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Mathematical model of the early incidence and spread of COVID-19 in Nigeria combined with control measure

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Abstract- This study shows the transmission dynamics of COVID-19 in Nigeria using a S-I-R model for a none constant population. The simplicity of the model allows for more use of estimated than assumed parameters in our computations. The available statistical information regarding COVID-19 in Nigeria from its date of arrival till 30th of March 2020 (22:00 WAT) was used to estimate some parameters, understand and predict the spread of the virus. The disease free and the endemic equilibrium points were obtained. The stability of the disease free equilibrium was investigated using Jacobian transformation. The analysis carried out using the estimated parameters showed that the disease free equilibrium point is stable. The basic reproduction number of the model was calculated and shown to be less than one using estimated parameters. Numerical simulation shows that with intensified control measure, the disease will fizzle out within a short period of time. The simulation was performed using MATLAB.

Index Terms- COVID-19, Epidemiology, Basic reproduction number, Stability, Numerical Simulation

1. INTRODUCTION

COVID-19 which means Coronavirus disease 2019 is an Infectious disease caused by Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) [1]. SARS-CoV-2 is a new virus of the same family as SARS-CoV [2] which is believed to have a zoonotic origin [3].

The first set of cases of the infection was reported in Wuhan (the capital of Hubei province), China on the 31st of December 2019 by health authorities [4] while the first case outside China was reported on the 13th of January 2020 [5]. The World Health Organization reported that the number of individuals getting infected with the virus outside China had exceeded the number of 1 new cases of infections reported in China for the first time on February 2020 [6]. Thus on the 11th of March 2020, it was declared a pandemic and a Public Health Emergency of International Concern (PHEIC) [7] and by 13th of March 2020, well over forty countries and territories had reported deaths on every continent as a result

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of the virus with Antarctica being an exception [8].

Globally, more than seven thousand deaths have been caused by COVID-19 as of 16th of March, 2020 [9]. China's National Health Commission also revealed that most of those who died were elderly and about eighty percent of deaths were in those over 60 years of age. Where 75% of them had underlying conditions including diabetes and cardiovascular disease [10].

This does not imply that the pandemic should be treated with levity by the younger ones. On the contrary, it is advised that younger people who feel perfectly healthy need to take the pandemic seriously because they can spread the virus even if they are not feeling any symptoms [11].

There are no specific symptoms of COVID-19 but the common symptoms that may be exhibited include fever, fatigue and dry cough while uncommon symptoms that have been observed to occur include head ache, nasal congestion, sore throat, shortness of breath, muscles and joint pains, nausea/vomiting, diarrhea etc. [12]

The time between infection and the onset of symptoms is most commonly five days [13], [14] and the major means of transmission is through respiratory droplets of infected persons much similar to the way influenza is being transmitted [15], [16].

Although symptoms can be managed, there are no approved vaccine and antiviral treatments for COVID-19 at the moment [17]. Some preventive measures aimed at curbing the spread of the virus such as regular hand washing and social distancing have also been recommended [18].

Nigeria, a country with approximately 200 000 000 populace located in West Africa recorded its first case of COVID-19 in February 27, 2020 [19] and as at 30th of March, 2020 (22:00 WAT) 131 individuals have been infected with the virus. The total number of recoveries being 8 and deaths, 2 [20]. Lagos State (Nigeria) has a larger number of infected persons followed by the country's capital Abuja. Presently, lock down have been declared in major cities of the country [21] and entry flights from countries with over 1000 cases have been banned [22].

The purpose of this study is to propose a mathematical model for COVID-19 using Ordinary Differential Equations to explain the early transmission dynamics of this disease in the Country (from the time of arrival till 30th of March 2020), to predict its spread and to check if the control measures that have been put in place already is enough to curb the spread of the virus. Optimal strategies aimed at intensifying control measure will be suggested.

Mathematical analysis of the model will be done and the results of the analysis interpreted. Sensitivity analysis of the basic reproduction number on various parameters are carried out which will help in suggesting strategies to curtail the spread of the illness.

2. LITERATURE REVIEW

Adam J Kucharski et al in their work estimated how transmission in Wuhan varied between December, 2019, and

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February, 2020 by combining stochastic transmission model with data on cases of COVID-19 in Wuhan and international cases that originated in Wuhan. Based on their estimated reproductive ratio and individual level variation in transmission of SARS-CoV and MERS-CoV, they concluded that one infectious individual will not necessarily lead to an outbreak in a new location [23] which is quite similar to the result gotten in this work.

Tian Mu Chen et al developed and proposed a Bat-Reservoir-People transmission model to understand and simulate potential transmission from zoonotic source to humans. They estimated reproductive ratio to be 3.58 from human to human. They concluded that the middle transmissibility of COVID-19 was higher than MERS in the Middle East Countries [24].

Qianying Lin et al used the SEIR frame work for a constant population to model the outbreak in Wuhan based on individual reaction and government action using some parameters of the 1918 influenza pandemic that occurred in London. [25].

An exposed compartment is however absent in this work because of some patients who can transmit the disease before/ without exhibiting symptoms (asymptomatic patients).

3. MODEL FORMULATION AND ASSUMPTIONS

In this paper, SIR (Susceptible-Infectious-Recovered/Removed) model for infectious disease as created by Kermack and Mckendrick (1927) is modified and utilized but a non-constant population will be considered.

Although study has shown that people who have suffered and recovered from infections caused by known coronaviruses develop time bound (like one to two years) immunity to those viruses but that of SARS CoV 2 is still being studied [29]. Since this study focuses more on Nigeria, the characteristic of its spread so far (even up till 10th of April) in the country permits the assumption in this model that recovered patients do not get re infected.

Individuals enter the S compartment at the rate of Λ. Interaction occurs between the Susceptible population and the Infectious individuals at the rate of β. The rate at which individuals move from S to I depends on the control measure k where $0 \le k \le 1$ that represents proportion of individuals' adherence to social distancing, personal hygiene and stay home policy. Individuals in I compartment die as a result of the disease at the rate δ.

People move from I to R compartment (or recover) at the rate of α which depends on q ($0 \le q \le 1$) which stands for the probability value of individuals with underlying health conditions (since it has been observed that it is mainly those with pre-existing health conditions that die as a result of the disease [10]. Thus as q approaches 0 the recovery rate increases. In this model, the recovery rate also depends on the rate at which individuals or patients respond to efforts aimed at managing their symptoms denoted as m. It can be

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observed that as m increases and as q tends to zero, the rate of movement from I to R tends to increase.

It is assumed that individuals die naturally in all the population classes at the rate of μ and finally, it is assumed that the immunity after recovery is lifetime.

4. MATERIALS AND METHODS

The total number of people N in the country as last estimated in [24] is 203, 452,505 as at July 2018. This number is used to estimate the COVID-19 induced death rate, infectious rate and recovery rate per 1000 population by using appropriate statistics of the disease (pertaining to Nigeria) obtained in [26]. The contact rate is also estimated using this information. The birthrate Λ and the natural death rate μ (with values 35.2 and 9.6) of the country as last estimated in [26] will also be used in our calculations where necessary.

The recovery rate α is estimated by taking m=1 and q=o based on an assumption that those who have recovered from the illness do not have underlying health conditions.

The infectious rate is estimated to be 0.000643. This was computed by dividing the total number of cases as at 30th of March 2020 (22:00) by the total population multiplied by 1000. The contact rate β is estimated using the infectious rate when k is equal to zero. That is, it is assumed that the individuals who got infected observed zero preventive measures.

The estimated value for the contact rate will be raised to 4.000 while we still take k=0. The effect of this increase will be observed on the basic reproduction number.

Following the impact of increasing the contact rate, the number of people who will contract the virus at such rate will be estimated.

The table below displays our values and parameter estimations:

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Variables/Parameter	Description	Value	Reference
S	Susceptible population	203,452,374	[26]
I	Infectious population	121 (after deducting the recovered and deceased individuals)	[20]
R	Recovered individuals	8	[20]
Λ	Birth rate	35.2	[26]
μ	Natural death rate	9.6	[26]
β	Contact rate	0.00000492 (that gave rise to 131 infected persons)	Estimated
δ	Induced death rate	0.00000983	Estimated
α	Recovery rate	0.0000393	Estimated
$q\ (0 \leq q \leq 1)$	Probability value that shows the proportion of individuals with pre-existing health conditions	0.00001(although q is assumed to be equal to zero when estimating α since most of those who did not recover had underlying health conditions)	Assumed
$k\ (0 \leq k \leq 1)$	Probability value that shows the proportion of the Susceptible population's adherence to preventive measures	0.6000	Assumed.
m	Rate of response by individuals or patients to efforts made by health workers to manage their symptoms	1.000	Assumed.

Table 1: Table of values for Variables, estimated parameters, estimated parameters, assumed probability values

Below is the flow chart of COVID-19 in a population

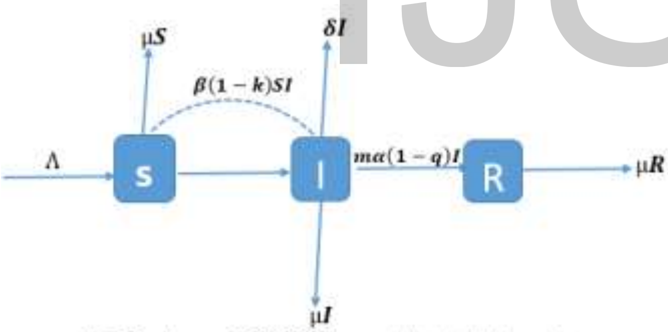

Fig 1: Flow diagram for COVID-19 in a population (with all parameters, probability values and state variables defined in table 1)

The model is given by the following Ordinary Differential Equations:

$$\frac{dS}{dt} = \Lambda - \beta(1-k)SI - \mu S$$
$$\frac{dI}{dt} = \beta(1-k)SI - \delta I - m\alpha(1-q)I - \mu I \qquad (1)$$
$$\frac{dR}{dt} = m\alpha(1-q)I - \mu R$$

With initial conditions, S>0, I>0 and $R \geq 0$ and all parameters (rates) greater than zero.

5. EQUILIBRIUM POINTS

The equilibrium points of the system need to be determined in order to investigate the stability of the system. Although the stability at DFE will be investigated only.

At Equilibrium, $\frac{dS}{dt} = \frac{dI}{dt} = \frac{dR}{dt} = 0$. The equilibrium points that will be determined are:

i. Disease Free Equilibrium points.
ii. Endemic Equilibrium points.

5.1 DISEASE FREE EQUILIBRIUM POINTS DFE ($\boldsymbol{E_1}$)

The disease free equilibrium point is the state when there is no disease in the system [27].

Equating the ordinary differential equations of the system 1 to zero and setting $I = 0$ and $R = 0$ because, before a COVID-19 patient was introduced into the system, only the Susceptible class was present. Thus $S \neq 0$

From 3.1, we have that

$$\Lambda - \mu S = 0,$$

$$S = \frac{\Lambda}{\mu}$$

Therefore, Disease Free Equilibrium $\boldsymbol{E_1}(\boldsymbol{S_1}, \boldsymbol{I_1}, \boldsymbol{R_1}) = \left(\frac{\Lambda}{\mu}, 0, 0\right)$.

5.2 ENDEMIC EQUILIBRIUM POINTS EEP ($\boldsymbol{E_*}$)

This is a non-negligible equilibrium point since it involves solving for the state variables while the differential equations in system 1 is set to zero.

The state variables are expressed in terms of parameters only

So, from the system of equations 1:

$$\Lambda - \beta(1-k)\boldsymbol{S_*}\boldsymbol{I_*} - \mu\boldsymbol{S_*} = 0 \qquad (2)$$

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$$\beta(1-k)\boldsymbol{S}_*\boldsymbol{I}_* - \delta\boldsymbol{I}_* - m\alpha(1-q)\boldsymbol{I}_* - \mu\boldsymbol{I}_* = 0 \qquad (3)$$

$$m\alpha(1-q)\boldsymbol{I}_* - \mu\boldsymbol{R}_* = 0 \qquad (4)$$

Making $\boldsymbol{S}_*$ the subject of the formula from equation 3 we have:

$$\boldsymbol{S}_* = \frac{\delta + m\alpha(1-q) + \mu}{\beta(1-k)} \qquad (5)$$

It can be observed that $\boldsymbol{S}_*$ in equation 5 is expressed in terms of parameters only.

Making $\boldsymbol{S}_*$ subject from equation 2 and using equation 5 on the result we have $\boldsymbol{I}_*$ expressed in terms of parameters only:

$$\boldsymbol{I}_* = \frac{\Lambda}{\delta + m\alpha(1-q) + \mu} - \frac{\mu}{\beta(1-k)} \qquad (6)$$

Making $\boldsymbol{R}_*$ subject in equation 4, and substituting 6 in the result we have $\boldsymbol{R}_*$ expressed in terms of parameters only:

$$\boldsymbol{R}_* = \frac{m\alpha(1-q)}{\mu}\left[\frac{\Lambda}{\delta + m\alpha(1-q) + \mu} - \frac{\mu}{\beta(1-k)}\right] \quad (7)$$

Therefore, the Endemic Equilibrium Points $\boldsymbol{E}_*$ is given as:

$$(\boldsymbol{S}_*, \boldsymbol{I}_*, \boldsymbol{R}_*) = \left(\frac{\delta + m\alpha(1-q) + \mu}{\beta(1-k)}, \frac{\Lambda}{\delta + m\alpha(1-q) + \mu} - \frac{\mu}{\beta(1-k)}, \frac{m\alpha(1-q)}{\mu}\left[\frac{\Lambda}{\delta + m\alpha(1-q) + \mu} - \frac{\mu}{\beta(1-k)}\right]\right)$$

5.3 BASIC REPRODUCTION NUMBER R_o

The basic reproduction number, also called reproductive ratio R_o is the average secondary infections that can occur in a completely Susceptible population when one infected individual is introduced into it [28]. It is usually calculated at disease free equilibrium point.

The basic reproduction number, R_o is calculated using the second equation in the system of equations 1 above which is given as:

$$\frac{dI}{dt} = \beta(1-k)SI - \delta I - m\alpha(1-q)I - \mu I$$

Rearranging, we have:

$$\frac{dI}{dt} = (\delta + m\alpha(1-q) + \mu)\left(\frac{\beta(1-k)S}{\delta + m\alpha(1-q) + \mu} + 1\right)I \qquad (8)$$

The term at the left hand side contained in the larger bracket in equation 8 is the basic reproductive number which is written as:

$$\frac{\beta(1-k)S}{\delta + m\alpha(1-q) + \mu}$$

Since the basic reproduction number is expressed at DFE, $\boldsymbol{E_1}(\boldsymbol{S_1}, \boldsymbol{I_1}, \boldsymbol{R_1}) = \left(\frac{\Lambda}{\mu}, 0, 0\right)$ then the equation above is expressed as:

$$\frac{\beta(1-k)S_1}{\delta + m\alpha(1-q) + \mu}$$

Replacing S_1 with $\frac{\Lambda}{\mu}$ in the equation above we finally have that

$$R_o = \frac{\beta\Lambda(1-k)}{\mu(\delta + m\alpha(1-q) + \mu)} \qquad (9)$$

If $R_o < 1$, it implies that the disease will fizzle out with time but if $R_o > 1$, it implies that the disease will invade the population [31].

6. STABILITY OF DISEASE FREE EQUILIBRIUM POINTS

To investigate the stability of the equilibrium points, the Jacobian of the system of equation 1 is found and utilized. The stability at DFE will be investigated.

The general Jacobian J of the system 1 is written as

$$J = \begin{bmatrix} -\beta(1-k)I - \mu & -\beta(1-k)S & 0 \\ \beta(1-k)I & \beta(1-k)S - \delta - m\alpha(1-q) - \mu & 0 \\ 0 & m\alpha(1-q) & -\mu \end{bmatrix}$$

At DFE the Jacobian J_1 of the matrix J above becomes:

$$J_1 = \begin{bmatrix} -\mu & -\beta(1-k)S & 0 \\ 0 & \frac{\beta(1-k)\Lambda}{\mu} - \delta - m\alpha(1-q) - \mu & 0 \\ 0 & m\alpha(1-q) & -\mu \end{bmatrix}$$

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The determinant of $|J_1 - \lambda I|$ is found and the eigenvalues needs to be determined to investigate the stability of the system at DFE

$$|J_1 - \lambda I| = \begin{vmatrix} -\mu - \lambda & -\beta(1-k)S & 0 \\ 0 & \frac{\beta(1-k)\Lambda}{\mu} - \delta - m\alpha(1-q) - \mu - \lambda & 0 \\ 0 & m\alpha(1-q) & -\mu - \lambda \end{vmatrix} = 0$$

$$|J_1 - \lambda I| = (-\mu - \lambda)(-\mu - \lambda)\left(\frac{\beta(1-k)\Lambda}{\mu} - \delta - m\alpha(1-q) - \mu - \lambda\right) = 0$$

From the equation above, the eigenvalues are:

$$\lambda_1 = -\mu, \lambda_2 = -\mu \text{ and } \lambda_3 = \frac{\beta(1-k)\Lambda}{\mu} - \delta - m\alpha(1-q) - \mu \quad (10)$$

observing the expressions above, λ_1 and λ_2 are negative because μ has a positive value, λ_3 is also negative and this will be shown later on in this work when all the parameters are substituted in the result. Thus the disease free equilibrium is asymptotically stable.

This result gets to also prove that $R_o < 1$. Hence the disease free equilibrium is asymptotically stable if $R_o < 1$ [32].

7. RESULTS AND DISCUSSION

Here, parameters are replaced with values in the expressions for the reproductive ratio and eigenvalues (as obtained in equation 10) and their results will be discussed. Some parameters will be varied and their effects observed. Sensitivity analysis will also be carried out by MATLAB

Recall from equation 9,

$$R_o = \frac{\beta\Lambda(1-k)}{\mu(\delta + m\alpha(1-q) + \mu)}$$

When $k = 0$ and $\beta = 0.00000492$ (estimated value from table 1) with other parameters having the values displayed in table 1 then,

$$R_o = \frac{0.000173}{92.1605} = 0.00000188 < 1 \quad (11)$$

This result implies that the contact rate that gave rise to 131 infected persons as at 30th of March, 2020 (22:00 WAT) is not enough to cause the disease to invade the population in a hurry as time goes on.

However, without control measure, the contact rate increases as the number of infected persons increases and R_o begins to approach a value that is greater 1.

This can be shown when $k = 0$ and $\beta = 4.000$ (increased) R_o becomes;

$$R_o = \frac{140.8}{92.1605} = 1.528 > 1$$

Recall that if $R_o > 1$ then the disease will invade the population. It is important to note here that a contact rate of 4.000 (with every other parameter held constant) implies that a population of approximately 106,523,052 have been infected.

Although the situation is not irredeemable because control measure is introduced, for instance let $k = 0.5$ the reproductive ratio becomes less than one as shown below:

$$R_o = \frac{70.4}{92.1605} = 0.764 < 1$$

It is however obvious that the reproductive ratio reduces faster to a value lesser than one if control measure is introduced into the system as at when $\beta = 0.00000492$.

Meanwhile, to ascertain that the DFE is asymptotically stable, the values provided in table 1 is replaced with the appropriate parameters in the expression for the eigenvalues as obtained in equation 13

$$\lambda_1 = -\mu, \lambda_2 = -\mu \text{ and } \lambda_3 = \frac{\beta(1-k)\Lambda}{\mu} - \delta - m\alpha(1-q) - \mu$$

Replacing parameters with values, we have:

$\lambda_1 = \lambda_2 = -9.6$ and $\lambda_3 = -9.600031$.

Note that λ_3 is calculated when $k = 0$.

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8. Numerical Simulation

It can be seen in section 7 that an increase in β results to the tendency of R_o having a value greater 1 there by increasing the chances of the disease invading the population with time. The value of k also have an impact on the system because an increase in control measure k will result to a decrease in R_o. The reverse happens if k is reduced.

Thus, in this section numerical simulation is carried out using MATLAB; k and β will be varied and the results will be observed and discussed.

The following population samples will be used for easy illustration;

Susceptible = 1000; Infected = 131; Recovered= 8.

Note that the value of β will be increased slightly (and not to 4.000 as originally done above) to check the effect of varying k on the dynamics of the system because it is only a sample of the total population that is being considered here in the numerical simulation.

The graph below illustrates the general dynamics of the system with estimated values

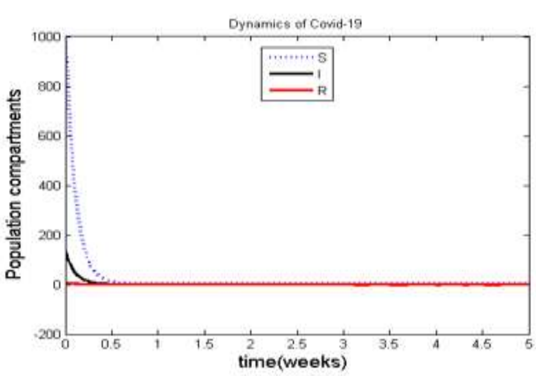

Fig 2: Graph of population classes against time (weeks) with β= 0.00000492 and k= o

As already shown in equation 11, that the current estimated value of β will not necessarily lead to an outbreak. It can be seen that the infected curve gradually diminishes with time.

It is pertinent to note that the susceptible population will not necessarily go to zero as depicted in the graph above because the estimated parameters used is this particular simulation is for that which was originally obtained from a population of approximately 200 000 000 individuals as opposed to this case where only a sample of 1000 individuals was selected.

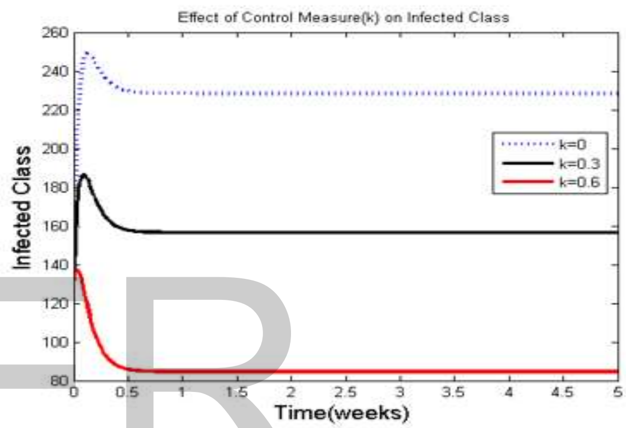

Fig 3: Graph of Infected population with varying k and increased β

Here β is increased to 0.035 and control measure k is varied.

It is observed that when k=0, the Infected population rises sharply from 131 to 252 then normalizes after 0.5 weeks where approximately 230 individuals remains in the compartment as time progresses.

When k=0.3, that is, when control measure is introduced, the infected population increases from 131 to approximately 185 after which the number drops and stays at 160.

With control measure intensified, that is when k= 0.6, the infected population reduces within a very short period of time and maintains a balance of about 90 individuals as time goes on.

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9. CONCLUSION

It has been shown here that the contact rate that led to 131 infected persons as at 30th of March 2020 (22:00 WAT) is not enough to lead to an outbreak in the population and that if control measure is introduced into the population, the disease has the tendency of fizzling out within a short period of time.

However, in the absence of control measure with increased contact rate the number of new cases rises but the situation is not unredeemable because when control measure is introduced into the system, the number of people who gets infected as time goes on begins to reduce.

Conclusively, with the existing control measures that have been put in place to curb the spread of the virus in the country such as lockdown in major cities, banning of entry flights from countries with over one thousand cases of Covid-19 and encouraging social distancing by maintaining that social gatherings be stopped as have already been declared in Lagos state, Nigeria [30], the disease will definitely fizzle out with time.

To intensify control measure in the country, the following recommendations are suggested:

- ❖ Heath workers who treat COVID-19 patients should be restricted to treating or attending only to COVID-19 patients to reduce the risk of patients with other form of illnesses from contracting the virus.
- ❖ Sanitation can be declared in every state at reasonable time intervals during and after the lockdown period to promote personal hygiene by the people in general.
- ❖ Commercial vehicles owners should be educated/encouraged to perform regular and thorough cleaning of their vehicles with reagents capable of deactivating the virus
- ❖ States that have the most occurrence of infected individuals should be fumigated.
- ❖ Twenty-four-hour regular monitoring by appropriate authorities aimed at checking that vehicles do not move in and out of the states where lockdowns have been declared.
- ❖ Close monitoring of those who have come in contact with the infected ones.

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