

Supplement 1

A Reproduction Numbers

The basic reproduction number $\mathcal{R}_0$ is the average number of secondary cases resulting from an infectious individual introduced in a fully susceptible population [1, 2]. In general, when $\mathcal{R}_0 > 1$, the infection spreads in the population and the epidemic grows; whereas when $\mathcal{R}_0 < 1$, the disease dies out. Similarly, the control reproduction number $\mathcal{R}_C$ is the average number of secondary infections resulting from an infectious individual introduced in a susceptible population when control measures are applied (i.e. $\epsilon_i \in [0, 1)$ for at least one i group). For $n = 1, \dots, i$ groups, equation (1) is as follows:

$$\frac{dS_i}{dt} = -q\psi_i\epsilon_i S_i \sum_{j=1}^n \mathcal{H}_{ij} \frac{I_j}{N_j}, \quad (1a)$$

$$\frac{dE_i}{dt} = q\psi_i\epsilon_i S_i \sum_{j=1}^n \mathcal{H}_{ij} \frac{I_j}{N_j} - \delta E_i, \quad (1b)$$

$$\frac{dI_i}{dt} = \delta E_i - \gamma I_i, \quad (1c)$$

$$\frac{dR_i}{dt} = \gamma I_i. \quad (1d)$$

We use the Next Generation Matrix method [1] to calculate $\mathcal{R}_C$. Let $\vec{X} = (\vec{E}, \vec{I})$. We revise (1) such that $\frac{d\vec{X}}{dt} = (\mathcal{F} - \mathcal{V})\vec{X}$, where matrix $\mathcal{F}$ consists of the rate of new infections entering each compartment and matrix $\mathcal{V}$ comprises all other between-compartment transition rates following infection [1].

Then, linearizing at the disease-free equilibrium (DFE) where $(\vec{S}, \vec{E}, \vec{I}, \vec{R}) = (\vec{S}^*, 0, 0, 0)$ and S^* is the susceptible population in each group, we obtain

$$\mathcal{F} = \begin{bmatrix} 0 & X_I \\ 0 & 0 \end{bmatrix} \text{ and } \mathcal{V} = \begin{bmatrix} \delta & 0 \\ -\delta & \gamma \end{bmatrix}$$

where

$$X_I = q \text{diag}(\vec{S}^*) \mathcal{H} \text{diag}^{-1}(\vec{S}^*) \text{diag}(\vec{\psi}) \text{diag}(1 - \epsilon)$$

We calculate the inverse of $\mathcal{V}$ such that

$$\mathcal{V}^{-1} = \begin{bmatrix} \frac{1}{\delta} & 0 \\ \frac{1}{\gamma} & \frac{1}{\gamma} \end{bmatrix}$$

Then, let $\mathcal{Z} = \mathcal{F}\mathcal{V}^{-1}$, such that

$$\mathcal{Z} = \begin{bmatrix} Y & Y \\ 0 & 0 \end{bmatrix}$$

Here,

$$Y = \frac{q}{\gamma} [\text{diag}(\vec{S}^*) \mathcal{H} \text{diag}^{-1}(\vec{S}^*) \text{diag}(\vec{\psi}) \text{diag}(1 - \vec{\epsilon})] \quad (2a)$$

The control reproduction number $\mathcal{R}_C$ is the spectral radius ρ of $\mathcal{Z}$ when at least one $(1 - \epsilon_i) \in [0, 1)$, indicating that control measures are being implemented in at least one population group:

$$\mathcal{R}_C = \rho \left(\frac{q}{\gamma} [\text{diag}(\vec{S}^*) \mathcal{H} \text{diag}^{-1}(\vec{S}^*) \text{diag}(\vec{\psi}) \text{diag}(1 - \vec{\epsilon})] \right)$$

When all $(1 - \epsilon_i) = 1$, no control measures are applied thus the spectral radius ρ of $\mathcal{Z}$ reduces to the basic reproduction number $\mathcal{R}_0$.

$$\mathcal{R}_0 = \rho \left(\frac{q}{\gamma} [\text{diag}(\vec{S}^*) \mathcal{H} \text{diag}^{-1}(\vec{S}^*) \text{diag}(\vec{\psi})] \right)$$

A.1 Control Reproduction Number - Two Groups

We consider two population groups: (K) Children and Youth (0 – 19 years); and (A) Adults (20+ years). We also incorporate age-specific susceptibility to wild-type SARS-CoV-2, where $\psi_K = 0.5$ reflects the reduced susceptibility in children and youth relative to adults [3, 4]. Therefore, given two population groups, equation (1) becomes equation (3) (i.e., equation (1) in the main text), as follows:

$$\frac{dS_K}{dt} = -q\psi_K\epsilon_K S_K (h_{KK} \frac{I_K}{N_K} + h_{KA} \frac{I_A}{N_A}) \quad (3a)$$

$$\frac{dS_A}{dt} = -q\epsilon_A S_A (h_{AA} \frac{I_A}{N_A} + h_{AK} \frac{I_K}{N_K}) \quad (3b)$$

$$\frac{dE_K}{dt} = q\psi_K\epsilon_K S_K (h_{KK} \frac{I_K}{N_K} + h_{KA} \frac{I_A}{N_A}) - \delta E_K \quad (3c)$$

$$\frac{dE_A}{dt} = q\epsilon_A S_A (h_{AA} \frac{I_A}{N_A} + h_{AK} \frac{I_K}{N_K}) - \delta E_A \quad (3d)$$

$$\frac{dI_K}{dt} = \delta E_K - \gamma I_K \quad (3e)$$

$$\frac{dI_A}{dt} = \delta E_A - \gamma I_A \quad (3f)$$

$$\frac{dR_K}{dt} = \gamma I_K \quad (3g)$$

$$\frac{dR_A}{dt} = \gamma I_A \quad (3h)$$

Using the Next Generation Matrix method [1] as above, the (1,1) position of matrix $\mathcal{Z}$ is as follows:

$$Y = \frac{q}{\gamma} [\text{diag}(\vec{S}^*) \mathcal{H} \text{diag}^{-1}(\vec{S}^*) \text{diag}(\vec{\psi}) \text{diag}(1 - \vec{\epsilon})] \quad (4a)$$

Then, we simplify Y to a two-group population structure, where subscript K represents the child and youth population (0-19 years) and subscript A represents the adult population (20+ years):

$$Y_2 = \frac{q}{\gamma} \begin{bmatrix} S_K & 0 \\ 0 & S_A \end{bmatrix} \begin{bmatrix} h_{KK} & h_{KA} \\ h_{AK} & h_{AA} \end{bmatrix} \begin{bmatrix} S_K & 0 \\ 0 & S_A \end{bmatrix}^{-1} \begin{bmatrix} \psi_K & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \epsilon_K & 0 \\ 0 & \epsilon_A \end{bmatrix}$$

This simplifies to:

$$Y_2 = \frac{q}{\gamma} \begin{bmatrix} h_{KK}\psi_K\epsilon_K & \frac{S_K}{S_A}h_{KA}\epsilon_A \\ \frac{S_A}{S_K}h_{AK}\psi_K\epsilon_K & h_{AA}\epsilon_A \end{bmatrix}$$

We want to find the spectral radius or dominant eigenvalue of Y_2 at the DFE to determine $\mathcal{R}_C$, so we calculate the determinant of Y_2 :

$$\det(Y_2 - \lambda I) = \det \begin{bmatrix} \frac{q}{\gamma}h_{KK}\psi_K\epsilon_K - \lambda & \frac{q}{\gamma}\frac{S_K}{S_A}h_{KA}\epsilon_A \\ \frac{q}{\gamma}\frac{S_A}{S_K}h_{AK}\psi_K\epsilon_K & \frac{q}{\gamma}h_{AA}\epsilon_A - \lambda \end{bmatrix}$$

where, the characteristic equation is then

$$\lambda^2 - \lambda \frac{q}{\gamma} (h_{KK}\psi_K\epsilon_K + h_{AA}\epsilon_A) + \frac{q^2}{\gamma^2} (h_{KK}\psi_K\epsilon_K h_{AA}\epsilon_A - h_{AK}\psi_K\epsilon_K h_{KA}\epsilon_A) = 0$$

We find that the two roots of the characteristic equation for Y_2 are

$$\lambda_1 = \frac{q}{2\gamma} \left(h_{KK}\psi_K\epsilon_K + h_{AA}\epsilon_A + \sqrt{(h_{KK}\psi_K\epsilon_K - h_{AA}\epsilon_A)^2 + 4h_{AK}\psi_K\epsilon_K h_{KA}\epsilon_A} \right)$$

$$\lambda_2 = \frac{q}{2\gamma} \left(h_{KK}\psi_K\epsilon_K + h_{AA}\epsilon_A - \sqrt{(h_{KK}\psi_K\epsilon_K - h_{AA}\epsilon_A)^2 + 4h_{AK}\psi_K\epsilon_K h_{KA}\epsilon_A} \right)$$

The spectral radius, or the dominant eigenvalue of Y_2 and therefore of $\mathcal{Z}$ when considering two groups is λ_1 . This is the control reproduction number $\mathcal{R}_C$ when control measures are applied (i.e., either $\epsilon_K < 1$ or $\epsilon_A < 1$, or both $\epsilon_K < 1$ and $\epsilon_A < 1$). Conversely, when both $\epsilon_A = 1$ and $\epsilon_K = 1$, $\mathcal{R}_C$ simplifies to the basic reproduction number $\mathcal{R}_0$:

$$\mathcal{R}_0 = \frac{q}{2\gamma} \left(h_{KK}\psi_K + h_{AA} + \sqrt{(h_{KK}\psi_K - h_{AA})^2 + 4h_{AK}\psi_K h_{KA}} \right)$$

B Model Variation: Case Importation

The COVID-19 pandemic in Canada was initiated by the importation of infectious cases from other global regions experiencing COVID-19 outbreaks [5]. While COVID-19 datasets from Ontario (Greater Toronto Area) and British Columbia (Greater Vancouver) provide travel-related exposure information for confirmed cases, the open-source dataset from Alberta (Calgary) does not.

Initial attempts to estimate the baseline transmission probability q and subsequent control parameters ϵ_K and ϵ_A using the reported cases data proved to be difficult. Thus, we revise our equation (3) (i.e., equation (1) in the main text) to incorporate constant age-specific importation rates (ν_K, ν_A) during the baseline period to account for the seeding of infectious cases in a fully susceptible population through travel importations prior to the implementation of widespread federal and provincial control measures. These importation parameters are the daily age-specific importation rates of exposed (E_K, E_A) individuals (i.e., infected but not yet infectious) during the initial baseline phase prior to travel restrictions and other major control measures. The equation variation (5) is then:

$$\frac{dS_K}{dt} = -q\psi_K\epsilon_K S_K(h_{KK}\frac{I_K}{N_K} + h_{KA}\frac{I_A}{N_A}) \quad (5a)$$

$$\frac{dS_A}{dt} = -q\epsilon_A S_A(h_{AA}\frac{I_A}{N_A} + h_{AK}\frac{I_K}{N_K}) \quad (5b)$$

$$\frac{dE_K}{dt} = \nu_K + q\psi_K\epsilon_K S_K(\mathcal{H}_{KK}\frac{I_K}{N_K} + \mathcal{H}_{KA}\frac{I_A}{N_A}) - \delta E_K \quad (5c)$$

$$\frac{dE_A}{dt} = \nu_A + q\epsilon_A S_A(\mathcal{H}_{AA}\frac{I_A}{N_A} + \mathcal{H}_{AK}\frac{I_K}{N_K}) - \delta E_A \quad (5d)$$

$$\frac{dI_K}{dt} = \delta E_K - \gamma I_K \quad (5e)$$

$$\frac{dI_A}{dt} = \delta E_A - \gamma I_A \quad (5f)$$

$$\frac{dR_K}{dt} = \gamma I_K \quad (5g)$$

$$\frac{dR_A}{dt} = \gamma I_A \quad (5h)$$

B.1 Calgary Baseline Period - Parameter Estimation

Given the addition of the unknown age-specific importation parameters to the model, we decided to estimate these unknown values rather than the transmission probability q for Calgary. We assumed that the baseline probability of transmission in urban regions were similar to one another in the absence of control measures, so we took the average of the q values estimated for Greater Vancouver ($q = 0.828$) and Greater Toronto Area ($q = 0.952$), which resulted in an average transmission probability q of 0.890. We fixed this value for Calgary in the baseline period, along with all other parameters found in Table 1.

As in the main text, we used maximum likelihood estimation (MLE) to estimate the importation parameters ν_K and ν_A during the baseline period by fitting model (5) to the re-

Table 1: Parameters used in the age-structured SEIR model with importations (Calgary).

Parameter	Description	Value	Source
$1/\delta$	Mean latent period	6 days	[6]
$1/\gamma$	Mean infectious period	10 days	[7]
ψ_K	Susceptibility to infection	0.5	[3, 4]
ϵ_K, ϵ_A	NPI level*	1	-
q	Transmission probability	Mean (GTA and Greater Vancouver)	-
$\mathcal{H} = \begin{bmatrix} h_{KK} & h_{KA} \\ h_{AK} & h_{AA} \end{bmatrix}$	Contact matrix	$\begin{bmatrix} 2.09 & 0.41 \\ 0.60 & 0.82 \end{bmatrix}$	[8]

*Subscripts K and A refer to the children and youth population (0 – 19 years) and the adult population (> 20 years), respectively. *In the absence of NPIs, both $\epsilon_K = 1$ and $\epsilon_A = 1$.

ported COVID-19 case data for Calgary. Specifically, we estimated ν_K and ν_A that minimized the negative log-likelihood ($-\ln \mathcal{L}(\theta)$), and used the likelihood ratio test (LRT) to determine the associated confidence intervals [9]. This process gave an estimate of $\nu_K = 0.220$ (0, 0.75) and $\nu_A = 6.46$ (4.90, 8.07).

Following this initial baseline fitting period, $\nu_A = 0$ and $\nu_K = 0$ for all subsequent control periods in Calgary due to travel restrictions; however, the mean q value of 0.890 remains fixed throughout the remainder of the parameter estimation process. Thus, equation (5) reverts to equation (3) (i.e., equation (1) in the main text).

Note that the in the case of equation (5), if $\nu_K > 0$ or $\nu_A > 0$, then the associated $\mathcal{R}_C$ cannot reduce to $\mathcal{R}_0$ as it does not logically exist due to the absence of a disease-free equilibrium.

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C NPI Parameter Estimates

Table 2: Age-specific and time-dependent NPI strength parameter estimates for Calgary Health Zone

	Start Date	End Date	ϵ_K (95% CI)	ϵ_A (95% CI)	-logLik
1	2020-03-16	2020-03-27	0 (NA)	0.432 (0.395, 0.469)	124.946
2	2020-03-27	2020-04-20	0 (NA)	0.267 (0.260, 0.273)	432.281
3	2020-04-20	2020-06-01	0.032 (0.022, 0.040)	0.006 (0, 0.012)	354.820
4	2020-06-01	2020-07-03	0.046 (0.014, 0.074)	0.189 (0.169, 0.203)	216.034
5	2020-07-03	2020-07-17	0 (NA)	0.400 (0.378, 0.422)	136.656
6	2020-07-17	2020-08-01	0.027 (0, 0.054)	0 (NA)	139.436
7	2020-08-01	2020-09-01	0.118 (0.097, 0.138)	0.145 (0.130, 0.159)	311.010
8	2020-09-01	2020-10-09	0.047 (0.033, 0.060)	0.128 (0.118, 0.137)	328.262
9	2020-10-09	2020-11-06	0.142 (0.130, 0.155)	0.275 (0.266, 0.283)	462.249
10	2020-11-06	2020-11-27	0.034 (0.023, 0.044)	0.183 (0.177, 0.189)	389.195
11	2020-11-27	2020-12-08	0.058 (0.039, 0.076)	0.132 (0.121, 0.143)	309.878
12	2020-12-08	2020-12-19	0 (NA)	0.067 (0.060, 0.075)	217.732
13	2020-12-19	2021-01-11	0.077 (0.068, 0.085)	0.087 (0.081, 0.092)	585.981
14	2021-01-11	2021-01-18	0.016 (0, 0.049)	0.041 (0.017, 0.065)	134.268
15	2021-01-18	2021-02-08	0.045 (0.034, 0.056)	0.058 (0.050, 0.067)	229.999

Table 3: Age-specific and time-dependent NPI strength parameter estimates for Greater Toronto Area

	Start Date	End Date	ϵ_K (95% CI)	ϵ_A (95% CI)	-logLik
1	2020-03-16	2020-03-28	0 (0, 0.006)	0.860 (0.838, 0.882)	316.749
2	2020-03-28	2020-04-13	0 (NA)	0.264 (0.258, 0.271)	668.986
3	2020-04-13	2020-05-04	0 (NA)	0.067 (0.063, 0.071)	746.723
4	2020-05-04	2020-05-19	0 (NA)	0.175 (0.169, 0.182)	308.702
5	2020-05-19	2020-06-19	0 (NA)	0.070 (0.068, 0.073)	499.032
6	2020-06-19	2020-07-24	0.017 (0.004, 0.030)	0.076 (0.071, 0.080)	292.749
7	2020-07-24	2020-09-08	0.008 (0, 0.027)	0.175 (0.169, 0.180)	464.659
8	2020-09-08	2020-09-18	0.069 (0.018, 0.118)	0.348 (0.327, 0.369)	176.832
9	2020-09-18	2020-10-03	0.023 (0.002, 0.044)	0.227 (0.217, 0.234)	226.165
10	2020-10-03	2020-10-10	0.028 (0, 0.062)	0.154 (0.137, 0.171)	146.273
11	2020-10-10	2020-11-07	0.040 (0.033, 0.047)	0.163 (0.160, 0.166)	494.714
12	2020-11-07	2020-11-23	0.022 (0.013, 0.032)	0.158 (0.153, 0.162)	323.249
13	2020-11-23	2020-12-19	0.029 (0.025, 0.035)	0.136 (0.134, 0.138)	422.243
14	2020-12-19	2020-12-26	0 (NA)	0.191 (0.184, 0.198)	275.178
15	2020-12-26	2021-01-04	0.025 (0.010, 0.040)	0.206 (0.199, 0.213)	347.545
16	2021-01-04	2021-02-08	0.002 (0, 0.005)	0.067 (0.066, 0.069)	705.895

Table 4: Age-specific and time-dependent NPI strength parameter estimates for Greater Vancouver

	Start Date	End Date	ϵ_K (95% CI)	ϵ_A (95% CI)	-logLik
1	2020-03-16	2020-03-20	0 (0, 0.047)	0.545 (0.427, 0.663)	112.952
2	2020-03-20	2020-03-27	0 (0, 0.008)	0.117 (0.065, 0.170)	141.198
3	2020-03-27	2020-05-19	0 (0, 0.0002)	0.083 (0.079, 0.088)	357.674
4	2020-05-19	2020-06-01	0.019 (0, 0.124)	0.127 (0.054, 0.181)	60.239
5	2020-06-01	2020-06-25	0 (0, 0.067)	0.182 (0.160, 0.204)	114.668
6	2020-06-25	2020-07-23	0.029 (0, 0.098)	0.181 (0.155, 0.202)	144.495
7	2020-07-23	2020-08-07	0 (0, 0.037)	0.356 (0.331, 0.382)	113.652
8	2020-08-07	2020-09-09	0 (0, 0.008)	0.193 (0.188, 0.199)	268.363
9	2020-09-09	2020-10-08	0.031 (0.007, 0.054)	0.164 (0.155, 0.171)	284.022
10	2020-10-08	2020-11-03	0.036 (0.015, 0.056)	0.283 (0.275, 0.290)	322.900
11	2020-11-03	2020-11-16	0.047 (0.022, 0.071)	0.210 (0.199, 0.221)	291.862
12	2020-11-16	2020-12-19	0.024 (0.017, 0.031)	0.110 (0.106, 0.113)	454.898
13	2020-12-19	2021-01-04	0.030 (0.011, 0.048)	0.130 (0.121, 0.138)	232.328
14	2021-01-04	2021-02-04	0.026 (0.015, 0.037)	0.124 (0.119, 0.129)	396.442