**Impact of continued closure of red-light areas on COVID-19 transmission in India**

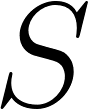
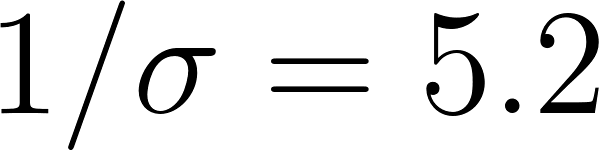
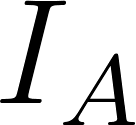
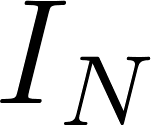
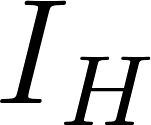
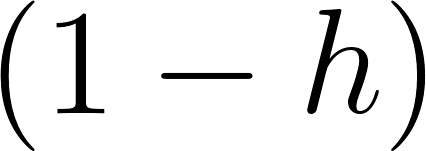
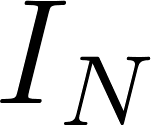
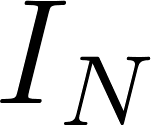
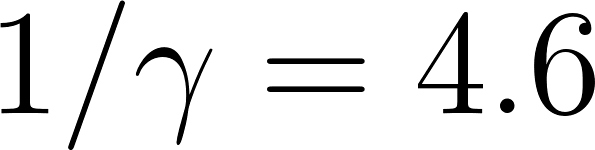
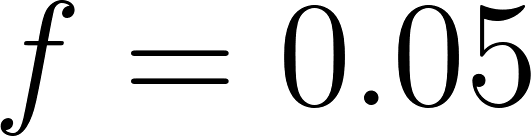
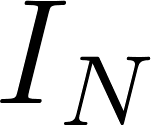
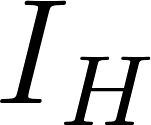
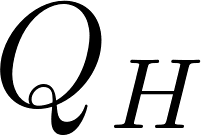
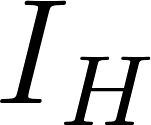
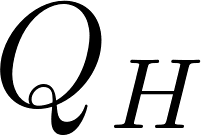
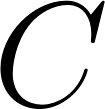
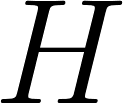
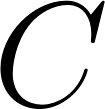
**Introduction**

**Method**We developed an age-structured SEIR-type dynamic model for COVID-19 transmission to understand the impact of continued closure of red light areas in five cities of India as well as nationally after the initial countrywide lockdown of 40 days from 24 March 2020 to 3 May 2020 (**Figure 1**). The population of each location compartmentalized into red-light area residents and the general population. Red-light area residents included sex workers as well as non-sex workers such as pimps, brothel managers, security, servants, and others performing miscellaneous roles in the area. The general population is the rest of the location's population. Each population was compartmentalized (**Table 2**) based on natural history of disease as well as interventions.

|  |  |
| --- | --- |
| **Table 2**. Model compartments | |
| Compartment | Definition |
|  | Susceptible |
|  | Incubation |
|  | Asymptomatic infections |
|  | Symptomatic severe infections (not isolated) |
|  | Symptomatic mild infections (not isolated) |
|  | Symptomatic severe infections (isolated) |
|  | Symptomatic mild infections (not isolated) |
|  | Hospitalization |
|  | Need ICU |
|  | Deaths |

### 

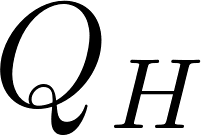
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| **Figure 1**. Model schematic. |

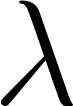
In our model, after a susceptible individual ([](https://www.codecogs.com/eqnedit.php?latex=S#0)) acquire infection, they remain in an non-infectious incubation period ([](https://www.codecogs.com/eqnedit.php?latex=E#0)) for an average of [](https://www.codecogs.com/eqnedit.php?latex=1%2F%5Csigma%20%3D%205.2#0) days (**Table 3**).. Following the incubation period, an infected individual either remains asymptomatic ([](https://www.codecogs.com/eqnedit.php?latex=I_A#0)) or develops symptoms ([](https://www.codecogs.com/eqnedit.php?latex=I_N#0),[](https://www.codecogs.com/eqnedit.php?latex=I_H#0)). A proportion of symptomatic individuals ([](https://www.codecogs.com/eqnedit.php?latex=(1-h)#0)) only develop mild symptoms ([](https://www.codecogs.com/eqnedit.php?latex=I_N#0)). Symptomatic individuals with mild symptoms ([](https://www.codecogs.com/eqnedit.php?latex=I_N#0),[](https://www.codecogs.com/eqnedit.php?latex=Q_N#0)) do not need hospitalization, and recover in an average of [](https://www.codecogs.com/eqnedit.php?latex=1%2F%5Cgamma%20%3D%204.6#0) days (Table 3). A proportion of individuals ([](https://www.codecogs.com/eqnedit.php?latex=f%20%3D%200.05#0)) with mild or severe symptoms are isolated within a day ([](https://www.codecogs.com/eqnedit.php?latex=I_N#0) → [](https://www.codecogs.com/eqnedit.php?latex=Q_N#0),[](https://www.codecogs.com/eqnedit.php?latex=I_H#0) → [](https://www.codecogs.com/eqnedit.php?latex=Q_H#0)). Symptomatic individuals with severe symptoms ([](https://www.codecogs.com/eqnedit.php?latex=I_H#0),[](https://www.codecogs.com/eqnedit.php?latex=Q_H#0)) either are hospitalized ([](https://www.codecogs.com/eqnedit.php?latex=H#0)), or are in an ICU within a hospital ([](https://www.codecogs.com/eqnedit.php?latex=C#0)). Those hospitalized ([](https://www.codecogs.com/eqnedit.php?latex=H#0),[](https://www.codecogs.com/eqnedit.php?latex=C#0)) either recover or die.

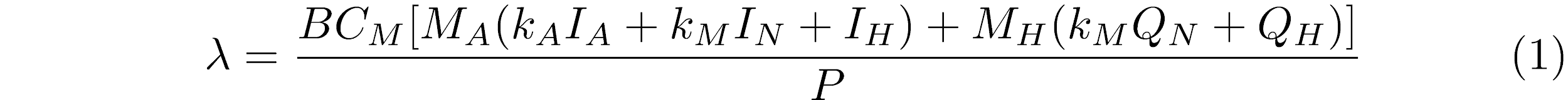
We stratified our model into four age groups: 0–19, 20–39, 50–64 and >65 years of age. We specified an age-distribution of each location based on the most recent census [[1]](https://paperpile.com/c/dN8otS/A429), and modeled to current population estimates for each location and for the red-light areas within it (Table 1).

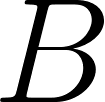
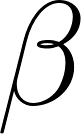
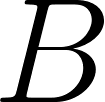
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| Table 1. Demography and red-light area data. | | | | | | |
| Location | Mumbai | Nagpur | Delhi | Kolkata | Pune | India |
| General population | 20,411,00 | 2,893,000 | 19,500,00 | 14,850,000 | 6,629,000 | 1,380,004,385 |
| Red-light area population | 5,471 | 2,310 | 4,048 | 16,000 | 6,345 | 637,500 |
| Total daily interaction between general population and red-light area | 441,000 | 252,000 | 777,000 | 2,112,000 | 820,000 | 20,475,000 |
| Contact rate between general population and red-light area () | 0.0216 | 0.0871 | 0.0398 | 0.1422 | 0.1237 | 0.01484 |

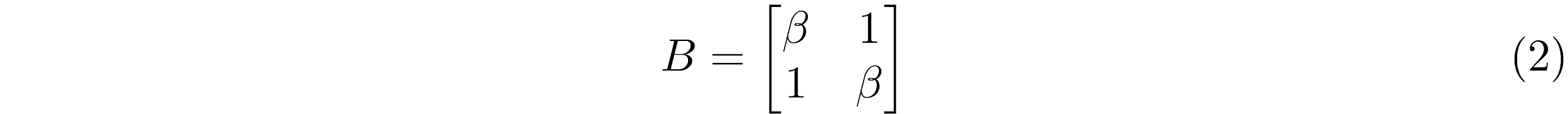
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Prem et. al [[2]](https://paperpile.com/c/dN8otS/Kwwz) estimated contact patterns between different age-groups in India overall and by different locations such as households. We use this estimate of overall contact pattern in India to inform the contact mixing between different age groups in our model. Contact mixing of individuals who are isolated ([](https://www.codecogs.com/eqnedit.php?latex=Q_N#0),[](https://www.codecogs.com/eqnedit.php?latex=Q_H#0)) is calibrated proportionally to contact patterns within households.

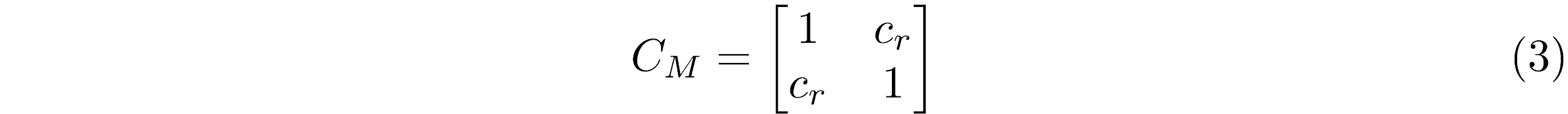
The force of infection [](https://www.codecogs.com/eqnedit.php?latex=%5Clambda#0) is given by

[](#D2L_code_render_ \begin{equation}
\lambda = \frac{B C_{M} [ M_{A}(k_{A} I_{A}+k_{M} I_{N}+I_{H})+M_{H}(k_{M}Q_{N}+Q_{H})]}{P}
\end{equation})

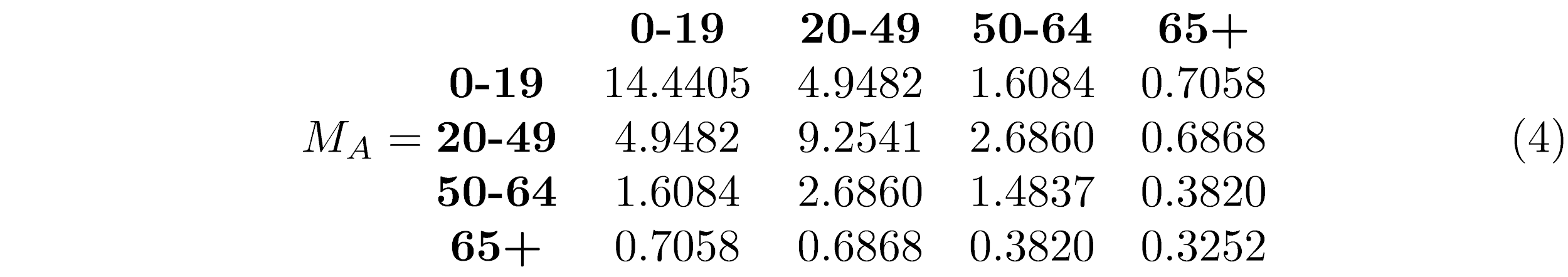
where [](https://www.codecogs.com/eqnedit.php?latex=B#0) is a matrix representing the probability of infection within and between a location and the red-light area within that location. Interaction between the general population and the red-light area occurs through customers from the general population.Given an interaction between a susceptible and infected individual, the probability of infection during an interaction between an individual from the general population and a resident of a red-light area is assumed to be 1. We specify a probability of infection within the red-light area or within in the general population of [](https://www.codecogs.com/eqnedit.php?latex=%5Cbeta#0), calibrated to the basic reproduction number [](https://www.codecogs.com/eqnedit.php?latex=R_0#0). Thus [](https://www.codecogs.com/eqnedit.php?latex=B#0) is given by

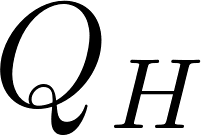
[](#D2L_code_render_\setcounter{equation}{1}
\begin{equation} 
B = \begin{bmatrix} \beta & 1 \\ 1 & \beta \end{bmatrix} \end{equation})

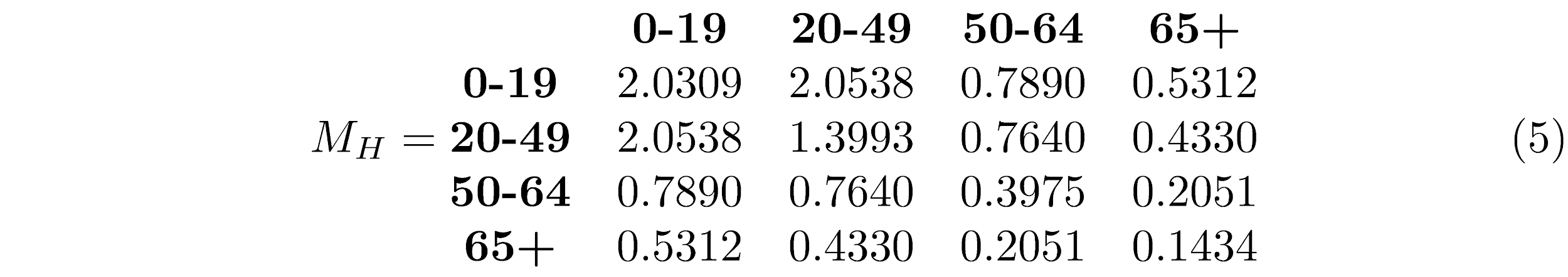
The interactions between the general population and the red-light area are informed in our model through a connectivity matrix [](https://www.codecogs.com/eqnedit.php?latex=C_M#0), where the contact rate [](https://www.codecogs.com/eqnedit.php?latex=c_r#0) (**Table 1**) between individuals from the general population and residents of the red-light area are calculated as a ratio of the daily total interaction of general population with red-light area residents and total population of the location (**Table 1**). The connectivity matrix [](https://www.codecogs.com/eqnedit.php?latex=C_M#0) is therefore

[](#D2L_code_render_\begin{equation} \tag{3}
C_M = \begin{bmatrix} 1 & c_r \\  c_r & 1 \end{bmatrix}
\end{equation})

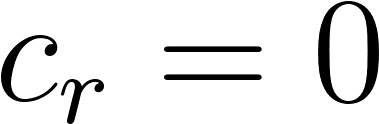
Individuals with mild infections are only 50% infectious compared to severe infections and we assume the relative infectiousness of asymptomatic cases to be the same (**Table 3**). The contact patterns between different age groups are informed by two matrices:

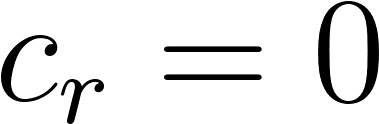
[](#"D2L_code_render_\setcounter{equation}{3})

when individuals are not isolated / quarantined in their home ([](https://www.codecogs.com/eqnedit.php?latex=Q_N#0),[](https://www.codecogs.com/eqnedit.php?latex=Q_H#0)), and

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when they are (matching contact patterns at the household level) [[2]](https://paperpile.com/c/dN8otS/Kwwz).

*Implementation of initial lockdown*To implement the 40 day national lockdown in our model, we specified that everyone remained at home, and their contact patterns were informed by the household matrix [](https://www.codecogs.com/eqnedit.php?latex=M_H#0) for the duration of lockdown. Moreover, set the interaction rate [](https://www.codecogs.com/eqnedit.php?latex=c_r%20%3D%200#0) between the general population and the red-light area at zero during this period.

*Post-lockdown*After the initial lockdown period, contact patterns were informed by the overall contact matrix [](https://www.codecogs.com/eqnedit.php?latex=M_A#0), and it was assumed that as a result of improved contact-tracing capacity achieved during lockdown, 50% of symptomatic cases were isolated after the lockdown period [[3]](https://paperpile.com/c/dN8otS/6qtn). For the scenario of continued closure of the red-light area after lockdown, we maintained the contact rate [](https://www.codecogs.com/eqnedit.php?latex=c_r%20%3D%200#0); with no lockdown it was reset at its original value (**Table 1**).

|  |  |  |  |
| --- | --- | --- | --- |
| **Table 3.** Model parameters | | | |
| Parameter | Definition | Value | Reference |
|  | Reproduction number | 1.75–2.25 | [[4,5]](https://paperpile.com/c/dN8otS/38yW+k1rM) |
|  | Probability of infection | Calibrated to | |
|  | Relative infectivity of asymptomatic infections | 0.5 | [[6]](https://paperpile.com/c/dN8otS/lLL3) |
|  | Relative infectivity of mild cases | 0.5 | [[6]](https://paperpile.com/c/dN8otS/lLL3) |
|  | Duration of incubation period | 5.2 | [[7]](https://paperpile.com/c/dN8otS/OWam) |
|  | Proportion of asymptomatic cases | 0.28 | [[8]](https://paperpile.com/c/dN8otS/tohb) |
|  | Proportion of severe symptomatic cases, age group 0–19 | 0.025 | [[9]](https://paperpile.com/c/dN8otS/ORd7) |
| Age group 20–49 | 0.32 |
| Age group 50–64 | 0.32 |
| Age group >65 | 0.64 |
|  | Number of days before isolation of symptomatic case | 1 | [[9]](https://paperpile.com/c/dN8otS/ORd7) |
|  | Proportion of symptomatic cases being isolated | 0.05 | [[9]](https://paperpile.com/c/dN8otS/ORd7) |
|  | Recovery period of mild and asymptomatic cases | 4.6 | [[9]](https://paperpile.com/c/dN8otS/ORd7) |
|  | Hospitalization rate | 1/3.5 | [[10]](https://paperpile.com/c/dN8otS/fwfy) |
|  | Proportion of symptomatic cases needing ICU in hospitals, age group 0–19 | 0.014 | [[9]](https://paperpile.com/c/dN8otS/ORd7) |
| Age group 20–49 | 0.042 |
| Age group 50–64 | 0.075 |
| Age group >65 | 0.15 |
|  | Proportion of hospitalized cases that are fatal | 0.2296 | [[9]](https://paperpile.com/c/dN8otS/ORd7) |
|  | Proportion of hospitalized cases needing ICU that are fatal | 0.1396 | [[9]](https://paperpile.com/c/dN8otS/ORd7) |
|  | Recovery rate of hospitalized cases | 1/10 | [[11]](https://paperpile.com/c/dN8otS/PFuL) |
|  | Recovery rate of hospitalized cases needing ICU | 1/13.25 | [[10]](https://paperpile.com/c/dN8otS/fwfy) |
|  | Mortality rate of hospitalized cases | 1/9.7 | [[10]](https://paperpile.com/c/dN8otS/fwfy) |
|  | Mortality rate of hospitalized cases needing ICU | 1/7 | [[12]](https://paperpile.com/c/dN8otS/SpsH) |

**Results**

**Discussion**

**References**

1. [MoHA I. Census of India Website: Office of the Registrar General & Census Commissioner, India. 2011. Available:](http://paperpile.com/b/dN8otS/A429) <http://censusindia.gov.in/2011census/C-series/C-13.html>

2. [Prem K, Cook AR, Jit M. Projecting social contact matrices in 152 countries using contact surveys and demographic data. PLoS Comput Biol. 2017;13: e1005697.](http://paperpile.com/b/dN8otS/Kwwz)

3. [Mandal S, Bhatnagar T, Arinaminpathy N, Agarwal A, Chowdhury A, Murhekar M, et al. Prudent public health intervention strategies to control the coronavirus disease 2019 transmission in India: A mathematical model-based approach. Indian J Med Res. 2020. doi:](http://paperpile.com/b/dN8otS/6qtn)[10.4103/ijmr.IJMR\_504\_20](http://dx.doi.org/10.4103/ijmr.IJMR_504_20)

4. [Singh R, Adhikari R. Age-structured impact of social distancing on the COVID-19 epidemic in India. arXiv [q-bio.PE]. 2020. Available:](http://paperpile.com/b/dN8otS/38yW) <http://arxiv.org/abs/2003.12055>

5. [Pandey G, Chaudhary P, Gupta R, Pal S. SEIR and Regression Model based COVID-19 outbreak predictions in India. arXiv [q-bio.PE]. 2020. Available:](http://paperpile.com/b/dN8otS/k1rM) <http://arxiv.org/abs/2004.00958>

6. [Li R, Pei S, Chen B, Song Y, Zhang T, Yang W, et al. Substantial undocumented infection facilitates the rapid dissemination of novel coronavirus (SARS-CoV2). Science. 2020. doi:](http://paperpile.com/b/dN8otS/lLL3)[10.1126/science.abb3221](http://dx.doi.org/10.1126/science.abb3221)

7. [Lauer SA, Grantz KH, Bi Q, Jones FK, Zheng Q, Meredith HR, et al. The Incubation Period of Coronavirus Disease 2019 (COVID-19) From Publicly Reported Confirmed Cases: Estimation and Application. Ann Intern Med. 2020. doi:](http://paperpile.com/b/dN8otS/OWam)[10.7326/M20-0504](http://dx.doi.org/10.7326/M20-0504)

8. [Qiu H, Wu J, Hong L, Luo Y, Song Q, Chen D. Clinical and epidemiological features of 36 children with coronavirus disease 2019 (COVID-19) in Zhejiang, China: an observational cohort study. Lancet Infect Dis. 2020. doi:](http://paperpile.com/b/dN8otS/tohb)[10.1016/S1473-3099(20)30198-5](http://dx.doi.org/10.1016/S1473-3099(20)30198-5)

9. [Moghadas SM, Shoukat A, Fitzpatrick MC, Wells CR, Sah P, Pandey A, et al. Projecting hospital utilization during the COVID-19 outbreaks in the United States. Proc Natl Acad Sci U S A. 2020;117: 9122–9126.](http://paperpile.com/b/dN8otS/ORd7)

10. [COVID-19. Github; Available:](http://paperpile.com/b/dN8otS/fwfy) <https://github.com/midas-network/COVID-19>. Accessed: February 22, 2020.

11. [Wang D, Hu B, Hu C, Zhu F, Liu X, Zhang J, et al. Clinical Characteristics of 138 Hospitalized Patients With 2019 Novel Coronavirus-Infected Pneumonia in Wuhan, China. JAMA. 2020. doi:](http://paperpile.com/b/dN8otS/PFuL)[10.1001/jama.2020.1585](http://dx.doi.org/10.1001/jama.2020.1585)

12. [Yang X, Yu Y, Xu J, Shu H, Xia J ’an, Liu H, et al. Clinical course and outcomes of critically ill patients with SARS-CoV-2 pneumonia in Wuhan, China: a single-centered, retrospective, observational study. Lancet Respir Med. 2020. doi:](http://paperpile.com/b/dN8otS/SpsH)[10.1016/S2213-2600(20)30079-5](http://dx.doi.org/10.1016/S2213-2600(20)30079-5)