (Shereen et, al, 2020). It is transmitted from human-to-human through direct contact with contaminated objects or surfaces and through inhalation of respiratory droplets from both symptomatic and asymptomatically infectious humans (WHO, 2020).

Patients of COVID-19 experience mild to severe illness including cough, fever, shortness of breath, fatigue, muscle or body aches, headache, new loss of taste or smell, sore throat, congestion or runny nose, nausea and diarrhea (CDC,2019).

This disease spread to other countries and was declared a public health emergency of international concern by the World Health Organization (WHO) on 30 January 2020. Global statistics of the cumulative cases of COVID-19 from the World Health Organization (WHO) COVID-19 weekly epidemiological updates as of 26 December 2021 was *278 714 484* cases with *5 393 950* deaths (WHO,2021).

Zambia recorded its first suspected COVID -19 case on 20 March, 2020 (Chipimo et al, 2021), and has since recorded about *238 383* confirmed cases and *3716* deaths as of 28 December, 2021 (Worldometer,2022). It is likely that these figures underestimate the actual burden of COVID-19 in Zambia, as recently revealed by postmortem surveillance (Mwananyanda et al, 2021). Lusaka Province had the highest number of cases at *31,234* with *507* deaths, while Muchinga Province had the lowest number (ZNPHI,2021). Because of the high rate of human interaction due to globalization and international travel among countries, the transmission of COVID-19 had been very fast, posing serious challenges to disease control.

COVID-19 has continued to spread, with new infections and deaths being recorded worldwide. In the absence of efficacious pharmaceutical measures for prevention or treatment, the WHO worked tirelessly with partners in a short period to ensure the availability, manufacture and deployment of safe and effective vaccines (WHO,2021).

According to an article by Sharma et al, (2021), as of June 2021, nineteen unique COVID-19 vaccines had received regulatory approval in at least one country. Most of these vaccines had provisional or emergency authorization only, often on the basis of interim phase III trial results, and in some cases without any available published clinical trial results (Sharma K et al, 2021).

These vaccines include BNT162b2 (Tozinameran), COVID-19 Vaccine Moderna, AstraZeneca (AZD1222), Johnson & Johnson (Ad26.COV2. S), Convidecia (Ad5-nCoV), Sputnik V Gam-COVID-Vac, Sputnik Light, BBIBP-CorV, COVIV, CoronaVac, Covaxin, QazVac, BBIBP-CorV, Abdala, Soberana 02/Soberana Plus, EpiVacCorona, Zifivax, COVIran Barakat, SARS-CoV-2 Vaccine (Vero Cells) KoviVac, BBV152/Covaxin (Sharma et al,2021; Basta et al, 2020)

A number of vaccines were evaluated as having met the necessary criteria for safety and efficacy and these include: Oxford/AstraZeneca, Pfizer/BioNTech, Moderna, Johnson and Johnson, Sinopharm, Sinovac, COVAXIN, Covovax and Nuvaxovid (WHO, 2022).

The main vaccines being used in most countries are Oxford/AstraZeneca (ASD), Pfizer/BioNTech (BNT162b2), Moderna (mRNA-1273) and Johnson&Johnson (Ad26.COV2. S). (WHO, 2021).

The Zambian Government through Ministry of Health (MOH, 2021) devised a plan in line with the November 2020 WHO and UNICEF interim guidance on developing a national deployment and vaccination plan (NDVP) for COVID19 vaccines.

However, success of vaccination programs lies mainly in the people's willingness to take the vaccine, which was influenced by various social and cultural factors (WHO, 2020).

For instance, the short period it has taken for COVID-19 vaccines to be developed, entwined with the dissemination of misleading information through the internet and social media platforms, contributed to vaccine hesitancy, where a section of a population refuses or delays its acceptance of a readily available vaccine (WHO,2014). The principal strategy to control COVID-19 has focused on community based, non-pharmaceutical interventions (NPIs) (Ferguson et al, 2020).

Non-Pharmaceutical Interventions (NPIs) are public health measures that aim to prevent and control SARS-CoV 2 transmissions in the community and include actions such as frequent hand washing, face masking, covering coughs and sneezes, isolating sick persons, contact tracing, quarantine of exposed persons and physical/social distancing measures for the general population. (ECDC,2020; Hiwote et al,2022).

In this study, a modified compartmental mathematical modelling method was used to explore and project the combined impact of NPI such as face masking, hand washing and social distancing in combination with vaccination in containing the spread of the COVID 19.

1.2 Problem statement

The COVID 19 pandemic has not only caused high severe morbidity and mortality rate worldwide but also continues to inflict devastating public health and economic challenges globally (Gumel et al, 2021). It has caused a strain on the health care system of every country, especially the already strained health care systems in developing countries like Zambia.

In an assessment on Frontline Health Service Readiness and Capacities in the Context of COVID-19 Pandemic, the Ministry of Health (MOH) in collaboration with World Health Organization (WHO) explained that the three waves of the pandemic have costed human lives with 349,304 confirmed cases and 4069 deaths recorded in Zambia as of 8 April, 2024 and has also challenged the nation’s health systems, for the sustained delivery of quality health services to all Zambians (MOH,2021; Worldometer, 2024).

Measures taken by most countries to control the pandemic particularly the lockdowns, has had severe socioeconomic challenges, leading to an increase in poverty levels due to loss of employment, income and in some cases loss of business (Ministry of Transport,2021).

NPIs were introduced to help control the pandemic in the absence of pharmaceutical interventions such as COVID-19 vaccines which were not readily available especially in developing countries, while awaiting disbursement and distribution from Global Alliance for Vaccines and Immunization (GAVI). COVID-19 vaccines have since become readily available globally.

Various factors such as vaccine hesitancy may negatively affect the uptake of vaccines in communities. There has been insufficient information on the expected COVID-19 vaccine uptake rates in Zambia and the impact of NPIs on the control of the pandemic in the country. This lack of information presents a challenge for adequately planning and successfully implementing the COVID-19 control strategy in Zambia.

The impact of the COVID-19 epidemic in Zambia has social and economic effects with increased burden on the health sector, hence it is vital to investigate the effect of vaccination and NPIs in light of the above-mentioned challenges for optimal control of the disease.

1.3 Study justification

The introduction of COVID -19 vaccines, was aimed at providing herd immunity against the pandemic in order to halt or reduce its spread. Despite COVID-19 vaccines being available globally, various factors such as vaccine hesitancy have negatively affected its uptake and therefore necessitated the continuation of NPI alongside vaccination.

Mathematical modelling methods can be used to project the combined impact of vaccines and NPIs in the control of the COVID 19 pandemic. A projection of the combined effects of various levels of community vaccine uptake rates and practice of NPIs on the spread or control of the COVID-19 pandemic using mathematical modelling methods could guide policymakers in planning effective community sensitization on use of NPIs and vaccination strategies to achieve herd immunity threshold adequate to control the epidemic in Zambia.

1.4 Research questions

1. What was the impact of NPIs on COVID-19 epidemic in Lusaka, Zambia?
2. How does community vaccine uptake and NPIs impact the basic reproduction number of the COVID-19 epidemic in Lusaka, Zambia?

1.5 Objectives

1.5.1 Main Objective

To evaluate the impact of NPIs combined with various levels of vaccine uptake on the COVID-19 control in Lusaka, Zambia.

1.5.2 Specific Objectives.

1. To model and project, the combined impact of NPIs and various levels of vaccine uptakes on the basic reproduction number of COVID-19 epidemic in Lusaka, Zambia.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Aetiology of COVID-19

The impact of COVID-19 has been felt across the globe, with essential health services suffering disruptions in nearly every country. Sadly, lower-income countries have been hit the hardest by these challenges (Yibeltal et, al, 2022; WHO, 2020).

COVID-19 has triggered the largest global economic crisis in over a century, leading to a surge in global poverty and inequality, particularly in developing countries (Alemayehu Geda, 2021; The World Bank, 2022).

The implementation of population-based interventions, such as lockdowns, has been crucial in controlling the spread of the virus. However, it also led to a significant reduction in economic activities as most businesses were forced to shut down temporarily and public transport was discouraged. The impact of these measures on the economy has been profound and will require long-term planning and support to ensure a steady recovery (Miyah Yousef et al, 2022).

The novel, severe acute respiratory syndrome coronavirus-2(SARS-CoV-2), which causes Coronavirus disease-2019 (Covid-19), is a member of the Coronaviruses (subfamily Coronavirinae, order Nidovirales), which are common human pathogens. They are enveloped, positive-sense, single-stranded RNA viruses that belong to the family Coronavirdiae, and are known to cause acute respiratory, hepatic and neurological diseases with varying severity in humans as well as animals (Sharma Atul et al,2020)

Coronaviruses have in the past two decades been responsible for two large-scale pandemics, severe acute respiratory syndrome (SARS) and Middle East respiratory syndrome (MERS) (Zhou et al, 2020).

The word “Coronavirus” is derived from the Latin word “Corona”, meaning crown or wreath, which is related to the characteristic appearance of the virions of the virus when viewed through a microscope. It is believed that human coronaviruses have their origins in bats and rodents, and some human activities, such as urbanization and poultry farming help in expediting their evolution (Gumel et al, 2020).

The origin of SARS-CoV-2 infection was first reported in people exposed to a wet market in Wuhan City, China in December 2019. It has been suggested that the infection is of zoonotic origin, most likely originating from bats and transmitted to humans through a not-yet-known intermediary host (CDC, 2021; Sharma Atul et al, 2020; Zhou et al, 2020).

2.2 Epidemiology

The novel human coronavirus (SARS-CoV-2,) which caused the COVID-19 outbreak initially emerged from Wuhan, China, in December 2019 and quickly spread to 198 countries and territories around the world (Achoki et al,2020; Africa CDC, 2020; WHO, 2020).

Global distribution

As of January 22, 2020, a total of 571 cases of the 2019-new coronavirus (2019-nCoV) had been reported in 25 provinces (districts and cities) in China and as of January 30, 2020, 7,734 cases had been confirmed in China and 90 other cases had also been reported from some countries that included Taiwan, Thailand, Vietnam, Malaysia, Nepal, Sri Lanka, Cambodia, Japan, Singapore, Republic of Korea, United Arab Emirates, United States, the Philippines, India, Australia, Canada, Finland, France, and Germany (Hussin A et al, 2020; Hongzhou Lu, 2020).

The World Health Organization as of 21 February 2023 recorded global cumulative cases of 757,264,511 and cumulative deaths of 6,850,594.

The first case of COVID-19 in Africa was reported in Egypt on Feb 14, 2020, just a few days after WHO had declared the outbreak a public health emergency of international concern on 30 January, 2020 (Achoki et al,2020; Africa CDC, 2020; WHO, 2020).

Africa had 9,494,590 cumulative cases and cumulative deaths of 175,289 and Zambia had cumulative cases of 342,317 and cumulative deaths of 4,051 (WHO Dashboard, 2023).

Despite the spread of COVID-19 to almost all countries in Africa within three months, country-reported case counts suggest that the pandemic had spread much slower on the continent than in the rest of the world (Slayer et al, 2021).

Drivers of COVID-19

COVID-19 remains a threat to global health and many studies have been carried out to determine the factors driving the continued spread of SARS-CoV- 2.

Studies have shown that climate and weather are factors associated with the severity of COVID-19 transmission. It has been hypothesized that heat and sunlight can reduce the spread and prevalence of the disease by supporting public health measures, such as outdoor meetings. However, it is important to note that even in areas that experience high temperatures or summer, COVID-19 is unlikely to completely disappear (Chen S et al, 2021).

Some studies have suggested that the virus might persist in human populations in cyclic or seasonal wave patterns (Yangying et al, 2020). The World Health Organization (WHO) stated that there was no conclusive evidence supporting climate as a driver for COVID-19 and advised that the virus spreads in all climates (WHO et al, 2020).

Another study by Mario Coccia showed that atmospheric factors (wind speeds) and air pollution may have supported the spread of COVID-19 in Northern Italian cities, leading to a higher number of infected individuals and deaths (Mario Coccia, 2021).

According to a study by Latkin et al, psychological factors may also play a role in the spread of COVID-19. The study explored the connection between COVID-19 skepticism (defined as the denial of the severity of the illness and the perception that the pandemic is exaggerated or fake) and its impact on COVID-19 prevention behaviour and information-seeking behaviour in various communities. The findings suggest that COVID-19 skepticism has led to poor COVID-19 prevention practices and lack of interest in accurate information related to the virus (Latkin et al, 2022).

Population density has also been identified as a key driver of COVID-19 transmission. High population density can facilitate the spread of the virus due to increased opportunities for contact between individuals, which can lead to increased transmission rates (Kucharski et al., 2020). In addition, crowded living conditions, such as in urban slums or refugee camps, can make it difficult to implement effective physical distancing measures, increasing the risk of transmission.

A study conducted in New York City found that neighborhoods with higher population densities had higher rates of COVID-19 cases and deaths (Chen et al., 2020). Another study conducted in Brazil found that municipalities with higher population densities had higher rates of COVID-19 cases and deaths (Arbex et al., 2021).

However, it is important to note that population density alone does not determine COVID-19 transmission rates. Other factors such as age distribution, comorbidities, and adherence to public health measures also play a role in the spread of the virus.

Age and comorbidities are important drivers of COVID-19 severity and mortality. Older age is a significant risk factor for severe disease and death from COVID-19, with those over the age of 60 being particularly vulnerable. A study published in The Lancet found that the case fatality rate for COVID-19 increased with age, ranging from 0.1% in those under the age of 50 to 7.8% in those over the age of 80 (Verity et al,2020).

Comorbidities, or pre-existing medical conditions such as cardiovascular disease, diabetes, chronic lung disease, and obesity, have been identified as risk factors for severe COVID-19. A meta-analysis of studies published in the Journal of Medical Virology found that patients with comorbidities were more likely to require intensive care unit admission and mechanical ventilation, and have a higher risk of mortality from COVID-19 (Yang et al, 2020; Guan et al, 2020).

Socio-economic factors such as international trade and tourism are other determinants driving transmission of COVID-19 due to increased social interactions (Bontempi et al, 2021). A review by Wu et al on the socioeconomic and environmental drivers of COVID-19 pandemic highlights four main drivers of the outbreak which are ecosystem conversion, consumption of contaminated meat (drivers of spillover risk) leading to zoonotic diseases, urban population concentration and domestic/international connectivity as shown in Figure 1 (Wu et al,2021).

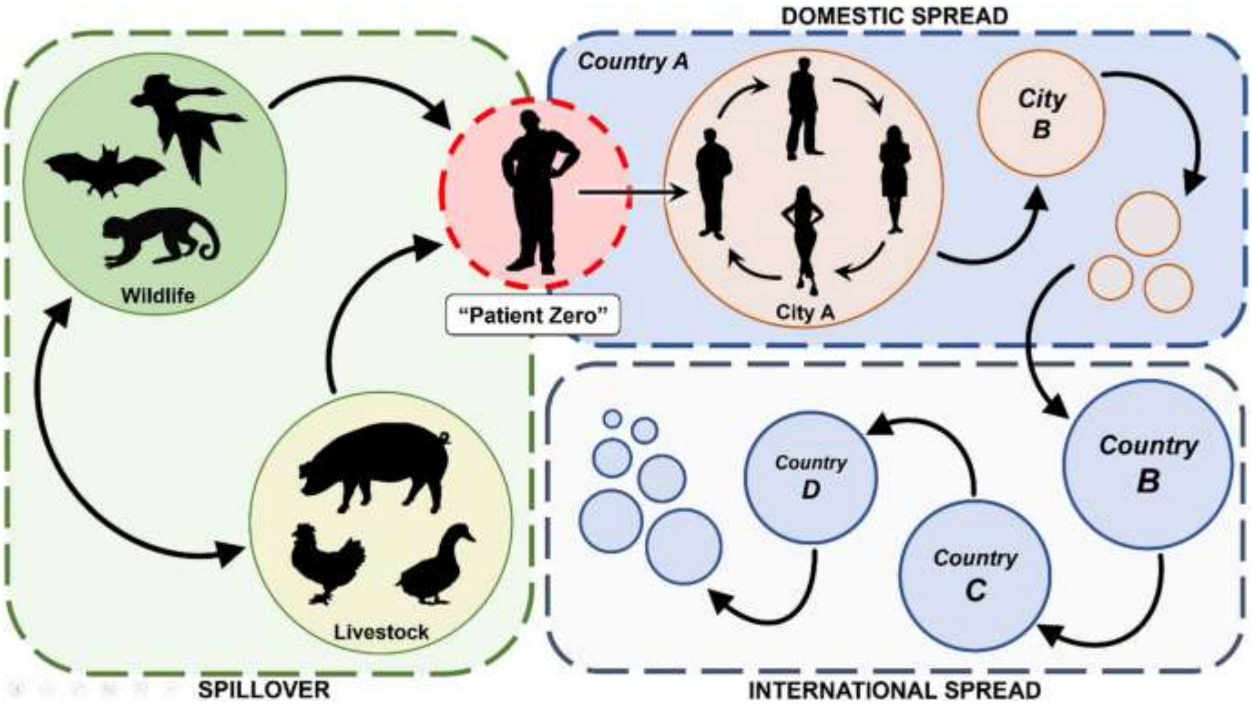

Figure 1: The anatomy of a pandemic: from pathogen spillover at the wildlife–livestock–human nexus to human-to-human transmission within cities, between cities, and across countries (Wu et al, 2021)

Transmission

The disease is transmitted from human-to-human through contact with respiratory droplets or aerosols produced by coughing and sneezing, and also inhalation of droplets from infected people as shown in Figure 2. (Melika Lotfi et al,2020; Sharma Atul et al,2020; Umakanthan S et al, 2020).

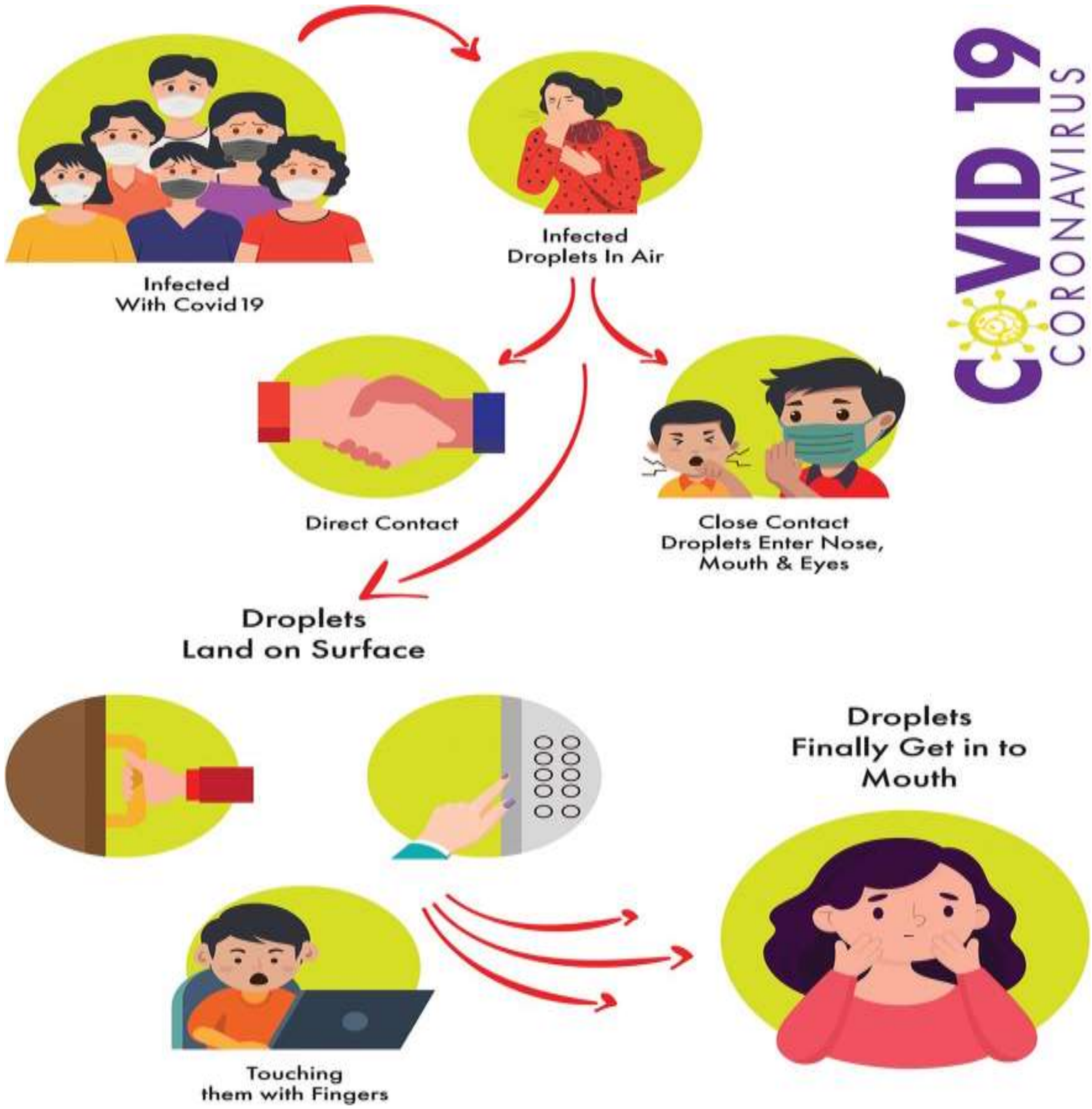

Figure 2: Modes of Transmission of COVID-19 Inhuman population

(Umakanthan et al, 2019)

2.3 Clinical signs

People with COVID-19 can either be asymptomatic or symptomatic with a wide range of symptoms, ranging from mild to moderate symptoms such as fever or chills, Cough, Shortness of breath or difficulty breathing, fatigue, muscle or body aches, headache, new loss of taste or smell, sore throat, congestion or runny nose, nausea or vomiting and diarrhea, while others experience severe illness with respiratory failure, septic shock, and/or multiple organ dysfunction and may lead to hospitalization. (CDC, 2021; NIH, 2021).

The World Health Organization (WHO) in a situation report delivered on 11 March, 2020 stated that the two groups of people at higher risk of suffering severe illness with COVID-19 were the elderly and those with co-morbidities such as individuals with diabetes, obesity, kidney disease, cardiovascular disease and chronic respiratory disease (WHO, 2020; CDC, 2021; NIH, 2021; Sanyaolu et al, 2020).

In an analysis of observations of the global epidemiology of COVID-19 from the pre-pandemic period using web-based surveillance, almost all cases occurred among adults (aged ≥18 years), with only 3% occurring among children (aged <18 years) with increased deaths being related to older individuals. (Dawood et al, 2020)

2.4 Reproduction number and Herd Immunity Threshold

The basic reproduction number (R_0) is a key parameter used to describe the transmissibility of infectious diseases. It is defined as the average number of secondary infections generated by an infectious individual in a population that is entirely susceptible to the virus (Diekmann et al, 1990). Estimating R_0 is important because it provides insight into how easily the virus can spread and helps inform public health policies aimed at controlling the pandemic.

However, it is important to note that R_0 is not a fixed parameter and can change over time as a result of various factors, such as changes in human behavior, the emergence of new variants, and the implementation of control measures (Delamater et al, 2019).

The estimation of R_0 has been used to evaluate the effectiveness of various interventions to control the spread of COVID-19. For instance, a study in China estimated that the implementation of strict control measures, including contact tracing, isolation of infected individuals, and quarantine of close contacts, reduced the R_0 from 2.35 to 0.32 (Wang et al., 2020). Another study in Italy showed that the nationwide lockdown measures implemented in March 2020 reduced the R_0 from 3.2 to 0.4 (Lavezzo et al., 2020).

R_0 is a useful metric for understanding the transmission dynamics of COVID-19 and evaluating the effectiveness of different interventions to control its spread. Estimation of R_0 on a regular basis is essential for monitoring the transmission dynamics of COVID-19 and informing evidence-based policy decisions.

A systematic review on the epidemiology of COVID-19 based on current evidence by Park et al, showed that the outbreak was growing fast with an infected individual infecting two to three persons on average and doubling in size every 3 to 7 days, with the incubation period ranging from 3 to 6 days (Park et al, 2020). Various studies have estimated the R0 for COVID-19 as ranging from 2 to 3 and another study estimated the R_0 at around 3.28 (Liu et al, 2020).

Another systematic review and meta-analysis to estimate the R_0 for COVID-19 by Alimohamamadi et al found that the overall R_0 was 3.32 (95% CI, 2.81 to 3.82) (Alimohamamadi et al, 2020).

SARS-CoV-2 is the first coronavirus outbreak to be characterized as a pandemic by WHO, compared with the coronaviruses that caused SARS (SARS-COV) and MERS (MERS-COV), SARS-COV-2 spread more rapidly in the early weeks of the global outbreak (Dawood et al, 2020.)

The pooled estimated case fatality rate (CFR) of COVID-19 in a review by Alimohamamadi et al differed between different patient groups and was higher in patients admitted in intensive care units (ICU) and those older than 50 years (Alimohamamadi et al,2021).

SARS-CoV-2 vaccines are relevant to achieving herd immunity to end the COVID-19 pandemic. Herd immunity is the indirect protection from an infectious disease that happens when a population is immune either through vaccination or immunity developed through previous infection (WHO, 2021).

The proportion of the population that must be vaccinated against COVID-19 to begin inducing herd immunity was not known until recently when WHO proposed that at least 70% vaccination coverage in all countries must be reached by all countries in order to generate sufficient herd immunity (WHO,2021; Pedro Plans Rubio, 2022).

Achieving the herd immunity threshold (HIT) requires immunizing at least $1 - 1/R_0$ of the population; assuming vaccine provides complete protection in those vaccinated (Driessche., 2017; Mukandavire *et al*., 2013, 2011; Dietz., 1993).

Herd immunity threshold (HIT) using R_0 but taking vaccine efficacy (i.e., AstraZeneca with vaccine efficacy of 76% against symptomatic disease) into consideration is calculated as follows:

$$c = \frac{1-\left(\frac{1}{R_0}\right)}{1-(1-r)(1-s)} = \frac{1-\left(\frac{1}{2.64}\right)}{1-(1-0)(1-0.76)} = 0.81738437$$

c = *0.81738437*100=81.7384368*

c*=82%*

- Where c is the minimum required vaccination coverage or herd immunity threshold (HIT);
- R_0 is the measure of the transmissibility of SARS-CoV-2 and indicates the number of secondary cases, arising from a primary case in a totally susceptible population;
- r is the fraction of the vaccinated population who are completely immunized (i.e., with zero susceptibility). In this case we set r = 0 for COVID-19;
- s is the proportional reduction of the susceptibility for those partially immunized (or the vaccine efficacy). (Mukandavire et al,2011; Dietz et al,1993; Nowogrodzki et al, 2021; Pedro Plans Rubio,2022; WHO,2022)

2.5 Vaccination

Until there was a vaccine available capable of protecting individuals from this disease, only non-pharmaceutical interventions (NPIs), aimed at reducing population contact rates and thus reducing virus transmission, could be implemented in the population (Machado et al,2021).

Though various vaccines have been authorized for use globally**,** considering the complexities of large-scale vaccine production, distribution, storage, and uptake, achieving high coverage would be challenging, therefore, critical questions remain regarding the need to continue non-pharmaceutical interventions (NPIs), such as physical distancing and face mask usage, as the public is vaccinated over time. (Patel et al, 2021).

Zambia was one of the thirteen countries considered as a high-risk priority for COVID-19 by WHO and as of 28 April, 2021 a total number of *17,851* vaccine doses had been administered from a population 0f 18.4 million. The projected number of vaccinated populations needed to achieve herd immunity are *10,635,200* with R_0=*2.37* at *57.8%* and *16,560,000* with R_0=*10* at *90%*. (Prisno et al, 2021; WHO, 2021).

Looking at where we were in terms of vaccination and how much more needed to be done to achieve herd immunity especially with challenges of vaccine hesitancy, we must factor in the importance of other strategies of control such as NPIs.

Vaccine hesitancy studies are relevant in determining the impact of vaccination in controlling an infectious disease in a population.

The basic reproduction number (R_0) shows the transmissibility of a disease, the higher the basic reproduction number the more transmissible a disease and vaccine effectiveness is dependent on the proportion of the population that receives the vaccine.

A systematic review of COVID -19 vaccine acceptance rates showed high vaccine acceptance in Ecuador, Malaysia, Indonesia, and China, but reported lower rates in Kuwaiti, Jordan, Russia, Italy, Poland, France, and the United States (Sallam et al., 2021).

In Africa, Echoru et al, (2020) found that only 53.6% of the 1067 respondents from western Uganda were willing to get vaccinated against COVID-19. Such poor attitudes towards COVID-19 vaccination stimulated discussions within the WHO’s Technical Advisory Group on behavioral Insights and Sciences for Health.

Despite hesitancy studies becoming a central issue in many organizations and countries, including some African countries such as Uganda and the DRC, such studies are lacking in Zambia.

Vaccination alone is not expected to be able to control the spread of the infection, and a carefully planned vaccination campaign needs to be coordinated with continued implementation of NPIs (Giordano et al, 2021).

2.6 Prevention and Control

COVID-19 can be prevented and controlled through vaccines and community adherence to NPIs such as practicing good hand hygiene which includes washing hands with clean water and soap, sanitizing hands with an alcohol-based hand sanitizer, face masking, social distancing and good cough etiquette as shown in Figure 3. (WHO, 2021; Adhikari et al, 2020).

All the available interventions rely on community sensitization which plays a crucial role in the prevention and control of COVID-19. Community sensitization through targeted messaging and education campaigns addresses common misconceptions and concerns around COVID-19. It involves prevention measures educating the public on the virus, how it spreads, and the measures that can be taken to prevent its transmission. Knowledge, attitudes, and practices (KAP) of the community are essential in determining the effectiveness of COVID-19 prevention interventions.

A study conducted in Nigeria found that KAP of the community significantly influenced their adherence to COVID-19 prevention measures. The study found that individuals with higher knowledge levels of the virus and prevention measures were more likely to consistently practice preventive measures, such as wearing masks and practicing social distancing (LLiyasu et al, 2020).

Another study conducted in Ethiopia found that community knowledge and attitudes towards COVID-19 were positively associated with their willingness to receive the COVID-19 vaccine (Getachew et al, 2020)

Behaviour change is a complex process that is influenced by several factors. Promoting behaviour change for COVID-19 prevention is not always easy, and several factors can affect an individual's willingness to adopt preventive measures. Some of the factors affecting behaviour change with regards to COVID-19 prevention are individual knowledge and awareness of the virus and its transmission which play a crucial role in their willingness to adopt preventive measures. According to a study conducted in Saudi Arabia, individuals who had more knowledge about COVID-19 were more likely to adopt preventive measures such as wearing masks and practicing social distancing (Al-Hanawi et al., 2020).

Perceived susceptibility or an individual's perception of their susceptibility to the virus can influence their behaviour change. A study conducted in China found that individuals who believed they were at a higher risk of contracting the virus were more likely to adopt preventive measures (Zhong et al., 2020).

Perceived severity of the virus also affects behaviour change, especially where an individual has lost a loved one to the disease. A study conducted in Nigeria found that individuals who believed that COVID-19 was a severe illness were more willing to adopt preventive measures (Olawore, Akinremi, & Afolabi, 2020).

Attitudes and beliefs towards preventive measures such as wearing masks, social distancing, and hand hygiene can also affect their behaviour change. A study conducted in the United States found that individuals who had positive attitudes towards wearing masks were more likely to adopt this preventive measure (Czeisler et al., 2020).

Social norms and most importantly social media platforms play a crucial role in behaviour change. A study conducted in the United Kingdom found that individuals were more likely to adopt preventive measures if they believed that others in their social group were also adopting them (Bavel et al., 2020).

Access to personal protective equipment such as masks, hand sanitizers, and clean water can also affect behaviour change. A study conducted in India found that individuals who had access to hand sanitizers were more likely to adopt hand hygiene practices (Gupta et al., 2020).

Trust in authorities most especially those responsible for the health of the public and their communication strategies also affect behaviour change. A study conducted in Italy found that individuals who trusted their authorities and their messaging were more likely to adopt preventive measures (Bertin et al., 2020).

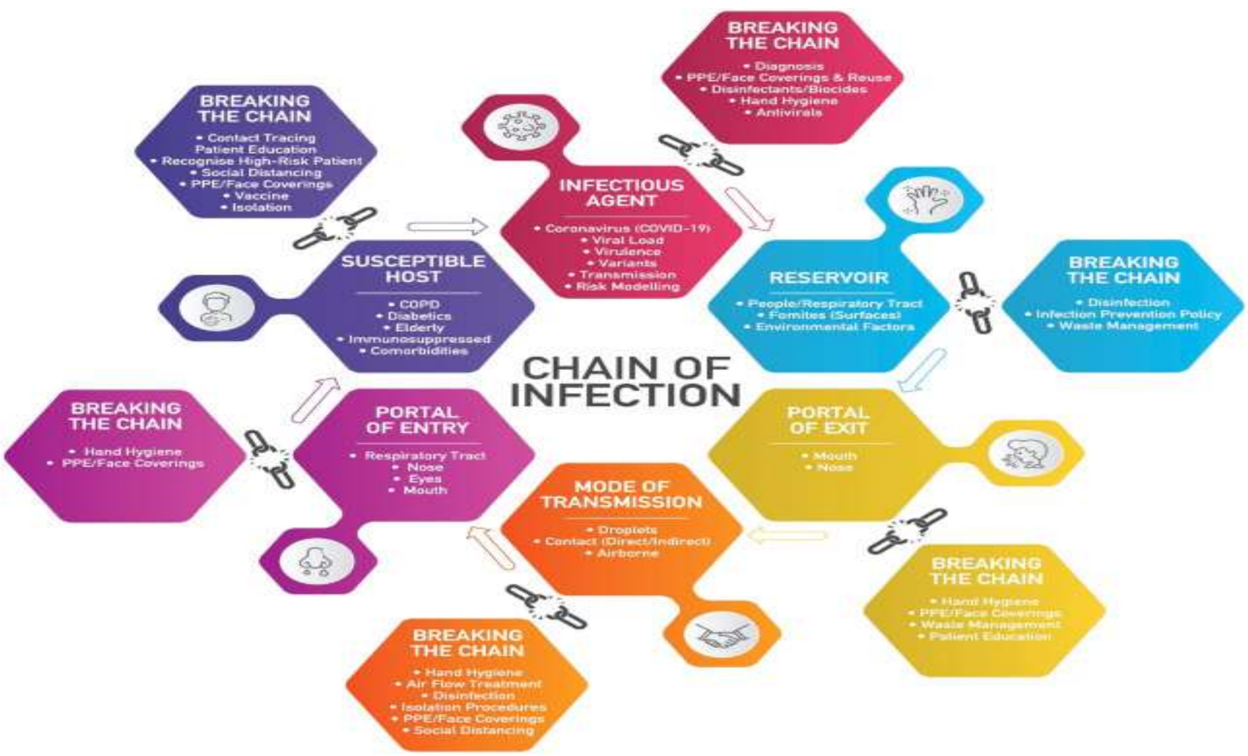

Figure 3: Breaking the chain of COVID 19 Infection: Contributions of different NPIs
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CHAPTER THREE:

3.0 MATERIALS AND METHODS

3.1 Study area

Lusaka city is the provincial capital and also the capital city of Zambia. It is the smallest and most urbanized province in Zambia (83.5% urbanization) with seven districts over an area of about *23,490* km² and a total population of about *3*,308,*438* with a density of 140.*8*/km², (Sichone et al, 2020; City Population, 2020). Lusaka, the capital city of Zambia, offers a unique perspective on the impact of COVID-19 in urban centers. It serves as a bustling hub of corporate and commercial activity, with numerous international and local visitors passing through its busy airport and bus terminals every day. However, Lusaka was unfortunately the site of the first COVID-19 case reported in Zambia and has recorded the highest number of cumulative COVID-19 cases and deaths in the country, according to reputable reports by ZNPHI (2021), Wikipedia (2021), and Sichone et al (2020). This highlights the urgent need to address the challenges faced by urban areas in controlling the spread of the virus and protecting public health.

3.1 Ethical considerations

No ethical considerations were required for this study as no human or animal subjects were used. Secondary data was collected from publicly available sources from the ZNPHI at http://znphi.co.zm/news/situation-reports-new-coronavirus-COVID-19-sitreps/ and all patient records were completely anonymized.

3.2 Study design

An analytical quantitative study with a deterministic compartmental mathematical model was used to simulate the simultaneous effect of vaccination with combined NPIs which are hand hygiene, social distancing, contact training and isolation of all confirmed cases termed as behavioural change, and also vaccination with face masking only against COVID-19 in the Lusaka population.

The model was adopted from two studies by Eikenberry et al, (2020) and Kim et al (2020). Eikenberry et al, (2020) used COVID-19 data from the states of New York and Washington to make model simulations on the impact of face masking on community transmissions by stratifying the general population into two groups of people, those who habitually wore face masks in public or other settings where transmission may occur and those who did not wear masks at all. The approach by Kim et al (2020), used COVID-19 data from Korea to model and simulate the impact of non-pharmaceutical interventions which they summed up as behaviour change using a Susceptible-Exposed-Infectious-Recovered model (SEIR) to show their impact on COVID-19 transmission.

In this study, the Lusaka population was stratified into groups that is, those that wore face masks or practiced behaviour change with vaccination and those that did not wear face masks nor practiced behaviour change with vaccination. Behaviour change is defined as the change that a person makes to comply with health rules which in this study accounts for social distancing interventions such

avoiding mass gatherings, and maintaining personal distance and hygiene habits which are hand hygiene, and cough etiquette (Bambang et al, 2023; Kim et al,2020).

Using a modified SEIR model the groups were separated into Susceptible, Vaccinated, Exposed, and Infectious compartments for each group, as well as total Confirmed and Removed individuals.

For the face mask model, the compartments were indicative of the disease state of individuals and these were denoted as $Susceptible_{masking}(t)$, *Susceptible(t)*, $Vaccinated_{masking}(t)$, *Vaccinated(t)*, $Exposed_{masking}(t)$, *Exposed (t)*, $Infectious_{masking}(t)$, *Infectious(t)*, *Confirmed(t)*, and *Removed(t)* respectively.

The total population N is assumed to be constant where $N = S_m(t) + S(t) + V_m(t) + V(t) + E_m(t) + E(t) + I_m(t) + I(t) + C(t) + R(t)$.

For the behavior change model, the compartments are indicative of the disease state of individuals and these were denoted as $Susceptible_{Behaviour\ Change}(t)$, *Susceptible (t)*, $Vaccinated_{Behaviour\ Change}(t)$, *Vaccinated(t)*, $Exposed_{Behaviour\ Change}(t)$, *Exposed(t)*, $Infectious_{Behaviour\ Change}(t)$, *Infectious(t)*, *Confirmed(t)*, and *Removed(t)* respectively.

The total population N is assumed to be constant where $N = S_{BC}(t) + S(t) + V_{BC}(t) + V(t) + E_{BC}(t) + E(t) + I_{BC}(t) + I(t) + C(t) + R(t)$.

The compartment $R(t)$ is a composite compartment of the total removed individuals and it comprises of the total removed individuals from the community $R_{com}(t)$ and total removed confirmed individuals $R_C(t)$.

An additional compartment *D(t)* was included to track disease induced deaths. Figure 4 shows the schematic diagram of the model while the model parameters are defined in Table 1**.**

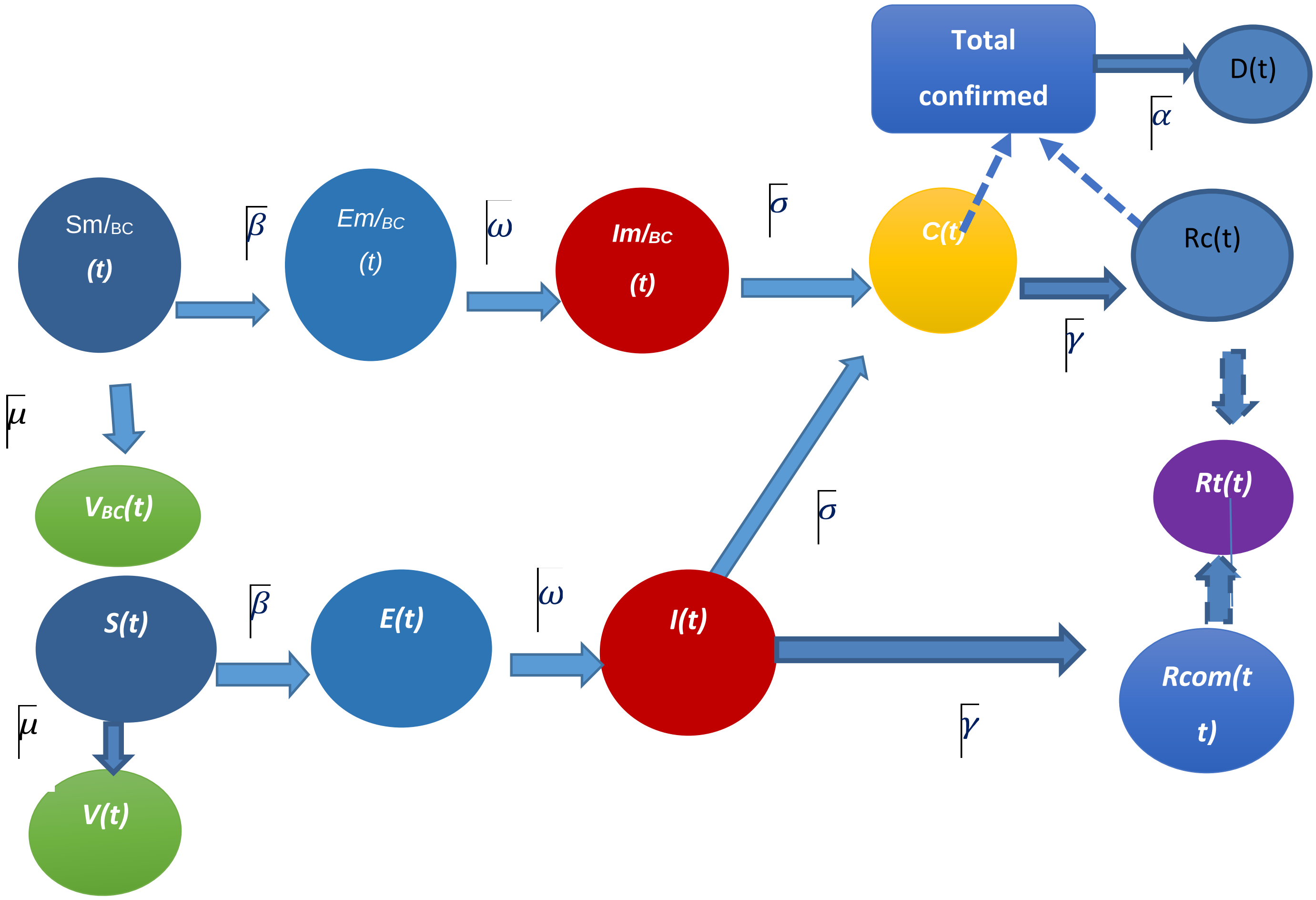


Figure 4: The Two-group model for the spread of COVID-19 in Lusaka province incorporating face masking and vaccination and/or vaccination and behaviour. The solid arrows represent flow between compartments, and the dotted arrows represent the additive contribution relationship to a compartment.

Table 1: Model Variables

VARIABLES	DEFINITION	ASSUMPTIONS
N	Total population	Latest Lusaka population. Estimated at 3,300,000 (City Population, 2020)
$S_M(t)/bc(t)$	Susceptible masked /behaviour changed	Susceptible people who habitually wear face masks or are behaviour changed
$V_M(t)/bc(t)$	Vaccinated masked/ behaviour changed	Vaccinated people who habitually wear face masks or are behaviour changed. It is assumed all vaccinated are immediately no longer susceptible to the infection and protection lasts more than 12 months i.e., throughout the modelled period for this study.
$E_M(t)/bc(t)$	Exposed masked/ behaviour changed	Exposed people who habitually wear face masks or are behaviour changed
$I_M(t)/bc(t)$	Infectious (unconfirmed) masked/ behaviour changed	Undiagnosed (unconfirmed) symptomatic, mildly symptomatic, and asymptomatic infectious Individuals who habitually wear face masks or are behaviour changed. For model simplification, it is assumed all these are equally infectious.
$S(t)$	Susceptible unmasked/ no behaviour change	Susceptible people who do not habitually wear face masks or not behaviour changed
$V(t)$	Vaccinated unmasked/ no behaviour change	Vaccinated people who do not habitually wear face masks or not behaviour changed. It is assumed all vaccinated are immediately no longer susceptible to the infection and protection lasts more than 12 months i.e., throughout the modelled period for this study
$E(t)$	Exposed unmasked/ no behaviour change	Exposed people who do not habitually wear face masks or not behaviour changed
$I(t)$	Infectious (unconfirmed) unmasked/ no behaviour change	Undiagnosed (unconfirmed) symptomatic, mildly symptomatic, and asymptomatic infectious Individuals who do not habitually wear face masks or not behaviour changed. For model simplification, it is assumed all these are equally infectious.
$C(t)$	Confirmed	Total combined laboratory diagnosed (confirmed) cases and are either hospitalized quarantined or just self-quarantined. It is assumed that the ability of all confirmed quarantined cases to transmit the infection to susceptible individuals is negligible due to effective quarantine.
$R_C(t)$	Removed confirmed	Total combined diagnosed (confirmed) cases that are no longer active i.e., have recovered or died
$C_T(t)$	Total cumulative confirmed cases	Total combined cumulative laboratory diagnosed (confirmed) cases either still active, recovered, or dead. $C_T(t) = C(t) + R_C(t)$
$D(t)$	Dead	Total combined confirmed COVID-19 related deaths only
$R_{COM}(t)$	Removed infectious	Total combined unconfirmed or community symptomatic, mildly symptomatic, and asymptomatic infectious individuals who are no longer active infectious because they have recovered or have died.
$R(t)$	Total removed	Total combined removed confirmed and community cases. $R(t)= R_C(t)+ R_{COM}(t)$

Table 2: Parameters

Parameter	Definition	Value	Units	Comment	Reference
R_0	Basic reproduction number	2.64	Secondary infections/ infectious period (days)	Data fitted	Yi Y et al, 2020 Shingai T, 2020 Anastassopoulou C et al, 2020 Choi S, Ki M, 2020
β	Transmission rate. The rate of effective contact per unit time between susceptible people and infectious people	γR_0	Effective contacts per day	Data fitted	**N/A**
μ	Vaccination rate	Varied	persons/day	Average estimate	Giordano, G et al,2021
ω	Incubation rate (The average rate to infectiousness	1/4.8	1/incubation period (days)	Average estimate	Velavan, T.P et al, 2020 Wang, Y, et al,2020 Chan, J.F.W et al, 2020
σ	Diagnosis rate (confirmation rate)	1/92	People/day	Seroprevalence study in Zambia	Mulenga, L.B et al, 2021
γ	Recovery rate	1/7.5	1/infectious period (days)	Average estimate	Wang, D et al,2020 Roser, M et al, 2020 Weiss, P et al, 2020 Zhou, F et al, 2020
α	Apparent case fatality rate (CFR)	0.05	Deaths/confirmed cases	Data fitted	Soliman, A et al, 2020
ε**(Total Behaviour Change)**	Efficiency of preventing transmission of COVID-19 through Behaviour Change.	0.02 (1/50)	**N/A**	The impact of social distancing and public behaviour changes on COVID-19 transmission dynamics in the Republic of Korea	Kim S et al, 2020
κ**(Face Mask)**	Efficiency of preventing transmission of COVID-19 through face masking.	0.5	N/A	To mask or not to mask: Modelling the potential for face mask use by the general public to curtail the COVID-19 pandemic	Eikenberry *et al,* 2020

Flow of individuals in the model

The flow of individuals between compartments was defined by a series of non-linear differential equations.

Table 3: Ordinary Differential Equations

Number	Ordinary Differential Equations
1	$\frac{dS(t)}{dt} = -\frac{\beta I(t)S(t)}{N} - \mu S(t)$
2	$\frac{dV(t)}{dt} = \mu S(t)$
3	$\frac{dE(t)}{dt} = \frac{\beta I(t)S(t)}{N} - \omega E(t)$
4	$\frac{dI(t)}{dt} = \omega E(t) - \sigma I(t) - \gamma I(t)$
5	$\frac{dC(t)}{dt} = \sigma I(t) - \gamma C(t)$
6	$\frac{dR_C(t)}{dt} = \gamma C(t)$
7	$\frac{dR_{COM}(t)}{dt} = \gamma I(t)$
8	$\frac{dR(t)}{dt} = R_C(t) + R_{COM}(t)$
9	$\frac{dC_T(t)}{dt} = C(t) + R_C(t)$
10	$\frac{dD(t)}{dt} = \alpha C_T(t)$

Table 4: Ordinary differential equations for Behaviour change

Number	**Ordinary Differential Equations**
1	$\frac{dS(t)}{dt} = -\frac{\beta I(t)S(t)}{N} - \frac{\beta\varepsilon I_{BC}(t)S(t)}{N} - \mu S(t)$
2	$\frac{dV(t)}{dt} = \mu S(t)$
3	$\frac{dE(t)}{dt} = \frac{\beta I(t)S(t)}{N} + \frac{\beta\varepsilon I_{BC}(t)S(t)}{N} - \omega E(t)$
4	$\frac{dI(t)}{dt} = \omega E(t) - \sigma I(t) - \gamma I(t)$
5	$\frac{dS_{BC}(t)}{dt} = -\frac{\beta\varepsilon I(t)S_{BC}(t)}{N} - \frac{\beta\varepsilon^2 I_{BC}(t)S_{BC}(t)}{N} - \mu S_{BC}(t)$
6	$\frac{dV_{BC}(t)}{dt} = \mu S_{BC}(t)$
7	$\frac{dE_{BC}(t)}{dt} = \frac{\beta\varepsilon I(t)S_{BC}(t)}{N} + \frac{\beta\varepsilon^2 I_{BC}(t)S_{BC}(t)}{N} - \omega E_{BC}(t)$
8	$\frac{dI_{BC}(t)}{dt} = \omega E_{BC}(t) - \sigma I_{BC}(t) - \gamma I_{BC}(t)$
9	$\frac{dC(t)}{dt} = \sigma I(t) + \sigma I_{BC}(t) - \gamma C(t)$
10	$\frac{dR_C(t)}{dt} = \gamma C(t)$
11	$\frac{dR_{COM}(t)}{dt} = \gamma I(t) + \gamma I_{BC}(t)$
12	$\frac{dR(t)}{dt} = R_C(t) + R_{COM}(t)$
13	$\frac{dC_T(t)}{dt} = C(t) + R_C(t)$
14	$\frac{dD(t)}{dt} = \alpha C_T(t)$

Table 5: Ordinary differential equations for Face Masking

Number	Ordinary Differential Equations
1	$\frac{dS(t)}{dt} = -\frac{\beta I(t)S(t)}{N} - \frac{\beta\kappa I_m(t)S(t)}{N} - \mu S(t)$
2	$\frac{dV(t)}{dt} = \mu S(t)$
3	$\frac{dE(t)}{dt} = \frac{\beta I(t)S(t)}{N} + \frac{\beta\kappa I_m(t)S(t)}{N} - \omega E(t)$
4	$\frac{dI(t)}{dt} = \omega E(t) - \sigma I(t) - \gamma I(t)$
5	$\frac{dS_m(t)}{dt} = -\frac{\beta\kappa I(t)S_m(t)}{N} - \frac{\beta\kappa^2 I_m(t)S_m(t)}{N} - \mu S_m(t)$
6	$\frac{dV_m(t)}{dt} = \mu S_m(t)$
7	$\frac{dE_m(t)}{dt} = \frac{\beta\kappa I(t)S_m(t)}{N} + \frac{\beta\kappa^2 I_m(t)S_m(t)}{N} - \omega E_m(t)$
8	$\frac{dI_m(t)}{dt} = \omega E_m(t) - \sigma I_m(t) - \gamma I_m(t)$
9	$\frac{dC(t)}{dt} = \sigma I(t) + \sigma I_m(t) - \gamma C(t)$
10	$\frac{dR_C(t)}{dt} = \gamma C(t)$
11	$\frac{dR_{COM}(t)}{dt} = \gamma I(t) + \gamma I_m(t)$
12	$\frac{dR(t)}{dt} = R_C(t) + R_{COM}(t)$
13	$\frac{dC_T(t)}{dt} = C(t) + R_C(t)$
14	$\frac{dD(t)}{dt} = \alpha C_T(t)$

Using Vensim behaviour change and face masking at different percentages together with varying vaccine uptake levels of low, moderate and high at basic reproduction number (R_0) of 2.64. In this model, vensim settings where set as following; Initial time at 0, Final time at 100, time step at 1 and RK auto integration type.

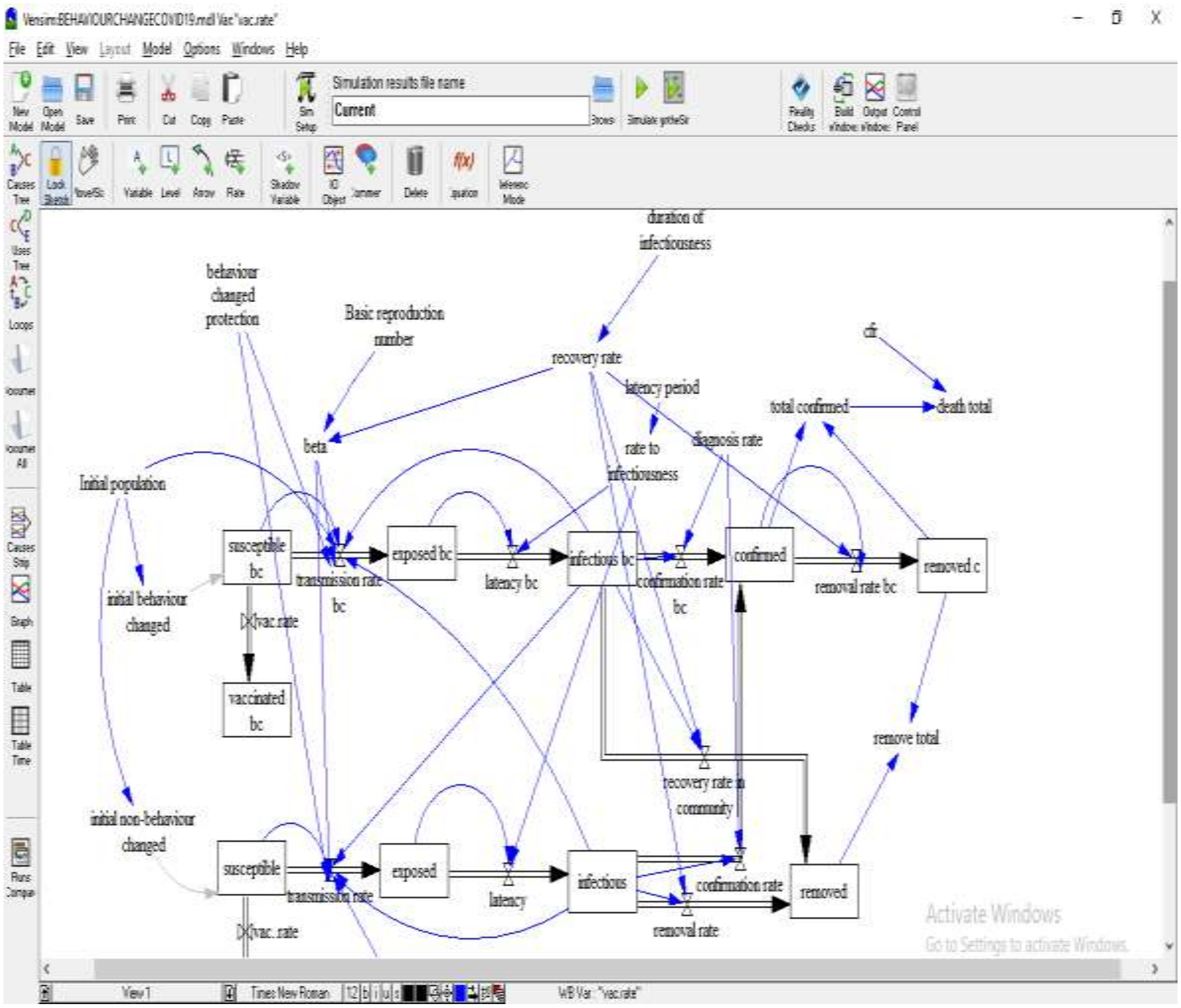


Figure 5: Stock and flow diagram in Vensim for behaviour change

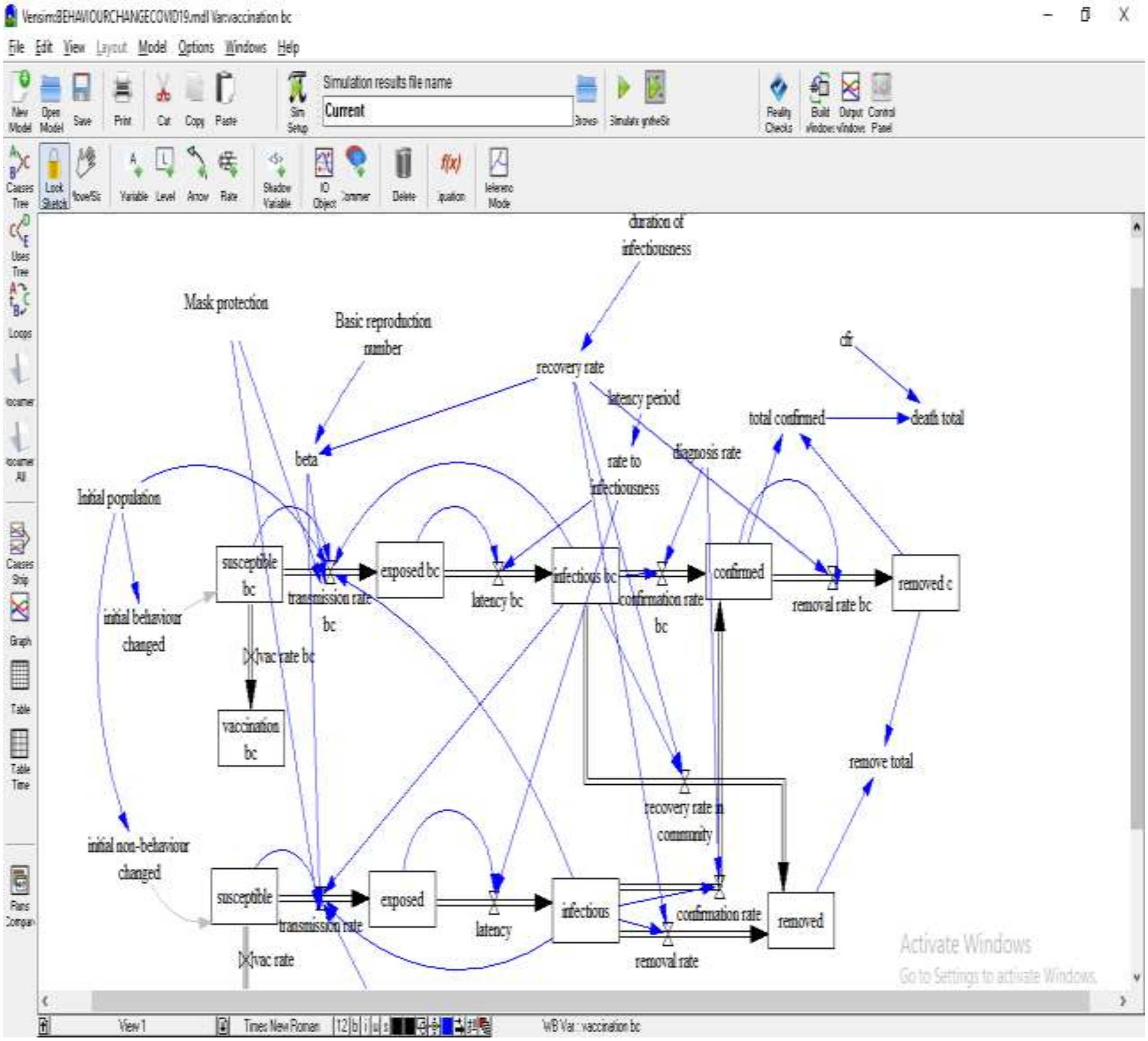


Figure 6: Stock and flow diagram in Vensim for masking with vaccination

Twelve different scenarios for groups of people who practice behaviour change or combined (NPIs) with vaccination and twelve scenarios for face masking with vaccination were modelled. For behaviour change the following scenarios where modelled; 10% behaviour change with low vaccination rate, 10% behaviour change with moderate vaccination rate,10% behaviour change with high vaccination rate, 20% behaviour change with low vaccination rate, 20% behaviour change with moderate vaccination rate, 20% behaviour change with high vaccination rate, 50% behaviour change with low vaccination rate, 50% behaviour change with moderate vaccination rate, 50% behaviour change with high vaccination,80% behaviour change with low vaccination rate,80% behaviour change with moderate vaccination rate and 80% behaviour change with high vaccination rate.

For Face masking the following scenarios where modelled; 10% face masking with low vaccination rate, 10%face masking with moderate vaccination rate,10% face masking with high vaccination rate, 20% face masking with low vaccination rate, 20% face masking with moderate vaccination rate, 20% face masking with high vaccination rate, 50% face masking with low vaccination rate, 50% face masking with moderate vaccination rate, 50% face masking with high vaccination,80% face masking with low vaccination rate,80% face masking with moderate vaccination rate and 80% face masking with high vaccination rate.

The different levels of vaccine uptake levels were estimated as follows; for low vaccination rate we used Zambia as our model country which began its vaccination roll out in April, 2021 and as of 27 May, 2022 had only a percentage of 13% as being fully vaccinated.

Taking the 13% of the Lusaka population (3.3 million) to give us *429,000* vaccinated in 405 days and *1059(0.032%)* people vaccinated in a day.

Low vaccination rate $= (13 \div 100) \times 3{,}300{,}000) \div 405$

Low vaccination rate = 1059(0.032%) people vaccinated per day

The high vaccination rate was estimated in a similar manner using the United Arabs Emirates as our model country, which according to Reuters COVID-19 Tracker as of 27 May, 2022 had the highest vaccination rate in the world at 98% fully vaccinated in *525* days and adapted the percentage to the Lusaka population (3.3 million) coming to 6160(0.19%) people vaccinated per day.

High vaccination rate $= (98 \div 100) \times 3{,}300{,}000) \div 525$

High vaccination rate $= 6160(0.19\%)$ people vaccinated per day

The moderate vaccination was estimated simply by finding the median of low vaccination rate (*1059)* and high vaccination rate (*6160)* giving us a vaccination rate of 3605 (0.11%) people fully vaccinated per day.

Moderate vaccination = 3605 (0.11%) people vaccinated per day

The model was split into two groups of behaviour changed/face masking and non behaviour changed/non face mask users. We started by denoting the infection states as the total number of susceptible *S(t),* exposed *E(t),* infectious *I(t),* Confirmed *C(t)* and removed *Rt(t)* at any given time *(t)* in the population of size *N.* The removed compartment R(*t*) was split into two groups where R*c(t*) is for those that were confirmed through the laboratory as being COVID-19 positive and R*com(t)* is for people who are positive in the community but are not laboratory confirmed and removed straight from the community without laboratory diagnosis.

The total population size for Lusaka was assumed to be constant and did not take into consideration new births or migration (Sichone et al, 2020; Prem K et al, 2020; Y Li M, 2018).

Table 1 shows the average values of parameters used in the ordinary differential equations (ODEs), describing the flow of individuals in the model.

The ODEs numbered 1-4 describe the spread of infection assuming that the rate of infection per day (beta) without any intervention will be relatively higher in susceptible individuals who were not behaviour changed or face masking, while ODEs 5- 8 describe the spread of infection under the assumption of reduced infection rate per day (beta) for susceptible individuals who are behaviour changed or face masking.

For the ODEs 1-4, the susceptible individuals who are not behaviour changed are infected at the rate $\frac{\beta I(t)S(t)}{N} + \frac{\beta \varepsilon I_{BC}(t)S(t)}{N}$ where I_{BC} is the total infectious individuals who are behaviour changed.

For face masking, susceptible individuals who are not face masking are infected at the rate $\frac{\beta I(t)S(t)}{N} + \frac{\beta \kappa I_m(t)S(t)}{N}$ and I_m is the total infectious individuals who are face masking.

For this model, two levels of Non-Pharmaceutical Interventions (NPIs) were considered namely (1) only compliance to face masking and (2) combined behavior change meaning compliance to a range of interventions such as hand hygiene, face masking, social-distancing, respiratory hygiene (cough and sneeze etiquette).

The infection rate β is reduced by 0.02 which is denoted as ϵ in behaviour change while the infection rate in face masking intervention is reduced by 0.5 and denoted by symbol κ(Kim et al,2020Eikenberry et al, 2020).

For the ODEs 5-8, it was assumed that susceptible individuals who are behaviour changed are infected at the rate $\frac{\beta\varepsilon I(t)S_{BC}(t)}{N} + \frac{\beta\varepsilon^2 I_{BC}(t)S_{BC}(t)}{N}$ where $I(t)$is the total number of infectious people who were non behaviour changed and $I_{BC}(t)$ is the total number of infectious individuals in the population of those that are behaviour changed.

For face masking, susceptible individuals are infected at the rate $\frac{\beta\kappa I(t)S_m(t)}{N} + \frac{\beta\kappa^2 I_m(t)S_m(t)}{N}$ and $I(t)$is the total number of infectious people who were non-face masking and $I_m(t)$ is the total number of infectious individuals in the population of those that are face masking.

In both the behaviour changed/face masking and the non behaviour changed/non face masking, after infection occurs at rate of infectiousness (β) , the susceptible individuals enter the exposed compartment $E(t)$ at an incubation rate (ω) of 4.8 days on average before they become infectious $I(t)$ and may either be asymptomatic or symptomatic. Some people from the infectious compartment either behaviour changed/face masking or non behaviour changed become confirmed through a diagnosis rate (σ) and move to the Recovery compartment (Rc(t)) at a recovery rate (γ) of 1/7.5.

Those who did not get laboratory confirmation from either behaviour changed/face masking or non behaviour changed/non face masking, move directly to the Recovered compartment R*com*(T) at a recovery rate ($\boldsymbol{\gamma}$) of 1/7.5.

The total removed individuals R(t) for the model is given as Rc(t) + Rcom(t), while the total confirmed cases are given as $I_{bc}(t) + IR(t)$ or of $I_m(t) + IR(t)$ with a fraction α (Case fatality rate -CFR) are recorded dead $D(t)$. Some susceptible individuals enter the vaccination compartment $V_{BC}(t)/V_m(t)$ or V(t) respectively at a varied vaccination rate ($\boldsymbol{k}$).

The effect of the different intervention scenarios on reducing the basic reproduction number (R_0) of the outbreak (as estimated by the null model without intervention) was similarly estimated using a model fitting approach. Model fit was statistically evaluated using Pearson's correlation at a significance level of 0.01.

3.4 Model optimization and simulation

Model optimization was done using Vensim PLE systems dynamics modelling software for Windows (version 7) (Vensim. VENTANA systems.inc. 2020). Data from the first three months of the outbreak in Lusaka (accessed between 10th March - 21st May 2020) as given in the Zambia COVID-19 situation reports No. 1-64 (MOH/ZNPH/WHO, Situation Reports) was used to configure the model and optimize parameters.

Only data from 10th April 2020 to 16th May 2020 was used despite that the first case was recorded in March, 2020.

This was because it had more consistent data without considerable variations in recorded cases between days and community infections that had no epidemiological link had been established (Sichone et al, 2020; MOH/ZNPH/WHO, Situation Reports).

The model initial conditions were estimated from the data in COVID 19 situation report as follows: $S(0) = N$=3.3 million, $E(0)$ = 38, $I(0)$ =28, $R(0)$ = 28, and $D(0)$ = 0.

Cumulative number of confirmed cases over time together with other parameter values were used to calibrate the model. This was done by manually adjusting values of basic reproductive number (R_0) until the best model fit was achieved at 2.64 (since R_0 was expectedly affected by the current mitigation measures).

The basic reproduction number (R_0) estimates the average number of secondary infections arising from a single infectious individual in a naive population.

Model fit was statistically evaluated using Pearson's correlation at a significance level of 0.01 as well as chi-square goodness of fit test at a significance level of 0.05.

After calibration, the model simulation was extended to 100 days (10 April 2020 – 09 April 2021) to predict the impact of Face masking/ Behaviour change combined with vaccination on the spread of the outbreak in Lusaka under the current transmission rate.

CHAPTER FOUR:

4.0 RESULTS

4.1 Results

The model had a significant fit to actual COVID-19 outbreak data in Lusaka as shown in Figure 7.

Using Pearson's correlation we estimated, r to be equal to .98 ($r=.98$) and p value was less than .001 ($p < .001$).

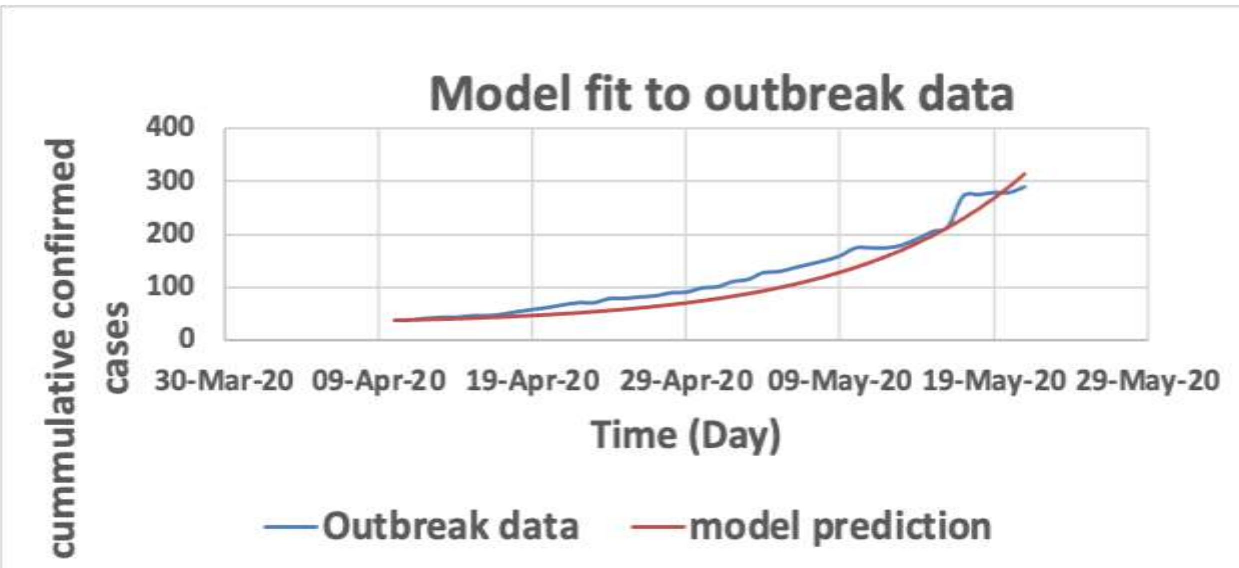


Figure 7: Showing Model data fit to Lusaka COVID-19 data

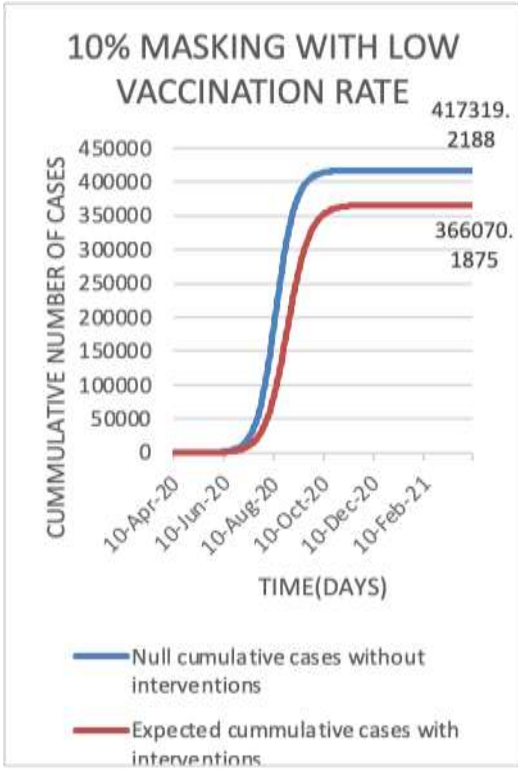
There was significant percentage reduction in the number of both cumulative cases and deaths in the models with behaviour change with vaccination as well as the models with face masking and vaccination as shown in Figures 8 and 9, which is also explained in Table 2. Scenarios of 10% and 20% at low and moderate rates of vaccination had smaller percentage reduction in cumulative cases and cumulative deaths of less than 50% (< 50%), except 20% behaviour change and masking with high vaccination rate which had a percentage reduction greater than 50% (>50%).

Scenarios of 50% behaviour change at all rates of vaccination showed a 99% percentage reduction in number of cumulative cases and cumulative deaths, while 50% face masking had varying percentage reduction at low (67.9%), moderate (96.2%) and high (99.4%) vaccination rate. Scenarios of 80% both behaviour change and masking at all rates of vaccination had percentage reduction of 99.9% in both number of cumulative cases and cumulative deaths.

Simulated results of Null cumulative cases (with no interventions) and expected cumulative cases with interventions in each scenario as shown in Figure 8 are as follows:

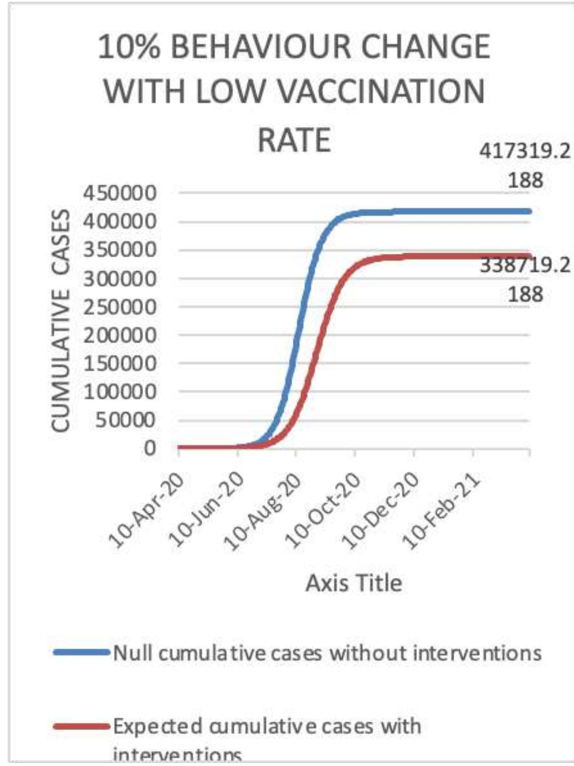
(a) 10 % Masking with low vaccination rate, (b) 10% Behaviour with low vaccination rate, (c)10% Masking with moderate vaccination rate, (d) 10% Behaviour with moderate vaccination rate, (e) 10 % Masking with high vaccination rate, (f) 10% Behaviour change with high vaccination rate, (g) 20% Masking with low vaccination rate, (h) 20% Behaviour change with low vaccination rate, (i) 20% Masking with moderate vaccination rate, (j)20% Behaviour change with Moderate vaccination rate, (k) 20% Masking with high vaccination rate, (l) 20% Behaviour change with High vaccination rate, (m) 50% Masking with low vaccination rate, (n) 50% Behaviour change with low vaccination rate, (o) 50% Masking with moderate vaccination rate, (p) 50% Behaviour with moderate vaccination rate, (q)50% Masking with high vaccination rate, (r) 50% Behaviour change with High vaccination rate, (s) 80% Masking with low vaccination rate, (t)Behaviour Change with low vaccination rate, (u) 80% Masking with moderate vaccination rate , (v) 80% Behaviour change with moderate vaccination rate, (w) 80% Masking with high vaccination rate (x)80% Behaviour change with High vaccination rate.

(a)



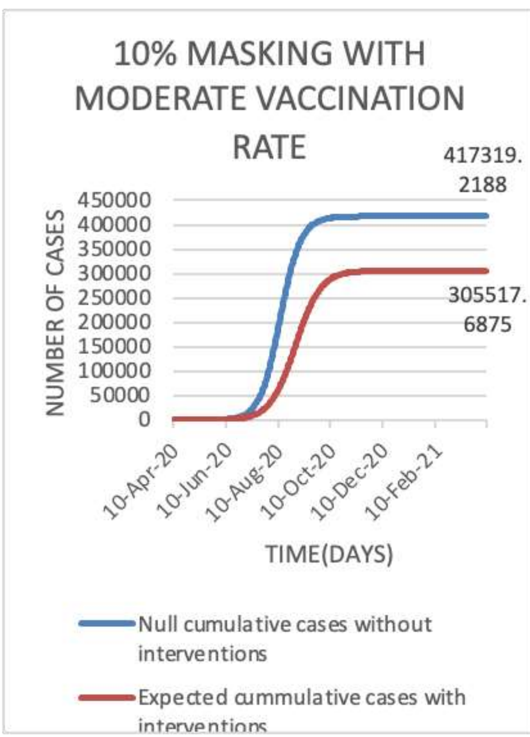
10% MASKING WITH LOW VACCINATION RATE
417319.2188
366070.1875
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
CUMMULATIVE NUMBER OF CASES
10-Apr-20
10-Jun-20
10-Aug-20
10-Oct-20
10-Dec-20
10-Feb-21
TIME(DAYS)
Null cumulative cases without interventions
Expected cummulative cases with interventions

(b)



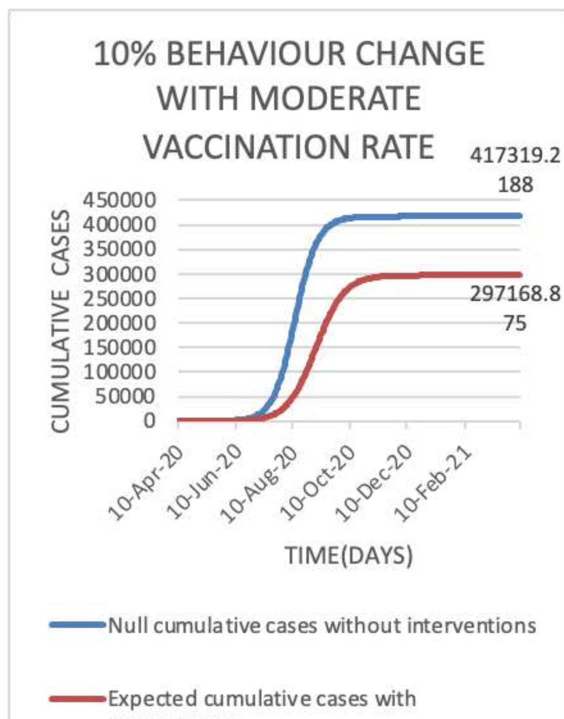
10% BEHAVIOUR CHANGE WITH LOW VACCINATION RATE
417319.2188
338719.2188
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
CUMULATIVE CASES
10-Apr-20
10-Jun-20
10-Aug-20
10-Oct-20
10-Dec-20
10-Feb-21
Axis Title
Null cumulative cases without interventions
Expected cumulative cases with interventions

(c)

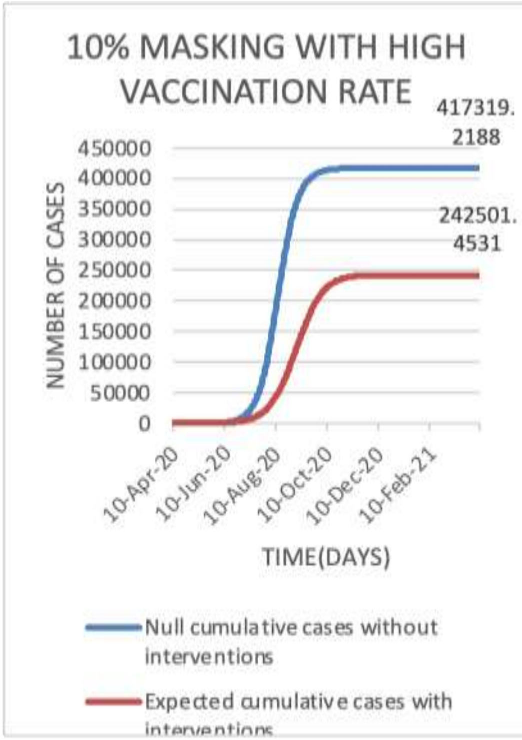


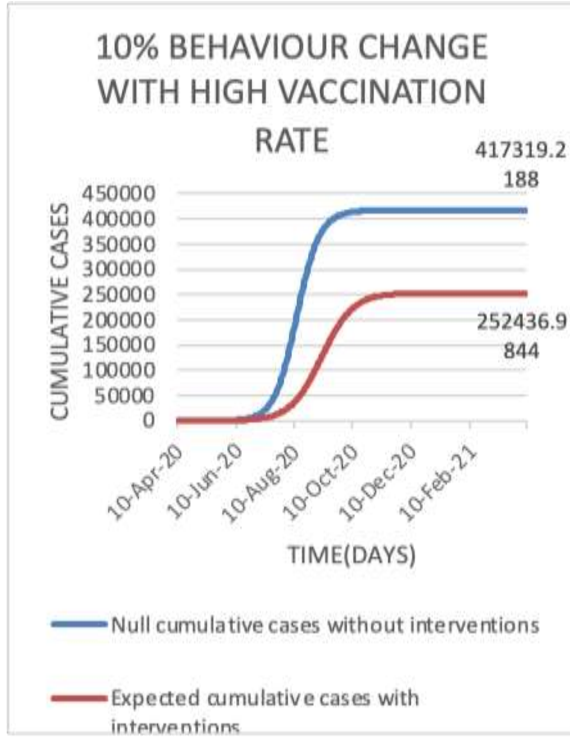
10% MASKING WITH MODERATE VACCINATION RATE
417319.2188
305517.6875
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
NUMBER OF CASES
10-Apr-20
10-Jun-20
10-Aug-20
10-Oct-20
10-Dec-20
10-Feb-21
TIME(DAYS)
Null cumulative cases without interventions
Expected cummulative cases with interventions

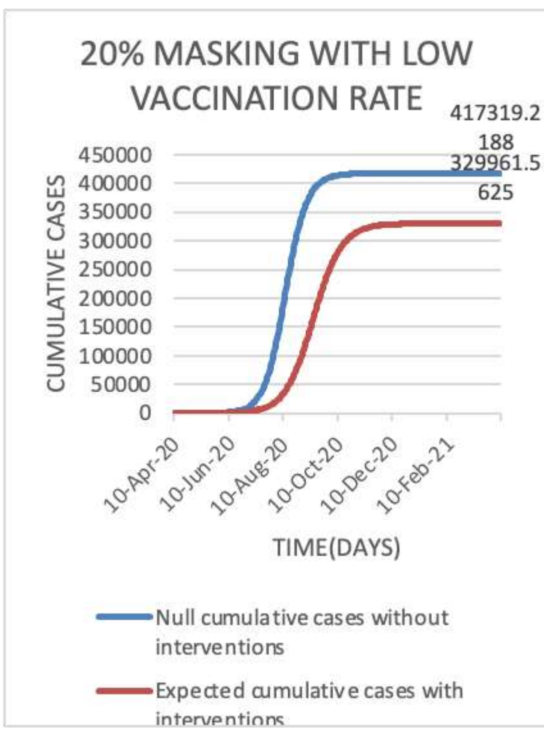
(d)

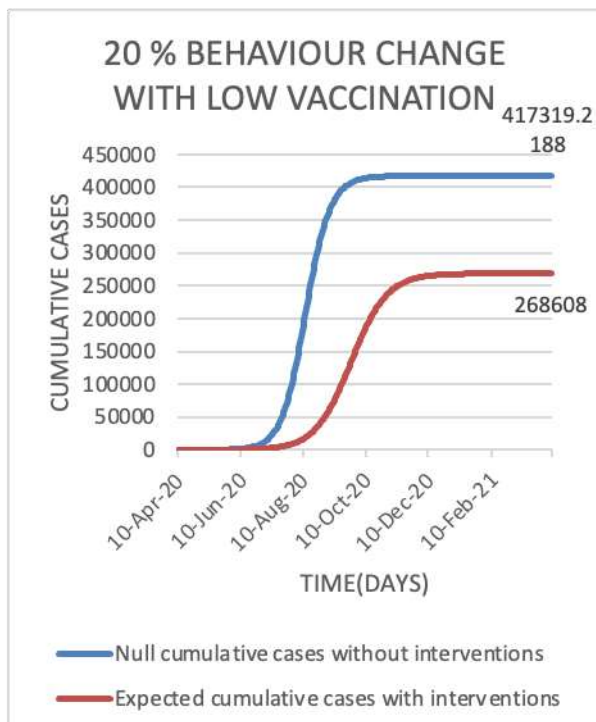


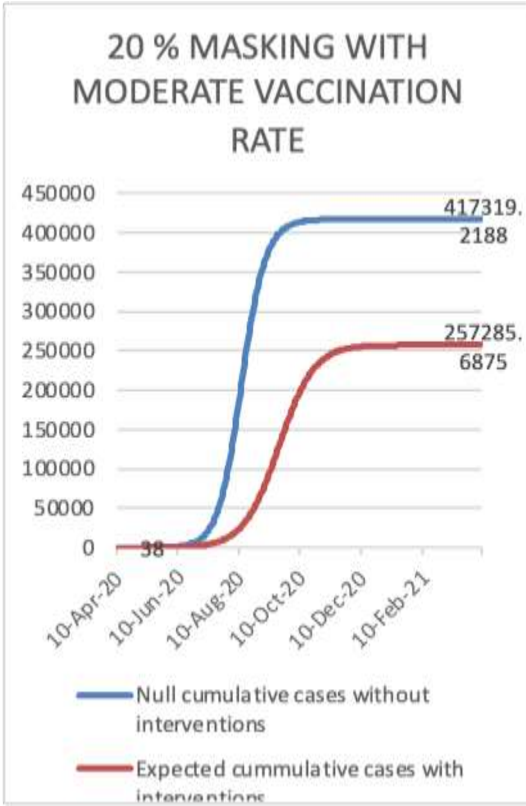
10% BEHAVIOUR CHANGE WITH MODERATE VACCINATION RATE
417319.2188
297168.875
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
CUMULATIVE CASES
10-Apr-20
10-Jun-20
10-Aug-20
10-Oct-20
10-Dec-20
10-Feb-21
TIME(DAYS)
Null cumulative cases without interventions
Expected cumulative cases with interventions

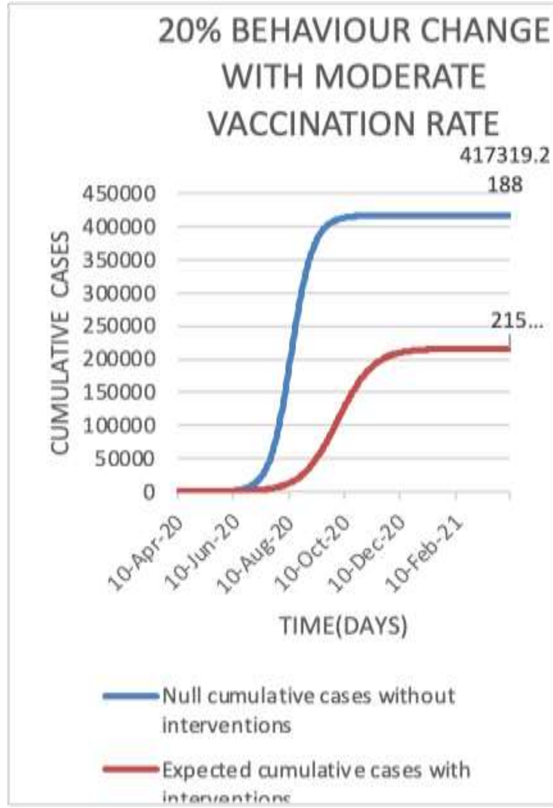
(e)

10% MASKING WITH HIGH VACCINATION RATE
417319.2188
242501.4531
NUMBER OF CASES
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
10-Apr-20
10-Jun-20
10-Aug-20
10-Oct-20
10-Dec-20
10-Feb-21
TIME(DAYS)
Null cumulative cases without interventions
Expected cumulative cases with interventions

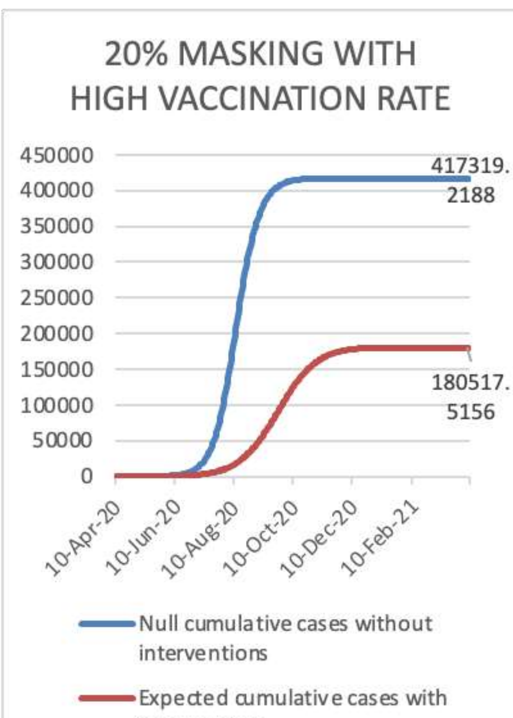
(f)

10% BEHAVIOUR CHANGE WITH HIGH VACCINATION RATE
417319.2188
252436.9844
CUMULATIVE CASES
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
10-Apr-20
10-Jun-20
10-Aug-20
10-Oct-20
10-Dec-20
10-Feb-21
TIME(DAYS)
Null cumulative cases without interventions
Expected cumulative cases with interventions

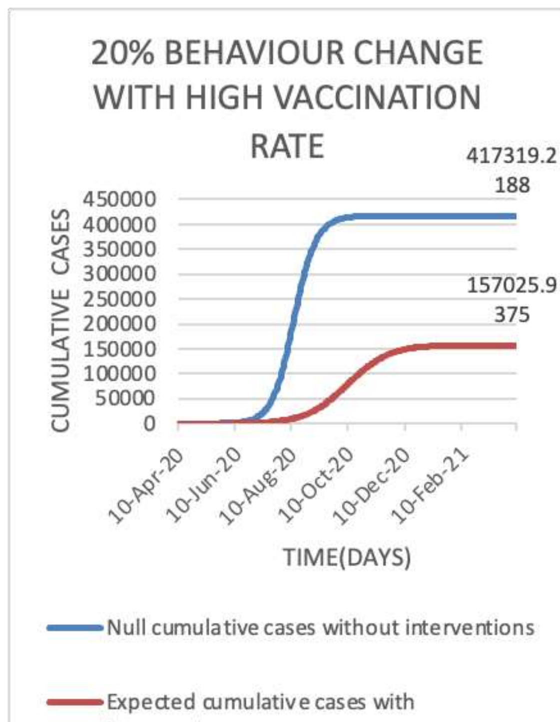
(g)

20% MASKING WITH LOW VACCINATION RATE
417319.2188
329961.5625
CUMULATIVE CASES
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
10-Apr-20
10-Jun-20
10-Aug-20
10-Oct-20
10-Dec-20
10-Feb-21
TIME(DAYS)
Null cumulative cases without interventions
Expected cumulative cases with interventions

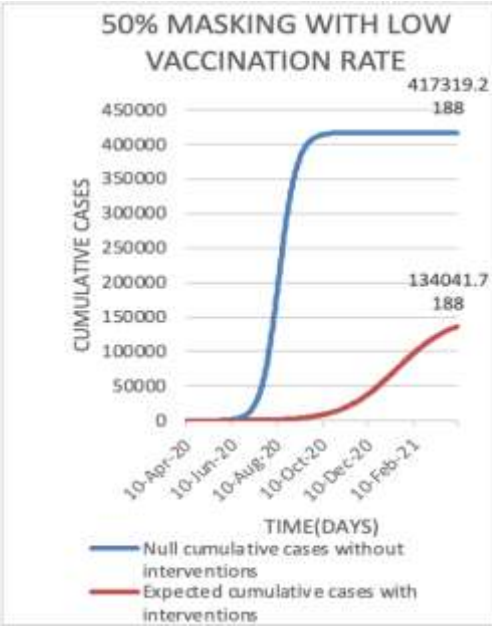
(h)

20 % BEHAVIOUR CHANGE WITH LOW VACCINATION
417319.2188
268608
CUMULATIVE CASES
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
10-Apr-20
10-Jun-20
10-Aug-20
10-Oct-20
10-Dec-20
10-Feb-21
TIME(DAYS)
Null cumulative cases without interventions
Expected cumulative cases with interventions

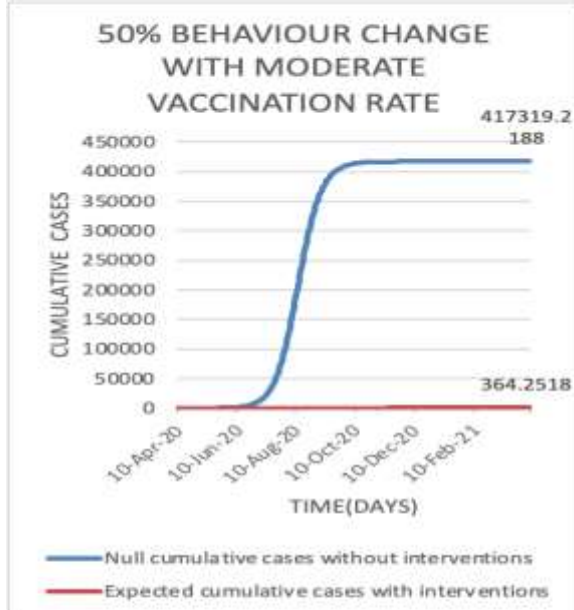

20 % MASKING WITH MODERATE VACCINATION RATE
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
417319.
2188
257285.
6875
38
10-Apr-20
10-Jun-20
10-Aug-20
10-Oct-20
10-Dec-20
10-Feb-21
Null cumulative cases without interventions
Expected cummulative cases with interventions
(i)

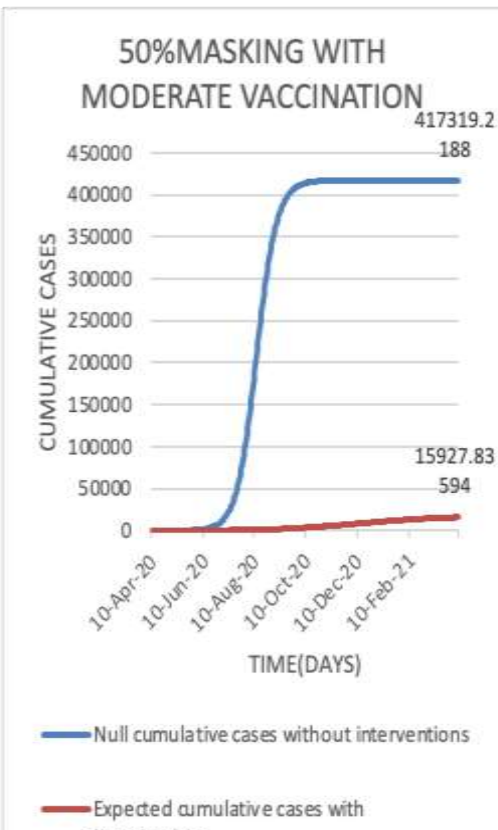

20% BEHAVIOUR CHANGE WITH MODERATE VACCINATION RATE
CUMULATIVE CASES
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
417319.2
188
215...
10-Apr-20
10-Jun-20
10-Aug-20
10-Oct-20
10-Dec-20
10-Feb-21
TIME(DAYS)
Null cumulative cases without interventions
Expected cumulative cases with interventions
(j)

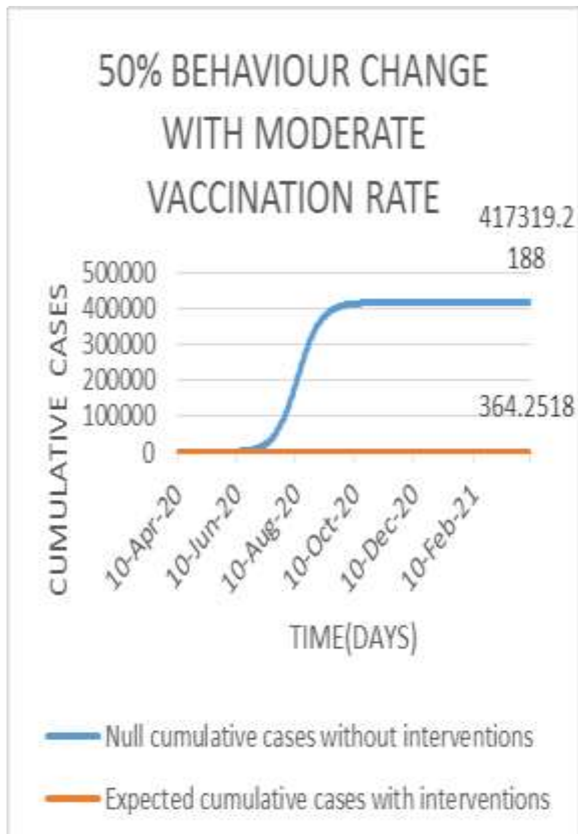

20% MASKING WITH HIGH VACCINATION RATE
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
417319.
2188
180517.
5156
10-Apr-20
10-Jun-20
10-Aug-20
10-Oct-20
10-Dec-20
10-Feb-21
Null cumulative cases without interventions
Expected cumulative cases with interventions
(k)

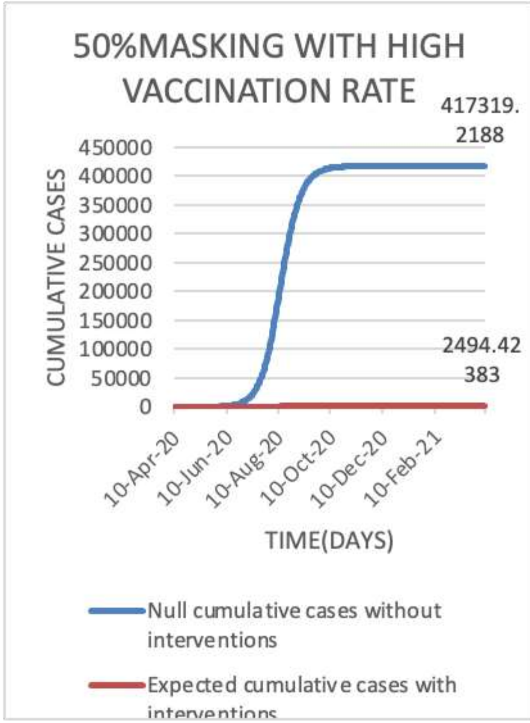

20% BEHAVIOUR CHANGE WITH HIGH VACCINATION RATE
CUMULATIVE CASES
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
417319.2
188
157025.9
375
10-Apr-20
10-Jun-20
10-Aug-20
10-Oct-20
10-Dec-20
10-Feb-21
TIME(DAYS)
Null cumulative cases without interventions
Expected cumulative cases with interventions
(l)


50% MASKING WITH LOW VACCINATION RATE
417319.2188
134041.7188
CUMULATIVE CASES
0
50000
100000
150000
200000
250000
300000
350000
400000
450000
10-Apr-20
10-Jun-20
10-Aug-20
10-Oct-20
10-Dec-20
10-Feb-21
TIME(DAYS)
Null cumulative cases without interventions
Expected cumulative cases with interventions
(m)

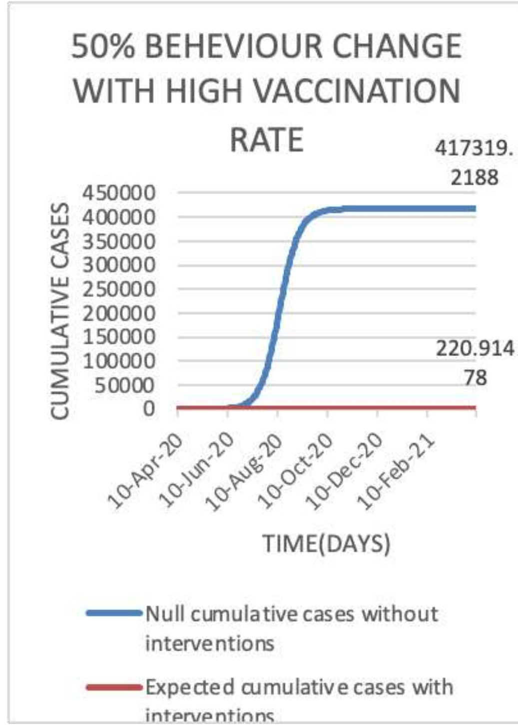

50% BEHAVIOUR CHANGE WITH MODERATE VACCINATION RATE
417319.2188
364.2518
CUMULATIVE CASES
0
50000
100000
150000
200000
250000
300000
350000
400000
450000
10-Apr-20
10-Jun-20
10-Aug-20
10-Oct-20
10-Dec-20
10-Feb-21
TIME(DAYS)
Null cumulative cases without interventions
Expected cumulative cases with interventions
(n)


50%MASKING WITH MODERATE VACCINATION
417319.2188
15927.83594
CUMULATIVE CASES
0
50000
100000
150000
200000
250000
300000
350000
400000
450000
10-Apr-20
10-Jun-20
10-Aug-20
10-Oct-20
10-Dec-20
10-Feb-21
TIME(DAYS)
Null cumulative cases without interventions
Expected cumulative cases with interventions
(o)

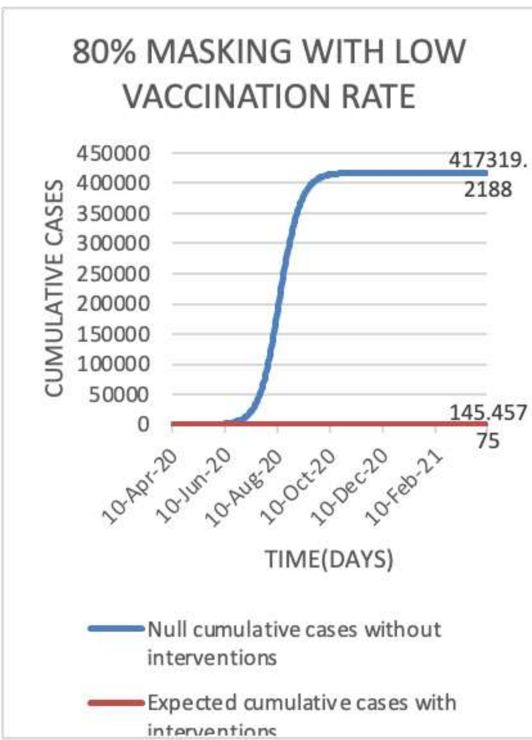

50% BEHAVIOUR CHANGE WITH MODERATE VACCINATION RATE
417319.2188
364.2518
CUMULATIVE CASES
0
100000
200000
300000
400000
500000
10-Apr-20
10-Jun-20
10-Aug-20
10-Oct-20
10-Dec-20
10-Feb-21
TIME(DAYS)
Null cumulative cases without interventions
Expected cumulative cases with interventions
(p)

(q)


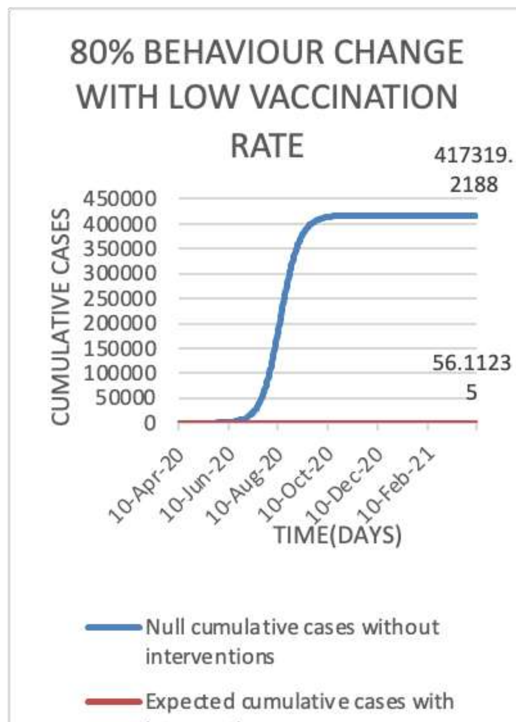
50%MASKING WITH HIGH VACCINATION RATE
417319.2188
2494.42383
CUMULATIVE CASES
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
10-Apr-20
10-Jun-20
10-Aug-20
10-Oct-20
10-Dec-20
10-Feb-21
TIME(DAYS)
Null cumulative cases without interventions
Expected cumulative cases with interventions

(r)


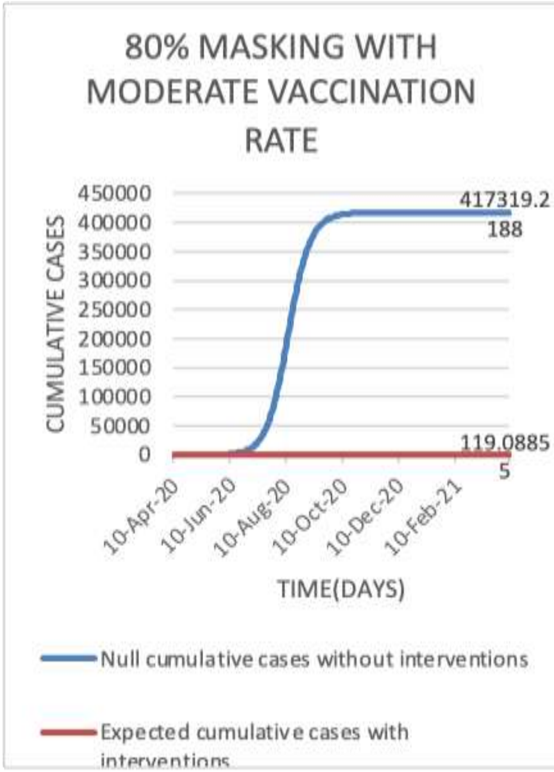
50% BEHEVIOUR CHANGE WITH HIGH VACCINATION RATE
417319.2188
220.91478
CUMULATIVE CASES
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
10-Apr-20
10-Jun-20
10-Aug-20
10-Oct-20
10-Dec-20
10-Feb-21
TIME(DAYS)
Null cumulative cases without interventions
Expected cumulative cases with interventions

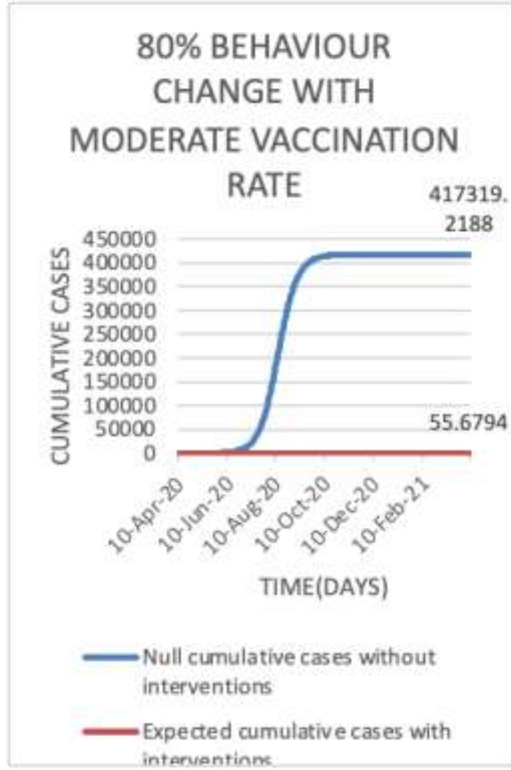
(s)


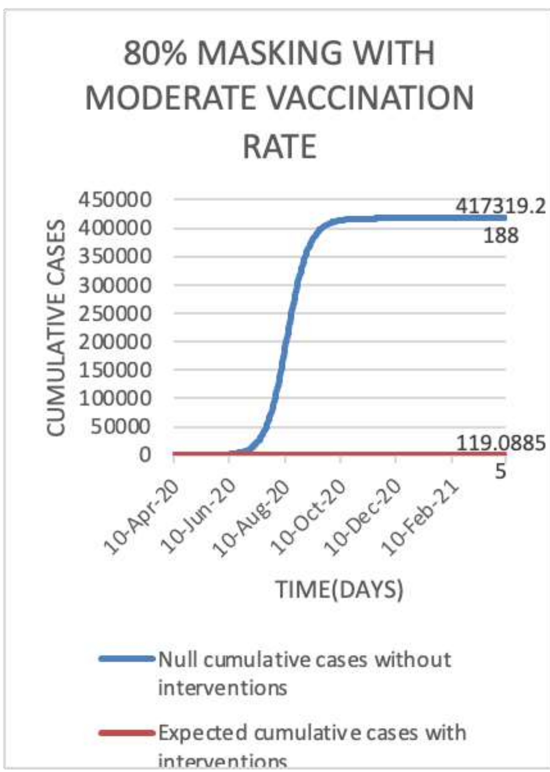
80% MASKING WITH LOW VACCINATION RATE
417319.2188
145.45775
CUMULATIVE CASES
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
10-Apr-20
10-Jun-20
10-Aug-20
10-Oct-20
10-Dec-20
10-Feb-21
TIME(DAYS)
Null cumulative cases without interventions
Expected cumulative cases with interventions

(t)


80% BEHAVIOUR CHANGE WITH LOW VACCINATION RATE
417319.2188
56.11235
CUMULATIVE CASES
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
10-Apr-20
10-Jun-20
10-Aug-20
10-Oct-20
10-Dec-20
10-Feb-21
TIME(DAYS)
Null cumulative cases without interventions
Expected cumulative cases with interventions

(u) 

(v) 

(w) 

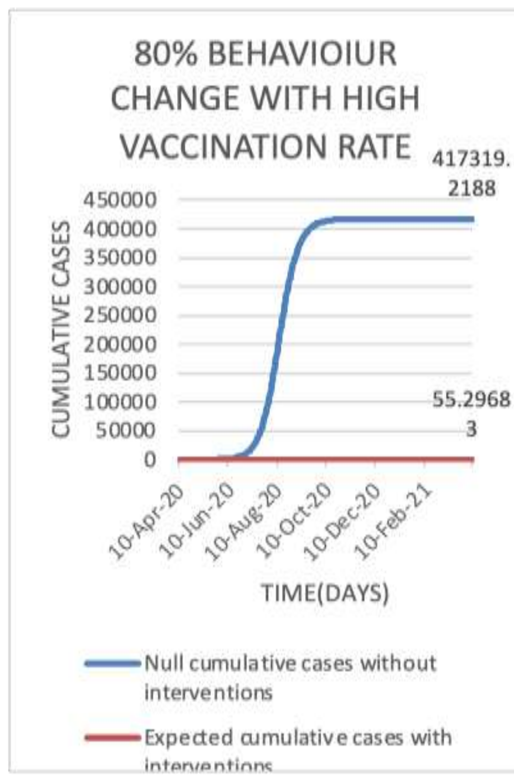
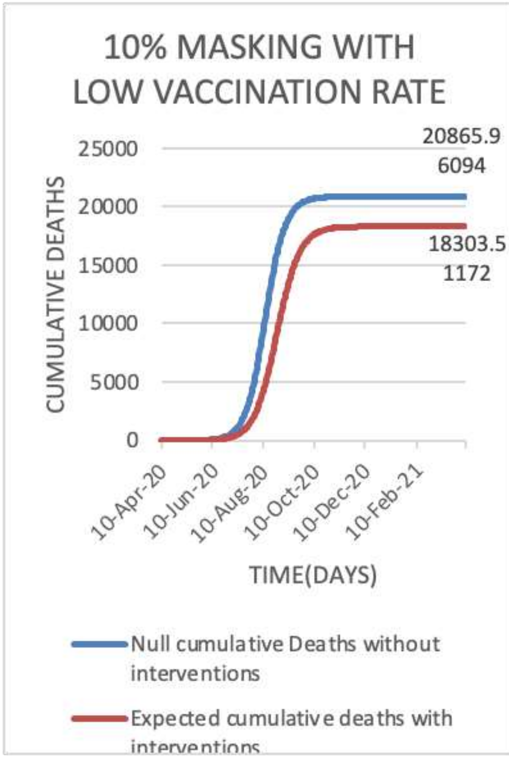
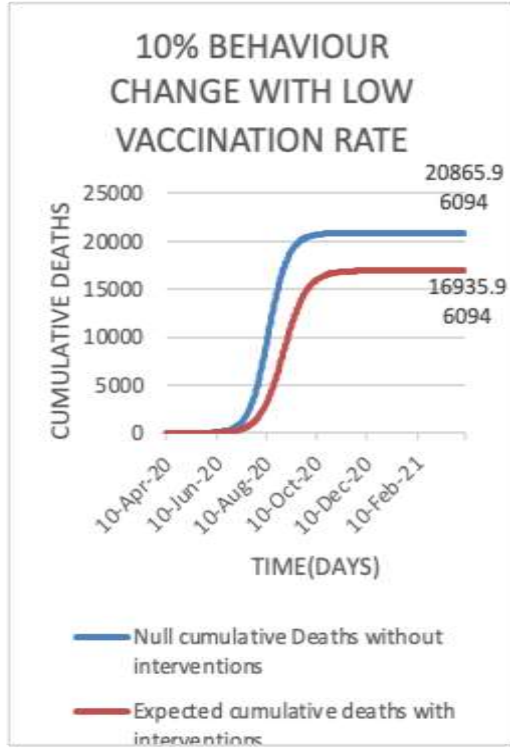
(x) 

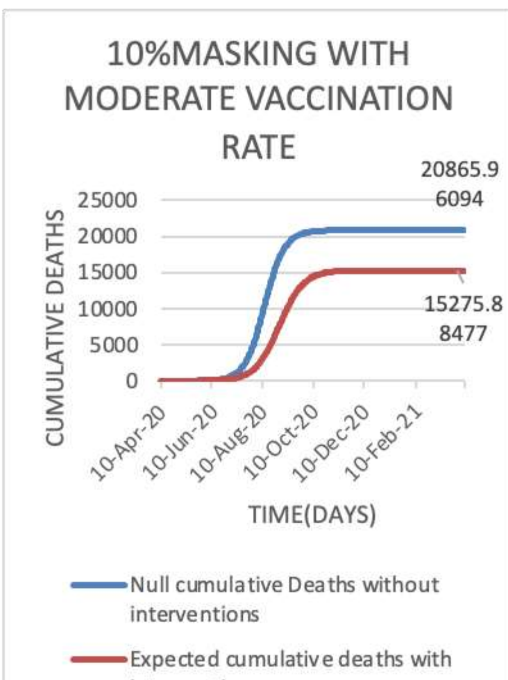
Figure 8: Null cumulative cases and expected cumulative cases from each of the simulates Scenarios a- x.

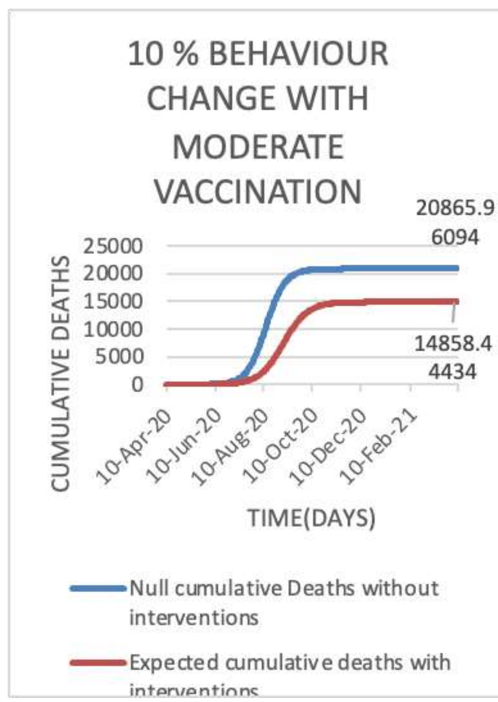
Simulated results showing Null cumulative deaths (with no interventions) and cumulative deaths total (with interventions in place) in Scenario as shown in Figure 9 are as follows:

(a) 10 % Masking with low vaccination rate, (b) 10% Behaviour with low vaccination rate, (c)10% Masking with moderate vaccination rate, (d) 10% Behaviour with moderate vaccination rate, (e) 10 % Masking with high vaccination rate, (f) 10% Behaviour change with high vaccination rate, (g) 20% Masking with low vaccination rate, (h) 20% Behaviour change with low vaccination rate, (i) 20% Masking with moderate vaccination rate, (j)20% Behaviour change with Moderate vaccination rate, (k) 20% Masking with high vaccination rate, (l) 20% Behaviour change with High vaccination rate, (m) 50% Masking with low vaccination rate, (n) 50% Behaviour change with low vaccination rate, (o) 50% Masking with moderate vaccination rate, (p) 50% Behaviour with moderate vaccination rate, (q)50% Masking with high vaccination rate, (r) 50% Behaviour change with High vaccination rate, (s) 80% Masking with low vaccination rate, (t)Behaviour Change with low vaccination rate, (u) 80% Masking with moderate vaccination rate , (v) 80% Behaviour change with moderate vaccination rate, (w) 80% Masking with high vaccination rate (x)80% Behaviour change with High vaccination rate.

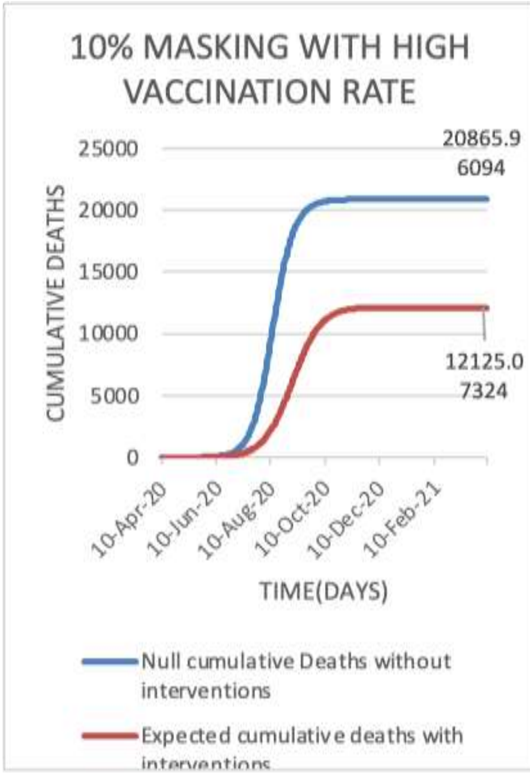

10% MASKING WITH LOW VACCINATION RATE
CUMULATIVE DEATHS
TIME(DAYS)
25000
20000
15000
10000
5000
0
10-Apr-20
10-Jun-20
10-Aug-20
10-Oct-20
10-Dec-20
10-Feb-21
20865.9 6094
18303.5 1172
Null cumulative Deaths without interventions
Expected cumulative deaths with interventions
(a)


10% BEHAVIOUR CHANGE WITH LOW VACCINATION RATE
CUMULATIVE DEATHS
TIME(DAYS)
25000
20000
15000
10000
5000
0
10-Apr-20
10-Jun-20
10-Aug-20
10-Oct-20
10-Dec-20
10-Feb-21
20865.9 6094
16935.9 6094
Null cumulative Deaths without interventions
Expected cumulative deaths with interventions
(b)


10%MASKING WITH MODERATE VACCINATION RATE
CUMULATIVE DEATHS
TIME(DAYS)
25000
20000
15000
10000
5000
0
10-Apr-20
10-Jun-20
10-Aug-20
10-Oct-20
10-Dec-20
10-Feb-21
20865.9 6094
15275.8 8477
Null cumulative Deaths without interventions
Expected cumulative deaths with interventions
(c)

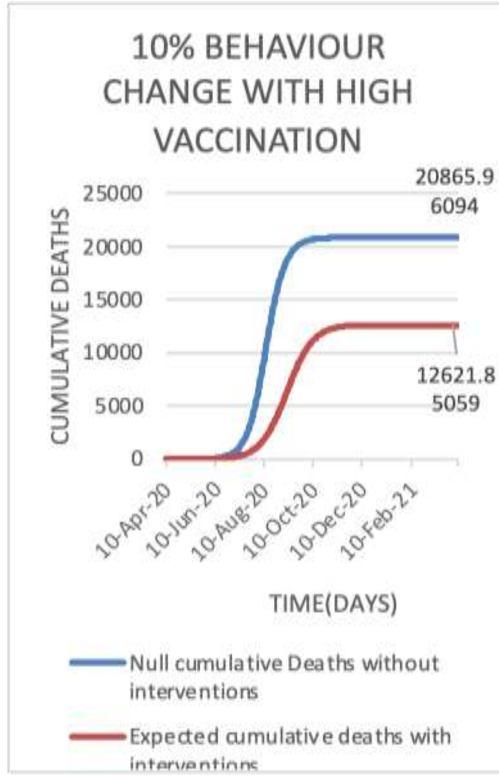

10 % BEHAVIOUR CHANGE WITH MODERATE VACCINATION
CUMULATIVE DEATHS
TIME(DAYS)
25000
20000
15000
10000
5000
0
10-Apr-20
10-Jun-20
10-Aug-20
10-Oct-20
10-Dec-20
10-Feb-21
20865.9 6094
14858.4 4434
Null cumulative Deaths without interventions
Expected cumulative deaths with interventions
(d)

(e)



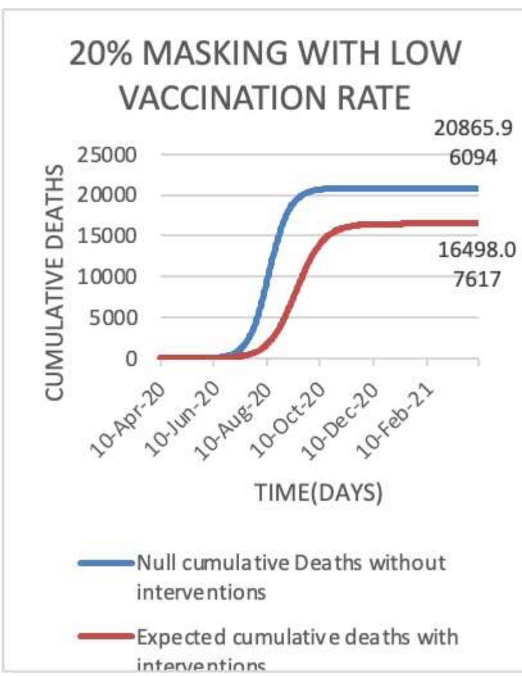
10% MASKING WITH HIGH VACCINATION RATE
CUMULATIVE DEATHS
25000
20000
15000
10000
5000
0
20865.9 6094
12125.0 7324
10-Apr-20
10-Jun-20
10-Aug-20
10-Oct-20
10-Dec-20
10-Feb-21
TIME(DAYS)
Null cumulative Deaths without interventions
Expected cumulative deaths with interventions

(f)



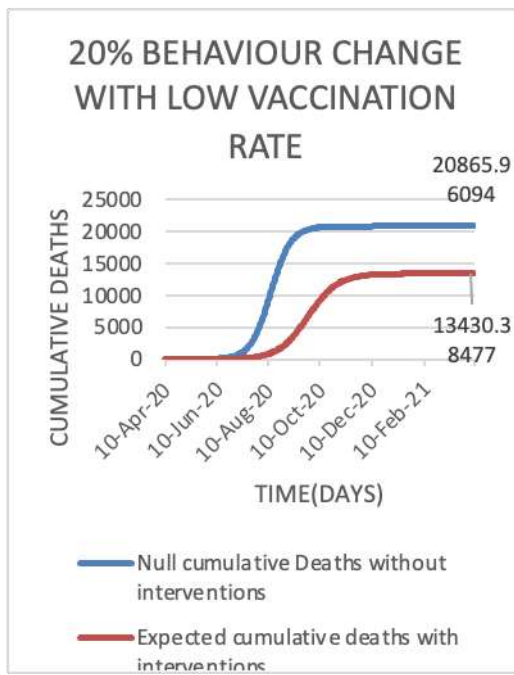
10% BEHAVIOUR CHANGE WITH HIGH VACCINATION
CUMULATIVE DEATHS
25000
20000
15000
10000
5000
0
20865.9 6094
12621.8 5059
10-Apr-20
10-Jun-20
10-Aug-20
10-Oct-20
10-Dec-20
10-Feb-21
TIME(DAYS)
Null cumulative Deaths without interventions
Expected cumulative deaths with interventions

(g)

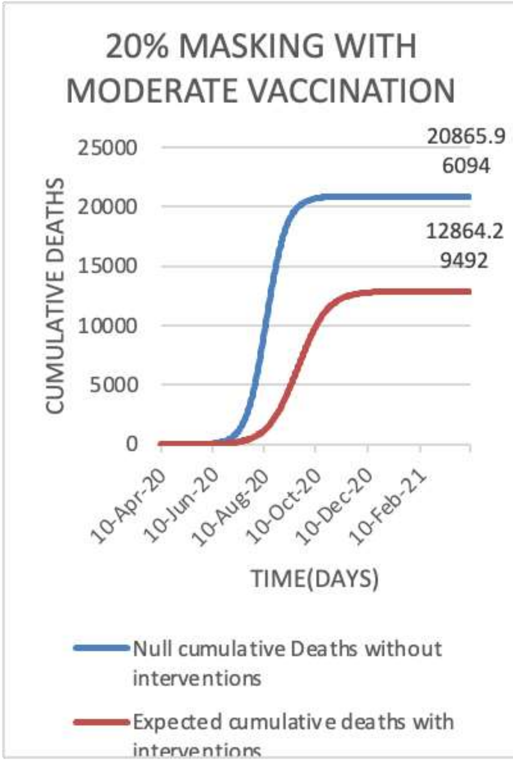


20% MASKING WITH LOW VACCINATION RATE
CUMULATIVE DEATHS
25000
20000
15000
10000
5000
0
20865.9 6094
16498.0 7617
10-Apr-20
10-Jun-20
10-Aug-20
10-Oct-20
10-Dec-20
10-Feb-21
TIME(DAYS)
Null cumulative Deaths without interventions
Expected cumulative deaths with interventions

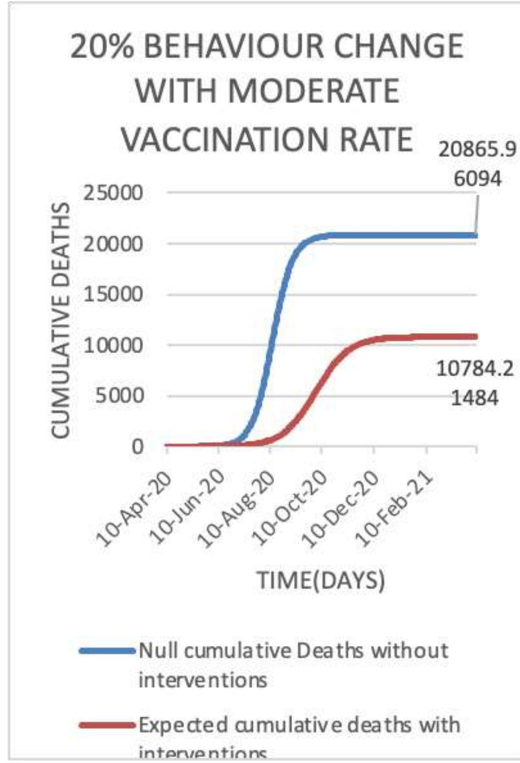
(h)



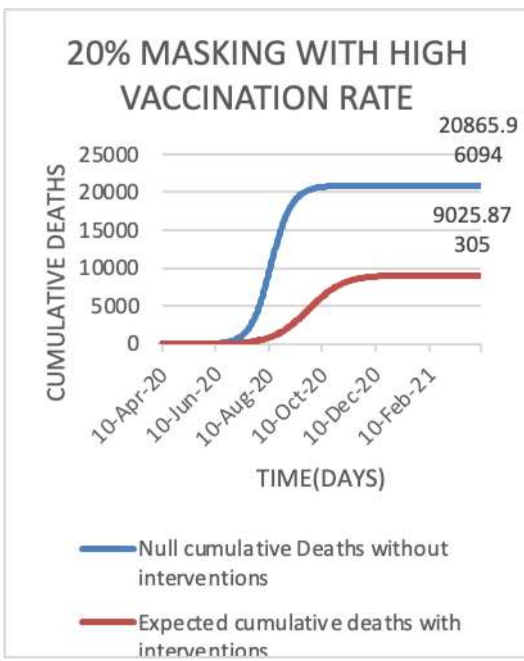
20% BEHAVIOUR CHANGE WITH LOW VACCINATION RATE
CUMULATIVE DEATHS
25000
20000
15000
10000
5000
0
20865.9 6094
13430.3 8477
10-Apr-20
10-Jun-20
10-Aug-20
10-Oct-20
10-Dec-20
10-Feb-21
TIME(DAYS)
Null cumulative Deaths without interventions
Expected cumulative deaths with interventions


20% MASKING WITH MODERATE VACCINATION
CUMULATIVE DEATHS
25000
20000
15000
10000
5000
0
20865.9 6094
12864.2 9492
10-Apr-20
10-Jun-20
10-Aug-20
10-Oct-20
10-Dec-20
10-Feb-21
TIME(DAYS)
Null cumulative Deaths without interventions
Expected cumulative deaths with interventions

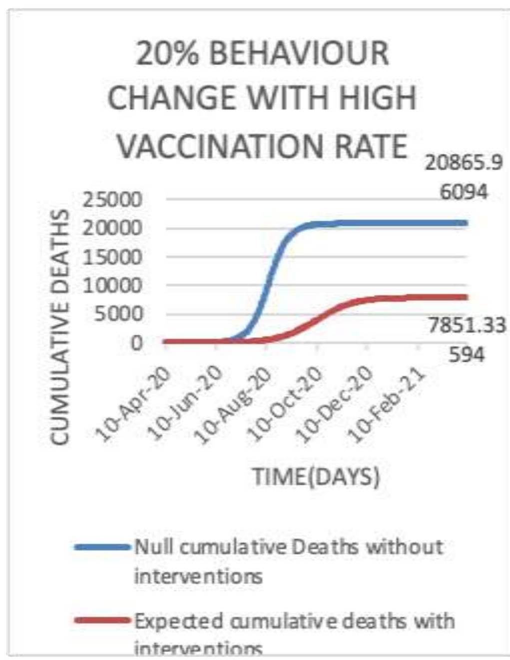
(I)


20% BEHAVIOUR CHANGE WITH MODERATE VACCINATION RATE
CUMULATIVE DEATHS
25000
20000
15000
10000
5000
0
20865.9 6094
10784.2 1484
10-Apr-20
10-Jun-20
10-Aug-20
10-Oct-20
10-Dec-20
10-Feb-21
TIME(DAYS)
Null cumulative Deaths without interventions
Expected cumulative deaths with interventions

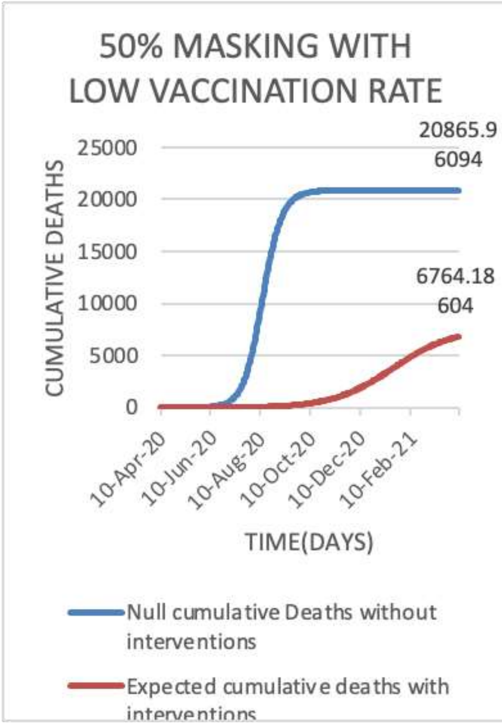
(j)

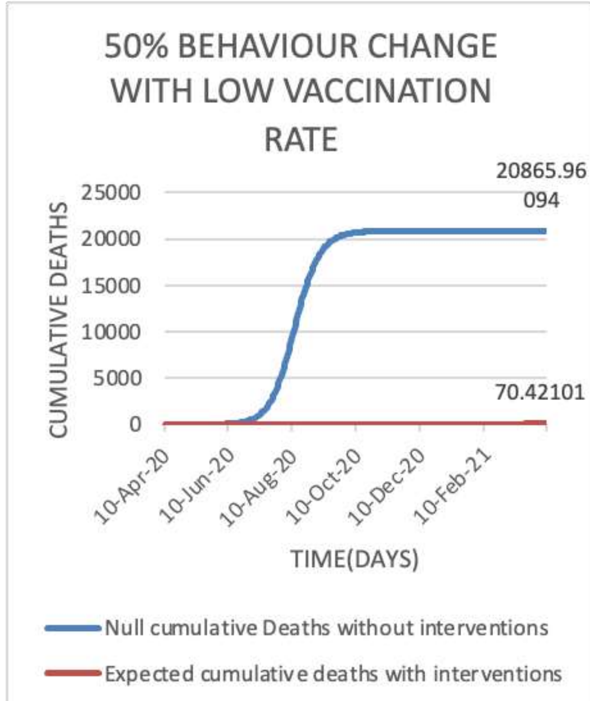

20% MASKING WITH HIGH VACCINATION RATE
CUMULATIVE DEATHS
25000
20000
15000
10000
5000
0
20865.9 6094
9025.87 305
10-Apr-20
10-Jun-20
10-Aug-20
10-Oct-20
10-Dec-20
10-Feb-21
TIME(DAYS)
Null cumulative Deaths without interventions
Expected cumulative deaths with interventions

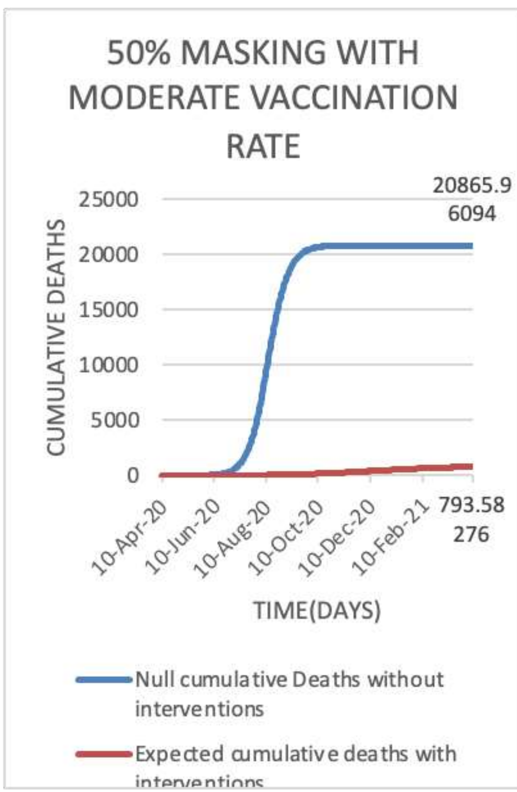
(K)


20% BEHAVIOUR CHANGE WITH HIGH VACCINATION RATE
CUMULATIVE DEATHS
25000
20000
15000
10000
5000
0
20865.9 6094
7851.33 594
10-Apr-20
10-Jun-20
10-Aug-20
10-Oct-20
10-Dec-20
10-Feb-21
TIME(DAYS)
Null cumulative Deaths without interventions
Expected cumulative deaths with interventions

(l)

(m)

50% MASKING WITH LOW VACCINATION RATE
CUMULATIVE DEATHS
25000
20000
15000
10000
5000
0
20865.96094
6764.18604
10-Apr-20
10-Jun-20
10-Aug-20
10-Oct-20
10-Dec-20
10-Feb-21
TIME(DAYS)
Null cumulative Deaths without interventions
Expected cumulative deaths with interventions

(n)

50% BEHAVIOUR CHANGE WITH LOW VACCINATION RATE
CUMULATIVE DEATHS
25000
20000
15000
10000
5000
0
20865.96094
70.42101
10-Apr-20
10-Jun-20
10-Aug-20
10-Oct-20
10-Dec-20
10-Feb-21
TIME(DAYS)
Null cumulative Deaths without interventions
Expected cumulative deaths with interventions

(o)

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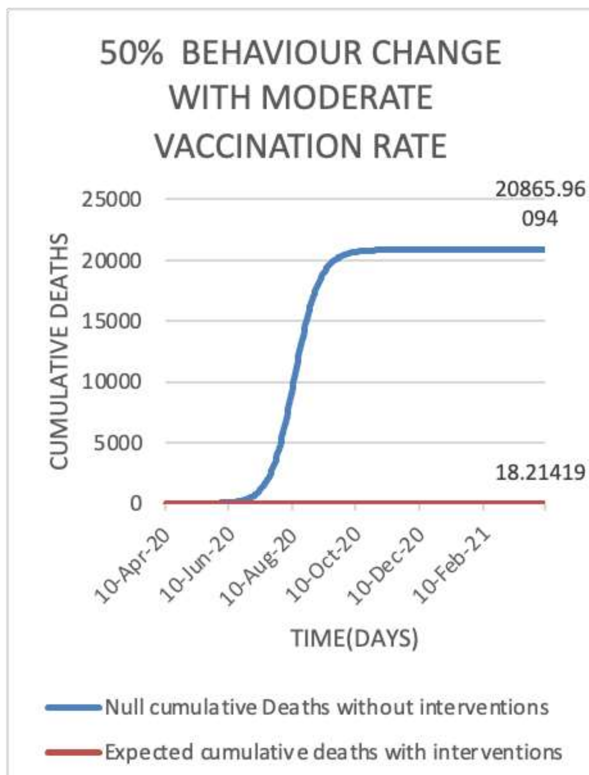
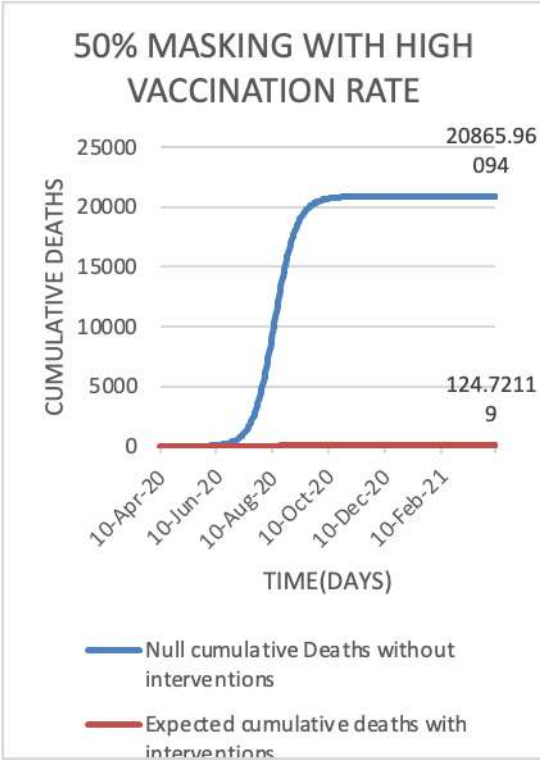
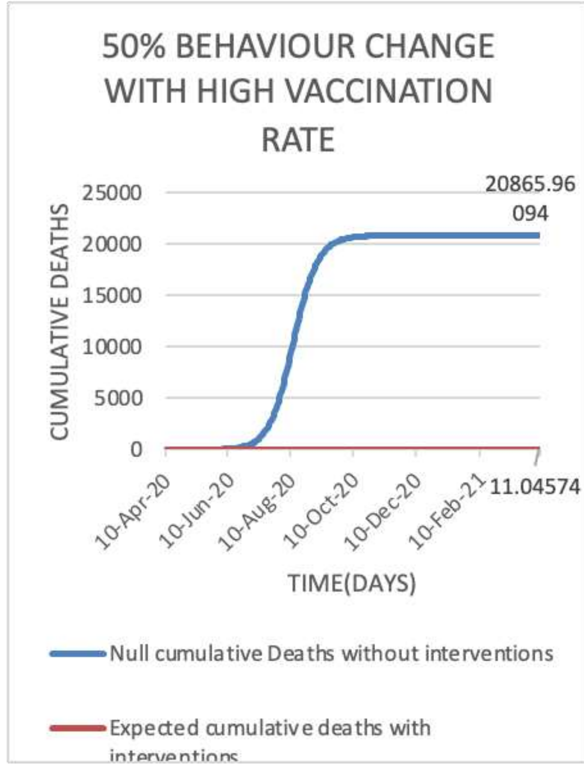
CUMULATIVE DEATHS
25000
20000
15000
10000
5000
0
20865.96094
793.58276
10-Apr-20
10-Jun-20
10-Aug-20
10-Oct-20
10-Dec-20
10-Feb-21
TIME(DAYS)
Null cumulative Deaths without interventions
Expected cumulative deaths with interventions

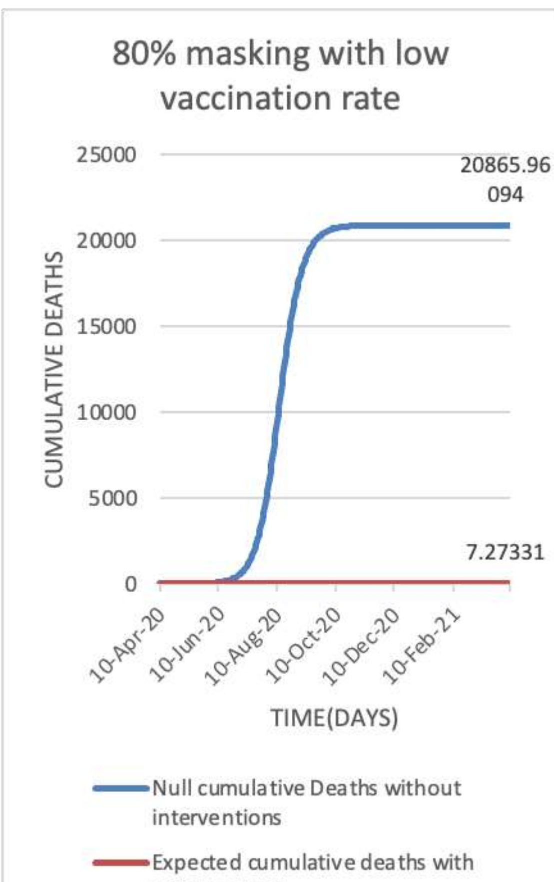
(p)

50% BEHAVIOUR CHANGE WITH MODERATE VACCINATION RATE
CUMULATIVE DEATHS
25000
20000
15000
10000
5000
0
20865.96094
18.21419
10-Apr-20
10-Jun-20
10-Aug-20
10-Oct-20
10-Dec-20
10-Feb-21
TIME(DAYS)
Null cumulative Deaths without interventions
Expected cumulative deaths with interventions


50% MASKING WITH HIGH VACCINATION RATE
25000
20000
15000
10000
5000
0
CUMULATIVE DEATHS
20865.96 094
124.7211 9
10-Apr-20
10-Jun-20
10-Aug-20
10-Oct-20
10-Dec-20
10-Feb-21
TIME(DAYS)
Null cumulative Deaths without interventions
Expected cumulative deaths with interventions

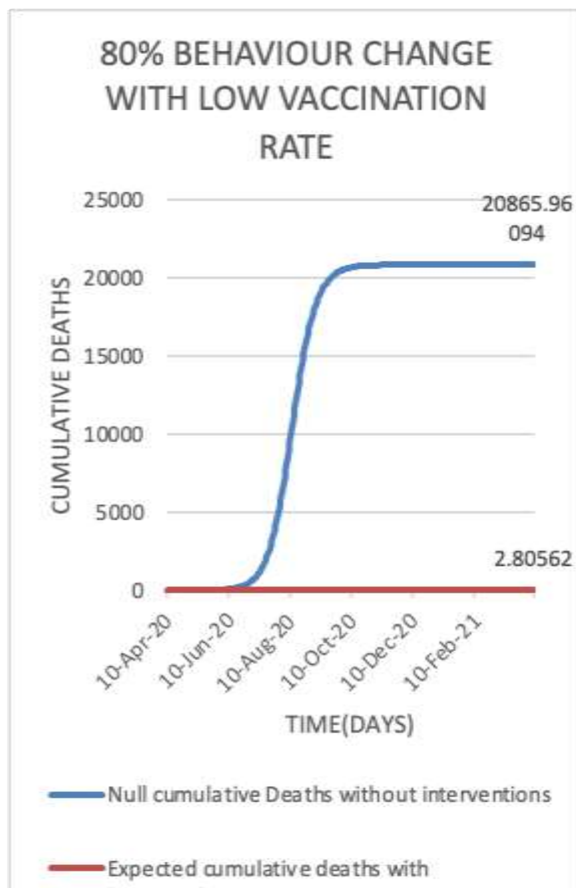
(q)


50% BEHAVIOUR CHANGE WITH HIGH VACCINATION RATE
25000
20000
15000
10000
5000
0
CUMULATIVE DEATHS
20865.96 094
11.04574
10-Apr-20
10-Jun-20
10-Aug-20
10-Oct-20
10-Dec-20
10-Feb-21
TIME(DAYS)
Null cumulative Deaths without interventions
Expected cumulative deaths with interventions

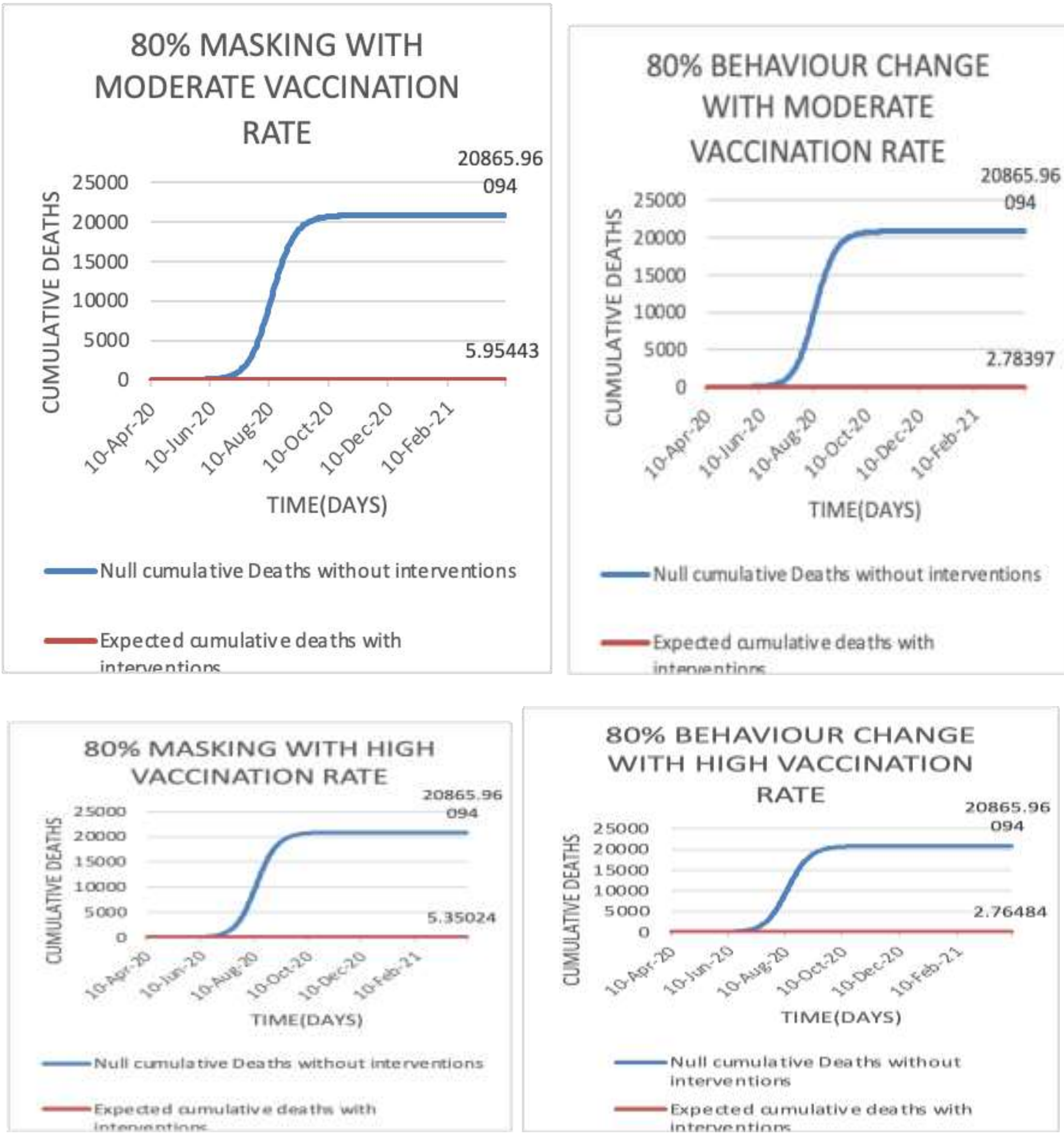
(r)


80% masking with low vaccination rate
25000
20000
15000
10000
5000
0
CUMULATIVE DEATHS
20865.96 094
7.27331
10-Apr-20
10-Jun-20
10-Aug-20
10-Oct-20
10-Dec-20
10-Feb-21
TIME(DAYS)
Null cumulative Deaths without interventions
Expected cumulative deaths with interventions

(s)


80% BEHAVIOUR CHANGE WITH LOW VACCINATION RATE
25000
20000
15000
10000
5000
0
CUMULATIVE DEATHS
20865.96 094
2.80562
10-Apr-20
10-Jun-20
10-Aug-20
10-Oct-20
10-Dec-20
10-Feb-21
TIME(DAYS)
Null cumulative Deaths without interventions
Expected cumulative deaths with interventions

(t)



(u) (v) (w) (x)

Figure 9: **Null cumulative deaths and cumulative deaths from each of the simulates scenarios** from a-x

Table 6: Percentage reduction in the expected cumulative number of confirmed cases for The different intervention scenarios from the null model prediction of no intervention.

SCENARIOS OF BEHAVIOUR CHANGE WITH VACCINATION	% REDUCTION IN EXPECTED CASES	% REDUCTION IN EXPECTED DEATHS	SCENARIOS OF MASKING WITH VACCINATION	% REDUCTION IN EXPECTED CASES	% REDUCTION IN EXPECTED DEATHS
10% BEHAVIOUR CHANGE WITH LOW VACCINATION	18.8%	18.8%	10% MASKING WITH LOW VACCINATION	12.3%	12.3%
10%BEHAVIOUR CHANGE WITH MODERATE VACCINATION	28.8%	28.8%	10% MASKING WITH MODERATE VACCINATION	26.8%	26.8%
10% BEHAVIOUR CHANGE WITH HIGH VACCINATION	39.5%	39.5%	10% MASKING WITH HIGH VACCINATION	41.9%	41.9%
20%BEHAVIOUR CHANGE WITH LOW VACCINATION	35.6%	35.6%	20% MASKING WITH LOW VACCINATION	20.9%	20.9%
20%BEHAVIOUR CHANGE WITH MODERATE VACCINATION	48.3%	48.3%	20% MASKING WITH MODERATE VACCINATION	38.3%	38.3%
20%BEHAVIOUR CHANGE WITH HIGH VACCINATION	62.4%	62.4%	20% MASKING WITH HIGH VACCINATION	56.7%	56.7
50%BEHAVIOUR CHANGE WITH LOW VACCINATION	99.6%	99.6%	50% MASKING WITH LOW VACCINATION	67.9%	67.6%
50%BEHAVIOUR CHANGE WITH MODERATE VACCINATION	99.9%	99.9%	50% MASKING WITH MODERATE VACCINATION	96.2%	96.2%
50%BEHAVIOUR CHANGE WITH HIGH VACCINATION	99.9%	99.9%	50% MASK ING WITH HIGH VACCCINATION	99.4%	99.4%
80%BEHAVIOUR	99.9%	99.9%	80% MASK WITH	99.9%	99.9%

CHANGE WITH LOW VACCINATION			LOW VACCINATION		
80%BEHAVIOUR CHANGE WITH MODERATE VACCINATION	99.9%	99.9%	80% MASK WITH MODERATE VACCINATION	99.9%	99.9%
80%BEHAVIOUR CHANGE WITH HIGH VACCINATION	99.9%	99.9%	80% MASK WITH HIGH VACCINATION	99.9%	99.9%

A significant percentage reduction was also seen in Ro. Ro which was initially set at 2.64 in our model was reduced to 2.37 in the scenario set at 10% behaviour change with low vaccination rate, to 2.34 in the scenario set at 10% Behaviour change with high vaccination rate, to 0.61 in the scenario set at 80% Behaviour change with low vaccination rate and 0.55 in the scenario set at 80% behaviour change with high vaccination rate as shown in Figure 10.

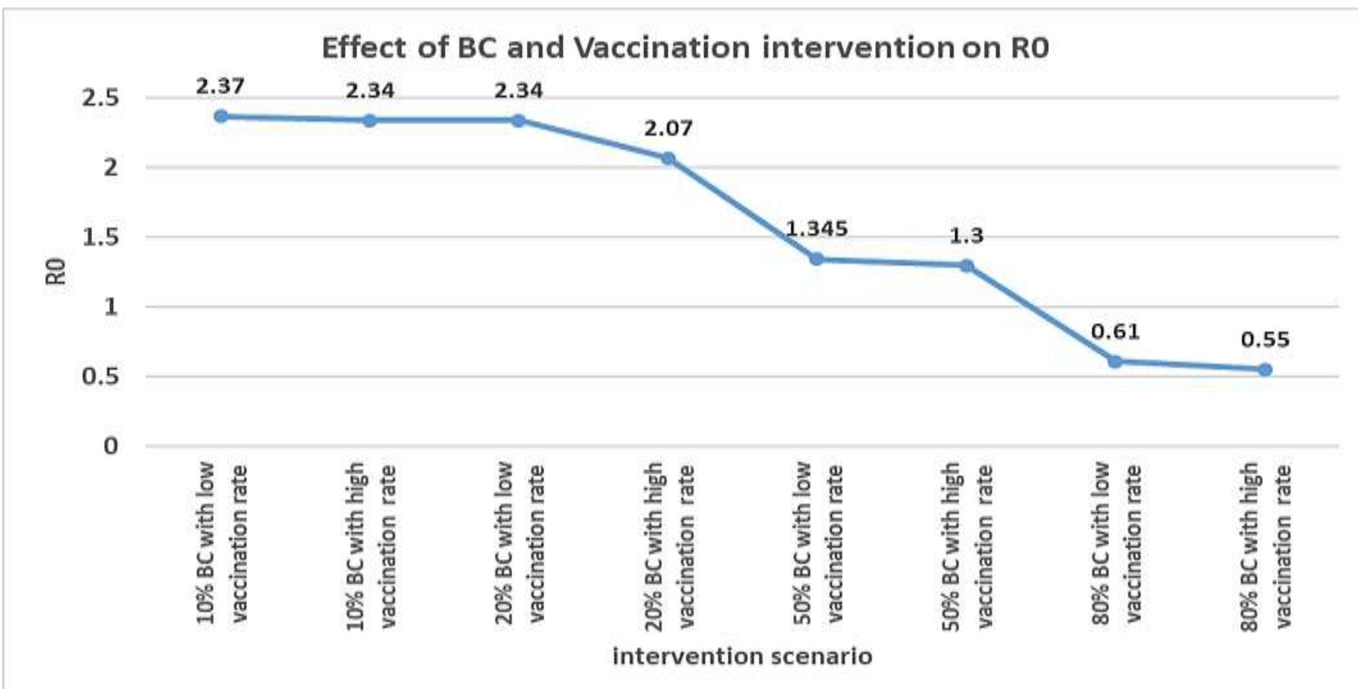


Figure 10: Effect of behaviour change (BC) and Vaccination interventions on Ro

Similarly in Masking scenarios with initial Ro set at 2.64 in our model, R was reduced to 2.45 in the scenario set at 10% Masking with low vaccination rate and 2.29 in the scenario set at 10% masking with high vaccination rate and 1.25 in the scenario set at 80% Masking with low vaccination rate and 1.24 in the scenario set at 80% Masking with high vaccination rate as shown in Figure 11.

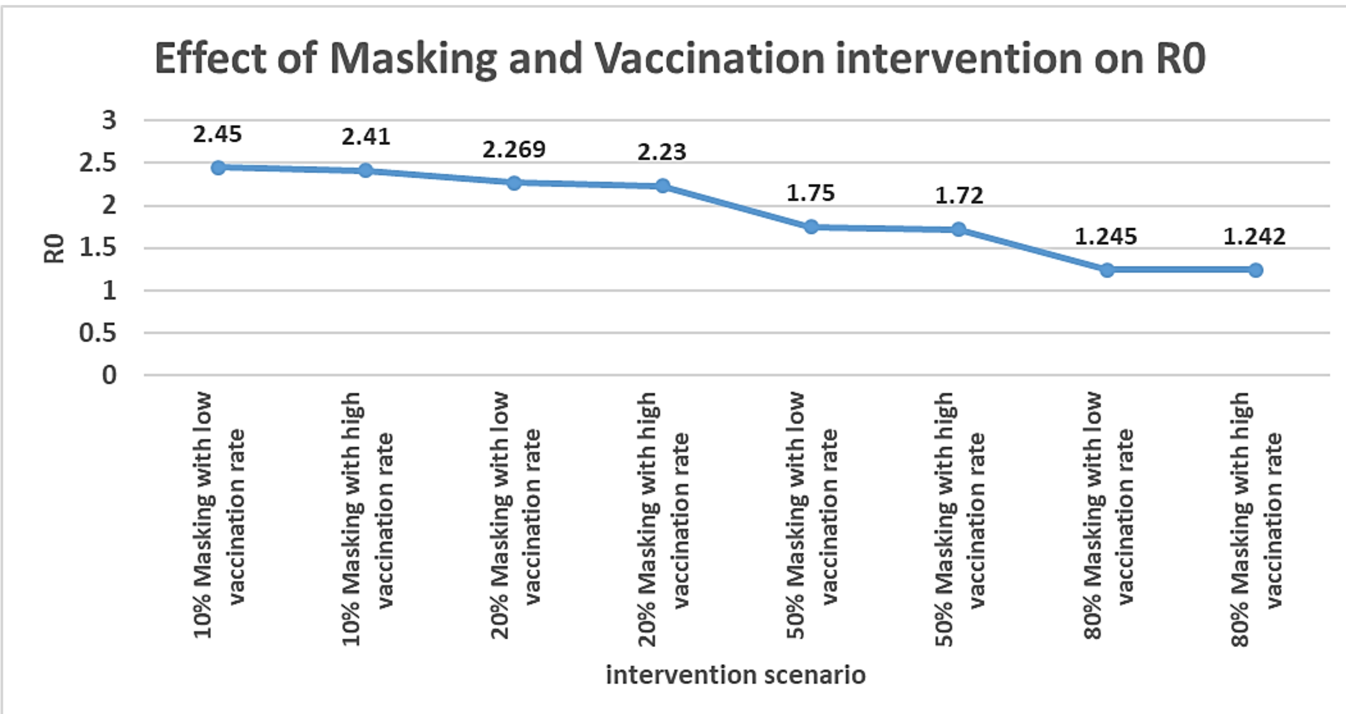


Figure 11: **Effect of Masking and Vaccination intervention on** Ro

As seen from Figures 10 and 11, behavior change (BC) combined with vaccination had a much larger impact on reducing the Ro than just masking in combination with vaccination.

CHAPTER FIVE:

5.0 DISCUSSION

In this study, a modified compartmental deterministic model was developed to predict the impact of combined NPIs and face masking combined with various levels of vaccine uptake on the control of COVID-19 in Lusaka, Zambia. The model as shown in Figure 7, was a near-perfect fit when compared to actual outbreak data of locally transmitted cases (non-imported cases) from 10 April to 21 May 2020, confirming the validity of the results.

The simulation model results have shown that the use of non-pharmaceutical interventions (NPIs) combined with vaccination has a significant impact on the cumulative number of COVID-19 cases and deaths. The study found that NPIs, such as wearing a mask and adopting behavioural change such as social distancing, hand hygiene and cough etiquette, have a modifying effect on the variation of the virus. Moreover, the study found that vaccination, when used in combination with masking or behavioural changes, can significantly reduce the basic reproduction number (R0). This is a crucial finding that indicates that the use of vaccination, along with NPIs, can be an effective strategy to curb the spread of COVID-19.

Altogether, while vaccination is a key intervention for COVID-19 prevention, the results of this study highlight the effect of NPIs in modifying disease impact.

Based on my findings, 50% behaviour change even at low vaccination rate in a population attained a flattened epidemic curve with reduced cumulative COVID -19 cases and cumulative COVID -19 deaths favouring it as the most viable strategy to control the spread of infection especially when the outbreak is fairly new and vaccines are in short supply, and many communities are dealing with vaccine hesitancy.

The findings of this study on behaviour change were consistent with many studies that sought to find the impact of vaccines and NPIs on COVID-19 transmission dynamics. One such study is by Kim et al, on combined behaviour change carried out in the Republic of Korea where varying behaviour change percentages from 25%, 50% and 75% were modelled and their findings showed a significant reduction in both new cases and cumulative cases at 50% behaviour change and an almost flattened epi curve at 75%, while 25% behaviour change had the least impact on new cases and cumulative cases of COVID-19 (Kim et al ,2020). Another study by Eikenberry et al on masking, modelled epidemiological data collected from the states of Washington and New York simulating the impact of face masks on the transmission rate of COVID-19 showed a reduction in both cumulative cases and deaths in nine scenarios of effective mask use at 20%, 50%, 80% if the varying percentage levels of 20%,50% and 80% of the general republic are masked (Eikenberry et al, 2020).

Despite the positive impact of face masks on reducing cases of COVID-19, many researchers have pointed out that face masking as a sole intervention may have little influence on the epidemic if not used together with other NPIs(Wibisono et al, 2020; Eikenberry et al, 2020; Rowan and Laffey, 2020).

Even with the introduction of pharmaceutical interventions, namely vaccines many studies similar to this one has encouraged the continued use of NPIs together with vaccination.

Moore S, et al in their mathematical modelling study on vaccinations and non-pharmaceutical interventions for COVID-19, predicted an increase in daily deaths from COVID-19 in the United Kingdom, if NPIs were relaxed early at start the COVID-19 immunization program (Moore et al, 2021).

In another study Patel et al, simulated the association between COVID-19 vaccine efficacy and coverage scenarios with and without non-pharmaceutical interventions (NPIs) with SARS-CoV-2 infections, hospitalizations and deaths. Their results showed that even in their best vaccination scenario of 95% vaccine efficacy and 75% vaccine coverage more infections occurred when NPIs were removed as compared to when they were maintained, resulting in increased infections, hospitalizations and deaths (Patel et al, 2020).

At the beginning of the COVID -19 vaccination roll out, many communities especially in African countries faced many challenges in achieving the WHO recommended 70% vaccination rate required for herd immunity such as slow onset of vaccination exercise, limited funds, vaccine hesitancy arising from concerns of vaccine safety, supply and logistics such as inadequate cold chain (Ayenigbara et al, 2021; WHO, 2021; Masresha B, 2022).

Currently there has been equitable access to COVID-19 vaccines through GAVI and COVAX facilities (UNICEF, 2024). There are many other issues regarding vaccines and many studies referred to in this research have highlighted the inadequacy of using COVID-19 vaccines only without continued adherence to NPIs.

These issues such as possible waning immunity and limited protection in those that only had one shot of a two shot vaccine or missed a booster shot, mutation of the virus with antibody resistance, the emergence of variants of concern (VoC) and generally insufficient knowledge on the epidemiology of COVID-19 have contributed to continued break through infections from SARS-CoV-2 even in fully vaccinated individuals (Caldwell et al, 2021; Hadizadeh et al, 2022; Vikram T et al, 2022; WHO, 2022; Ikbel Hadji Hassine, 2021; Patel et al, 2020: Moore et al, 2021)

Therefore, this study emphasizes continued use of NPIs alongside vaccination roll out even when the vaccination coverage of 70% as recommended by WHO to generate sufficient herd immunity has been achieved and this should be encouraged especially in risk populations such as health workers, the elderly and people with co morbidities (WHO,2022; Pedro Plans- Rubio, 2022).

Limitations

This study had some limitations such as gaps in the COVID-19 data collected in the early phase of the epidemic, due to inadequate laboratory diagnosis capacity and surveillance of the novel virus. Most cases were not reported or captured especially asymptomatic cases from contacts of positive cases and even symptomatic cases from some communities who believed that the disease was a hoax.

Due to the complexity of the study, no conceptual model was developed.

Behaviour change as an intervention with combined NPIs failed to determine which of its component contributed the most to the observed difference in Ro, and masking scenarios did not take into consideration of different makes of masks or correct usage of masks.

The dynamics of COVID-19 transmission was also another limitation, as there was little knowledge regarding the characteristics of the new virus and different VOC which kept emerging with different transmission patterns influencing the number of new cases and deaths and may not be represented in the initial data fitting.

Despite the many NPIs that were introduced, this study did not include lockdown which was partially introduced in Zambia in schools, some shops, restaurants, entertainment activities and religious activities.

CHAPTER SIX:

6.0 CONCLUSION AND RECOMMENDATIONS.

6.0 Conclusion

Combining the use of NPIs with vaccination coverage resulted in a reduced number of cases and deaths. Simulated scenarios of both masking with vaccination and behaviour change with vaccination even in minimal applications have shown that they can reduce transmission of COVID-19 in the community by lowering the basic reproduction number. The most realistic and feasible scenario to adopt in our community is the behavioural change scenario of 50% behaviour with at least moderate vaccination rate in light of vaccine hesitancy and COVID-19 skepticism.

6.1 Recommendation

The government must advocate for and implement laws that promote the practice of behaviour change in indoor public places. This is a crucial step towards creating a safe and healthy environment for all citizens. Public places such as malls, restaurants, and offices are frequented by large numbers of people, making them potential vectors for the spread of diseases and illnesses. Encouraging behaviour change in these spaces, such as wearing masks, maintaining social distancing, and practicing good hygiene, can significantly reduce the risk of transmission of infectious diseases such as COVID-19.

These policies can take various forms, including public education campaigns, signage, and regulations mandating the use of protective equipment. By implementing these measures, we can foster a culture of safety and awareness, and encourage everyone to take responsibility for their actions.

The government must implement a multi-sectoral One Health approach. This approach emphasizes the interconnectedness of human, animal, and environmental health, recognizing that the health of one sector can have a significant impact on others. By adopting this approach, the government can ensure that all relevant sectors are working together to effectively respond to the pandemic and mitigate the risk of future outbreaks.

In addition to this, the government must also prioritize the development of a comprehensive Risk Communication and Community Engagement (RCCE) action plan. This plan should focus on promoting behavioural change among the general public and encouraging vaccination efforts. Effective communication and engagement with communities can help to build trust, increase understanding of the pandemic, and encourage individuals to take appropriate measures to protect themselves and their communities.

The government and other stakeholders must provide sustained and substantial support towards research aimed at understanding the epidemiology of COVID-19. With the emergence of several variants of the virus, it has become increasingly important to deepen our understanding of the virus's behavior, transmission patterns, and genetic makeup. Such research endeavors will help us identify the specific factors that contribute to the emergence and spread of new variants, as well as provide insights into the efficacy of existing treatments and vaccines against these variants.

To this end, it is imperative that research efforts are both comprehensive and rigorous, with a focus on the development of vaccines that are effective against all known variants. This will require the collaboration of experts from various disciplines, including virology, immunology, and epidemiology, among others. Research teams must also adopt state-of-the-art tools and techniques to ensure the accuracy and reliability of their findings.

CHAPTER SEVEN

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