# The current state of COVID-19 in Colorado and projected course of the epidemic in the coming weeks


## Prepared by the Colorado COVID-19 Modeling Group

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**Summary / Key findings:**

- Mobility has continued to increase in Colorado. Mobility, as measured by time spent away from home using anonymized and aggregated mobile device data, was lowest in early April and has been increasing steadily since mid-April.
- COVID-19 hospitalizations have declined in Colorado since mid-April. Whether the decline will continue is not certain.
- We estimate that the net effect of social distancing, mask-wearing and case isolation has been to reduce the reproductive number below 1 during the state-wide Stay at Home order, which ended statewide on April 26 and was extended to May 8 for six counties of the Denver metro region.
- It is too early to say with confidence what the impact of the transition to Safer at Home has been on the course of the COVID-19 epidemic in Colorado. There is an approximately 13-day lag between infection and hospitalization, the indicator that guides the modeling. Additionally, the change to Safer at Home was not abrupt (e.g., retail did not open until May 4) and approximately 50% of the state's population remained under Stay at Home through May 8 because of the extension of Stay at Home in the metro-Denver region. We anticipate the earliest we will be able to make preliminary estimates as to the impact of the transition to Safer at Home statewide would be May 29.
- The updated modeling results in this report continue to indicate that all control measures available, including relatively high levels of social distancing need to be utilized. Increases in case detection and isolation, mask-wearing and social distancing of approximately 65% can prevent a surge in infections in excess of hospital capacity in the coming summer months.
- If Colorado moves to lower levels of social distancing (55%), older adults will need to maintain social distancing at the level seen during Stay at Home in order to avoid exceeding hospital capacity. If only half of older adults adopt high levels of social distancing under a 55% social distancing scenario, the state is at risk of exceeding hospital capacity this summer. We recommend that policy measures continue to emphasize the need for older adults to adopt measures to minimize their close physical contacts outside of their homes, thereby reducing

their risk for infection, hospitalization, and death and preventing exceedance of hospital capacity.

- Relaxation of social distancing to lower levels (45%) is predicted to lead to a surge in sick people in excess of hospital capacity by mid-summer, even if implemented with mask wearing, increased case detection and isolation, and higher levels of social distancing by all older adults.
- Around mid-August, the date at which schools generally open, the epidemic curves under all scenarios are rising.
- The uncertainty highlighted in this report regarding the current course of the COVID-19 epidemic under Safer at Home, will lessen over the coming days. Estimates of the trajectory of the outbreak under Safer at Home will be valuable for making decisions concerning further relaxation of social distancing.

## Introduction

The goals of this report are to:

1. Evaluate the current state of COVID-19 in Colorado, including the estimated collective impact of interventions to promote physical distancing, mask wearing and other disease control measures to date (Part 1);
2. Use information on the current state of the COVID-19 epidemic in Colorado to project the likely number of cases and hospitalizations in the coming months under different scenarios (Part 2);

We use the previously developed age-structured SEIR model, as described in prior reports [1, 2]. The model has been updated to use daily reported hospital census data of COVID-19 confirmed hospitalized cases for model calibration, and Colorado-specific estimates of the probability of hospitalization and critical care among cases (see Methods Appendix). With these updates we no longer rely on reported COVID-19 case data, as the case numbers are sensitive to testing capacity and consequently may represent a variable proportion of actual infections over time. These changes also allow us to better account for the underlying health status of the population of Colorado, which is a strong predictor of the number of people with more severe disease. We also now use near real-time mobility data to identify inflection points – points at which we see changes in population movement that may indicate changes in the extent of interactions among people ("contact rates"). Such changes represent one factor (in combination with measures like physical distancing and mask wearing) that contribute to the potential for virus spread. Because our model is now fit to hospitalization data, we use model outputs to estimate the proportion of infected individuals being detected by surveillance systems (see Appendix – Case Detection).

## Part 1. Current state of COVID-19 in Colorado estimated cumulative impact of interventions to date

We used our age-structured SEIR model and EMR-hospital census data reported through 5/19/2020 to estimate the current status of the COVID-19 epidemic in Colorado and the collective impact of current efforts to reduce the spread of the SARS-CoV-2 virus. Our model presently includes three interventions to slow the spread of infections: 1) social distancing; 2) mask wearing; and 3) case isolation, described in detail, below. We use our model output to estimate the effective reproductive number – the average number of infections directly generated by each case – over time, which provides an approximation of the cumulative impact of these interventions to date. In addition, we use near real-time mobility data to evaluate changes in population movement in relationship to social distancing policies. Because there is an approximately 13-day lag, on average, between infection and hospitalization (this interval includes an average 5-day incubation period and 8 days between the onset of infectiousness and hospitalization), these estimates relate to the state of COVID-19 transmission up to May 6.

**Interventions included in the model of COVID-19 to date.**

***Case isolation***. From the beginning of the pandemic, health officials have recommended that anyone with symptoms, or a diagnosis of COVID-19 should self-isolate. We assume that a proportion of symptomatic individuals self-isolate, albeit imperfectly, starting on March 5, the date the first case of COVID-19 was reported in Colorado (CDPHE). We assume that a proportion of symptomatic cases self-isolate 48 hours after the onset of infectiousness. In addition, we assume isolation primarily reduces the spread of infection to members outside of an individual's household. As approximately 23% of contacts

occur within the home [3], self-isolation is assumed to decrease the 76% of contacts that occur outside of the home. Accounting for both the delay in isolation and the fact that some household contacts will continue under self-isolation, we model self-isolation as a 57% decrease in contacts among those that self-isolate. We use prior model fits based on hospitalization data through 5/11/2020 – the best parameter value fit to the data suggests that ~53% of symptomatic cases have been self-isolating, regardless of testing positive, since March 5.

***Social distancing.*** Social distancing measures were adopted in Colorado starting in mid-March, to reduce person-to-person contacts and slow the spread of infection. As previously, we model social distancing, using a parameter that describes the percent decrease in effective contacts between susceptible and infectious individuals. This parameter accounts for social distancing policies intended to avoid contact altogether (e.g., through workplace and school closures) as well as policies and individual behaviors to reduce potential contact with the virus (e.g., maintaining at least 6 feet of distance between people outside of one's household, and handwashing). To account for the changes in the degree of social distancing over time, we model three phases of social distancing.

- Phase 1 (3/17-3/25): Social distancing measures were implemented in Colorado starting in mid-March in Colorado. Ski resorts were closed on 3/14, many schools by 3/16, and bars, restaurants, theatres and casinos were closed 3/17. For the purpose of the model, we assign a start date of 3/17. Figure 1 indicates that declines in population interaction may have begun earlier. We use prior model fits based on hospitalization data through 5/11/2020 – the best parameter value fit to the data suggests that the phase 1 social distancing parameter reached approximately 52%.
- Phase 2 (3/26-4/26): State-wide stay at home order, which began on 3/26 and ended on 4/26. We use prior model fits based on hospitalization data through 5/11/2020 – the best parameter value fit to the data suggests the phase 2 social distancing parameter is approximately 80%.
- Phase 3 (4/27-5/6): Safer at home. Colorado transitioned to Safer at home on 4/27 but six of the seven counties of the Denver metro region, comprising approximately 50% of the Colorado population was under a regional stay at home policy through 5/8. Due to the aforementioned lags between infection and hospitalization, this parameter does not yet account for the state-wide transition to Safer at Home. We use model fitting to estimate level of social distancing for this phase.

The level of reduction in contact rate is assumed to be equal across all age groups. We evaluate the potential impacts of higher levels of social distancing by older populations, who are at higher risk of morbidity and mortality in Part 2.

***Mask wearing.*** As of April 4, Coloradoans have been advised to wear masks in public. Masks are intended to trap droplets containing viral particles shed by infectious individuals. We model the effectiveness of mask wearing as a reduction in transmission by asymptomatic and pre-symptomatic individuals (details in the Methods Appendix, below). We use prior model fits based on hospitalization data through 5/11/2020 – the best parameter value fit to the data suggests approximately 40% of the population has been wearing masks beginning on 4/4, coinciding with the Governor's press conference advising Coloradoans to wear masks. We assumed a further increase in mask wearing to 50% of the population beginning on 4/27, corresponding with orders to wear masks in businesses in most major metropolitan areas in Colorado.

**Changes in population movement in relationship to social distancing orders**

We used anonymized and aggregated mobile device data to evaluate the relationship between social distancing interventions and the amount of time people spend at home (for further details see [4]). These data are available aggregated at the Census block group level.

Figure 1 shows that time spent at home, an indirect indicator of mobility and contact with others, had been increasing since the start of the epidemic in early March and continued to increase following the Phase 1 closures and the Phase 2 stay at home order. The amount of time spent at home begins to decline in mid-April, ahead of the expiration of the Stay at Home order on April 26. We caution that a decline of time at home does not necessarily indicate that time is spent in ways that increase transmission risk. For example, people may practice physical distancing and wear masks outside of their home, and/or spend time outside of the home partaking in low-risk activities such as taking walks in their neighborhood. The temperature warmed across the month, perhaps encouraging outdoor activity.

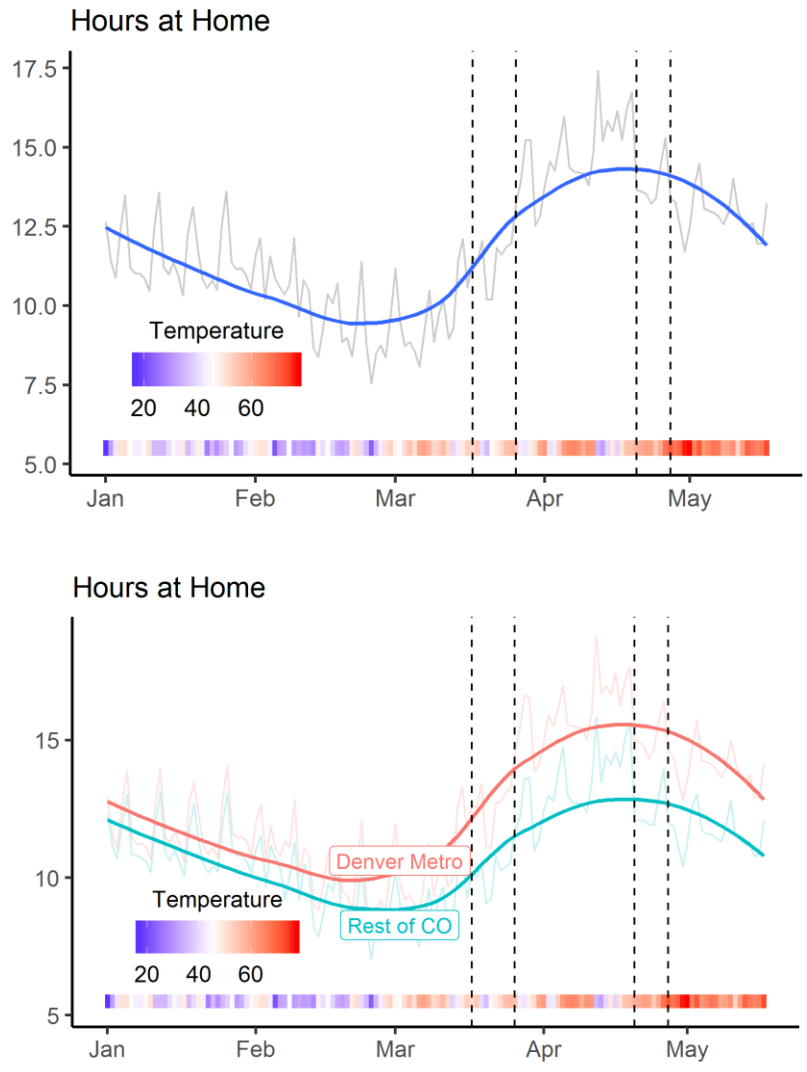


**Figure 1.** The median number of hours spent at home based on SafeGraph from 1/01/20 to 5/17/20 for all of Colorado (top panel) and stratified by the Denver metro region (bottom panel). Dashed lines

indicate the beginning of social distancing measures in mid-March (assigned a date of 3/17), the state-wide stay at home order (3/26), the announcement of the end of the state-wide stay at home order (4/20) and the actual transition to Safer at Home (4/27). The Denver metro region, comprising 50% of the Colorado population, transitioned to Safer at Home on 5/9. The color ribbon indicates CO average maximum daily temperature where blue is cool and red is warm (white is mean 45 degrees F).

**Estimated cumulative impact of interventions to date**

The number of hospitalized COVID-19 patients in Colorado plateaued in early April and has declined since mid-April (Figure 2). This pattern suggests that high levels of social distancing, in addition to mask wearing and case isolation through, and perhaps beyond, the end of Stay at Home on 4/26 led to declines in COVID-19. Because the Denver metro region, including approximately 50% of the Colorado population, transitioned to Safer at Home on May 9, it is too early to say with confidence what the state-wide impact of Safer at Home has been. There is a 13-day lag, on average, between infection and hospitalization (this includes an average 5-day incubation period and 8 days between the onset of infectiousness and hospitalization). We anticipate the earliest we will be able to make preliminary estimates with some certainty as to the impact of the transition to Safer at Home statewide would be May 29, when we would see the impact through May 16 approximately.

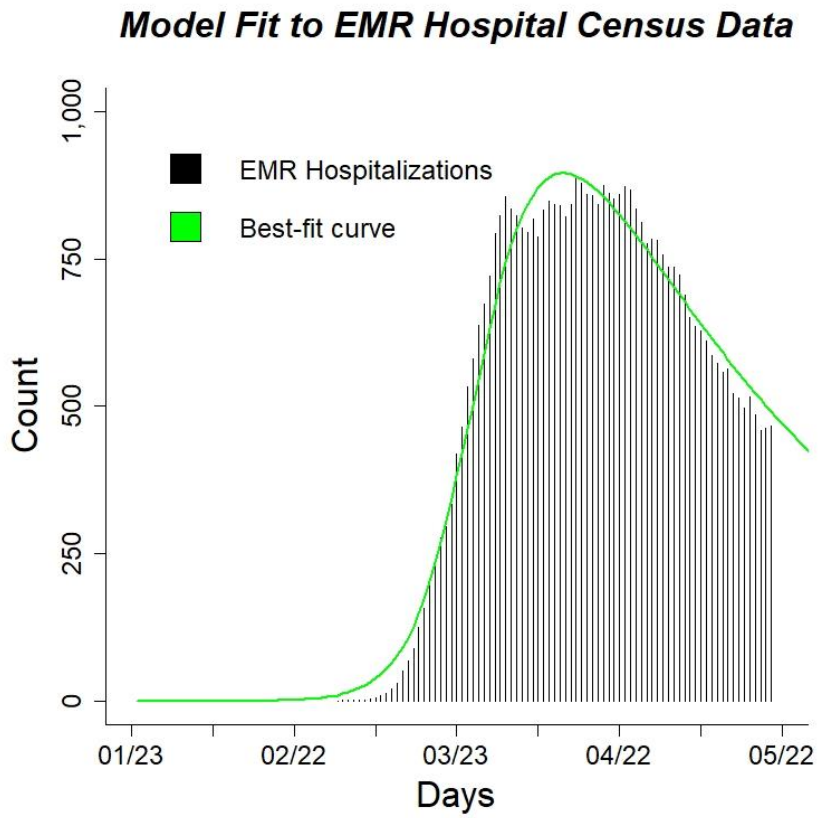


**Figure 2.** Current model fit to hospitalized COVID-19 cases using the age-structured SEIR model. Hospitalized COVID-19 cases are from CDPHE reported COVID-19 hospitalizations and EMResource (EMR) hospital census data provided by CDPHE through 5/19/2020.

We estimate that social distancing has not yet meaningfully changed between phase 2 and phase 3 and remains at approximately 80% (Table A1). However, given the lags described above, it is unclear if this is due to the extended stay at home order for the Denver metro region. We also examined whether there was evidence for a change in social distancing starting on April 20, as our mobility data indicate shifts in population movement starting on 4/20. When we shifted the start date of phase 3 to 4/20, we still did not find evidence that social distancing has changed. We will re-examine evidence for changes in the social distancing parameter as more data accrue.

The model estimates that the overall impact of the interventions to slow the spread of COVID-19 to date has been to reduce the reproductive number below 1 for most of April and into early May (Figure 3). This decline in the reproductive number underlies the drop in the number of cases.

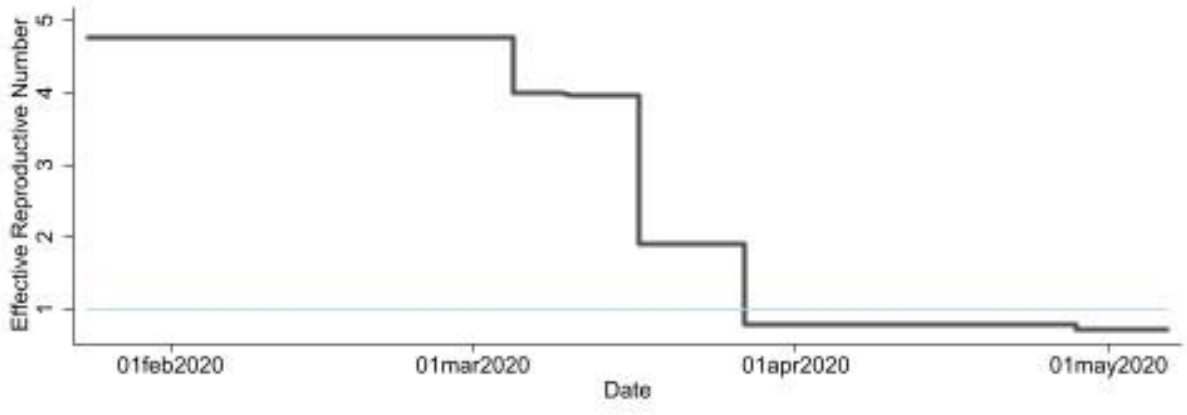


**Figure 3.** The estimated effective reproductive number in Colorado through May 6, describing the average number of infections directly generated by each case, plotted as a function of time. Blue line shows a reproductive number of 1. When the reproductive number is above 1, infections are increasing; when below 1, infections are decreasing. Estimation methods are described in the Methods Appendix.

## Part 2. What do we project for the coming months?

We used the age-structured SEIR model to project the expected number of total hospitalizations and need for critical care in the coming months under a set of scenarios that include relaxation of social distancing and recommendations that older populations maintain high levels of social distancing. In these scenarios, we maintain the assumptions that approximately 50% of the population wears masks outside of their homes indefinitely across the time span modeled. Additionally, we assume a gradual increase in case isolation as result of increased testing capacity. We assume that individuals who test positive will be more likely to self-isolate and, as a result of increases in testing going forward, the proportion of symptomatic individuals who choose to self-isolate will increase over time, rising by 5% weekly starting on June 1, with a maximum of 80% of symptomatic individuals self-isolating. Additionally, we assume social distancing is at 65% from May 9 to May 27 to account for potential reductions in social distancing corresponding with the later transition to Safer-at-Home in the Denver region. The parameter estimates and methods are described in detail in the Methods Appendix and Table 1A.

We considered the following scenarios for reducing social distancing.

***Set 1. Population-wide decreases in social distancing***

| Scenario | Social distancing by the general population starting 5/27* |
|---|---|
| 1A | 65%, maintained indefinitely |
| 1B | 55%, maintained indefinitely |
| 1C | 45%, maintained indefinitely |
| 1D | 55% until 6/26, reduced to 45% 6/27, maintained indefinitely |

*All scenarios assume social distancing is 65% starting 5/9, corresponding with modest declines in social distancing anticipated under the end of stay at home order in all Colorado counties.

***Set 2. Decreases in social distancing, with vulnerable populations maintaining high levels of social distancing.*** We modeled the same four scenarios, above, with the additional assumption that adults age 60 and over maintain 80% social distancing indefinitely.

| Scenario | Social distancing by the general population starting 5/27* | High social distancing by older adults (age>60)* |
|---|---|---|
| 2A | 65%, maintained indefinitely | 80% |
| 2B | 55%, maintained indefinitely | 80% |
| 2C | 45%, maintained indefinitely | 80% |
| 2D | 55% until 6/26, reduced to 45% 6/27 maintained indefinitely | 80% |

*All scenarios assume social distancing is 65% for ages 0 to 59 starting 5/9, corresponding with modest declines in social distancing anticipated under the end of stay at home order in all Colorado counties. Social distancing by older adults is modeled at 80% from the start of the stay at home order, maintained indefinitely.

***Set 3. Decreases in social distancing, with about half of vulnerable populations maintaining high levels of social distancing.*** We modeled the same four scenarios, above, assuming approximately half of adults age 60 and over maintain 80% social distancing indefinitely.

| Scenario | Social distancing by the general population starting 5/27* | High social distancing by approximately 50% of older adults (age>60)** |
|---|---|---|
| 3A | 65%, maintained indefinitely | *5/9 forward:* Half at 80%, Half at 65% (modeled as SD=72.5%) |
| 3B | 55%, maintained indefinitely | *5/9 – 5/26:* Half at 80%, Half at 65% (modeled as SD=72.5%)<br>*5/27 forward:* Half at 80%, Half at 55% (modeled as SD=67.5%) |
| 3C | 45%, maintained indefinitely | *5/9 – 5/26:* Half at 80%, Half at 65% (modeled as SD=72.5%)<br>*5/27 forward:* Half at 80%, Half at 45% (modeled as SD=62.5%) from 5/27 |
| 3D | 55% until 6/26, reduced to 45% 6/27 maintained indefinitely | *5/9 – 5/26:* Half at 80%, Half at 65% (modeled as SD=72.5%)<br>*5/27 to 6/27:* Half at 80%, Half at 55% (modeled as SD=67.5%)<br>*6/27 forward:* Half at 80%, Half at 45% (modeled as SD=62.5%) |

*All scenarios assume social distancing is 65% for ages 0 to 59 starting May 9, corresponding with modest declines in social distancing anticipated under the end of stay at home order in all Colorado counties.

** We assume approximately half of older adults maintain high levels of social distancing (80%) and the other half maintain the level of social distancing by the general population, which is 65% from 5/9 to 5/26, and as indicated by the scenario from 5/27 forward.

The key findings are in Table 1 and in the panels of Figure 4. The vertical line is at August 15, 2020, the data at which school openings would begin. Our current projections indicate that if social distancing is maintained at approximately 65%, mask wearing is maintained at current levels, and case detection and isolation is gradually increased (Scenario 1A, 2A and 3A), we do not expect to exceed hospital capacity over the summer (Figure 4, Table 1). If social distancing is relaxed further to approximately 55%, older populations will need to maintain high levels of social distancing in order to prevent exceedance of hospital capacity (Scenario 1B, 2B and 3B). If social distancing is relaxed to 55% and only 50% of older populations maintain high levels of social distancing (Scenario 3B), we expect to exceed hospital capacity by the end of summer. In reality, we do not know what proportion of older adults will adopt and maintain more stringent social distancing practices.

Greater reductions in social distancing (e.g., to 45%, Scenarios 1-3C and 1-3D) have the potential to create a surge in cases this summer that greatly exceeds hospital capacity, even if older populations maintain high levels of social distancing. Note that in all scenarios, the epidemic curve is rising at the vertical line at August 15.

These projections do not account for the potential impacts of contact tracing (discussed below) or any seasonal impacts on transmission, which remains unresolved. Moreover, they do not address the important and complex question of how individuals will respond to changes in policy – whether they will continue to adopt behaviors to reduce transmission (e.g. staying at home, maintaining at least 6 feet of distance between people outside of the household) in this next phase of the pandemic.

Contact tracing, either manual or digital, has been proposed for helping manage the pandemic in the absence of a vaccine. While Feretti et al. [5] suggested possible large reductions in R0 due to digital contact tracing strategies, more recent assessments of contact tracing with mathematical modelling frameworks suggest more muted impacts. For example, Ferrari et al. [6] found that the effectiveness of contact tracing was reduced in areas of higher population density [5]. Bradshaw et al. [7] found that the impact of contact tracing, manual or digital, was relatively ineffective in containing outbreaks based on R0 values that were more plausible than those considered in Feretti [5]. Bilinksi et al. [8] found that the intensity of contact tracing has to be quite substantial in order for it to lead to substantial reductions in R0. This may be more feasible when infection levels are low and/or social distancing is high.

**Table 1.** Projected date that ICU bed capacity is reached in Colorado under model projections assuming different levels of phase 3 social distancing. ICU capacity is estimated at 1,800 critical care beds, a figure provided by CDPHE.

| | Set 1 Population-wide decreases in social distancing | Set 2: Decreases in social distancing with high levels of social distancing (80%) by older adults (age 60+) | Set 3: Decreases in social distancing with high levels of social distancing by half of vulnerable populations |
|---|---|---|---|
| Scenario A: 65% SD* | N/A | N/A | N/A |
| Scenario B: 55% SD | 07/31 | N/A* | 08/27 |
| Scenario C: 45% SD | 07/08 | 08/12 | 07/22 |
| Scenario D: 55% SD in June, 45% July forward | 07/22 | 08/26 | 08/04 |

*Under these scenarios, ICU capacity is not expected to be exceeded. ICU capacity of is fixed at 1,800 critical care beds, which accounts for increased ICU need as social distancing is relaxed and elective surgeries are resumed.

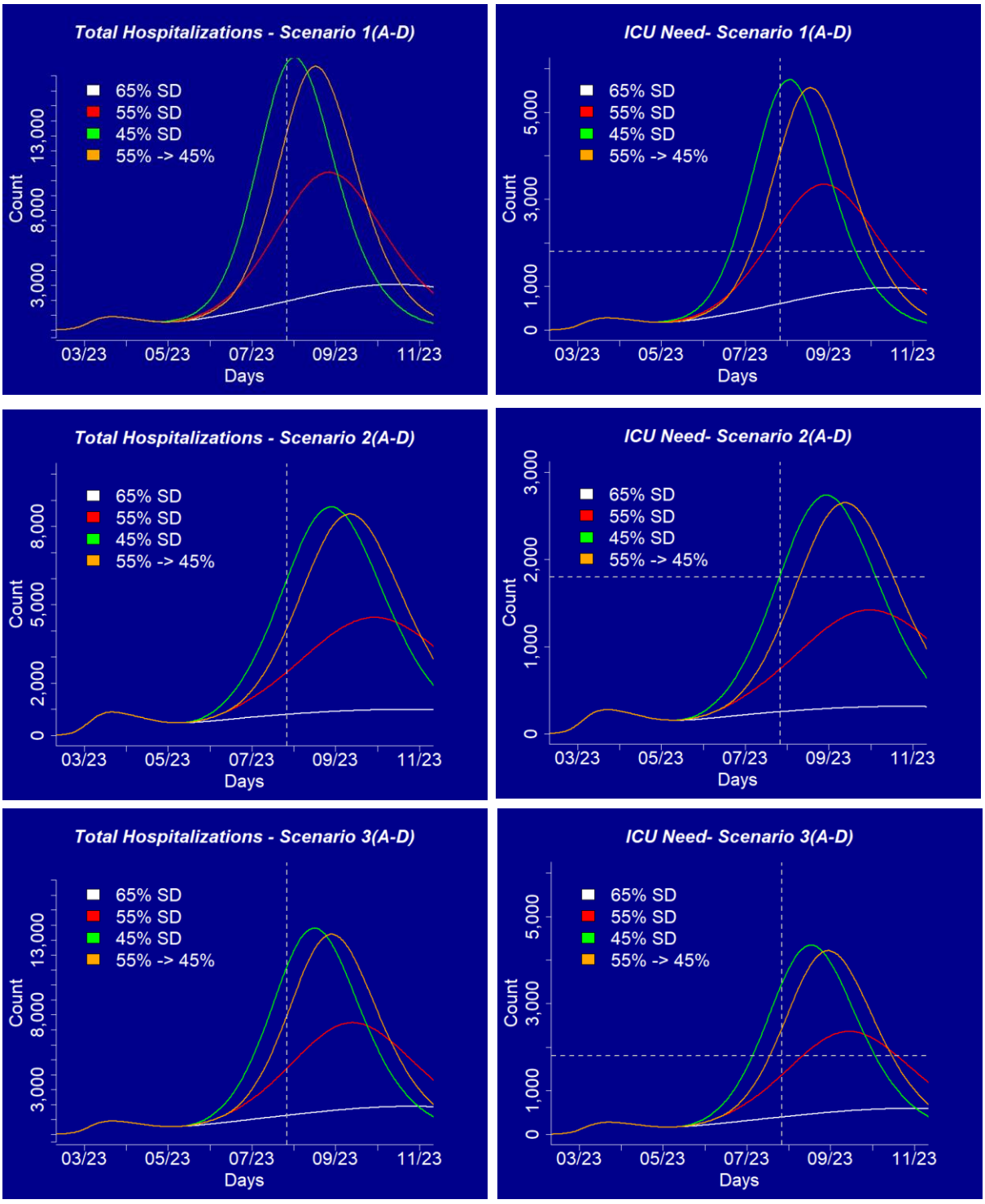


**Figure 4.** Projected total hospitalizations (left) and ICU needs (right) using the age-structured SEIR model for four scenarios that include relaxation of social distancing on 5/27 to 65%, 55%, 45% as well as a scenario that considers relaxation of social distancing to 55% on 5/27 and to 45% on 6/27. These scenarios are modelled as population-wide changes in social distancing (top), changes in social distancing assuming older populations (age >60) maintain high levels (80%) of social distancing (middle), and changes in social distancing assuming half of older populations (age >60) maintain high levels (80%) of social distancing (bottom). These projections assume that the indicated levels of social distancing are

maintained indefinitely, mask-wearing is maintained at current levels, and case isolation gradually increases up to 80% of symptomatic cases self-isolating within 48 hours of infectiousness. Grey vertical dashed line indicates August 15. Horizontal dashed line indicates ICU threshold of 1,800 beds. All scenarios assume social distancing is at 65% from 5/9 to 5/26.

## Methods Appendix

In this report, we used the previously described age-structured SEIR model [1, 2], with updates as detailed, below.

***Colorado-specific estimates of the probability of hospitalization and critical care need.*** The severity of symptoms and the need for hospital care is linked to both age and comorbidities and thus, may vary regionally due to differences in underlying population health. Initially, we used the estimates of Verity [9] to estimate the probability a symptomatic case would become hospitalized and/or need critical care. We now update these estimates to Colorado-specific clinical data. In order to calculate estimates of age-specific probability of hospitalization and needing critical care among COVID-19 patients in Colorado, we used a sequential curve-fitting method. For each curve-fitting step, the model output was fit to Colorado data using a two-part optimization. First, total hospitalization in the model was fit to total hospitalization data using presumed date of admission (based on the sample collection date from CDPHE data). After parameter values were determined from fitting the model to total hospitalizations, additional curve fitting was done to obtain estimates for the parameters for probability of hospitalization by age and probability of ICU admission by age by fitting to each of the following six curves: hospitalizations among individuals under 30, 30-59, and over 60 and ICU admission among individuals under 30, 30-59, and over 60. The Colorado-specific parameter estimates are described in Table A1. These estimates are comparable to estimates emerging from US and Europe [10, 11].

**Table A1.** Estimated probability that a symptomatic case will need hospital care based on Colorado case and hospitalization data, compared to prior estimates obtained from the literature, adjusted to the age-structure of the Colorado population.

| Age Group | Probability of non-ICU hospitalization given symptomatic COVID-19 | Probability of needing ICU care given symptomatic COVID-19 |
|---|---|---|
| **Colorado*** | | |
| Under 30 | 0.00419 | 0.004 |
| 30 – 59 | 0.056 | 0.019 |
| 60 + | 0.089 | 0.035 |
| **Verity et al*** | | |
| Under 30 | 0.006 | 0.0003 |
| 30 – 59 | 0.059 | 0.0045 |
| 60 + | 0.207 | 0.0808 |

*The Colorado estimates were based on two-part optimization using Colorado hospitalization data and our age-structured SEIR model.
**The Verity estimates [9] were based on case reports from China and other countries in the early stages of the epidemic (through February) and were summarized by [12]. The Verity et al. estimates presented in the table are standardized using Colorado population age distribution from CDPHE 2020 estimates.

***Colorado-specific estimates of hospital and critical-care stay duration.*** We previously assumed that the average length of hospital stay is 8 days if critical care is not required and 10 days if critical care is required based on estimates from Ferguson et al [12]. We examined clinical data from 12 hospitals in the University of Colorado Health hospital system and found the Ferguson et al. estimates to be consistent with the typical length of stays for COVID-19 patients in Colorado.

***Model fitting and parameter estimation.*** We use established methods to fit reported COVID-19 hospitalizations to our model outputs in order to estimate the extent to which the trajectory of the

outbreak is being impacted by disease-control measures including physical distancing, handwashing, mask wearing and case containment.

As has been done previously, best-fitting parameter values were identified via a least squares cost function minimizing the comparison between the observed data and our model projections. However, in this update, we fit our model to the reported vs. projected number of hospitalized individuals with confirmed COVID-19 rather than all reported COVID-19 cases. Given the increase in testing capacity and changes in detection rates over time, we view hospitalizations to be a more stable estimate of the true burden of COVID-19 in Colorado. The number of hospitalized COVID-19 patients per day was obtained from two sources, COVID-19 case reports and EMResource hospital census, both provided by CDPHE (Figure A1). COVID-19 case reports include hospitalization status of each case but not the dates or duration of hospital stay. To infer the number of hospitalized patients per day, hospitalization was assumed to start on the date a sample was collected and last 8 days on average. As shown in Figure A1, these data sources do not align perfectly and, as of April, we view the hospital census to be a more precise source. We therefore used the CDPHE case reports to infer hospitalizations through 3/31 and the EMResource hospital census of hospitalizations starting 4/1.

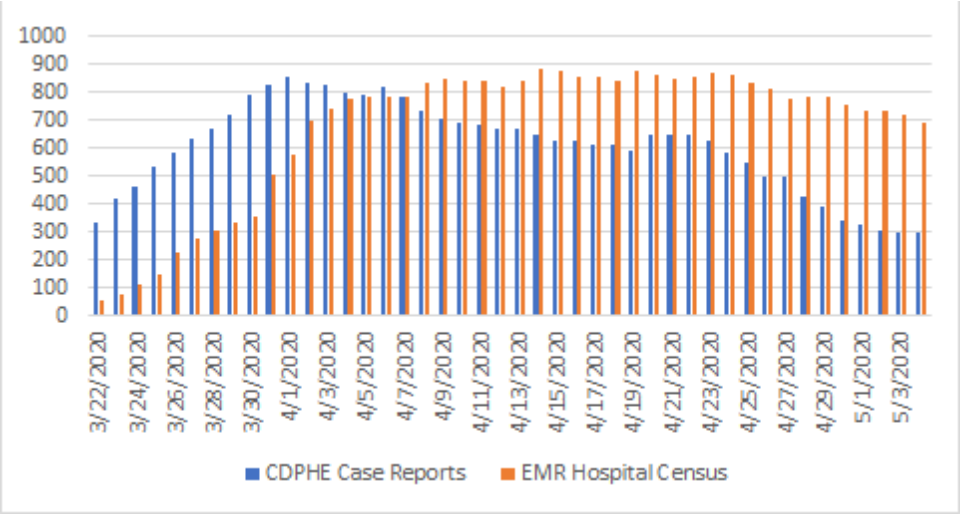


**Figure A1.** The daily number of hospitalized COVID-19 patients based on CDPHE case reports (blue lines) and EMResource hospital census data.

***Mask wearing.*** We accounted for potential reductions in transmission due to mask wearing by asymptomatic and pre-symptomatic individuals. We assume masks made from basic household materials are approximately 50% effective at trapping droplets containing viral particles shed by infectious individuals when worn properly based on the evidence from [13, 14] cautioning that there remains considerable uncertainty about both of these assumptions. Given that approximately 1/3 of an individual's contacts are with household members, mask wearing outside the home is assumed to impact the approximately 67% of total contacts that are outside the home. Recognizing that some transmission may also be occurring via fomites (including via touching masks), we model the effectiveness of masks as a net 27% percent reduction in infectiousness by asymptomatic individuals wearing masks. Additionally, we assume mask wearing reduces transmission by pre-symptomatic individuals (assuming an individual who ultimately becomes symptomatic is infectious for 8 days and asymptomatic for the first day – this is modeled as a 3.4% reduction in infectiousness for symptomatic

individuals wearing masks). This does not account for potential reduction in infectiousness by symptomatic individuals by wearing masks, as most are assumed to be isolated, but we note that this would result in an additional benefit of mask wearing [15]. We assumed the proportion of individuals wearing mask was uniform across all asymptomatic and pre-symptomatic individuals.

**Table A1.** Model parameters estimated using our age-structured SEIR model, by fitting our model outputs to Colorado COVID-19 hospital census data, provided by CDPHE.

| | Range of possible values | Fitted value | Fit using data through: |
|---|---|---|---|
| **Social distancing*** | | | |
| Phase 1. Estimated social distancing from mid-March until the start of the stay at home order, modeled as 3/17 - 3/25 | 10 – 70% | 52% | 05/11 |
| Phase 2. Estimated social distancing during the state-wide stay at home order, modeled as 3/26 to 4/26 | 50 – 99% | 80% | 05/19 |
| Phase 3. Estimated social distancing during the state-wide Safer at Home, modeled as 4/27 to present† | 50 – 99% | ~80% | 05/19 |
| **Mask wearing** | | | |
| Proportion of individuals wearing masks, 4/4 to 4/26 | 0.1 - 0.5 | 0.40 | 05/11 |
| Proportion of individuals wearing masks, 4/4 to 4/26 | | 0.50 | Assumed¶ |
| **Case isolation** | | | |
| Decrease in infectious - symptomatic contact rate due to self-isolation by symptomatic after March 5 (dividing by 0.57 gives proportion that self-isolate)** | 0.3 - 0.8 (Ferguson et al) | 0.30 | 05/11 |
| Transmission parameters | | | |
| The rate of infection (beta) | 0.2 - 0.6 (MIDAS†) | 0.48 | 05/11 |
| Ratio of infectiousness for symptomatic vs. asymptomatic individuals (lambda) | 1.0 - 4.0 (Li et al., Zou et al.) | 1.65 | 05/11 |

*Fit using This accounts for measures to encourage people stay at least 6 feet from people outside of their household as well as measures to promote handwashing and sanitizing to reduce fomite-based transmission.
†We caution that due to the typical lag between infection and hospitalization (13 days, on average) this estimate is preliminary, based on limited data and does not yet account for the extension of Stay at Home in the metro Denver region through 5/8.
¶Given the temporal correlation of potential increases in mask wearing and changes in social distancing challenging parameter estimation, we assumed a 25% increase in mask wearing starting on 4/27.
**Self-isolation by symptomatic cases is assumed to occur 48 hours after the onset of infectiousness and decrease the 76% of contacts that typically occur outside of the home, leading to a 57% decrease in contacts among those that self-isolate. This parameter jointly accounts for the percent of symptomatic individuals that self-isolate and

the imperfect decline in contacts. Dividing the value in the table by 0.57 gives the proportion of symptomatics that self-isolate.
††The range of potential parameter estimate values were obtained from the MIDAS Online COVID-19 compilation of parameter estimates available here.

Our estimate of the level of social distancing during the stay at home period is consistent with our estimates from the report published on 4/20 [1]. We previously estimated the phase 2 social distancing parameter to be 75-78%. Our estimate of the phase 1 social distancing parameter has changed from 65% in our April 20 report to 50%. This change is likely due to several factors including 1) the availability of more complete data, 2) our updated model fitting strategy focused on hospitalization data instead of reported cases, and 3) the inclusion of mask wearing in our current model.

***Estimating the effective reproductive number.*** We consider the subset of our SEIR model differential equations describing all compartments with infectious individuals (i.e., only Exposed, Infectious, and Asymptomatic). The Jacobian matrices describing only infection (F) and flux between compartments (V) were computed using Colorado-specific fitted parameters. The basic reproductive number R0 for a system is described by the spectral radius of the next generation matrix F*V^(-1) and the effective R0 as a function of the time course of the epidemic is depicted in Figure 3 [16]. Note that the discrete jumps correspond to state policy changes concerning social distancing.

***Estimating the proportion of cases detected.*** In order to estimate the number of cases being detected by state surveillance systems, we compared model outputs of the daily number of symptomatic cases and all cases (symptomatic + asymptomatic) to the reported number of provided by CDPHE. We used this information to estimate proportion of symptomatic cases being detected each day. Reported case data were evaluated using the date of symptom onset. For cases with missing onset date, we imputed onset date by taking the date of report and subtracting 7 days based on typical lags. This comparison can be used to estimate the proportion of symptomatic cases detected by the state surveillance system over time, as well as the total number of infected individuals detected.

**Code.** Code for our models is posted on Github: https://github.com/agb85/covid-19

## Appendix – Case Detection

There is considerable interest in the proportion of COVID-19 cases being detected by state surveillance systems. We used the daily number of new symptomatic infections estimated by the SEIR model and compared that to the daily number of new cases reported by CDPHE (Figure A2). We estimate that the proportion of symptomatic cases reported to public health likely declined in late March, corresponding with the initial surge in cases, and has increased since early April to approximately ~42% in early May.

We estimate that approximately 170,000 people in Colorado have been infected with SARS-CoV-2 through 5/11, or approximately 2.9% of the Colorado population. These estimates are based on our model projections through 5/11 using the parameter estimates in Table A1.

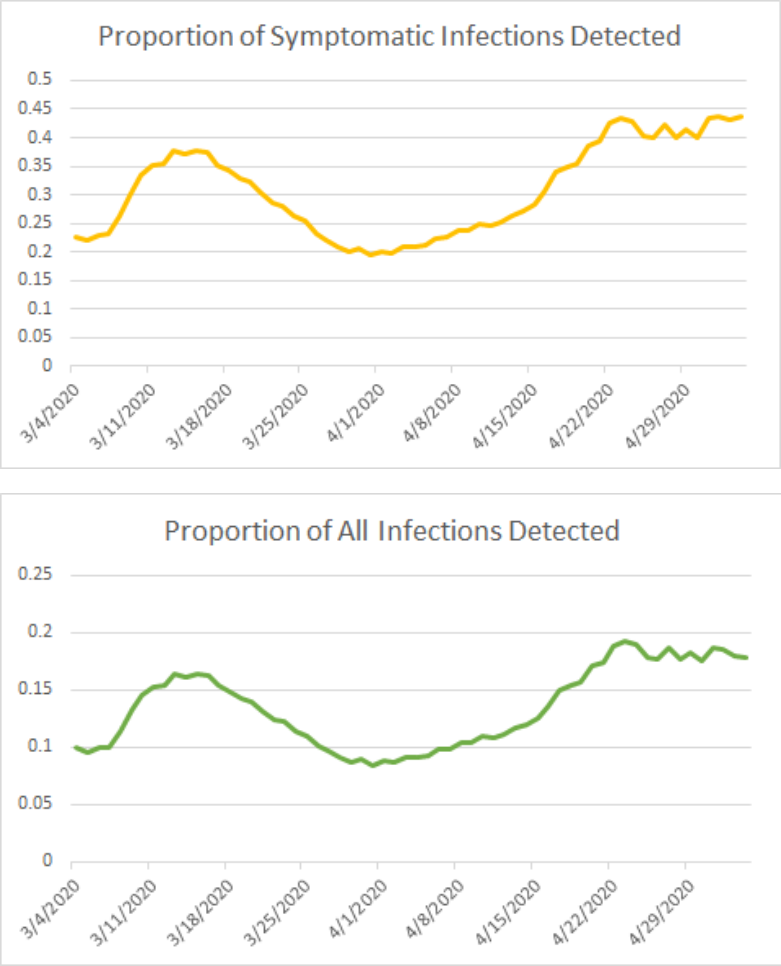


**Figure A2.** Estimated proportion of symptomatic COVID-19 cases (top) and all COVID-19 infections (including both asymptomatic and symptomatic infections) (bottom) that are being captured by Colorado state surveillance systems, over time. The daily number of new cases are based on SEIR model outputs. The number of cases captured by state surveillance systems is the number of cases reported by CDPHE, using the onset date of symptoms or, if this is not available, the date of report minus 7 days based on typical lags.

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