A Sir Model for Viral Growth of Coronavirus: A System Dynamics Approach

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Abstract. In this paper, a system dynamics model depicts the viral growth of COVID-19 at an exponential rate. The outbreak of Corona virus was started from the Feb 26, 2020 when the first case was reported in Pakistan. Local bodies and law enforcing agencies had taken initial preventive measures to restrict the COVID-19 to a particular locality but all in vain. The infected people were increasing every day rising the stocks of recoveries and deaths. Numbers of infected people were alarming and a need was felt to develop the model to calculate the existing reproduction number and transmission rate and highlight its varied values in coming days. People-oriented measures and government-based policies must be explored to fight against this deadly disease. This paper aims the development of epidemic model using the system dynamic framework on simulation software STELLA. The objective of the research is to experiment with the model to replicate the progression of the communicable disease and probe the multiple combinations of the people-based and government-based measures to reduce its spread. The containment measures are of two types; people-based measures and government-based measures and both directly affect the reproduction number and infection growth fraction for mitigating the spread of deadly coronavirus. Combined efforts of public and government can combat this pandemic. Reduced degree of reproduction number and infection growth fraction are the key metrics to judge and evaluate the effectiveness of containment measures.

This research points to more holistic combination of public and government-oriented measures that play the vital role to flatten the curve and reduce its spread affecting the reproduction number. Simulation results have been traced to replicate the real-life settings against four combinations of containment measures in tabular form and graphical form.

Keywords: COVID-19 · Epidemic models · System dynamics · Containment measures · Simulation software · People-based measures · Government-based measures

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1 Introduction

COVID-19 is an emerging biohazard which has drastically influenced millions of people globally causing many deaths with its exponential transmission rate.

In our study, we have devised a system dynamic model (Forrester 1958) based on well-known (Susceptible-Infected-Recovered) SIR model (Kermack and McKendrick 1927) which is an epidemiological model that consists of three coupled non-linear equations (Sterman 2001) that represent the real life setting and grounded in the data gathered from the secondary source i.e., government website. In our research, the system dynamics model is developed in computer based simulation software STELLA Professional version 1.1.2 using system dynamics modelling framework (Sterman 2000). Simulated SIR model replicates the real-life data gathered over the period of 55 days and experimentation with the model helps to explore the possibilities of containment measures that flatten the curve and reduce the spread of infectious disease. It also predicts that to draw a comparison between people vs government-based measures.

Outbreak of COVID-19 was reported in late December in 2019 in Wuhan which is a province of China. It is a highly contagious disease with an expeditious transmission rate and because of this, the WHO has announced a Public Health Emergency of International Concern on 31st January 2020 (Wu and McGoogan 2020). On account of its accelerated global spread, it was declared a pandemic, by World Health Organization on 11th March 2020, due to thirteen-fold increase in cases in two weeks. The basic reproduction number for corona virus is estimated to be around 2.2 (range 1.4 to 6.5) (Wu and McGoogan 2020). In Pakistan first case of COVID-19 was reported on 26th February 2020 owing to its geographical association with China and Iran with continuous immigration of people (Waris et al. 2020). Unluckily the first immigrant was from Iran in Sind province. In order to combat COVID-19, preventive measures were enforced by the provincial government and unprecedented measures were taken to delay the epidemic peak. Till March 26, 2020, 1197 cases of COVID-19 were reported with 9 deaths. Lockdown was enacted on march 2020 and it was gradually eased till 9th May 2020 to shore up the economy although the proportion of infected people had a rising trend. Over the period 55 days till April 20, 2020 the total number of infected cases in Pakistan had amounted to 8418 with 1970 recoveries and 176 deaths.

Pakistan is currently fighting two battles; one against corona virus and the other against poverty. This economic meltdown is due to disruption of supply chains, lockdown and sudden closure of businesses leading to decreased livelihood opportunities. In addition to this, money is being consumed for implication of safety measures, PPEs, testing kits and increasing health care facilities. Favero et al. (2020) has categorized the effectiveness of strategic policies for COVID-19 on basis of their costs and fatalities in his research article ''Restarting the economy while saying lives under COVID-19" on 8th May 2020 to optimize the management strategies from the ecological viewpoint.

In another research article "Why is it difficult to accurately predict the COVID-19 epidemic" Roda et al. (2020) have mentioned that detected cases are only a fraction of total infected people using the metaphor of an iceberg since many asymptomatic patients are not even tested making it difficult to predict the disease course. In his article he has mentioned that SIR model is better in predicting the disease progression than SEIR and other complex models. SIR model provides a theoretical verification of effectiveness of the mitigating strategies as strict implication of these can halt the epidemic surge and it can be used to address the risk of second peak if occupational S activities are started during the disease course.

The objective of the research article is to understand what containment measures should be deployed to flatten the curve, push down the infection rate and mitigate the spread of COVID-19.

2 Research Methodology

System Dynamics is a versatile methodology to deal with the non-linear, dynamic and complex problems (Saeed 2014) in industrial, social and in medical science. System Dynamics masterly attempts to combine the key concepts like feedback controls, mutual causality, non-linearity in the functions, cybernetics, complexity, counterintuitive behavior, deviation correcting and deviation amplifying processes to the organizational systems (Sweeney and Sterman 2007).

COVID-19 has enhanced the importance of disease epidemiological modelling. A well-known epidemiological model SIR (Susceptible, infected and resolved) is now a days talk of the town (Kermack and McKendrick 1927). Even the common man is interested to know about the infection rate and resolution rate. There is a need to develop the SIR model using system dynamics modelling framework and determine the containment measures to control the governing factors BETA (Infection rate) and GAMMA (Resolution rate) that cause the spread of this infectious disease.

Figure 1 Indicates the simplified representation of the SIR Epidemic Model. Saturation loop **(S)**, reinforcing loop **(R)** and balancing loops **(B)** exist in the model and generate the model behaviour. The loop dominance may change over the period of time and creating the various modes of behaviour as the time pass on. As the transmission rate increases due to increase in infected people, there is a decline in susceptible people (people who are healthy but are at risk) and it is going to saturate till all the susceptible persons become infected people. Model structure represents the Stock and Flow diagram and symbols used in the model are shown in Appendix A.

The value of the GAMMA recovery rate strength the balancing loop. No doubt the constant value of gamma does not bring significance effect of the resolved people. Changing values of the BETA (infection rate) keep on increasing the stock of infected people and susceptible people becomes the infected at exponential rate (Rahmandad and Lim, 2021) if there is no vaccine for susceptible (Ghaffarzadegan and Rahmandad 2020). The spread of COVID-19 is with a jet speed. Limited testing and screening facilities, non-availability of the testing kits, poor quality of kits and low quality personal protective equipment are the hurdles to catch the viral growth of coronavirus (Table 1).

The model consists of three non-linear differential equations based on Euler method where 't' is the time, Beta is the infection rate and gamma are the resolution rate.

$$\mathbf{dS/dt} = -\mathbf{Beta} * \mathbf{S} * \mathbf{I} \tag{1}$$

$$\mathbf{dI/dt} = \mathbf{Beta} * \mathbf{S} * \mathbf{I} - \mathbf{Gamma} * \mathbf{I} \tag{2}$$

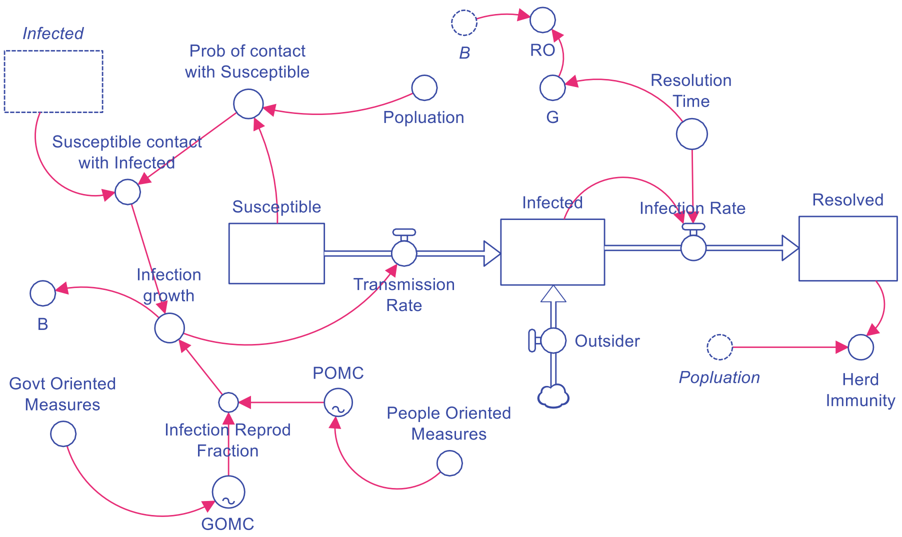

Fig. 1. Stock and Flow Diagram of SIR Epidemic Model

Table 1. Anatomy of SIR model

Symbol	Nomenclature	Description
S	Susceptible	How many available for infection
I	Infected	How many are infected
R	Resolved	How many are resolved either recovered or died (no longer part of total population)
B	Beta	Number of contacts per infected person per day
G	Gamma	Number of recoveries per person per day
R0	Reproduction Number	Reproduction number is used to measure the transmission potential of a disease. It is the average number of secondary infections produced by a typical case of an infection in a population where everyone is susceptible
N	N	Total Population i.e. N = S + I + R

$$\mathbf{dR/dt = Gamma * I} \tag{3}$$

$$\mathbf{N = S + I + R} \tag{4}$$

Beta is the infection rate that is controlling variable that transmission from susceptible to infected and ratio of Beta to Gamma called reproduction number (RO) determine the spread of epidemic COVID-19 (Wu et al. 2020). It is interesting to note that infection rate (Beta) and reproduction number (RO) both exponentially rise. The model is calibrated fifty-five days for value of infection rate (Beta) and resolution rate (gamma) shown in Fig. 2 and Fig. 3.

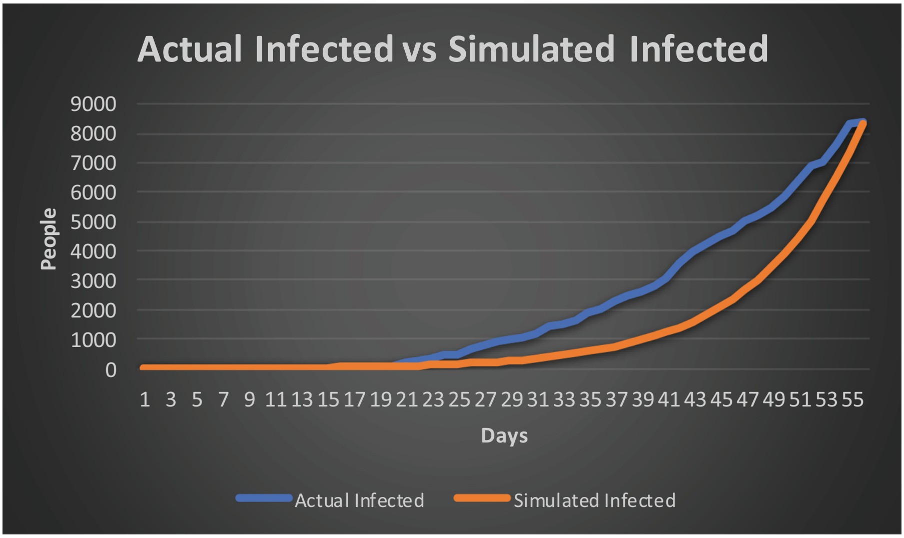

Fig. 2. Actual infected vs simulated infected

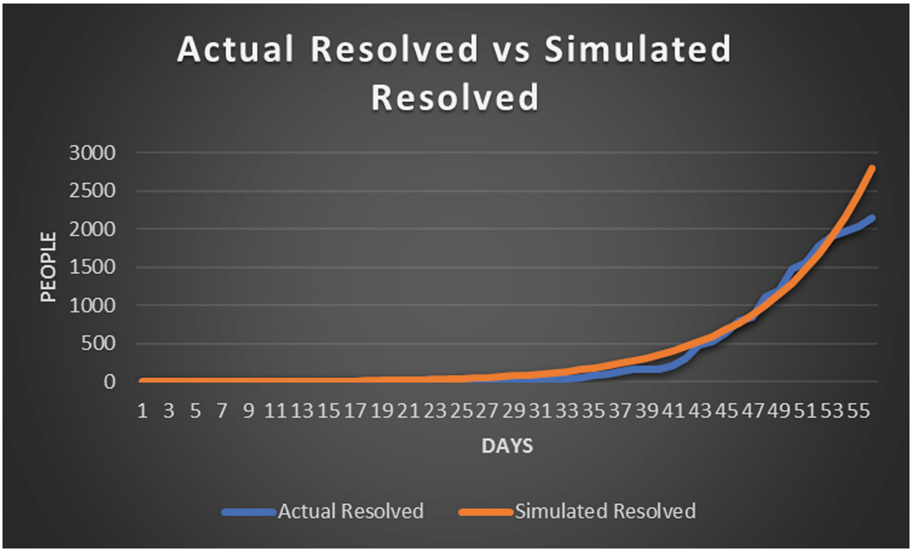

Fig. 3. Actual resolved vs simulated resolved

The days to resolved either recovered or died usually it takes around 23 days. The model is the third order differential equation with associated flows (Forrester 1968). The order of the model depends upon the number of levels and the number of delays (Sushil 1993). The detail listing of the variables of the model are highlighted in Appendix B.

Base Line Model Equations.

SIR model based on Euler Integration that are as under:

Susceptible = INTEGRAL (- Transmission rate) * dt -- (1)
Transmission rate = Infection growth --------------------------------- -----------------------------(1.1)
Infection growth = Infection reproduction fraction * susceptible contract with infected -------(1.2)
Susceptible contact with infected = prob of contact with susceptible * infected contact -------(1.3)
Infected contact = Contact rate * Infected ---(1.4)
Prob of contact with susceptible = Susceptible / population --------------------------------------(1.5)
B = Infection growth (Beta represents infection rate)--(1.6)

Infected = INTEGRAL (Transmission rate – infection rate + outsider inflow) * dt--------(2)
Infection rate = Infected / Resolution time --(2.1)
Outsider Inflow = One person per day (Constant)--(2.2)

Resolved = INTEGRAL (Infection rate) * dt --(3)
Herd Immunity = Resolved / Population --------------------- --------------------------------------(3.1)
G = 1/resolution time (Gamma represents the resolution rate) ------------------------------------(3.2)
RO= B/G -- (3.3)

The summation of all the stocks and rates are equal to the total population that depicts the dynamic balance (Saeed et al. 2018). The system dynamic model has following assumptions:

1) There is a fixed recovery time that in case of COVID-19
2) People are well mixed and cannot segregate the asymptomatic with people with healthy people.
3) There is no information about the immunity loss period.
4) Infected person is not to be infected again.

On the basis of the actual time series data, the system dynamics model is calibrated for fifty-five days data highlighted in Fig. 2 and Fig. 3 representing the true picture of COVID-19 spread in Pakistan considering the people-oriented measures and government-based measures. The detail of model equations has been shown in Appendix C. The value of Beta (infection rate) and Gamma (resolution rate) derived from the time series data of Pakistan and world statistics on COVID-19 (Cori et al. 2013) and tracing of the behavioral pattern for various simulation periods validated the estimations. The various containment measures as shown in the Table 2 have been proposed for experimentation. The only fifty-five days had passed so far and level of awareness was minimal. If we project the model behaviour for next 365 days the results are shown in Fig. 4 that indicate the peak will appear after 146 days and by that time 80 million people will be infected and around 120 million people will be resolved. The figures are so alarming that compel the researcher to go for experimentation and explore the effectiveness of the containment measures to lower the infection rate. The model consists of positive and negative loops (Lane 2007) and dominance of the polarity and its shift from positive to negative and negative to positive adds complexity (Saeed 1992).

Table 2. Containment measures people based versus government based

People-based measures	Government-based measures
Hand washing	Lock down duration
Social Distancing	Lock down effectiveness
Avoid meetings, get-togethers, parties, festivals	Contact trancing and quarantine people on quarantine centers
Self-isolation and quarantine	Smart Lock Down-Open up with Standard Operating Procedures (SOPs) like temperature gun, PPEs, Face mask, frequent medical checkup
Maintaining the 6 feet distance between two individuals	Usage of Facemask is mandatory for visiting the shops and all public places
Using the hand sanitizers	Walk through Dis-infected tunnels for company employees and entrants in shopping malls, hospitals, factories, airports, retail outlets

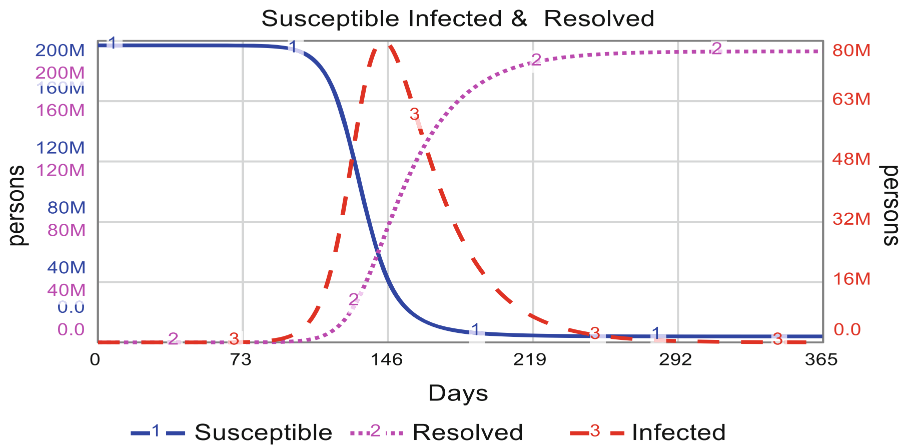

Fig. 4. Susceptibles, infected and resoved during the simulation period 365 days

Graphical functions based on people oriented measures and government oriented measures have been introduced shown in Appendix D and designed to understand the behavioral patterns arising out of the model structure rather than point prediction of the future deaths and recoveries (Saeed et al. 2018).

3 Results and Discussion

People based measures like social distancing is a non-pharmaceutical prevention containment measure that is outcome of people behaviour and attitude (Raouf and Yusuf 2011).

Knowledge, understanding and attitude of medical students (Bostanudin et al. 2020) contribute to run the awareness campaign about wearing face mask, hand washing, usage of sanitizers, maintaining social distance, avoid parties, social get togethers, festivals and funerals. It is all about the people attitude and behaviour of the individuals. Government based measures associated with lock down duration, lock down effectiveness, contract tracing, enhancing health care capacity, Smart lock down with the effective implementation of standard operating procedures (SOPs) and personal protective equipment (PPEs). Lock down duration in days stops everything and other government-oriented initiatives are very much impeded in it as highlighted in Table 2.

The model was calibrated for initial 55 days and then under the government-based measures and people-based measure the actual data was replicated till July 10, 2020 with the simulation numbers indicating the reduced reproduction number. The details are shown in Table 3.

Table 3. Lowering reproduction number shows effectiveness of the containment measures

Period	Days	Actual infected	Simulated infected	Actual resolved	Simulated resolved	Reproduction number	Measures reference	People based measures (%)	Government based measures days
Ist Period	55	8418	8400	2146	2800	3.97	Base Case N0. 1	15	30
2nd Period	85	45898	44000	14086	19000	3.29	Measure No 2	17	55
3rd Period	116	171666	171000	66886	89000	2.92	Measure No. 3	21.5	62
4rth Period	136	243599	255000	154151	152000	2.68	Measure No. 4	24.5	65

The effectiveness of the containment measures people based and government based are equally important and both are significant to reduce the reproduction number shown in Fig. 7 leading to lowering in infected people highlighted in Fig. 5 due to reduced level of Beta-Infection fraction shown in Fig. 8. This diversity of the patterns of behaviors is under the influence of multiple combinations of people based and government based containment measures (Richardson and Pugh III 1981). Measure reference indicates the set of combination (people-based and government-based) of containment measure. The number 1 measure represents the base value and that was the source of model calibration after passing fifty-five days. Reproduction number has gone down from 3.97 to 2.68 that shows the government strategy is at the right track shown in Table 3.

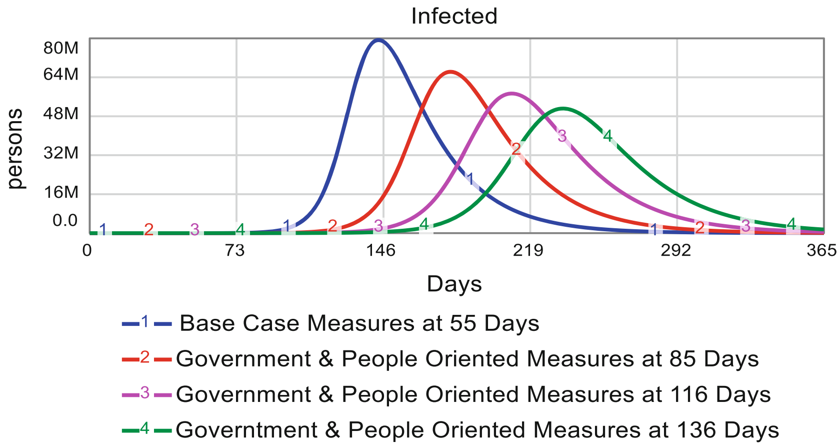

Fig. 5. Affect of containment measures on infected people at varied time interval

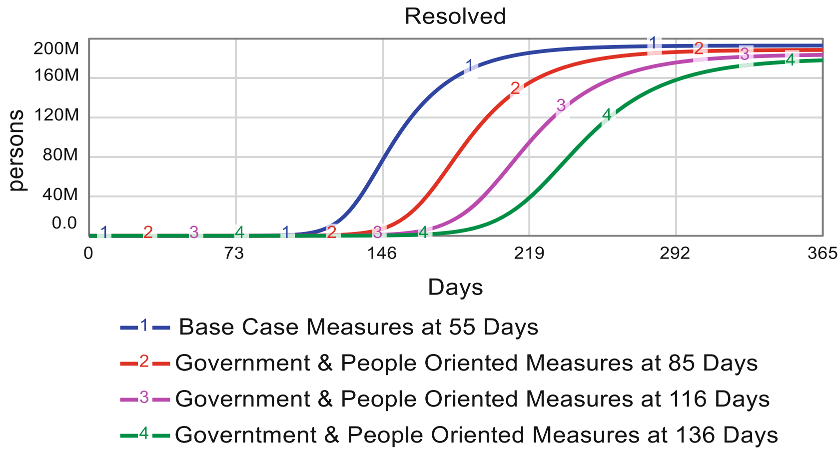

Fig. 6. Affect of containment measures on resolved people at varied time interval

Number of resolved cases have gone down due to decrease in infected people highlighted in Fig. 6. Beta- infection fraction has declined from 0.18 to 0.11 as shown in Fig. 8. This is the result of people attitude and fear due to deaths reported in the media every day.

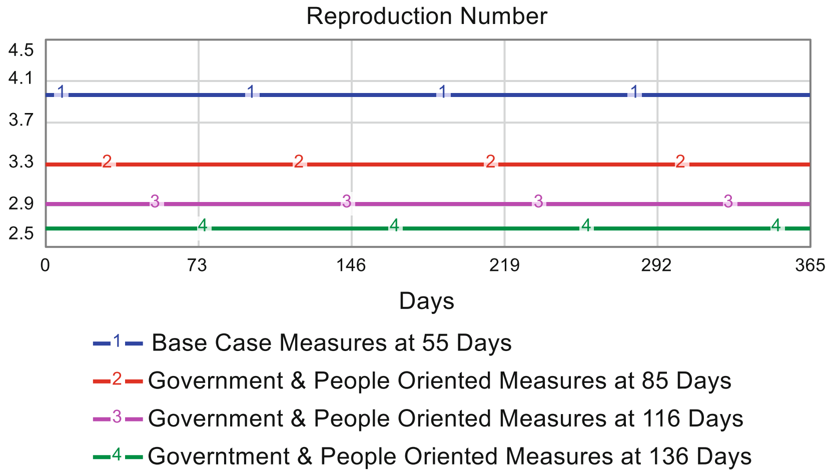

Fig. 7. Affect of containment measures on reproducton numbers at varied time interval

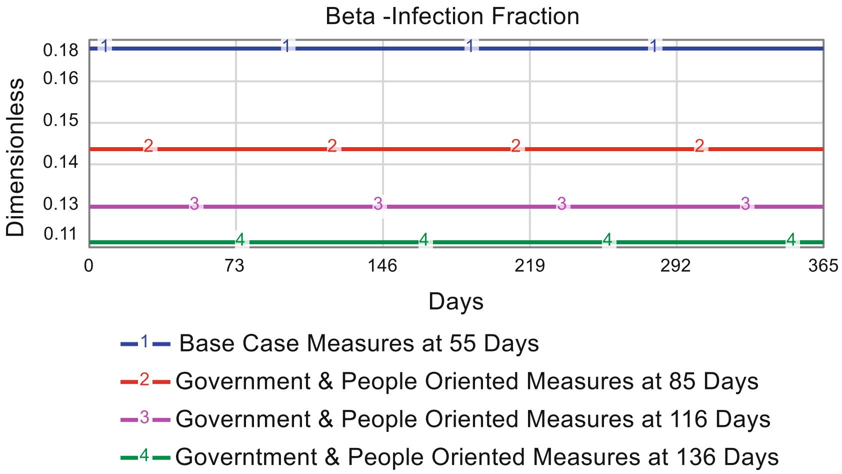

Fig. 8. Affect of containment measures on beta-infection fraction at varied time interval

4 Conclusion

System dynamics model is used to be explored and experimented with various combinations of containment measures (Saeed 2017) and determining the various levels of reproduction number and beta-infection fraction to mitigate the spread of infectious disease COVID-19. It is quite obvious that government-oriented measures are more effective than people-oriented measures. People oriented measures based on education level, effectiveness of the awareness campaign, attitude and mind-set of the social fabric. Measure based on attitude are time depended and cannot be achieved quickly. Government has the power to establish the writ of its government and can implement the policies using stick or carrot. With lock down duration not only can restrict the movement of the people but as well take the time to build the health care capacity to reduce the rising death toll. Contact tracing and territorial lock down effectiveness can contribute for the reduction of Beta-Infection fraction and open up industry with SOPs and PPEs can lessen the economic pressure and give the breathing space to the poor people.

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