Lessons Learnt from NPI Effectiveness Modelling throughout the COVID-19 Pandemic

Mrinank Sharma



Research happens in teams. Many collaborators :)



And more who I couldn't find photos of

Governments across the world implemented a suite of non-pharmaceutical interventions to control the COVID-19 pandemic.

• This article is more than **1 year old**

Geneva motor show cancelled as Switzerland bans large events

Ruling to prevent coronavirus spread covers events likely to attract more than 1,000 people

Coronavirus - latest updates



▲ Covered cars are pictured at the Palexpo exhibition centre, which had been due to stage the Geneva motor show from 2-15 March. Photograph: Pierre Albouy/Reuters

The Geneva International Motor Show has been cancelled after the Swiss government banned large events of more than 1,000 people as a measure to help combat the spread of coronavirus.

Governments across the world implemented a suite of non-pharmaceutical interventions to control the COVID-19 pandemic.

UK schools to be closed indefinitely and exams cancelled

Schools will remain open only for key workers' children and 'the most vulnerable' $% \mathcal{L}^{(2)}$

- Coronavirus latest updates
- See all our coronavirus coverage



▲ Coronavirus: UK schools to close indefinitely, says Boris Johnson – video

Governments across the world implemented a suite of non-pharmaceutical interventions to control the COVID-19 pandemic.

Italy set to quarantine whole of Lombardy due to coronavirus

Government's draft decree would impose fines on anyone caught entering or leaving northern region



A The deserted Piazza Duomo in Milan. Photograph: Piero Cruciatti/AFP via Getty Images

Governments across the world implemented a suite of non-pharmaceutical interventions to control the COVID-19 pandemic.

As we know, **interventions have** costs—socially, economically, ...

Italy set to quarantine whole of Lombardy due to coronavirus

Government's draft decree would impose fines on anyone caught entering or leaving northern region



The deserted Piazza Duomo in Milan. Photograph: Piero Cruciatti/AFP via Getty Images

COVID-19 in the UK: The Policymaker's Choice



COVID-19 in the UK: The Policymaker's Choice





COVID-19 in the UK: The Policymaker's Choice

Policymaker:

How do we balance the social costs of interventions with control of COVID?



Data-driven NPI effectiveness modelling



2	Gatherings limited to 1000 people or less			•		
22	Gatherings limited to 100 people or less				-	
	Gatherings limited to 10 people or less		 	_	•	
•	Some businesses closed			•		
00	Most nonessential businesses closed			•••	_	
00	Schools and universities closed		1			
0	Additional effect of a stay-at-home order on top of above NPIs		-	•		
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Data-driven NPI effectiveness modelling

Data: timeline of different interventions across regions, number of reported cases and deaths in those regions



Data-driven NPI effectiveness modelling.

Bayesian Generative Model:

"What is the probability of observing data D if the intervention X has effect Y?"







Data-driven NPI effectiveness modelling

Prior distribution:

"Before observing any data, what is our belief about the effectiveness of intervention X?"





Learning #1: Garbage in, Garbage Out

- Our inferences combine data with a probabilistic model. The **quality of data** critically determines the "quality" of our inferences.
- Data collection is difficult—it requires judgement calls, proper scoping, effective teamwork, ...

But, contributions to data can be undervalued by academia. How can we incentivise high quality, "modelling ready" data collection?

Learning #2: Effectiveness Changes in Time.

- Our inferences are made in the context of our data.
 - Midpandemic schools ≠ prepandemic schools

- During the pandemic, organisations implemented **safety measures** and people changed their **behaviour**.
 - If people in the population no longer meet in large groups, banning large gatherings doesn't affect transmission although it previously did!

How to communicate limitations and nuance to policymakers?

Learning #3: Adapting to time sensitivity

- Exponential growth leads to **incredible time sensitivity.** A delay by a few days can *drastically change* the number of infections/cases/deaths.
 - E.g., consider investigation into transmission advantage of new variants of concern.

How can we produce **decision relevant research** in a timely fashion?

Having tools ready, and releasing high quality, documented tools so others can easily build upon them!

Alternative peer review protocols, with more dialogue and real time discussion?

Summary

- Understanding the effectiveness of different interventions is crucial for smart policy.
- We can tackle this question by combining Bayesian modelling with high quality collected data.
- What have we learnt?
 - In short, academic structures and incentives are not well designed for performing time-sensitive research in a pandemic. How can we equip researchers with the skills to perform and communicate research in emergencies?
 - Data, communication of limitations and nuance, changes to peer review and publicly releasing code and data, making high quality modelling data available, training for time sensitive situations, ...

Our work

[A] Inferring the effectiveness of government interventions against COVID-19. Jan Brauner^{*}, Sören Mindermann^{*}, Mrinank Sharma^{*}, Anna B Stephenson, Tomáš Gavenčiak, David Johnston, Gavin Leech, John Salvatier, George Altman, Alexander John Norman, Joshua Teperowski Monrad, Tamay Besiroglu, Hong Ge, Vladimir Mikulik, Meghan A. Hartwick, Yee Whye Teh, Leonid Chindelevitch, Yarin Gal, Jan Kulveit (2020). Science.

[B] How robust are the estimated effects of nonpharmaceutical interventions against **COVID-19?** Mrinank Sharma^{*}, Sören Mindermann^{*}, Jan Markus Brauner^{*}, Gavin Leech, Anna B. Stephenson, Tomáš Gavenčiak, Jan Kulveit, Yee Whye Teh, Leonid Chindelevitch, Yarin Gal (2020). **NeurIPS**.

[C] Understanding the effectiveness of government interventions against resurgence of COVID-19 in Europe. Mrinank Sharma^{*}, Sören Mindermann^{*}, Charlie Rogers-Smith, Gavin Leech, Ben Snodin, Janvi Ahuja, Jonas B. Sandbrink, Joshua Teperowski Monrad, George Altman, Gurpreet Dhaliwal, Lukas Finnveden, Alexander John Norman, Sebastian B. Oehm, Julia Fabienne Sandkühler, Thomas Mellan, Jan Kulveit, Leonid Chindelevitch, Seth Flaxman, Yarin Gal, Swapnil Mishra, Samir Bhatt, Jan Markus Brauner. Nature Communications.

Our work

[D] Gavenčiak, Tomáš, Joshua Teperowski Monrad, Gavin Leech, Mrinank Sharma, Sören Mindermann, Jan Markus Brauner, Samir Bhatt, and Jan Kulveit. "Seasonal variation in SARS-CoV-2 transmission in temperate climates." *MedRxiv* (2021).

Thank you for your attention Check out the papers for more detail, limitations, ...

Why study the second wave?

Safety Measures

Coronavirus: pubs and restaurants across England to be forced to shut at 10pm

Boris Johnson to set out limited nationwide coronavirus restrictions on Tuesday

- Coronavirus latest updates
- See all our coronavirus coverage



A Hospitality venues in England will have to close their doors at 10pm and offer table service only from Thursday.

Could maximum class sizes of 15 pupils significantly improve our children's school life?

When children begin to return to school in June, they will be in classes of up to 15 pupils. How will that change British education?

By Sally Peck, FAMILY, EDUCATION AND CAREERS EDITOR 12 May 2020 • 3:17pm



Behaviour Stability

YouGov COVID-19 behaviour changes tracker: \equiv Avoiding crowded public places

% of people in each market who say they are: Avoiding crowded public places



YouGov COVID-19 behaviour changes tracker: \equiv Avoiding going to work

% of people in each market who say they are: Avoiding going to work (e.g. by working from home).



The first wave effects will not generalise to the second (and future waves)

The first wave effects will not generalise to the second (and future waves)

Also: New NPI constellations (and more data) allow new insights.

How to study the second wave?

Local epidemics



Lockdown tightened in north-east England as Covid-19 infections rise

For first time since pandemic began it will be illegal for people from different households to mix in pubs and restaurants

Coronavirus - latest updates
See all our coronavirus coverage



▲ Shoppers in Newcastle, one of seven north-east council areas subject to tighter restrictions after a rise in the coronavirus infection rate. Photograph: Ian Forsyth/Getty Images

New interventions

CORONAVIRUS TIER 3 VERY HIGH ALERT

gov.uk/coronavirus

Around 1 in 3 people with Covid-19 have no symptoms so will be spreading the virus without realising. We must all take action to protect each other and our hospital capacity.

	BARS, PUBS AND	RETAIL	WORK AND BUSINESS
No mixing of households indoors, or most outdoor places, apart from support bubbles. Maximum of six in some outdoor public spaces (e.g. parks, public gardens).	Hospitality is closed, with the exception of sales by takeaway, drive-through or delivery.	Open.	Everyone who can work from home should do so.
Early years settings, schools, colleges and universities open. Childcare, other supervised activities for children, and childcare bubbles permitted.	Open. Group activities and classes should not take place.	Closed (with limited exceptions)	Open.
	WEDDINGS AND FUNERALS		
We advise against overnight stays other than with household or support bubble.	15 guests for weddings, civil partnerships and wakes; 30 for funerals. Wedding receptions not permitted.	Indoor venues closed.	Open, but cannot interact with anyone outside household or support bubble.
TRAVELLING	EXERCISE 2		LARGE 🔗
Auoid travelling outside your area, other than where necessary such as for work or education. Further exemptions apply. Reduce the number of journey where possible. Plan ahead and avoid bury times and routes on public transport. Avoid car sharing with those outside of your household or support bubble.	Classes and organised adult sport can take place outdoors, but people whould avoid higher-risk contact activity: Group exercise activities and sports indoors should not take place, unless with your household or hubble. Organised activities for eilte athletes, under-IBs and disabled people can continue.	COVID-secure arrangements such as substantial screens, visiting pods, and window visits. Outdoor/aitright visits only forillout of rapid testing will enable indoor visits including contact).	Events should not take place. Drive-in events permitted.

Second Wave NPI Effectiveness Estimates

- Problems with existing intervention datasets:
 - National level intervention data
 - Intervention definitions not suitable for second wave
 - Lack of validation procedures (low data quality)

- How to start? Proper scoping!
 - Questions
 - What NPIs mattered?
 - What level of geographic granularity?
 - Is case and death data available at that level?
 - What period of analysis?
 - Solutions
 - Exploratory data collection
 - Talking to local epidemiologists
 - Many judgement calls -> this is a job for a team

- We collect fine grained intervention data in 114 areas from 7 European countries.
 - We use stratification by deaths in the first wave to ensure our estimates generalise.
- NPIs:
 - Gathering and Household Limits (Public/Private/Indoor/Outdoor)
 - School Closures (primary/secondary school)
 - University Closures
 - Gastronomy/Nightclubs/Leisure Venues/Retail Business Closures
 - Curfews
 - Mask Wearing (5 stringency levels)

Countries	7				
Regions of analysis	114				
Period	1 August 2020 - 9 January 2021				
Days across all regions	19,000				
NPI entries in the dataset	> 5,800				
Data validation (manual)	Semi-independent double entry; interviews with local epidemiologists; validation against external sources; cross-country consistency checks				
Time spent on data collection (excluding exploratory collection and design)	950 hours (9 researchers)				




Figure S28: Number of days across all regions available to distinguish NPI effects. For every pair of NPIs (row - column), the entry shows the number of days on which exactly one of the two NPIs was active.





Switzerland

Zurich

Austria | Wien



1000

383 500

Man 250

g 1000

New cas

\$ 750



Genève









Night clubs closed Leisure and entertainment venues closed Gastronomy closed Retail and close-contact services closed Primary schools closed Secondary schools closed Universities closed All public gatherings banned Public gatherings limited to 2 people Public gatherings limited to ≤10 people from 2 households Public gatherings limited to ≤10 people Public gatherings limited to ≤30 people All household mixing in private banned Household mixing in private limited to 2 people Household mixing in private limited to ≤10 people from 2 households Household mixing in private limited to ≤10 people Household mixing in private limited to ≤30 people Night time curfew Stricter mask-wearing policy

Stricter mask-wearing policy Night time curfe isehold mixing in private limited to ≤30 pec limited to ≤ 10 pe gatherings ba from 2 house om 2 house ent venues Gastronomy Retail and close-contact services Primary schools Night clubs Secondary schools Universities Public gatherings limited to 2 Public gatherings limited to ≤10 id to ≤30 private of to All public limited to ≤10 people ings Household mixing in private à \$10 c Public gath private limited to a mix arre All hot Ξ Public gatherings 운 Household

Figure S28: Number of days across all regions available to distinguish NPI effects. For every pair of NPIs (row - column), the entry shows the number of days on which exactly one of the two NPIs was active.

Data

Modelling

Modelling Approach - First Wave



- We observe increases in transmission unrelated to changes in NPIs.
- Solution: random walk term in transmission.



Weekly Random Walk Noise

Allows for smooth changes in R every week. This can explain the increases in transmission unrelated to NPIs.



• The number of infections N is determined by a renewal equation:

$$\overline{N}_{t,l} = R_{t,l} \sum_{\tau=1}^{32} (\overline{N}_{t-\tau,l} \cdot \pi_{GI}[\tau])$$

- First wave NPI effectiveness estimates use national data (usually).
- In the second wave, you have to go local.
 - Problem: fewer cases and deaths in each area! More difficult to estimate R.
 - **Solution:** additional noise in the modelling, reducing the influence of small case and death counts.

If cases increase from 1 to 2 in a week, is this R=2?

 $N_{t,l} = \text{softplus}[\tilde{N}_{t,l} + \epsilon_{t,l}]$

If cases increase from 1000 to 2000 in a week, is this R=2?

- R tells us the amount of infections generated by the currently infected people.
- Therefore, we can predict the number of infections that will occur in the future.
- Infections today show up as cases and deaths in the future.
 - These infections are **smoothed and delayed.**
 - Then, they are matched to the observed cases and deaths.

Now, given a probabilistic model and a dataset, we can perform Bayesian inference using standard MCMC sampling algorithm. *Big thanks to the Numpyro team!*

All non-essential businesses closed	
Night clubs closed	
Leisure and entertainment venues closed	
Gastronomy closed	
Retail and close-contact services closed	
All gatherings banned	
All gatherings limited to 2 people	
All gatherings limited to ${\leq}10$ people from 2 households	<u></u>
All gatherings limited to <10 people	
All gatherings limited to ≤30 people	
All educational institutions closed	
Night time curfew	
Stricter mask-wearing policy	
-10	0 10 20 30 40 50
	Reduction in R (%)

Overall, the interventions **that regions** *actually used in the second wave* were less effective.

The most **stringent** set of NPIs in each region reduced Rt by average \sim 55%.

But, in the first wave estimates are 76%-82%.

Behaviour changes & safety measures.



- - -

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All gatherings limited to <10 people	
All gatherings limited to ≤30 people	
All educational institutions closed	
Night time curfew	
Stricter mask-wearing policy	
-10	0 0 10 20 30 40 50
	Reduction in R (%)

Business closures were very important!

Similar effects for nightclubs, retail businesses and gastronomy.

Smaller effects for Leisure Venues.

A)

All non-essential businesses closed	
Night clubs closed	
Leisure and entertainment venues closed	
Gastronomy closed	
Retail and close-contact services closed	
All gatherings banned	
All gatherings limited to 2 people	
All gatherings limited to ≤ 10 people from 2 households	
All gatherings limited to ≤ 10 people	
All gatherings limited to ≤30 people	
All educational institutions closed	
Night time curfew	
Stricter mask-wearing policy	
-1	10 0 10 20 30 40
	Reduction in R (%)

Education institutions were very important in the first wave. Smaller

effects in the second wave suggest successful safety measures.

All non-essential businesses closed	
Night clubs closed	
Leisure and entertainment venues closed	
Gastronomy closed	
Retail and close-contact services closed	
All gatherings banned	
All gatherings limited to 2 people	
All gatherings limited to ${\leq}10$ people from 2 households	
All gatherings limited to ≤ 10 people	
All gatherings limited to \leq 30 people	
All educational institutions closed	
Night time curfew	
Stricter mask-wearing policy	
-1(10 0 10 20 30 40 50
	Reduction in R (%)

Weaker gathering bans were not particularly effective.

Significant reductions in transmission from the **strictest** bans, namely banning **all** gatherings, or only allowing gatherings with 1 other person.

All non-essential businesses closed	
Night clubs closed	
Leisure and entertainment venues closed	
Gastronomy closed	
Retail and close-contact services closed	
All gatherings banned	
All gatherings limited to 2 people	
All gatherings limited to ${\leq}10$ people from 2 households	
All gatherings limited to ${\leq}10$ people	
All gatherings limited to ≤30 people	
All educational institutions closed	
Night time curfew	
Stricter mask-wearing policy	
-10	0 0 10 20 30 40 50 Reduction in R (%)

Curfews and mandatory mask wearing also helped.

Robustness / validation

All non-essential businesses closed		Key lesson: be s
Night clubs closed Leisure and entertainment venues closed Gastronomy closed Retail and close-contact services closed All gatherings banned All gatherings limited to 2 people All gatherings limited to 2 households All gatherings limited to 2 households All gatherings limited to ≤10 people from 2 households All gatherings limited to ≤10 people		Other validation ch - Posterior predict - Prior predict - Confounder simulations - Empirical po calculations - Single-mode meta-analys
All gatherings limited to <30 people All educational institutions closed Night time curfew Stricter mask-wearing policy		- Multivariate - Data sanity - Double - Expert intervie
n `	-20 0 20 Median reduction in R (%) Delay	Prior distributions ● Unobserved factors distributions ● Model structure ●

n: be skeptical!

ation checks:

- erior predictive
- predictive
- ounder lations
- irical power ulations
- le-model a-analysis
- variate sensitivity
- sanity checks:

Double entry

Data

Expert interviews

Robustness / validation

How to interpret results under misspecification / when model assumptions are broken?

Theorem 2. The ML solution of α_i , given $\{\alpha_j\}_{j \neq i}$, under the Simplified Default Model satisfies: $\exp(-\alpha_i) = \left(\sum_{(t,c)\in\Phi_i} \tilde{R}_{(-i),t,c}^{1/\nu} \bar{R}_{t,c}^{1/\nu}\right)^{\nu} / \left(\sum_{(t,c)\in\Phi_i} \tilde{R}_{(-i),t,c}^{1/\nu} \tilde{R}_{(-i),t,c}^{1/\nu}\right)^{\nu} = \frac{M_{1/\nu}^{W_i}(\{\bar{R}_{t,c}\}_{\Phi_i})}{M_{1/\nu}^{W_i}(\{\bar{R}_{(-i),t,c}\}_{\Phi_i})}$ (10)

Limitations

- Correlation analysis.
- Unobserved factors may be assigned to NPIs.
- Assume constant IFR/IAR.
- NPI effects assumed to be the same across countries.
- How will these effects generalise e.g., to the new variants of concern?

Take Home Story

- 1. We believed that second wave effects would be markedly different to the first wave...
- 2. ... and that's exactly what we found.
- 3. **But, our estimates are historic,** and policymakers *still* need to balance the costs of COVID control and COVID transmission.
- For now, a combination of second wave effects with real-time monitoring and surveillance may be the best we can do.

First wave slides



• Governments worldwide implemented nonpharmaceutical interventions (NPIs) to control the spread of COVID-19.

○ e.g., closing schools, restaurants, etc...

- We know, *in combination*, that these interventions were successful at reducing transmission significantly.
- But, how effective was each NPI?
- And why do we care?

Possible approaches and challenges

- 1) Controlled trials Politically and ethically challenging
- 2) Simulations
 - Assumptions lead to foregone conclusions
- 3) Cohort studies Confounding

 - Only works for some interventions

4) Observational multi-region studies Need diverse data Need high-quality intervention data Need assumptions that can affect conclusions Confounding Past and future effectiveness may be different

Our NPI Data 41 Countries

- The European response was somewhat uncoordinated!
- Different countries implement different NPIs at different times!
- Verified with independent double entry!

Albania			X				Lithuania					7	í		×	*** ***
Andorra					X	1/2	Malaysia		4				X	*		
Austria]		%		Malta			*			×	•		
Belgium					A		Mexico		1	***						
Bosnia and Herzegovina					1/4		Morocco	-2		14						
Bulgaria					X		Netherlands		** *	*				×		
Croatia	- <u>-</u> - 2		X	1	× ×	*	New Zealand		121							
Czech Republic	2 R 4 4		14	1		1/2	Norway		,	-22.			🛪 🕡	****		
Denmark	11 <u>4</u>		×	,	/		Poland			1		1/4	X			
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Our NPI Data

Why collecting our own data?

- Many public datasets, but the data quality is poor. (Focus on breadth rather than accuracy.)
- Verified with independent double entry!



Cases and deaths

- Several possible sources: John Hopkins University, ECDC, WHO
- Obvious problems:
 - O Changes in testing
 - O Reporting is chaotic

Epidemiological parameters

- You need at a minimum:
 - O Serial Interval/Generation Interval
 - O Delay from infection to case confirmation
 - O Delay from infection to death
- This is handled sloppily in most work.
- You want:
 - O Distributions
 - O Uncertainty over parameters

Model Overview



Modelling Challenges

- Constant, country-level differences in the:
 - ascertainment rate the proportion of infections reported.
 - infection-fatality rate the proportion of infections that lead to death.
- Time-varying differences in the ascertainment rate and infection-fatality rate.
- Biases in testing and reporting

• NPI Interactions:



• NPI Interactions:



• Infection Model: • Cases: $N_{t,c}^{(C)} = N_{t-1,c}^{(C)} g_{t,c} \cdot \exp \varepsilon_{\tau,c}^{(C)}$ $\varepsilon_{\tau,c}^{(C)} \sim \operatorname{Normal}(\mu = 0, \sigma = \sigma_g)$ Transmission Noise An infection that *later* is confirmed

Infections on previous day

• NPI Interactions:



- Infection Model:
 - **Cases:** $N_{t,c}^{(C)} = N_{0,c}^{(C)} \prod_{\tau,c}^{t} [g_{\tau,c} \cdot \exp \varepsilon_{\tau,c}^{(C)}]$
 - Deaths: $N_{t,c}^{(D)} = N_{0,c}^{(D)} \prod_{\tau=1}^{t} [g_{\tau,c} \cdot \exp \varepsilon_{\tau,c}^{(D)}]$

An infection that later dies

Latent initial sizes

 $g_{\tau,c} = f(R_{t,c}, \mathbf{GI})$

$$\varepsilon_{\tau,c}^{(C)} \sim \text{Normal}(\mu = 0, \sigma = \sigma_g)$$

$$\varepsilon_{\tau,c}^{(D)} \sim \text{Normal}(\mu = 0, \sigma = \sigma_g)$$

Transmission Noise

NPI Interactions:



Observation model

$$\overline{C}_{t,c} = \sum_{\tau=1}^{t} N_{t-\tau,c}^{(C)} P_C(\text{delay} = \tau)$$
$$\overline{D}_{t,c} = \sum_{\tau=1}^{t} N_{t-\tau,c}^{(D)} P_D(\text{delay} = \tau),$$

Recap: Key Model Features

- We extend the model of Flaxman, S., Mishra, S., Gandy, A. *et al.* Estimating the effects of non-pharmaceutical interventions on COVID-19 in Europe. *Nature* 584, 257–261 (2020). <u>https://doi.org/10.1038/s41586-020-2405-7</u>
- Our model observes **both cases and deaths.**
- We account for uncertainty in key epidemiological parameters, such as the delays between infection and case/death reporting.
- We add noise to the measure of transmission i.e., we use transmission noise.

Main Results

Default Settings

- Note: with *priors* over uncertain epidemiological parameters.
- (obtained under default settings)

2	Gatherings limited to 1000 people or less			•		
22	Gatherings limited to 100 people or less		 	-0		
	Gatherings limited to 10 people or less		 _			
F	Some businesses closed					
	Most nonessential businesses closed		I I	•		
00	Schools and universities closed		 •	-•		
0	Additional effect of a stay-at-home order on top of above NPIs	-				
		5% 0	 %	25%	50%	75%

Reduction in R_t in the context of our data

Default Settings

- Note: with priors over uncertain epidemiological parameters.
- Adjustment required for local circumstances.

Gatherings limited to 1000 people or less Gatherings limited to 100 people or less Gatherings limited to 100 people or less Gatherings limited to 10 people or less Gatherings limited to 10 people or less Some businesses closed Most nonessential businesses closed Schools and universities closed Additional effect of a stay-at-home order on top of above NPIs							
 Gatherings limited to 100 people or less Gatherings limited to 10 people or less Gatherings limited to 10 people or less Some businesses closed Some businesses closed Most nonessential businesses closed Schools and universities closed Additional effect of a stay-at-home order on top of above NPIs 		Gatherings limited to 1000 people or less					
Gatherings limited to 10 people or less Some businesses closed Most nonessential businesses closed Schools and universities closed Additional effect of a stay-at-home order on top of above NPIs		Gatherings limited to 100 people or less		1 1 1	•		
 Some businesses closed Most nonessential businesses closed Schools and universities closed Additional effect of a stay-at-home order on top of above NPIs 		Gatherings limited to 10 people or less		 			
Image: Second stay-at-home order on top of above NPIs		Some businesses closed					
Schools and universities closed Additional effect of a stay-at-home order on top of above NPIs 25% 0% 25% 50% 75	00	Most nonessential businesses closed			••		
Additional effect of a stay-at-home order on top of above NPIs	00	Schools and universities closed		 	•••		
	0	Additional effect of a stay-at-home order on top of above NPIs	-				
		0	 = 0/	1) DE9/ E(09/	750

Reduction in R_t in the context of our data

NPI Combinations



Sensitivity analyses (206 conditions)

2	Gatherings limited to 1000 people or less	-						
22	Gatherings limited to 100 people or less							
	Gatherings limited to 10 people or less				►			
	Some businesses closed	••	\diamondsuit	•				
00	Most nonessential businesses closed							
00	Schools and universities closed				•			
0	Additional benefit of stay-at-home order on top of above NPIs							
		0.0%	17.5%	35.0%	52.5%			
		Median reduction in R ₊						
Mitigation Calculator

http://epidemicforecasting.org/calc



Some Limitations

- Assumed that NPI effectiveness doesn't vary across countries and time.
- Assumed that NPIs don't interact.
- Our model doesn't account for numbers of susceptible people *changing* over time.
- No age-stratification ...

More **Limitations**

(There are many others too ...)

• General comment: we've made a lot of assumptions.

○ e.g., NPI interactions, infection model, parameter values,

- How much are unobserved factors attributed to our NPIs?
 - O And, we know we have unobserved factors! Behaviour change, unrecorded NPIs, ...

Can we trust our estimates?

Holdout Validation

- We don't aim to forecast cases and deaths.
- But if our estimates don't *help* us to predict cases and deaths, they aren't useful!



Can we trust our estimates?

How to test for unobserved factors?



Model Comparison

Transmission noise helps!



Sensitivity Analysis I



Sensitivity Analysis II



Structural Sensitivity

Mask-wearing mandatory in (some) public spaces

Gatherings limited to 1000 people or less

Gatherings limited to 100 people or less

Gatherings limited to 10 people or less

Some businesses closed

Most nonessential businesses closed

Schools and universities closed

Stay-at-home order (with exemptions)

