

Risk for Fomite-Mediated Transmission of SARS-CoV-2 in Child Daycares, Schools, Nursing Homes, and Offices

Appendix

Model Details

This model has previously been described in detail, but in brief, the population is classified as susceptible (S), infectious (I), or recovered (R). Infectious individuals can shed pathogens directly onto fomites (F) or onto hands (H compartments, either H_S , H_I , or H_R). Hands have the same infection status as individuals (i.e., all susceptible individuals, S, have susceptible hands H_S). Hands may become contaminated through direct excretion (self-inoculation) by an infectious individual or through touching contaminated fomites. Hand contamination is not dependent on an individual's infection status, thus, a recovered individual (H_R) could have contaminated hands. Susceptible individuals can become infected through touching their face and/or mouth with contaminated hands (self-inoculation) based on the linear dose-response function, P . Pathogens on hands and on fomites are inactivated based on the persistence properties of the pathogen. In addition to natural inactivation, pathogens may be removed from hands or surfaces through cleaning interventions, which is determined by both the frequency and efficacy of the cleaning. The parameter values considered in this model and their definitions are shown in Appendix Table 1. The model equations and the corresponding R_0 equations are shown below. A model diagram is shown in Appendix Figure 1.

In our model, we assume a cleaning and decontamination efficacy of 100%, consistent with initial data on the efficacy of standard cleaning agents (I). However, if cleaning without disinfection is used (i.e., removing only organic matter on surfaces without using disinfection agents, such as bleach), higher frequencies of cleaning would be unlikely to reduce risk unless pathogen shedding on surfaces can also be substantially reduced.

$$\frac{dS}{dt} = -\rho P \left(\frac{\chi H_S}{S} \right) S$$

$$\frac{dI}{dt} = \rho P \left(\frac{\chi H_S}{S} \right) S - \gamma I$$

$$\frac{dR}{dt} = \gamma I$$

$$\frac{dF}{dt} = \alpha_F I - (\rho_{FH} N + \mu_F + \theta_F) F + \rho_{HF} (H_S + H_I + H_R)$$

$$\frac{dH_S}{dt} = \rho_{FH} S F - (\mu_H + \rho_{HF} + \chi \rho + \theta_H) H_S - (1 - \chi) \rho P \left(\frac{\chi H_S}{S} \right) H_S$$

$$\frac{dH_I}{dt} = \rho_{FH} I F - (\mu_H + \rho_{HF} + \chi \rho + \theta_H) H_I + \alpha_H I + (1 - \chi) \rho P \left(\frac{\chi H_S}{S} \right) H_S - \gamma H_I$$

$$\frac{dH_R}{dt} = \rho_{FH} R F - (\mu_H + \rho_{HF} + \chi \rho + \theta_H) H_R + \gamma H_I$$

$$R_0 = \frac{1}{\gamma} \left[\frac{\chi \rho \pi}{\mu_H + \rho_{HF} + \chi \rho + \theta_H} \right] \left[\left(\frac{\frac{\rho_{FH} N}{\rho_{FH} N + \mu_F + \theta_F}}{1 - \frac{\rho_{HF} \rho_{FH} N}{(\mu_H + \rho_{HF} + \chi \rho + \theta_H)(\rho_{FH} N + \mu_F + \theta_F)}} \right) (\alpha_F + \alpha_H \left[\frac{\rho_{HF}}{\mu_H + \rho_{HF} + \chi \rho + \theta_H} \right]) \right]$$

Deriving model parameters for SARS-CoV-2 and uncertainty

For unknown persistence and transfer efficiency parameters, we used influenza values because SARS-CoV-2, like influenza, is an enveloped virus, which tend to have lower persistence than non-enveloped viruses on surfaces (34). For uncertain infectivity parameters, we used values from other coronaviruses (if available) or rhinovirus because of the similarity in symptoms likely to drive transmission.

Infectivity parameters—shedding rate and dose response curves

To provide the most accurate infectivity data, we used shedding rates that were in terms of TCID₅₀ units, as this excludes potential bias from measuring genetic material from inactive virus. TCID₅₀ units describe the concentration of virus that would be expected to infect 50% of challenged cells, whereas PFU units describe the number (count) of plaques likely to be formed

in a cell culture containing a given concentration of infectious virus. Based on this definition, when $TCID_{50} = 1$, the expected number of observed plaques is 0. Therefore, for parameters in PFU units, we converted between the two scales as follows, applying the Poisson distribution, where the expected number of plaques observed is dependent on μ , the PFU/mL (35,36):

$$P(\text{Count of plaques} = y) \sim \text{Pois}(\mu = \text{PFU}) = \frac{e^{-\mu} \mu^y}{y!}$$

$$P(\text{Count of plaques} = 0) = \frac{e^{-\mu} \mu^0}{0!}$$

$$0.5 \text{ TCID}_{50}/\text{mL} = e^{-\text{PFU}}$$

Thus,

$$\text{TCID}_{50} = -\ln(0.5) \text{ PFU}$$

Decay rates on fomites

For SARS-CoV-2, decay rates on different surfaces were calculated based on the slope of the decay curves first 24 hours for cloth (highest decay rates), plastic (lowest decay rates) and stainless steel (medium decay rates). For cloth, the decay rates were calculated based on the first 30 minutes of decay because most samples became undetectable after the first 30 minutes of observation and were then multiplied by 2 to get the corresponding hourly decay rates. Because experimental data was presented on the log10 scale, the decay rates from the different experimental studies were initially calculated on the log10 scale. To convert these numbers to the exponential scale, the decay rate on the log10 scale was multiplied by $\ln(10)$.

Decay rates on hands

For SARS-CoV-2, there were no reliable pathogen-specific data for the decay rate of pathogen on hands. One study used skin samples from corpses to estimate this quantity and calculated decay rates for both influenza and SARS-CoV-2. In this study, decay rates on hands were substantially lower for SARS-CoV-2 compared with influenza, with SARS-CoV-2 surviving for about eight times as long as influenza (22). However, the decay rates from influenza obtained using this method differed substantially from prior decay rate estimates for influenza (14,21), casting doubt on this model system for estimating the absolute decay rates. Moreover, this study used a method that pipetted pathogen directly onto hands rather than first

transferring pathogen from an inanimate surface to hands. Given that decay rates on hands vary based on the surface from which they are transferred (even after accounting for transfer efficacy) (21), these data were inappropriate for use in our fomite model. For this reason, we relied on decay rates previously estimated for influenza and considered a lower hand decay rate as a sensitivity analysis, where the decay rate on hands for SARS-CoV-2 was 11.02/hour, $\approx 1/8$ the decay rate previously estimated for influenza.

Transfer efficacy

For SARS-CoV-2, there were no data available on transfer efficacy, so we relied on the transfer efficacy parameters previously estimated for influenza.

Handwashing

We initially considered a handwashing intervention that removed all pathogens on hands at regular intervals. However, SARS-CoV-2 is predicted to have very low persistence on hands (Appendix Table 1). For this reason, even hourly handwashing with 100% effectiveness had almost no impact on transmission risk. To illustrate, we reran Figure (<https://wwwnc.cdc.gov/EID/article/27/4/20-3631-F1.htm>) assuming hourly handwashing and the results were nearly identical to the version in the main text with no handwashing (Appendix Figure 2).

Shedding Sensitivity Analysis

Baseline hand persistence

As a sensitivity analysis, we considered how the basic reproduction number would change if the hourly shedding rate were slightly different, using stainless steel as the surface for comparison. Preliminary data suggest a shedding rate of 1800 pathogens/person/hr (1.8E3) (6), which is the estimate used in the main text. We considered 2E3 as a potential upper bound on shedding for SARS-CoV-2 (Appendix Figure 3). Widespread use of masks might also lower the overall shedding rate. To approximate the impact of mask wearing, we reduced both shedding (α) and the rate of self-inoculation (ρ) by 75% ($\alpha = 450, \rho = 3.95$), consistent with estimates of viral reduction in droplets during speech with mask wearing (13).

Shedding might be lower or higher than expected for several reasons. First, initial studies were limited in sample size, which may have reduced the precision and accuracy of early

estimates. In addition, overall shedding might vary by level of symptoms. While viral load has been found to be similar in secretions of symptomatic and asymptomatic cases, they may not have similar contributions to overall transmission if shedding is influenced strongly by symptoms. For example, the number of droplets expelled during coughing, a common symptom of SARS-CoV-2, is much higher than during speech (37). On the other hand, symptomatic individuals may be more likely to take precautions to limit viral spread, making asymptomatic transmission relatively more important. With mask wearing, transmission from surfaces was unlikely, even when surface decontamination was set to its minimum value (once every 8 hours).

Higher hand persistence

We repeated the same sensitivity analysis varying shedding while also allowing persistence to be higher, based on data from (22). When hand persistence was higher, transmission from surfaces could not be controlled unless both mask wearing and frequent surface disinfection were used (Appendix Figure 4). Even with hourly handwashing and mask wearing, transmission from surfaces would only be controlled in office settings.

Alternative cleaning frequencies

For comparison, we reran Figure 2 considering cleaning frequencies every 2 hours (Appendix Figure 5). The impacts were intermediate between cleaning every 4 hours and hourly cleaning.

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Appendix Table 1. List of pathogen-specific parameters values and references*

Parameter type	Influenza	Rhinovirus	SARS-CoV-2
Pathogen-specific parameters			
$1/\gamma$: Infectious period (days)	6 (2–4)	10.4 (5)	8 (6,7)
α : Shedding rate (pathogen hours ⁻¹ people ⁻¹)	1×10^4 (8–10)	1×10^3 (11,12)	1.8×10^3 (6,13) (450, 2×10^3)
μ_F : Inactivation rate in fomites (hours ⁻¹)	0.121 (14–16)	1.44 (17,18)	0.148 (1,19) (0.131, 9.21)
μ_H : Inactivation rate in hands (hours ⁻¹)	88.2 (14,16,20)	0.767 (21)	88.2 (14,16,20,22)
τ_{FH} : Transfer efficacy (F to H) (proportion)	0.1 (14,20,23,24)	0.2 (21,25–27)	0.1 (14,20,23,24)
τ_{HF} : Transfer efficacy (H to F) (proportion)	0.025 (14,20,23,24)	0.2 (21,25–27)	0.025 (14,20,23,24)
ϕ_H : Pathogens excreted to hands (proportion)	0.15	0.15	0.15
ϕ_F : Pathogens excreted to fomites (proportion)	$1 - \phi_H$	$1 - \phi_H$	$1 - \phi_H$
π : Infectivity parameter in contact with x pathogens (unitless, $P'(0)$)†	6.93×10^{-5} (28)	2.46×10^{-3} (28)	3.55×10^{-3} (29–31)
α_H : rate pathogens are added to hands (pathogen hours ⁻¹ people ⁻¹)	$\alpha\phi_H$	$\alpha\phi_H$	$\alpha\phi_H$
Venue-specific parameters			
λ : Accessible surfaces (proportion)	(0, 0.6)	(0, 0.6)	(0, 0.6)
κ : fingertip to surface ratio per individual (1/people)‡	6×10^{-6}	6×10^{-6}	6×10^{-6}
ρ_T : rate of fomite touching (hours ⁻¹)	(0, 60)	(0, 60)	(0, 60)
ρ_{FH} : rate of fomite pick up from fomites to hand (1/(hours x people))	$\rho_T\tau_{FH}\kappa$	$\rho_T\tau_{FH}\kappa$	$\rho_T\tau_{FH}\kappa$
ρ_{HF} : rate of fomite pick up from hands to fomites (1/(hours x people))	$\rho_T\tau_{HF}$	$\rho_T\tau_{HF}$	$\rho_T\tau_{HF}$
α_F : rate pathogens are added to fomites (pathogen hours ⁻¹ people)	$\alpha\phi_F\lambda$	$\alpha\phi_F\lambda$	$\alpha\phi_F\lambda$
Cleaning parameters			
Θ_F : Rate of fomite cleaning (hours ⁻¹)	(1/8, 1)	(1/8, 1)	(1/8, 1)
Θ_H : Rate of hand cleaning (hours ⁻¹)	(1/8, 1)	(1/8, 1)	(1/8, 1)
q_F : Fomite cleaning efficacy (proportion)	1	1	1
q_H : Hand cleaning efficacy (proportion)	1	1	1
θ_F : Effective fomite cleaning rate (hours ⁻¹)	$q_F\Theta_F$	$q_F\Theta_F$	$q_F\Theta_F$
θ_H : Effective hand cleaning rate (hours ⁻¹)	$q_H\Theta_H$	$q_H\Theta_H$	$q_H\Theta_H$
Fixed parameters (across pathogens and venues)			
ρ : Self-inoculation (hours ⁻¹)	15.8 (32,33)	15.8 (32,33)	15.8 (3.95, 15.8) (13,32,33)
χ : Proportion of pathogens absorbed when self-inoculation occurs (proportion)	1	1	1

*Parameter values for rhinovirus and influenza are shown for comparison. A range is also included for parameters that were used to perform a sensitivity analysis (frequency of cleaning, infectious period, shedding rate, and persistence on surfaces). Derived parameters are shown as a function of the parameters used to derive them. Decay rates on fomites for influenza and rhinovirus are for stainless steel. For SARS-CoV-2, the decay rates shown in parentheses are the range of observed for plastic (lowest decay rates), stainless steel, and cloth (highest decay rates). For SARS-CoV-2, parameters that were extrapolated based on data from other pathogens are shown in bold.

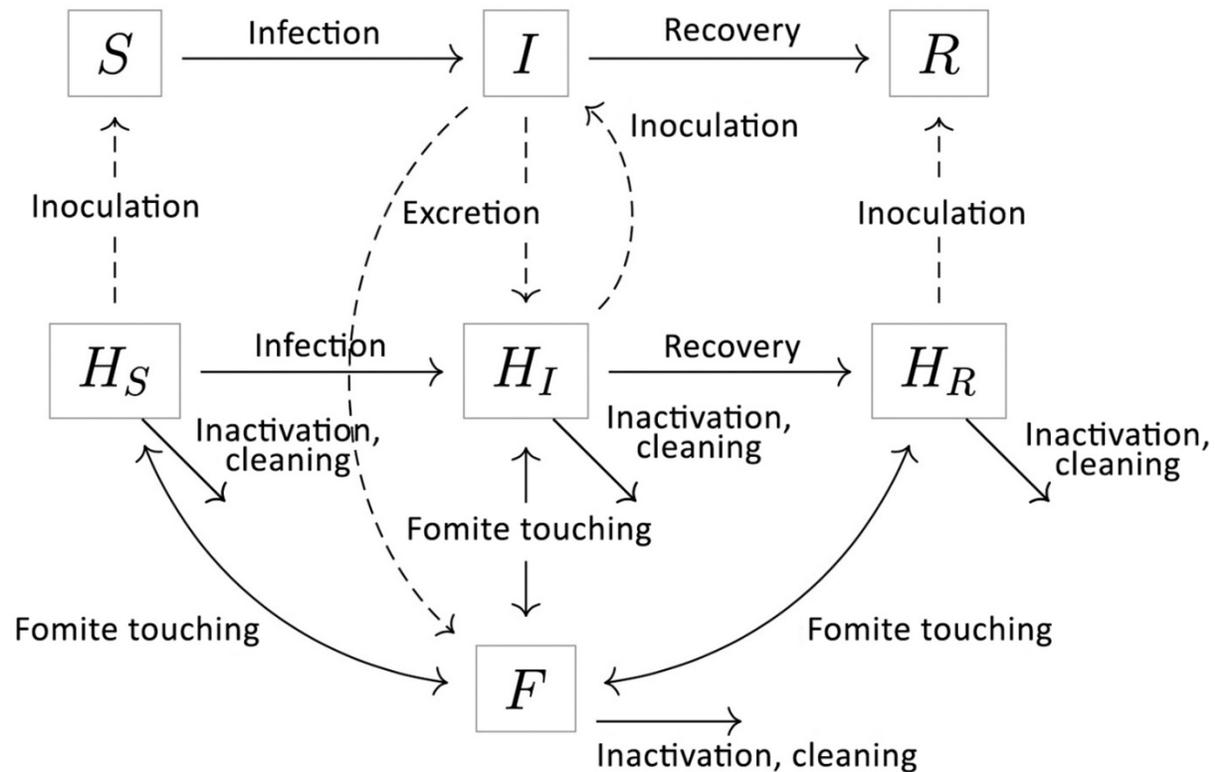
†Parameter fixed based on linearization of the dose-response curve, P.

‡Parameter fixed based on relative finger to body size

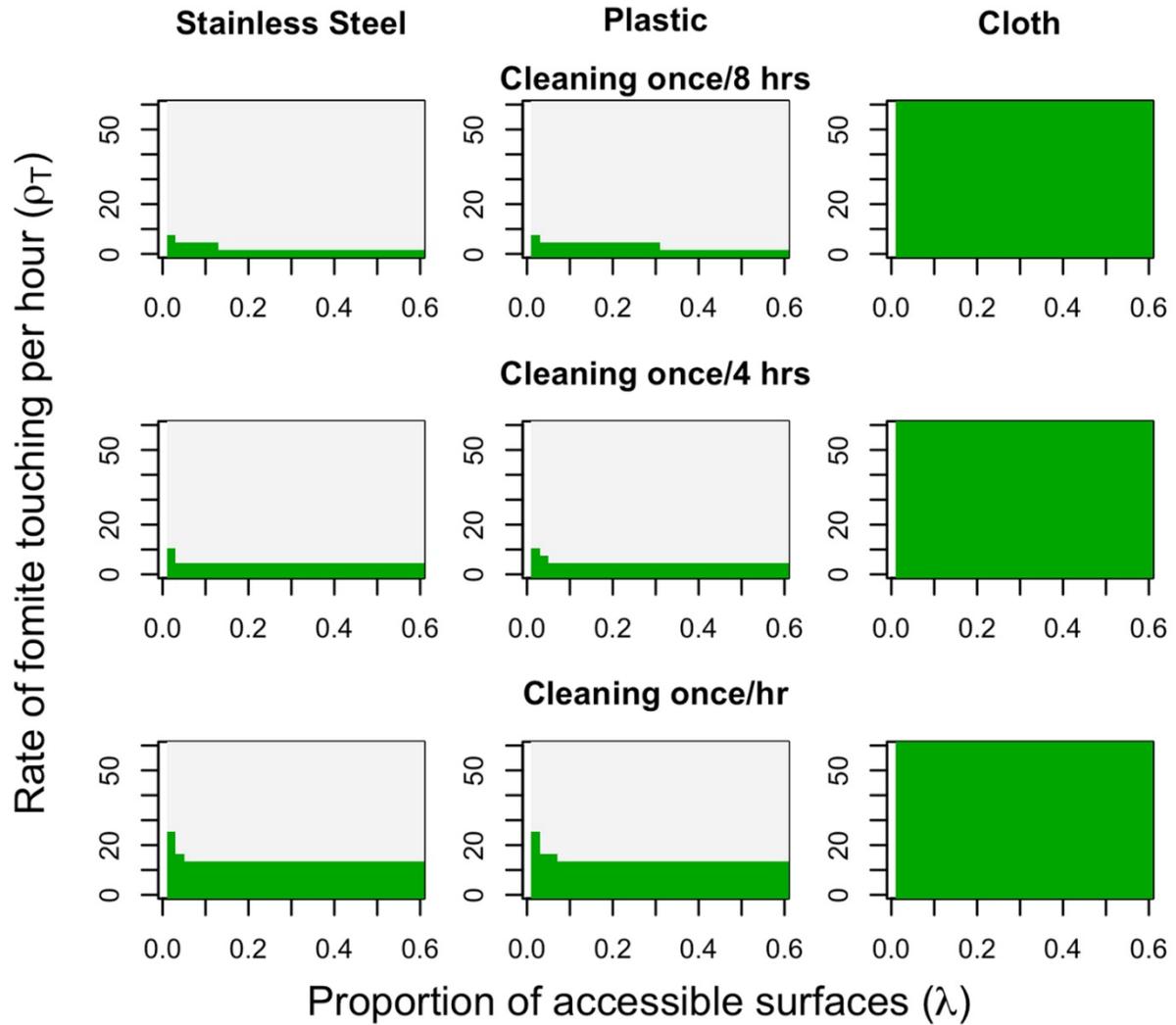
Appendix Table 2. Decay rates for each surface*

Surface	Doremalen et al. (19)	Chin et al. (1)	Average
Stainless steel (ln/hr)	0.170	0.092	0.131
Plastic (ln/hr)	0.108 (3.64, 2.52)	0.184	0.146
Cloth (ln/hr)	NA	9.21	9.21

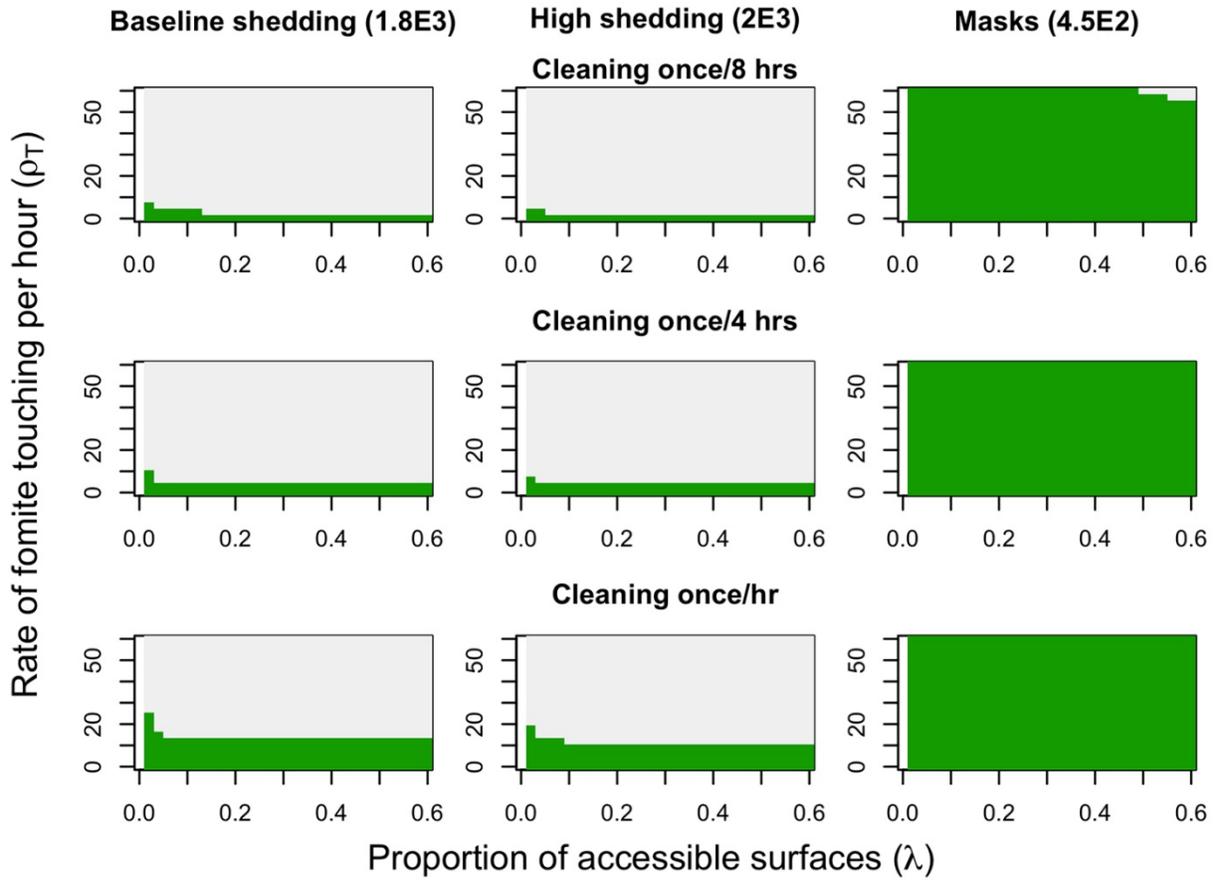
*NA, not available.



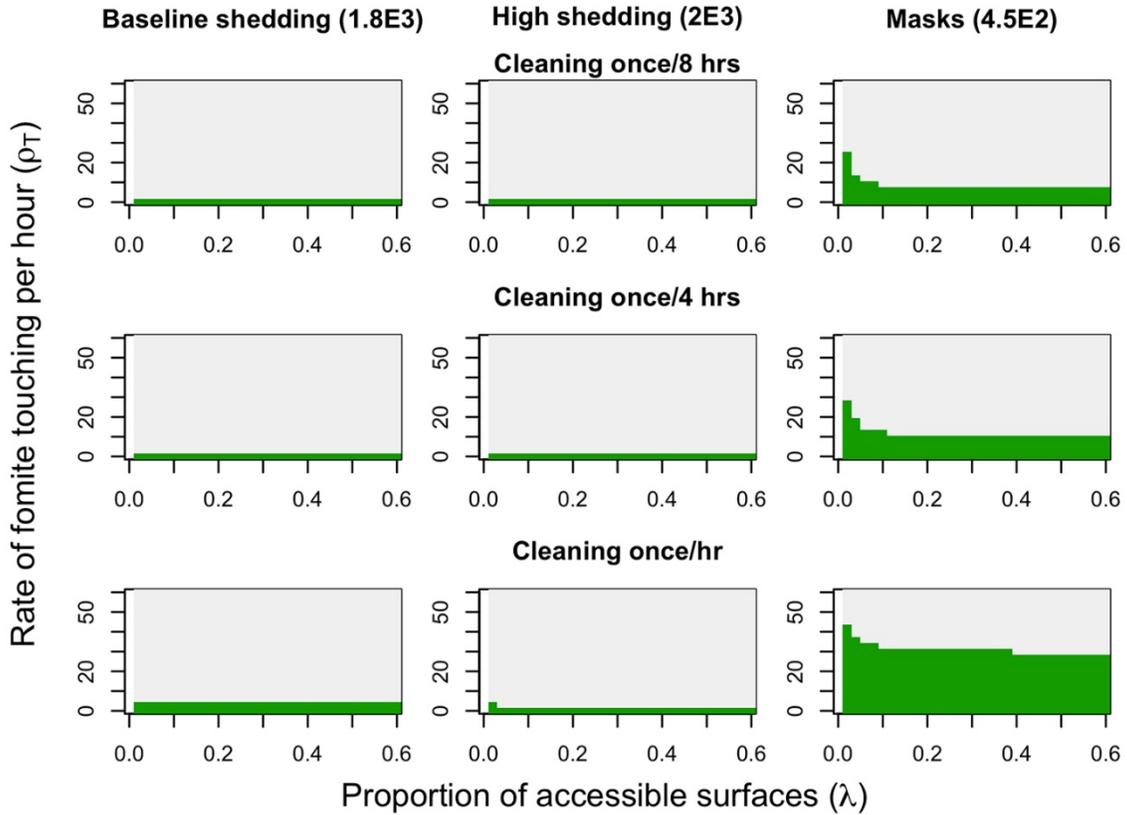
Appendix Figure 1. Model tracks individuals (in compartments S , I or R) and pathogens on fomites (F) and hands (hands of susceptible individuals, H_S ; hands of infected individuals, H_I ; hands of recovered individuals; H_R). The six events (inoculation, fomite touching, excretion, pathogen inactivation, cleaning, and recovery) are represented by arrows in the direction of the corresponding flow.



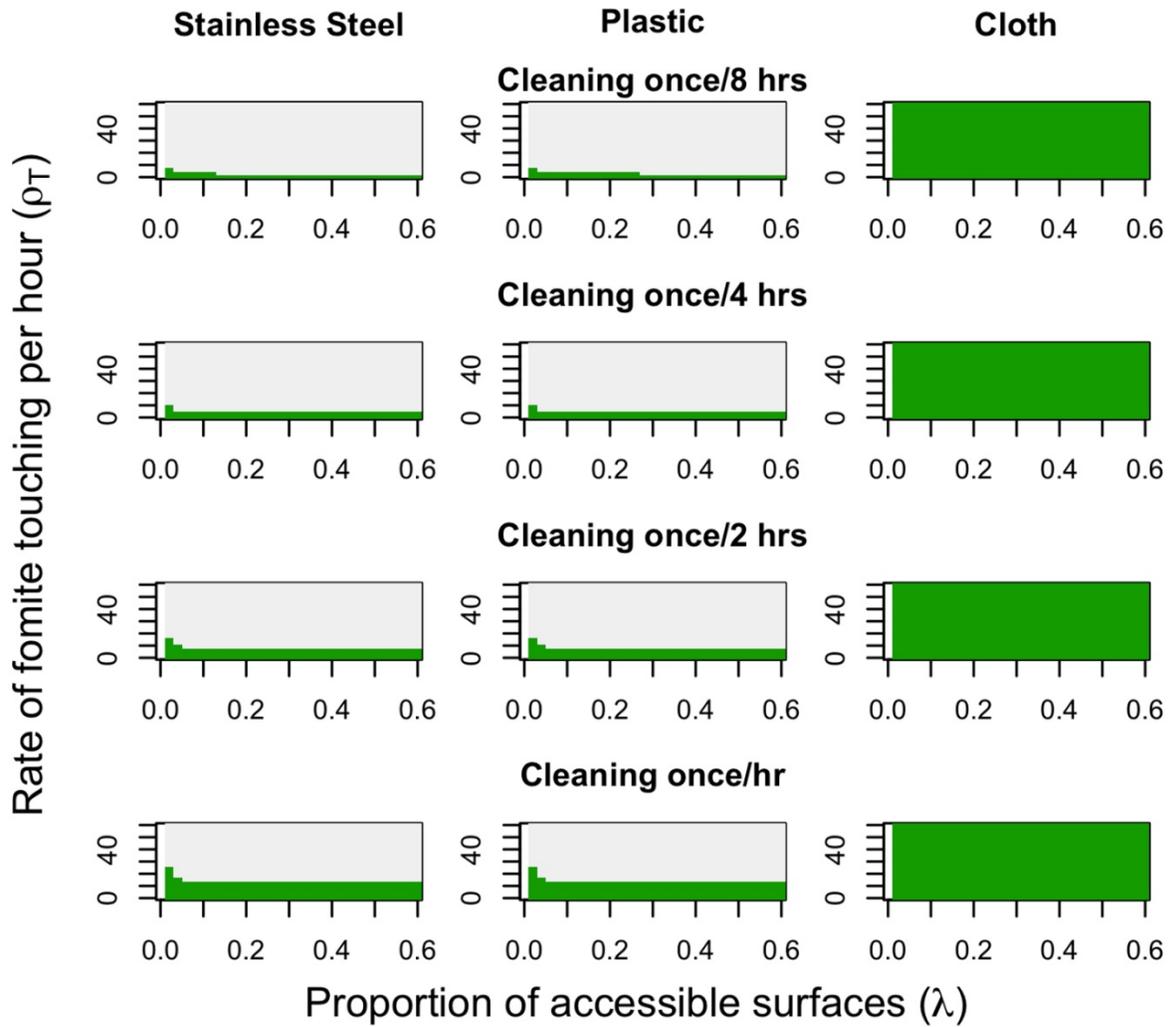
Appendix Figure 2. Reductions in the basic reproduction number by cleaning strategy and surface with hourly handwashing included. For areas in green, the projected reproduction number from fomite transmission is below 1.



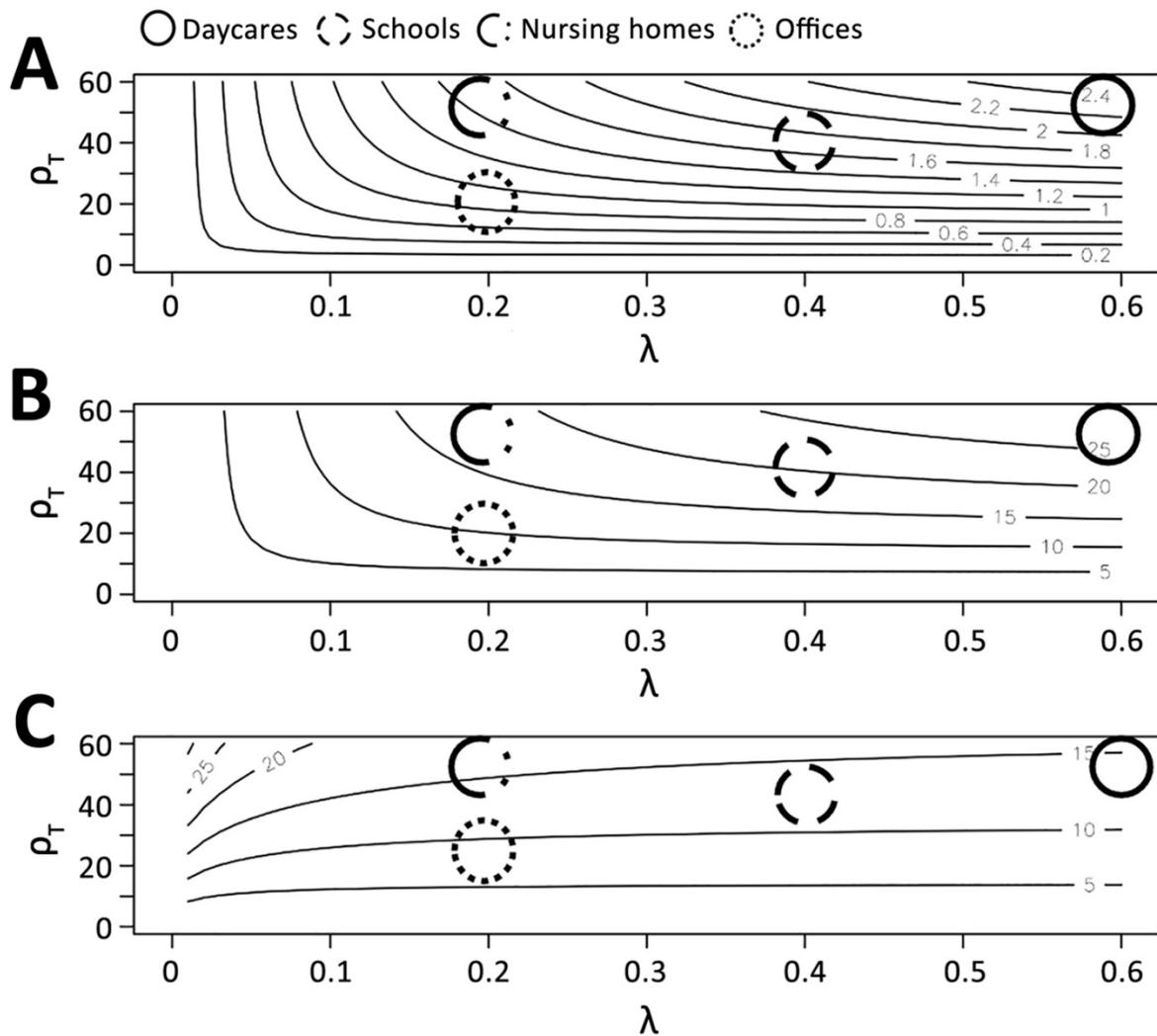
Appendix Figure 3. Reductions in the basic reproduction number by cleaning strategy for different shedding rates (baseline, upper bound of shedding, and mask wearing). For areas in green, the projected reproduction number from fomite transmission is below 1.



Appendix Figure 4. Reductions in the basic reproduction number by cleaning strategy for different shedding rates (baseline, upper bound of shedding, and mask wearing) for stainless steel surfaces assuming higher hand persistence. For areas in green, the projected reproduction number from fomite transmission is below 1.



Appendix Figure 5. Reductions in the basic reproduction number for different surfaces. For areas in green, the projected reproduction number from fomite transmission is below 1.



Appendix Figure 6. Predicted basic reproduction number for the fomite pathway for A) influenza, B) severe acute respiratory syndrome coronavirus 2, and C) rhinovirus without any interventions, by setting. Hourly fomite touching rates (ρ_T) and proportion of accessible surfaces (λ) are not known precisely, so larger circular symbols are used to reflect uncertainty, highlighting the plausible range. All 3 pathogens are shown using decay rates from stainless steel surfaces. Parameters used for each pathogen are shown in Appendix Figure 1.