Eight-week model projections of COVID-19 in New York City

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We present the results of model projections of COVID-19 epidemic outcomes under different control scenarios, including number of total infections, hospitalizations, ICU admissions, and deaths by week for the next 8 weeks (i.e. March 15 – May 9, 2020).

1. Model Form

Susceptible-Exposed-Infectious-Removed (SEIR) model accounting for reporting delay for case diagnosis, and delay from infection to hospitalization, ICU admission, and death for estimating the numbers of hospitalization, ICU, and death by week, respectively.

2. Data

Confirmed cases of COVID-19 in New York City (Weeks 9-11 of 2020, as of March 13, 2020), provided by NYC DOHMH.

3. Model Training and Assumptions

Bayesian inference approach in which the DOHMH data are used to partially constrain the model parameters and state variables prior to making a projection. The form is similar to that used for influenza forecasting; however, here the data are very limited (3 weeks) so the model is less well constrained. Initial prior ranges are set as: transmission rate (β): [0.5, 1]; latency period (T_{ei}): [2, 5] days; infectious period (T_{ir}): [2, 5] days; reporting delay (mean: Td.mean): [3, 9] days; reporting delay (SD: Td.sd): [1, 3] days; and reporting rate (α): [5, 80]%. These parameters are estimated based on the weekly confirmed case data.

In addition, for the delay from infection to hospitalization, ICU, and death, we used reported time from symptom onset of SARS-CoV-2 to the corresponding event (Yang et al. 2020). To compute the numbers of different health outcomes from the model estimated total infections, we used the following probability ranges: 2.25-7.5% for hospitalization (severe and critical cases); 0.6-2% for ICU and 0.15-1.25% for mortality. These probabilities are based on reported numbers among diagnosed cases in China (China CDC, 2020) and other countries and assuming a 15-25% ascertainment rate (Li et al., 2020). See further details below.

4. Model Scenarios

Seasonality: There are 4 endemic coronaviruses infecting humans (OC43, 229E, NL63, HKU1). These viruses typically cause mild cold-like symptoms and exhibit a pronounced seasonality with peak incidence in January-February and very little incidence in summer. The cause of this seasonality is unknown, but its presence has led to speculation that SARS-CoV-2, the virus causing COVID-19, may wane during summer months in New York City. Consequently, we used the seasonality of OC43, which is well observed and a betacoronavirus, like SARS-CoV2, to estimate a seasonal reduction of transmissibility for SARS-CoV2 during summertime. We then generated projections from the 2 forms for all scenarios: 1) With seasonal changes to virus transmissibility; and 2) Without seasonality.

No Control (i.e. Worst Case) Scenario: For these projections, the model posterior (i.e. an ensemble of model simulations with parameters and state variables as estimated following

training with NYC DOHMH data) was integrated 8 weeks into the future to create a reference, no control, "worst case" scenario. As for the control scenarios, these projections were repeated 10 times to provide a distribution of possible outcomes.

Control Scenarios: Five control scenarios were also repeated 10 times, again using the model posterior as initial conditions and adjustment of model parameters as specified below to represent different levels of interventions:

1. Moderate (10-30%) reduction in contact rate (via social distancing)
2. Moderate (10-30%) reduction in contact rate (via social distancing) and moderate (10-25%) reduction in infectious period (via case isolation/self-quarantine/treatment, etc.)
3. Large (30-50%) reduction in contact rate (via social distancing) and no reduction in infectious period
4. Large (30-50%) reduction in contact rate (via social distancing) and moderate (10-25%) reduction in infectious period (via case isolation/self-quarantine/treatment, etc.)
5. Large (30-50%) reduction in contact rate (via social distancing) and large (30-50%) reduction in infectious period (via case isolation/self-quarantine/treatment, etc.)

Note there is no particular specification of how reductions in contact rates or spread are achieved. In a model of this form different reduction options (e.g. isolation vs. quarantine) are not represented explicitly; rather, they are effected by adjusting the estimated (posterior) contact rate and infectious period within the model.

Model Output

We use the model to estimate total infections, reported/observed infections, hospitalizations, patients in ICU, and deaths. For the latter three health outcomes we accounted for delay from infection to corresponding event as described above.

- Total infections are directly estimated by the model without a delay, and are an unobserved quantity that includes subclinical/undiagnosed infections.
- Reported/observed infections include a reporting delay and are estimated with the posterior reporting rate estimates.
- For hospitalizations, we assume 15-30% of reported infections are hospitalized. We base this from a study in China, which found that ~20% of confirmed cases in China were severe or critical (China CDC, 2020).
- For ICU, we assume 4-8% of reported infections are critical and enter ICU (China CDC, 2020).
- For deaths, we assume 1-5% of individuals with reported infections die (WHO, 2020).

We also report the estimated attack rate as the number of New Yorkers infected in the next 8 weeks.

Results

Estimation of infection numbers and health outcomes through March 13, 2020.
The model-inference system (assuming seasonality the same as OC43 coronavirus) estimated that there were 2012 [median and interquartile range (IQR): 1701 – 2371; same below] total infections by March 13, 2020. In comparison, a total of 134 confirmed cases were reported during this period. This discrepancy likely stemmed from the delay in reporting and under-

reporting (i.e. many infected individuals experience mild symptoms and do not seek medical care). This stresses the need for continuous monitoring of suspected infections for transmission control, increased rates of testing, and improved reporting for better situation awareness. In addition, the model-inference system estimated a total of 51 (IQR: 27 – 82) hospitalizations, 6 (IQR: 3 – 11) ICU admissions, and 0.6 (IQR: 0.3 – 1.6) deaths by March 13, 2020 (note that the mean was 3 deaths). Table 1 shows the estimated numbers by week for total infections, hospitalizations, ICU admissions, and deaths, using models assuming the same seasonality as OC43 coronavirus and no seasonality, separately. In general, estimates assuming no seasonality were slightly higher than those assuming OC43 seasonality (Table 1). Below, we mainly present results from the model runs with seasonality.

Projections for the coming 8 weeks.

Figures 1-5 show the projected epidemic curves under different control scenarios for total infections, confirmed cases, hospitalizations, ICU admissions, and deaths, separately. Estimates under the two seasonality assumptions are also compared in the figures. Table 2 and 3 show the projected cumulative and weekly numbers of total infections, hospitalizations, ICU admissions, and deaths for the model runs (only for runs with seasonality in Table 3).

The projected attack rate for the no control ('worst case'), as run with seasonality, had a median of 4.3 million total infections (IQR: 1.8 M – 6.5 M) during the next 8 weeks. Under Control Scenario 1 (i.e. 10-30% reduction in contact rate), the attack rate, while reduced, would remain at a high level at 579 K (IQR: 183 K – 1.7 M). The attack rate would be substantially reduced to 163 K (IQR: 58 K – 511 K) and 71 K (IQR: 30 K – 183 K) under Control Scenario 2 (i.e. 10-30% reduction in contact rate and 10-25% reduction in the infectious period) and Control Scenario 3 (i.e. 30-50 reduction in contact rate) respectively. The attack rate would be further reduced to 31 K (IQR: 17 K – 68 K) and 12 K (IQR: 9 K – 21 K) under Control Scenarios 4 and 5 with 30-50% reduction in contact rate as well as a similar reduction in the infectious period. Accordingly, other health outcomes would be reduced under all five control scenarios and more substantially under scenarios with reductions in both contact rate and infectious period (Tables 2-3 and Figures 1-5).

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Table 1. Estimated numbers of total infections, hospitalization, ICU admissions, and deaths in Weeks 9 to 11 of 2020, the three weeks with data. Numbers are median and (interquartile range, IQR).

Seasonality	Week	Total Infections	Hospitalizations	ICU	Deaths
Per OC43	9	118.5 (67.7, 187.9)	1.9 (1, 3.2)	0 (0, 0)	0 (0, 0)
Per OC43	10	165.3 (55.5, 371.8)	4.9 (1.5, 10.4)	0.3 (0.1, 0.7)	0 (0, 0)
Per OC43	11	1756.2 (1450.6, 2020.4)	43.8 (21.9, 70.1)	5.4 (2.9, 9.7)	0.6 (0.3, 1.6)
None	9	133.1 (77.1, 205.8)	2 (1.1, 3.5)	0 (0, 0)	0 (0, 0)
None	10	173.2 (15.8, 423.1)	4.6 (0.4, 11.2)	0.3 (0, 0.7)	0 (0, 0)
None	11	2526.4 (1972.8, 2927.5)	49.6 (9.8, 85.6)	5.9 (2.5, 11.3)	0.7 (0.2, 1.8)

Table 2. Estimated cumulative numbers of total infections, hospitalization, ICU admissions, and deaths for the coming 8 weeks. Numbers are median and (interquartile range, IQR).

Seasonality	Intervention	Total Infections	Hospitalizations	ICU	Deaths
Per OC43	No Control	4297786 (1798685, 6487555)	154821 (61000, 274146)	22426 (8162, 49741)	2664 (816, 7200)
Per OC43	Scenario 1	578913 (183407, 1699624)	21511 (7132, 65222)	3271 (1224, 9752)	456 (154, 1367)
Per OC43	Scenario 2	162957 (57710, 510949)	6704 (2481, 20715)	1256 (524, 3602)	205 (73, 580)
Per OC43	Scenario 3	70509 (30499, 182995)	2946 (1315, 7723)	603 (294, 1450)	104 (41, 249)
Per OC43	Scenario 4	30743 (16511, 68180)	1382 (739, 3113)	329 (180, 690)	61 (27, 136)
Per OC43	Scenario 5	12479 (8778, 20645)	597 (377, 1011)	155 (98, 262)	30 (15, 58)
None	No Control	5395385 (2771161, 7011520)	197827 (92822, 317794)	33819 (13491, 61200)	3995 (1388, 10103)
None	Scenario 1	1005410 (311319, 2612591)	37592 (11437, 101287)	5856 (2073, 15703)	752 (264, 2318)
None	Scenario 2	289520 (94689, 861435)	11744 (3906, 34639)	2205 (862, 5875)	327 (125, 986)
None	Scenario 3	121874 (49166, 313454)	5064 (2050, 12812)	1013 (474, 2347)	162 (67, 419)
None	Scenario 4	50959 (26137, 113602)	2296 (1127, 5079)	534 (281, 1101)	94 (42, 219)
None	Scenario 5	19509 (13482, 32268)	917 (563, 1554)	238 (149, 398)	45 (22, 92)

Table 3. Projected weekly epidemic outcomes under different control scenarios for the coming 8 weeks. Numbers are median and (interquartile range, IQR).

Intervention	Week	Total Infections	Hospitalizations	ICU beds	Deaths
No control (worst case)	12	4877 (3769, 6603)	154 (102, 227)	14 (9, 20)	1 (0, 1)
	13	13460 (9091, 21695)	430 (261, 719)	44 (28, 66)	4 (2, 8)
	14	38600 (21344, 75554)	1199 (634, 2366)	119 (71, 212)	12 (6, 23)
	15	109350 (48408, 250906)	3379 (1500, 8005)	330 (173, 719)	34 (15, 70)
	16	295352 (109056, 754056)	9271 (3483, 24829)	924 (409, 2344)	95 (36, 236)
	17	705308 (241300, 1573537)	23332 (7841, 58477)	2494 (949, 7000)	264 (89, 747)
	18	1135234 (445808, 1817563)	43450 (16176, 80753)	6067 (2104, 15426)	690 (205, 2018)
	19	1151858 (493289, 1640426)	49769 (22714, 80715)	11009 (4215, 20340)	1497 (452, 3654)
Ctrl 1: 10-30% reduction in contact rate	12	4358 (3400, 5863)	145 (97, 212)	14 (9, 20)	1 (0, 1)
	13	9121 (6341, 14182)	328 (206, 528)	40 (26, 60)	4 (2, 8)
	14	16744 (9699, 30720)	624 (349, 1143)	87 (54, 148)	11 (6, 20)
	15	28968 (13779, 62131)	1076 (516, 2324)	162 (90, 322)	22 (10, 44)

	16	50132 (19537, 126038)	1860 (757, 4682)	277 (131, 645)	40 (16, 90)
	17	85802 (28487, 246510)	3163 (1100, 9234)	475 (193, 1298)	67 (23, 180)
	18	144914 (40610, 455424)	5407 (1577, 17365)	812 (276, 2531)	113 (36, 350)
	19	232026 (57501, 708458)	8849 (2251, 28643)	1371 (395, 4736)	195 (52, 656)
Ctrl 2: 10-30% reduction in contact rate & 10-25% in infectious period	12	4154 (3254, 5548)	142 (95, 206)	14 (9, 20)	1 (0, 1)
	13	7647 (5359, 11854)	291 (184, 465)	39 (25, 57)	4 (2, 8)
	14	11682 (6704, 21496)	473 (262, 864)	76 (47, 127)	10 (5, 18)
	15	15696 (7266, 34205)	647 (311, 1410)	120 (66, 234)	18 (8, 36)
	16	20055 (7553, 52176)	840 (339, 2176)	162 (76, 375)	27 (11, 61)
	17	25710 (7825, 79488)	1073 (350, 3289)	209 (81, 576)	35 (12, 93)
	18	32755 (7972, 119947)	1360 (360, 4870)	267 (84, 878)	45 (13, 141)
	19	41681 (8199, 173943)	1698 (370, 7131)	339 (88, 1304)	56 (14, 207)
Ctrl 3: 30-50% reduction in contact rate	12	3451 (2724, 4514)	128 (86, 183)	13 (9, 20)	1 (0, 1)
	13	4973 (3603, 7482)	208 (134, 322)	34 (22, 49)	4 (2, 7)
	14	6256 (3800, 10723)	273 (160, 476)	53 (34, 85)	8 (4, 15)
	15	7350 (3668, 14657)	317 (164, 639)	68 (39, 125)	12 (6, 22)
	16	8661 (3585, 20248)	372 (165, 876)	80 (40, 168)	14 (6, 31)
	17	10299 (3496, 28374)	440 (161, 1207)	92 (40, 230)	16 (6, 41)
	18	12205 (3416, 39170)	518 (159, 1647)	109 (39, 316)	19 (6, 55)
	19	14173 (3339, 53607)	610 (156, 2249)	127 (38, 440)	22 (6, 74)
Ctrl 4: 30-50% reduction in contact rate and 10-25% reduction in infectious period	12	3310 (2630, 4313)	126 (84, 180)	13 (9, 20)	1 (0, 1)
	13	4232 (3061, 6339)	187 (121, 287)	33 (22, 48)	4 (2, 7)
	14	4480 (2672, 7738)	209 (125, 368)	47 (30, 74)	8 (4, 14)
	15	4111 (1972, 8396)	199 (102, 402)	52 (30, 93)	10 (5, 19)
	16	3621 (1379, 8890)	174 (75, 421)	48 (24, 102)	10 (4, 22)
	17	3153 (990, 9455)	154 (53, 437)	43 (18, 107)	9 (3, 22)
	18	2752 (700, 9948)	134 (37, 446)	38 (12, 111)	8 (2, 23)
	19	2424 (482, 10456)	117 (26, 468)	33 (9, 115)	7 (2, 24)
Ctrl 5: 30-50% reduction in both contact rate & infectious period	12	2982 (2392, 3874)	120 (81, 171)	13 (9, 20)	1 (0, 1)
	13	2846 (2032, 4232)	143 (93, 218)	31 (21, 44)	4 (2, 7)
	14	1997 (1148, 3512)	112 (67, 195)	35 (23, 54)	7 (4, 12)
	15	1121 (500, 2439)	68 (33, 139)	27 (16, 48)	6 (3, 12)
	16	623 (221, 1647)	37 (15, 92)	16 (8, 33)	4 (2, 9)
	17	347 (96, 1137)	21 (7, 61)	9 (3, 22)	2 (1, 6)
	18	191 (44, 774)	12 (3, 42)	5 (2, 15)	1 (0, 4)
	19	106 (20, 527)	6 (1, 28)	3 (1, 10)	1 (0, 3)

Figure 1. Projected total number of **infections** under different control scenarios. Blue lines and points show median estimates for the model training period; red lines show projected median numbers with seasonality (solid lines) or without seasonality (dashed lines); shaded regions shown the interquartile ranges (IQR) for model estimates with seasonality (in orange) or without seasonality (in yellow).

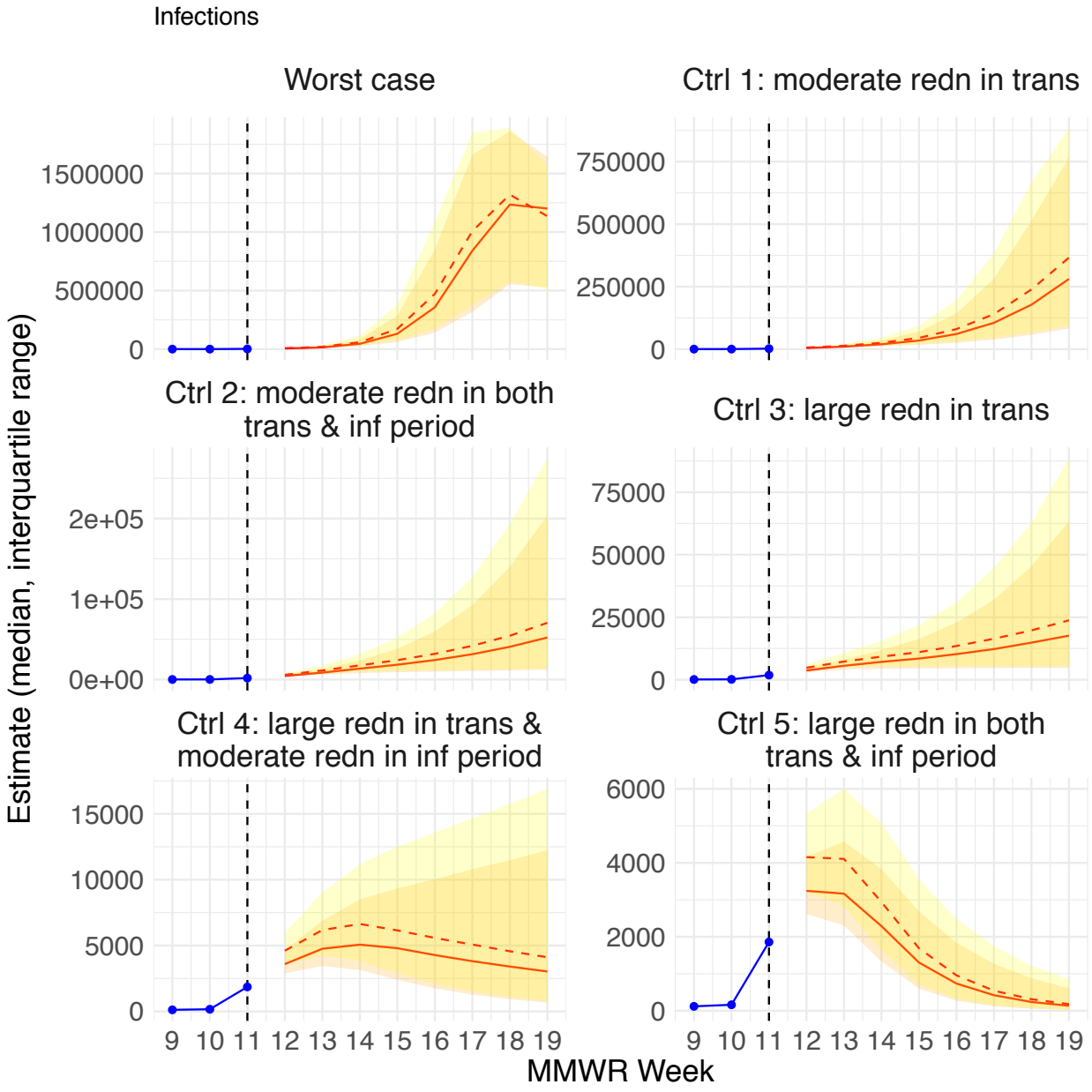

Figure 2. Projected total number of **confirmed cases** under different control scenarios. Blue lines and points show median estimates for the model training period; red lines show projected median numbers with seasonality (solid lines) or without seasonality (dashed lines); shaded regions shown the interquartile ranges (IQR) for model estimates with seasonality (in orange) or without seasonality (in yellow).

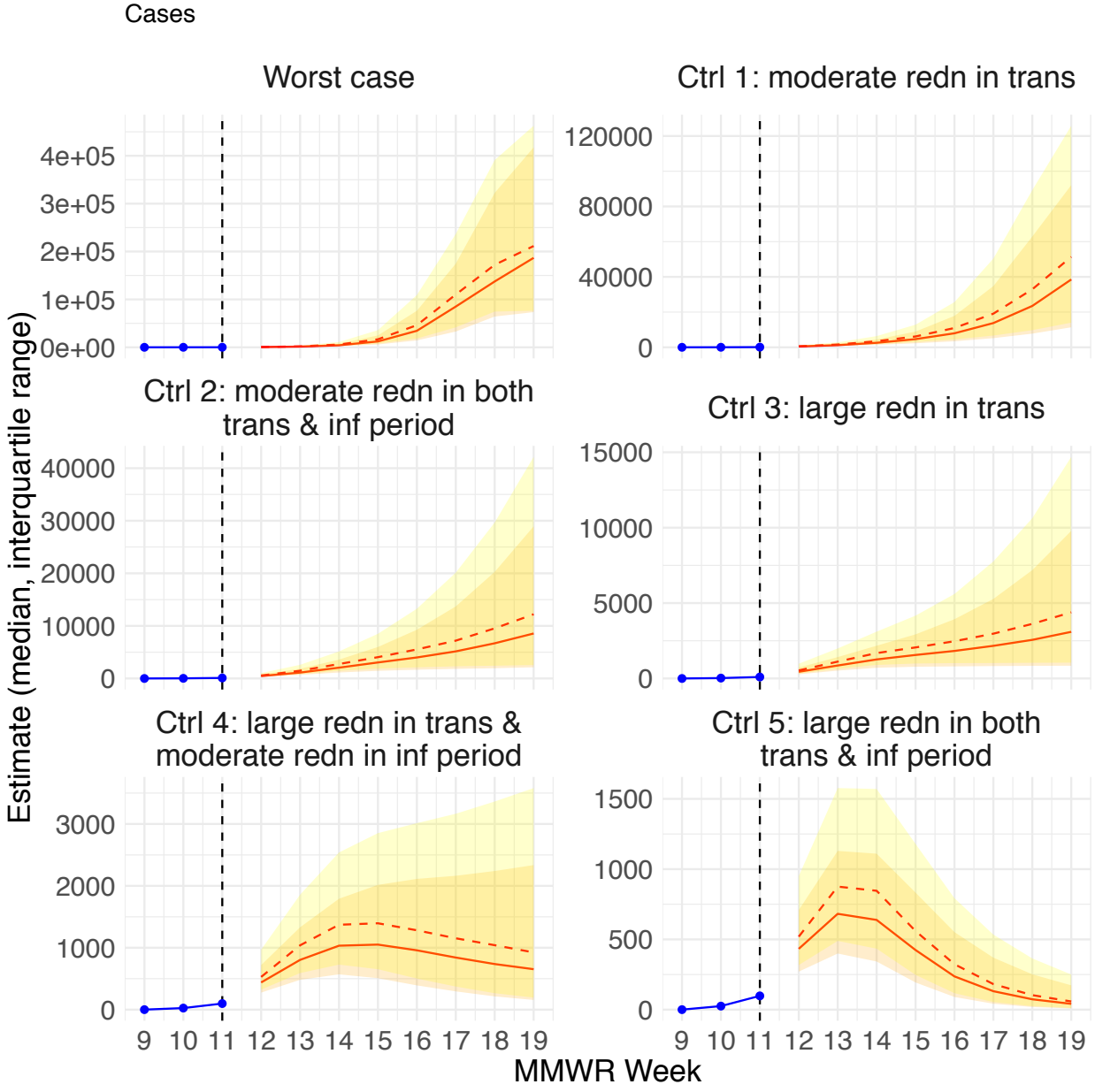

Figure 3. Projected total number of **hospitalizations** under different control scenarios. Blue lines and points show median estimates for the model training period; red lines show projected median numbers with seasonality (solid lines) or without seasonality (dashed lines); shaded regions shown the interquartile ranges (IQR) for model estimates with seasonality (in orange) or without seasonality (in yellow).

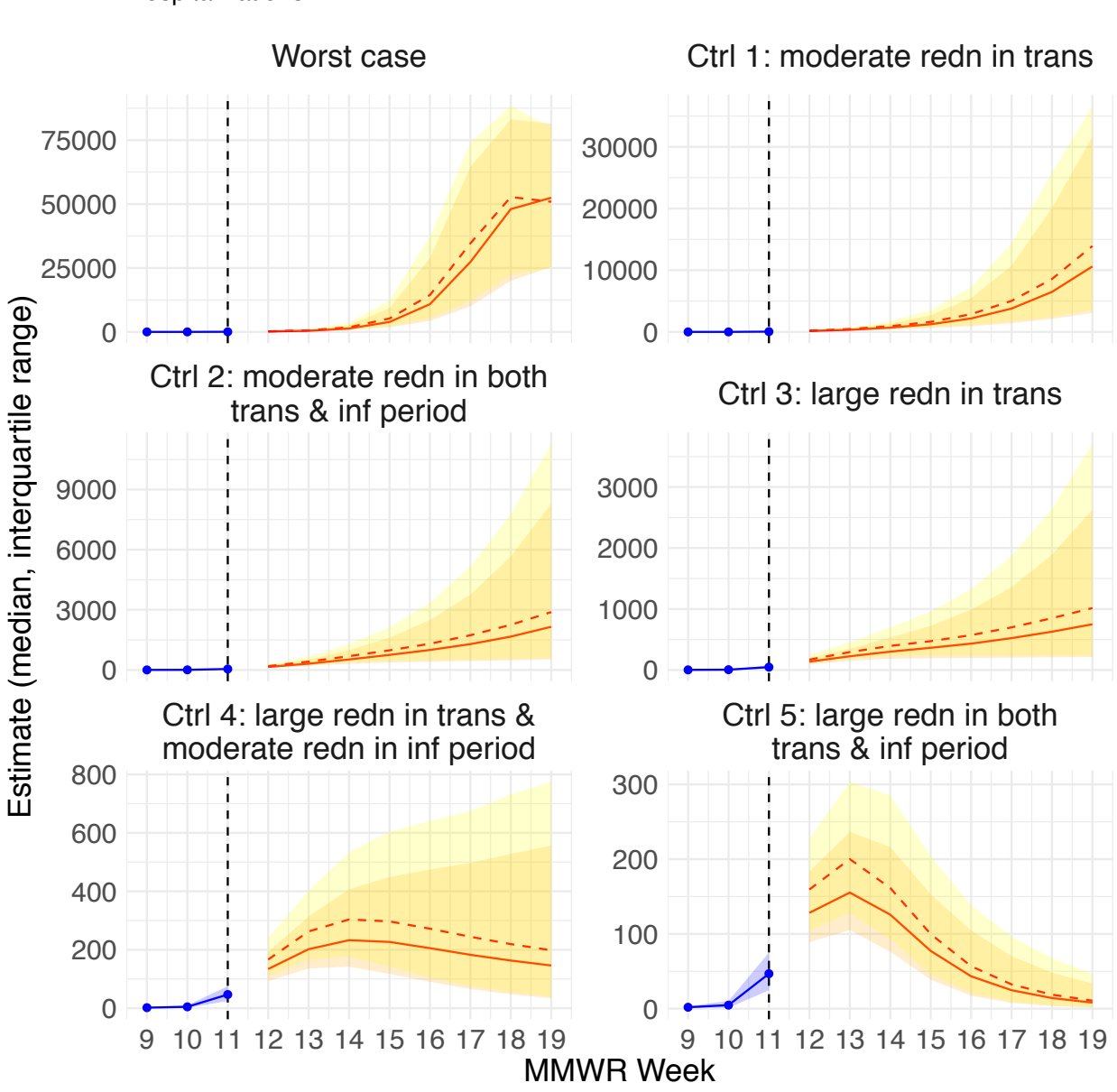

Figure 4. Projected total number of **ICU admissions** under different control scenarios. Blue lines and points show median estimates for the model training period; red lines show projected median numbers with seasonality (solid lines) or without seasonality (dashed lines); shaded regions shown the interquartile ranges (IQR) for model estimates with seasonality (in orange) or without seasonality (in yellow).

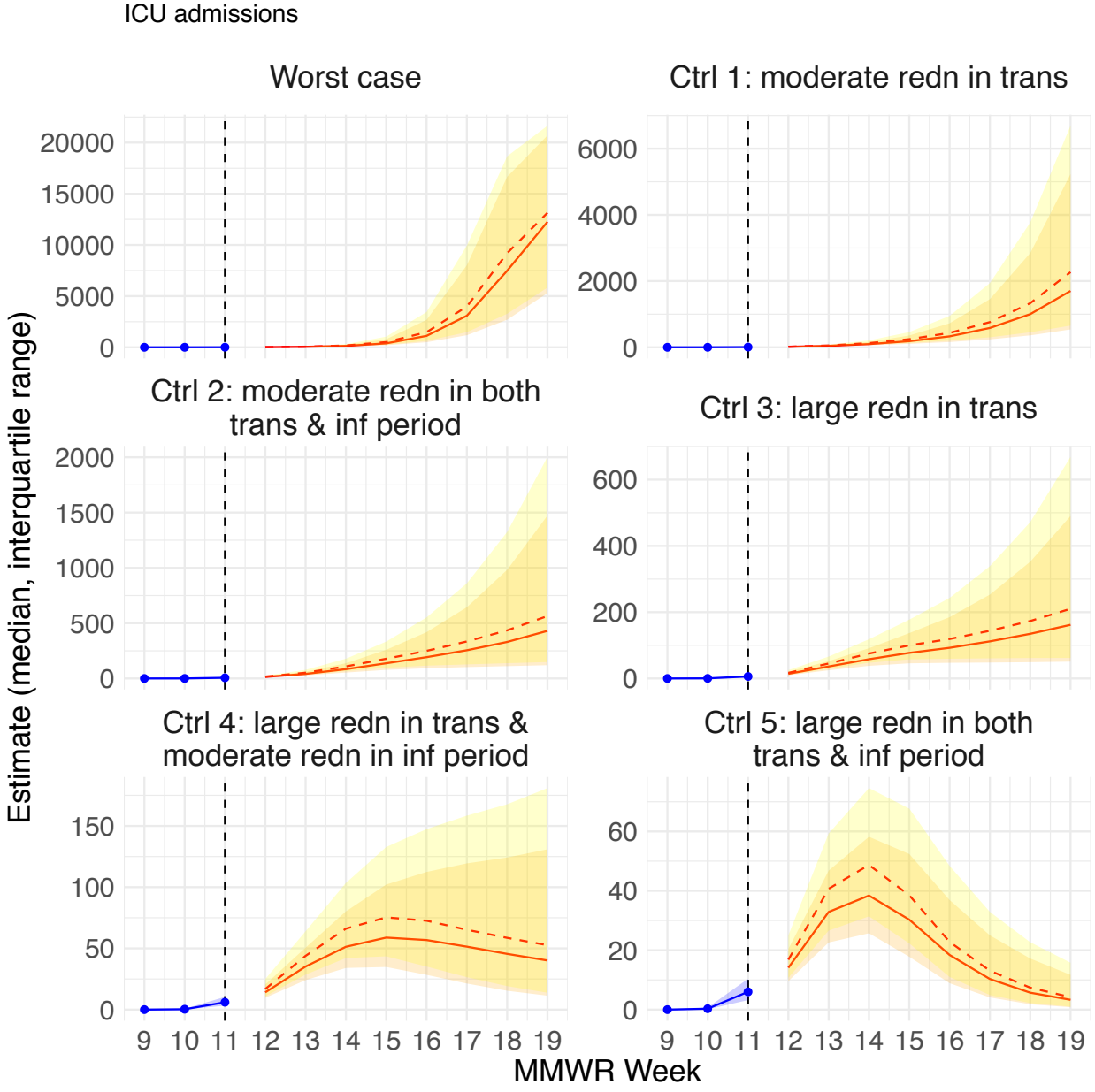

Figure 5. Projected total number of **deaths** under different control scenarios. Blue lines and points show median estimates for the model training period; red lines show projected median numbers with seasonality (solid lines) or without seasonality (dashed lines); shaded regions shown the interquartile ranges (IQR) for model estimates with seasonality (in orange) or without seasonality (in yellow).