

Supplementary Materials for

Transmission dynamics of and insights from the 2018–2019 measles outbreak in New York City: A modeling study

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Table S1. Comparison of model estimates on initial susceptibility and model performance under different assumptions on vaccination campaigns. The baseline setting is as reported in the main text and alternative settings 1 to 3 are as described in the section "*Sensitivity analysis on vaccination campaigns settings.*" The results are summarized by pooling all 10 model-inference runs (10,000 particles each run and 100,000 model realizations in total). The numbers are the mean and, for the susceptibilities, 95% credible intervals in the parentheses. The initial susceptibilities, estimated at the end of Sep 2018, were computed by adding the total numbers of individuals immunized by the vaccination campaigns in Oct 2018 to the posterior estimates at the end of Oct 2018.

		Model Settings on Vaccination Campaigns			
	Age group	Baseline	Alternative 1	Alternative 2	Alternative 3
Estimated initial susceptibility (%) at end of Sep 2018	<1 year	53.2 (49, 57.5)	54.2 (50, 58.4)	54.2 (50, 58.5)	54.2 (50, 58.5)
	1-4 years	24.9 (20.4, 29.7)	24.9 (20.4, 29.7)	24.9 (20.4, 29.7)	29.9 (25.4, 34.7)
	5-17 years	6.0 (4.1, 7.9)	7.5 (5.1, 9.9)	7.5 (5.1, 9.9)	6.0 (4.1, 7.9)
	18-49 years	6.0 (4.1, 7.9)	7.5 (5.2, 9.9)	7.5 (5.2, 9.9)	7.5 (5.2, 9.9)
	50+ years	6.0 (4.1, 7.9)	6.0 (4.1, 7.9)	6.0 (4.1, 7.9)	6.0 (4.1, 7.9)
Log-likelihood		-255.25	-265.52	-255.25	-257.42
Relative error of total number of cases over the outbreak	<1 year	0.39%	-11.96%	-11.56%	-17.91%
	1-4 years	-0.04%	-7.80%	-6.90%	-8.07%
	5-17 years	-4.13%	14.38%	0.33%	1.84%
	18+ years	-4.70%	7.24%	5.97%	7.95%
	All ages	-1.79%	-0.65%	-3.48%	-4.25%
Root-mean-square-error (RMSE), over Oct 2018 – July 2019	<1 year	1.74	1.86	1.80	2.55
	1-4 years	8.72	8.13	8.17	7.70
	5-17 years	3.91	5.27	3.00	5.10
	18+ years	5.08	4.62	4.30	4.25
	All ages	7.31	7.52	5.88	6.29
Correlation, over Oct 2018 – July 2019	<1 year	0.99	1.00	1.00	0.99
	1-4 years	0.95	0.96	0.96	0.97
	5-17 years	0.99	0.97	0.99	0.97
	18+ years	0.97	0.97	0.97	0.97
	All ages	0.99	0.99	1.00	1.00
1-step-head prediction RMSE, over Oct 2018 – Mar 2019	<1 year	4.37	4.46	4.40	4.60
	1-4 years	17.13	17.34	17.35	25.12
	5-17 years	8.27	8.39	8.37	8.50
	18+ years	4.34	4.93	4.93	5.06
	All ages	27.79	28.23	28.16	35.02

Table S2. Estimated negative impact of “measles parties” and positive impact of vaccination campaigns during Oct 2018 – July 2019. Column 2 shows the observed numbers of cases, reported as of Aug 6, 2019. Column 3 shows the estimated numbers of cases if there had been no “measles parties”. Columns 4-6 show the estimated total numbers of cases (4th column), hospitalizations (5th column), and individuals in intensive care unit (ICU) for different age groups (rows 3 to 6) and overall (last row), if there had been no vaccination campaigns. Columns 7-9 show the estimated numbers of cases, hospitalizations, and ICU cases averted by the vaccination campaigns. Numbers are the median (and 95% confidence intervals) of 10,000 simulations. See Table 2 in the main text for the median and interquartile ranges.

Age group	No. cases reported	No. cases, if no measles parties	No. if no vaccination campaigns			No. averted by vaccination campaigns		
			Cases	Hospitalizations	ICU cases	Cases	Hospitalizations	ICU cases
<1	100	26 (0, 204)	1302 (0, 1430)	97 (0, 106)	20 (0, 22)	1202 (0, 1330)	89 (0, 99)	18 (0, 20)
1-4	275	62 (3, 472)	3914 (3, 4096)	291 (0, 305)	60 (0, 63)	3639 (0, 3821)	271 (0, 284)	56 (0, 59)
5-17	138	26 (1, 336)	1412 (1, 1692)	105 (0, 126)	22 (0, 26)	1274 (0, 1554)	95 (0, 116)	20 (0, 24)
18+	129	29 (1, 272)	1141 (1, 1343)	85 (0, 100)	18 (0, 21)	1012 (0, 1214)	75 (0, 90)	16 (0, 19)
All	642	152 (5, 1246)	7810 (5, 8443)	581 (0, 628)	120 (0, 130)	7168 (0, 7801)	533 (0, 580)	110 (0, 120)

Table S3. Main model parameters and prior ranges tested. In total, we tested 5040 combinations of prior ranges. Each combination was used as the lower and upper bounds of Latin Hypercube sampling. The optimal prior ranges used in the final model-inference runs are bolded if multiple ranges were tested.

Parameter	Symbol/Equation	Ranges tested	Source/rationale
Initial susceptibility in <1 year-olds	$S_1(t=0)$; Eqn 1	Based on susceptibility in 18-49 year-olds (i.e., the mothers)	N/A
Initial susceptibility in 1-4 year-olds	$S_2(t=0)$; Eqn 1	[5, 15], [10, 20], [15, 25], [20, 30], [25, 35], [30, 40], [35, 45]% of population	Unclear; use a wide range
Initial susceptibility in 5-17 year-olds	$S_3(t=0)$; Eqn 1	[4, 8], [5, 10], [5, 15], [10, 20], [15, 25]% of population	Unclear; use a wide range
Initial susceptibility in 18-49 year-olds	$S_4(t=0)$; Eqn 1	[4, 8], [5, 10], [5, 15], [10, 20]% of population	Higher vaccination rate for this age group (see data from the WHO (37))
Initial susceptibility in 50+ year-olds	$S_5(t=0)$; Eqn 1	[4, 8]% of population	High immunity due to natural infection in this group
Initial number of infants with maternal immunity	$M(t=0)$; Eqn 1	Based on susceptibility in 18-49 year-olds (i.e., the mothers)	N/A
Latent period	Z ; Eqn 1	[7, 9] days	Mean = 8 days in (38)
Infectious period	D ; Eqn 1	[2, 6] days	4-6 days in (26)
Mixing parameter for the susceptibles	m_1 ; Eqn 1	1 (perfect mixing), [0.95, 1], [0.9, 0.95]	1 for well-mixed models
Mixing parameter for the infectious	m_2 ; Eqn 1	1 (perfect mixing), [0.95, 1], [0.9, 0.95]	1 for well-mixed models and 0.97 estimated in (29)
Relative contact rate among <1 year-olds	β_1 ; Eqn 2	Set to 1	N/A
Relative contact rate among 1-4 year-olds	β_2 ; Eqn 2	[3, 30]	Unclear; use a wide range
Relative contact rate among 5-17 year-olds	β_3 ; Eqn 2	[25, 50]	1.3-1.9 times of 0-4 year-olds (39)
Relative contact rate among 18-49 year-olds	β_4 ; Eqn 2	[20, 40]	1.3-1.6 times of 0-4 year-olds (39)
Relative contact rate among 50+ year-olds	β_5 ; Eqn 2	[1, 5]	.7-1.4 times on 0-4 year-olds (39)
Relative contact rate between 1-4 and 5-17	β_6 ; Eqn 2	[1, 5]	Unclear; use a wide range

year-olds (sibling interactions)			
Contact rate between 18-49 and 1-4 or 5-17 year-olds (parent-child interactions)	β_7 ; Eqn 2	[1, 5]	Unclear; use a wide range
Amplitude of school term-time forcing	b_I ; Eqn 3	[0.25, 0.75], [0.5, 1]	Possible between 0-1.
Basic reproductive number	R_0 ; Eqn 4	[5, 10] , [7, 12]	Common range: 12-18; possible values: 1.4-770 (6)
Reporting rate	r ; Eqn 6	[80, 100]%	Probably high as a later version of case report was used here.

Fig. S1. Estimates of model parameters not listed in Fig. 4. (A) amplitude of school term-time forcing, (B) latent period, (C) reporting rate, (D) relative contact rate among 50+ year-olds, (E) relative contact rate between 1-4 and 5-17 year-olds (i.e. sibling interactions), and (F) relative contact rate between 18-49 and 1-4 or 5-17 year-olds (i.e. parent-child interactions). Red lines and surrounding regions (y-axis on the left) show the mean and 50% and 95% credible intervals of estimates pooled over all 10 model-inference runs (100,000 model realizations in total) made at the end of each month from Oct 2018 to July 2019. For comparison, the grey bars (y-axis on the right) show monthly incidence for all ages. Note that m_1 and m_2 are not shown as both optimal priors are the value 1 (Table S3).

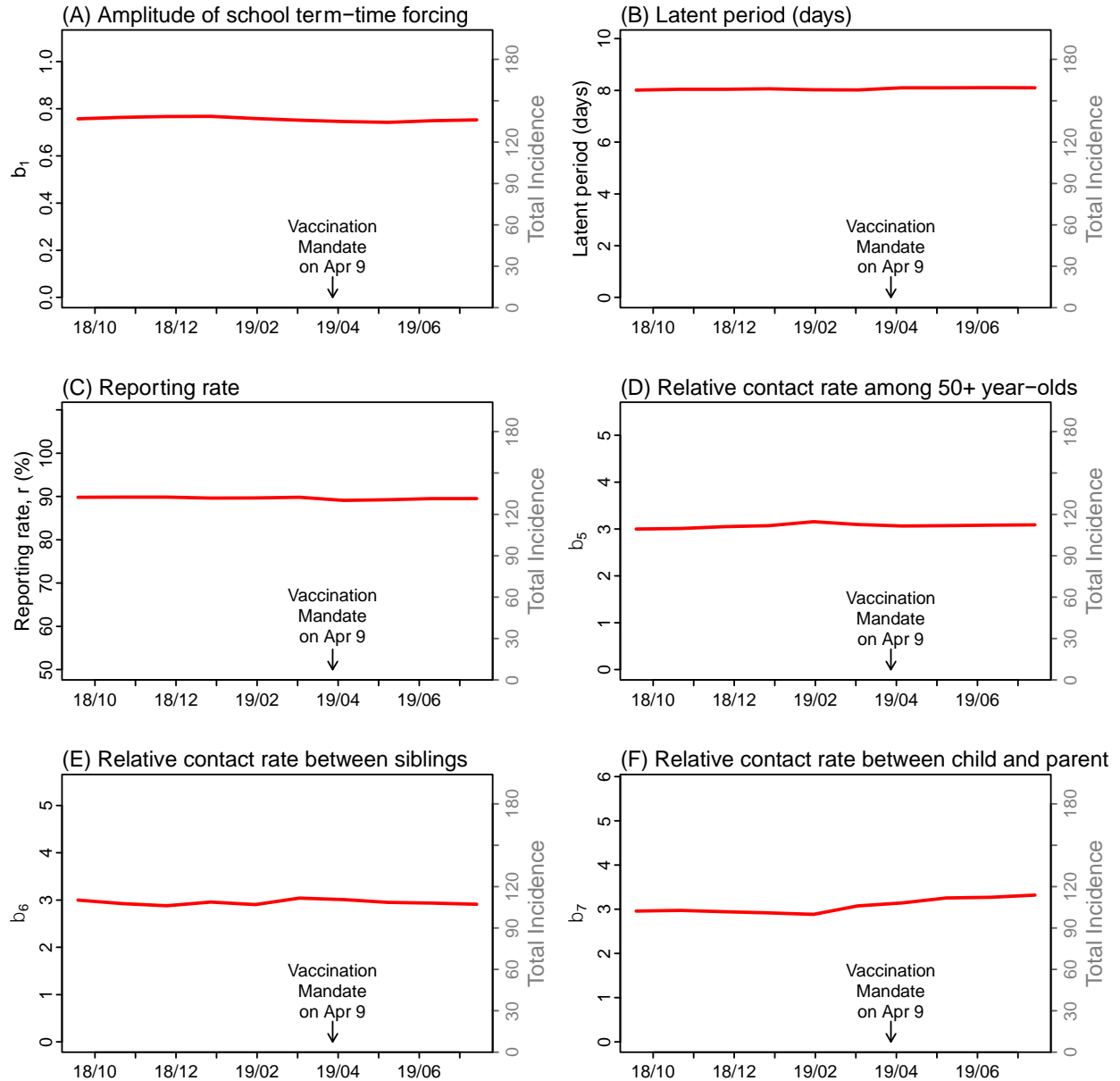
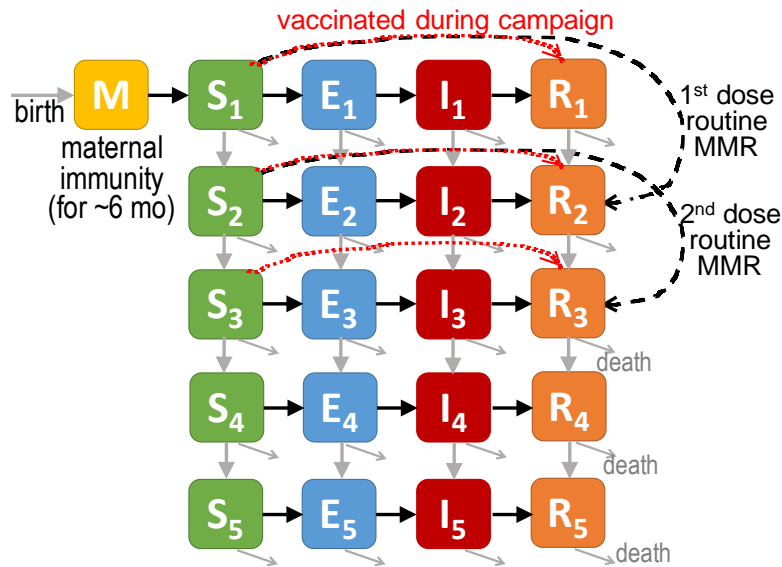


Fig. S2. Schematic of the measles transmission model. Measles transmission model follows the susceptible (S), exposed (E) and latently infected, infectious (I), and recovered/removed via vaccination (R) SEIR dynamics and includes 5 age-groups as indicated by the subscripts (i.e., <1, 1-4, 5-17, 18-49, and 50+ year-olds, respectively) and a group (M) for infants with maternal immunity. Black solid arrows show the disease-related processes; grey solid arrows show the demographic processes including birth (horizontal), aging (vertical), and death (tilted). Black dashed arrows show processes related to the routine 2-dose measles vaccination where susceptible individuals are vaccinated at ages 1 and 5 and move to the respective immune groups. Red dotted arrows show processes related to vaccination of susceptible individuals under 18 during the vaccination campaigns.



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