Influence of the Environment on Transmission

Professor Cath Noakes, OBE, CEng, FIMechE, FIHEEM

School of Civil Engineering, University of Leeds

C.J.Noakes@leeds.ac.uk

Modelling Scales

Population Scale

- SEIR transmission models
- Contact rate based on observed transmission
- Doesn't link directly to physical mechanisms

Building Scale

- Compartmental SEIR models
- Agent based models
- Some attempt to link to micro-scale (e.g. air via zonal Wells-Riley)

Micro Scale

- Mechanistic models of exposure
- Detail of human-environment interaction
- CFD/experiment
- QMRA methods
- Wells-Riley

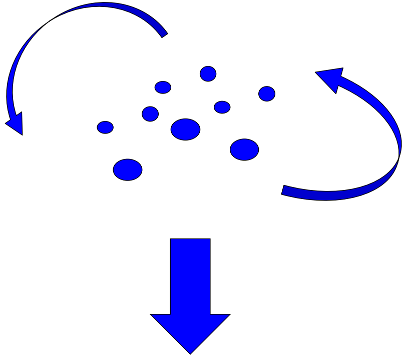
Viral Transmission Dynamics

Source

CDC, USA

- Respiratory source
- Treatment/environment source
- Size distribution
- Location & duration

Transport and deposition



Microbe characteristics
Human characteristics
Fluid Dynamics

Exposure

Tang J et al. *J Hosp Infect* 2006; **64:** 100-11

- Inhaled Aerosol
  - Short & long range
- Larger droplet
  - direct deposition
  - Via surfaces/fomites

Microscale factors

Emission rate

- Viral load
- Aerosol size range
- Activity

- Mask wearing
- Hygiene behaviours

Environment

- Ventilation rate/strategy
- Distancing

- Virus survival
- Temp/RH

- Cleaning

Exposure

- Hand hygiene
- Mask wearing
- Face and surface touching
- Breathing rate

- In-host efficiency of viral deposition
- Dose-response

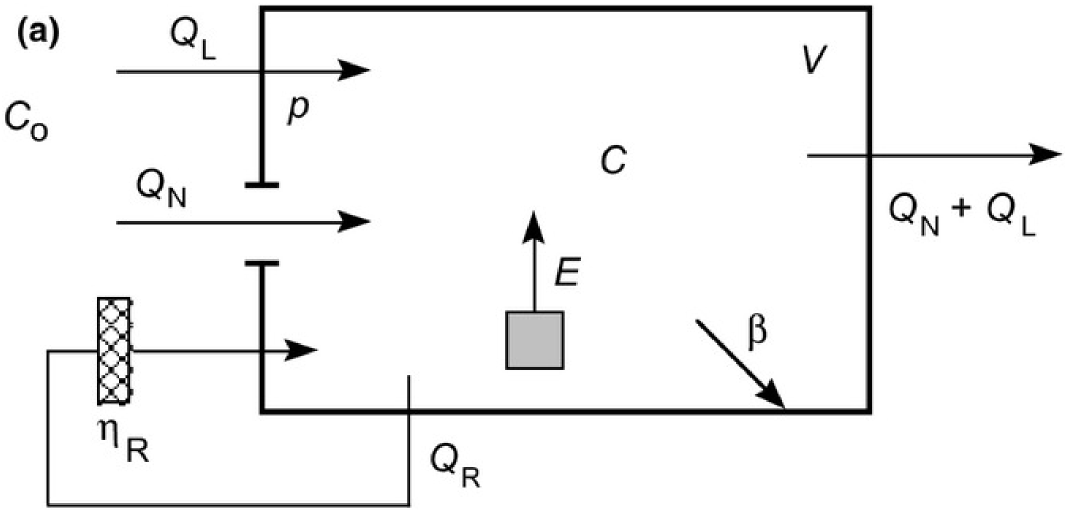
Simple airborne dynamics

Concentration of virus given by mass balance model

Loss by ventilation, filtration, deposition and decay

$V\frac{dC}{dt} = E - C(Q_N + Q_L + \eta_R Q_R + \beta V + \gamma V)$

Exposure = C x breathing rate x time



Nazaroff, 2014, Indoor Air

Viral Emission

Number of virus and size distribution of particles

Viral load X **Aerosol emission rate** X **Duration**

Viral load:
- Base viral load
- Stage of infection

Aerosol emission rate:
- Activity
- Individual factors
- Temp & RH
- Breathing rate
- Mask wearing

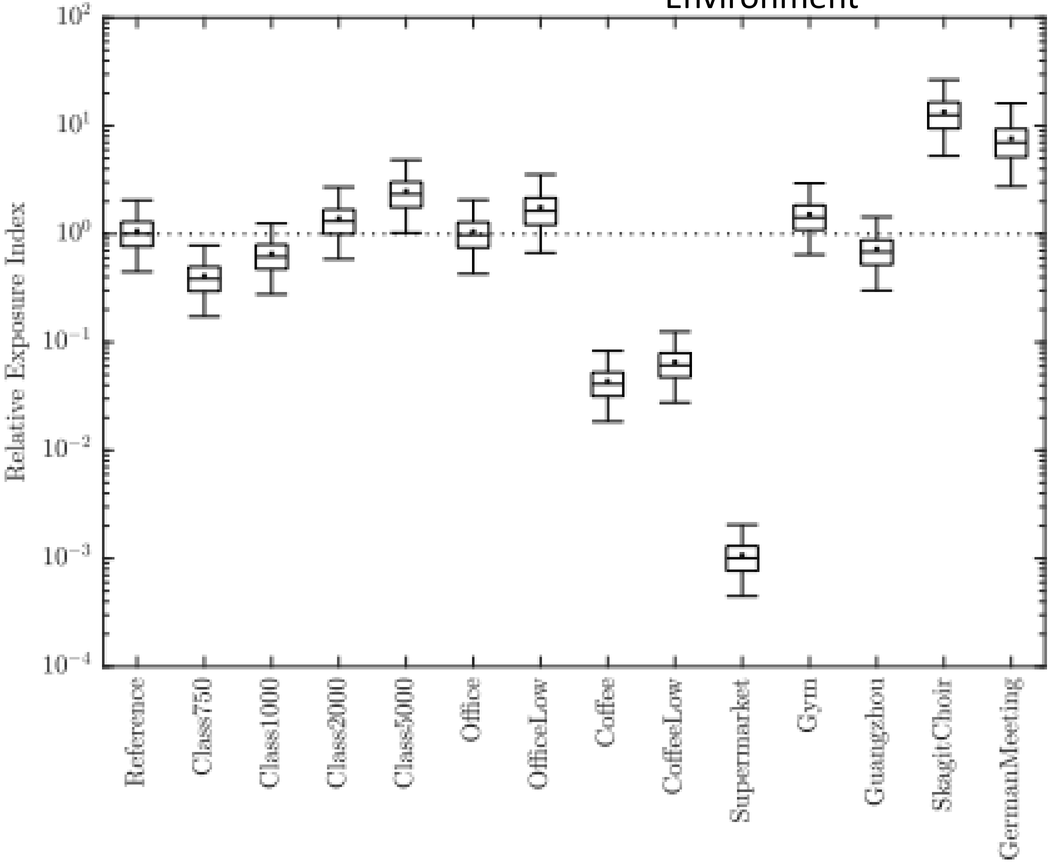
Estimating Relative Exposure

Jones et al (2021) Building and Environment

Relative to classroom designed to 1500 ppm CO_2 standard

Depends on:

- Duration of exposure
- Ventilation
- Size of space
- Aerosol emission/ vocalisation



Linking exposure to risk of infection

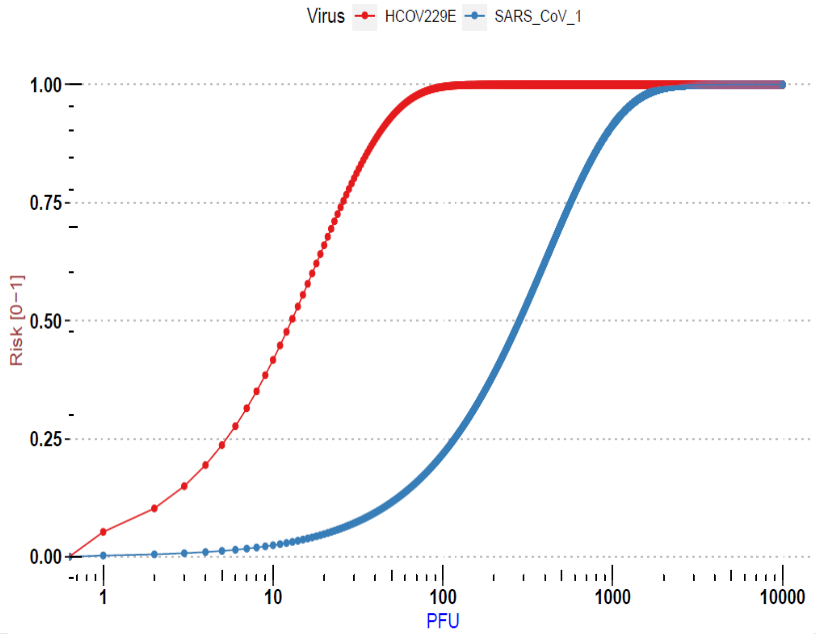
Wells-Riley Approach

$$N_c = S\left[1 - e^{\left(\frac{Iqpt}{Q}\right)}\right]$$

New infections (N_C) with time (t):

- S = number of susceptibles,
- I = number of infectors
- Q = room ventilation rate
- P = occupant breathing rate
- q = Quanta, number of infectious doses generated per unit time

Dose-response Approach

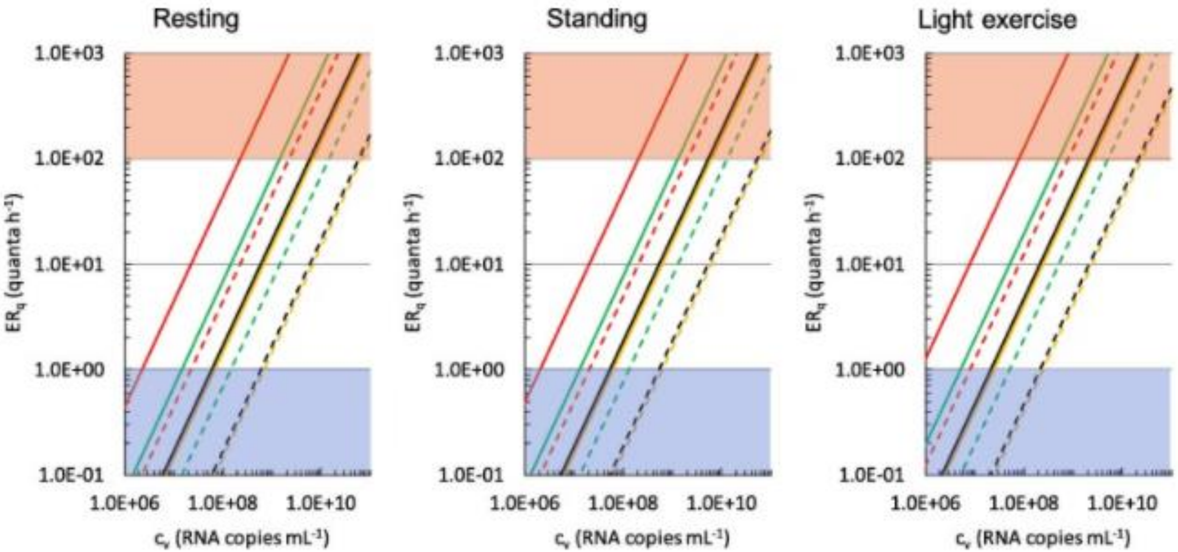


Quanta values

Disease	Case	Quanta/h	Reported by
TB	Average TB patient	1.25	Nardell et al (1991)
	Outbreak in office building	12.7	Nardell et al (1991)
	Human to guinea pig transmission	0.3-44	Escombe et al (2007)
	Human to guinea pig transmission (MDR-TB)	40,52,226	Escombe et al (2008)
Measles	Outbreak in a school	570	Rudnick &Milton(2003)
Influenza	School cases in Taiwan	66.91 (LN*)	Liao et al (2005)
	Aircraft outbreak	79-128	Rudnick &Milton(2003)
	Human challenge studies	0.11	Bueno de Mesquita et al (2020)
	Data from exhaled breath studies	0.17-630	Bueno de Mesquita et al (2020)
SARs	Taipei Hospital outbreak	28.77 (LN*)	Liao et al (2005)
Rhinovirus	Experimental data of Dick et al 1987	1-10	Rudnick &Milton(2003)

Quanta for SARS-CoV-2

- Buonnano et al (2020) estimated quanta from respiratory viral load (RNA copies) and aerosol generation rates
- Range from 0.1 to 1000 quanta/hr
- Miller et al estimated ~950 quanta/hr for Skagit choir outbreak



Skagit Choir

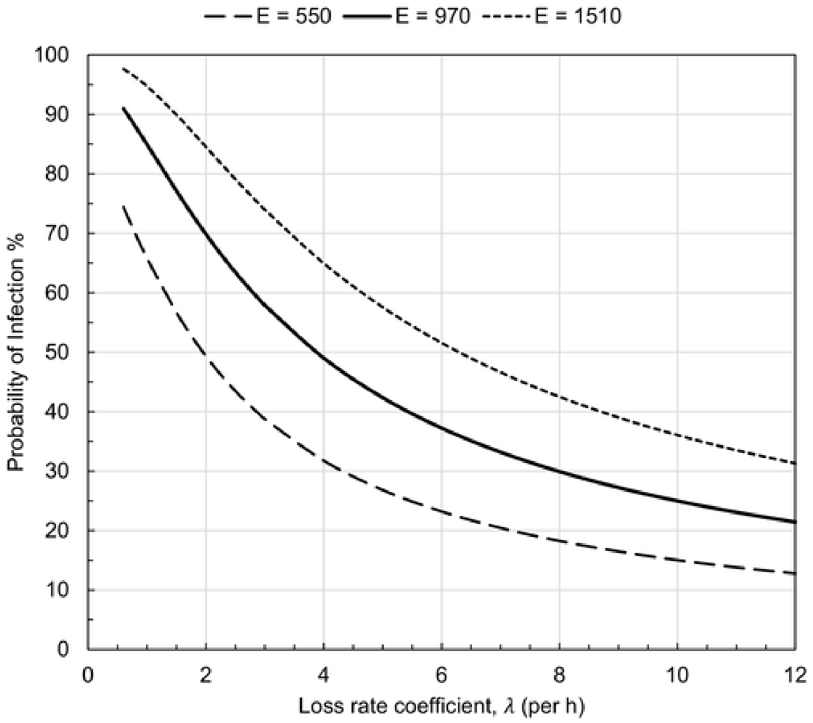
Outbreak

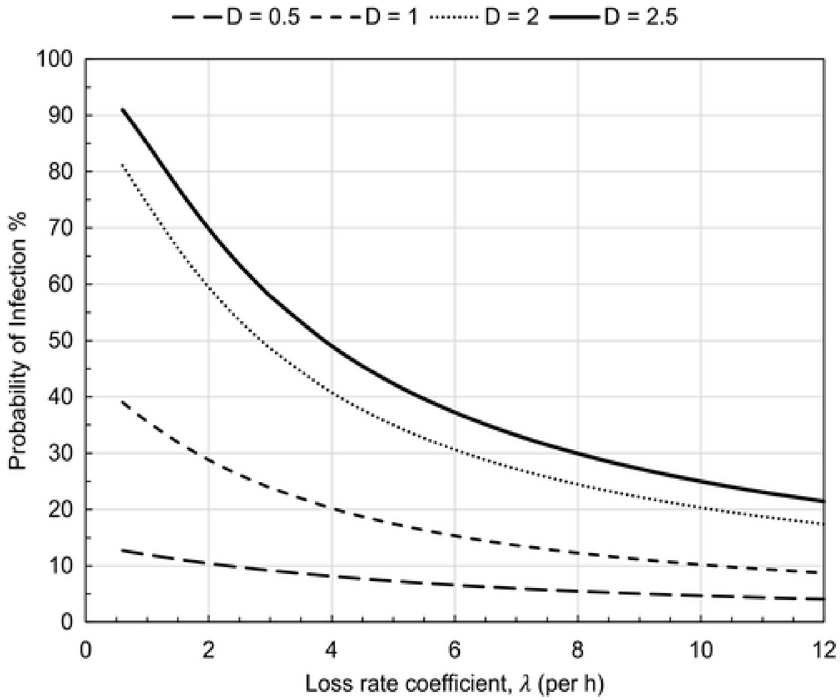
- 61 attendees (~half normal)
- 2.5 hour rehearsal
- 1 infector – mild symptom
- 53 cases, 33 with testing
- Use of sanitizer, no contact
- Distance 0.75-1.4m
- Cases dispersed throughout the room

Model assumptions

- Transient Wells-Riley model
- Monte-Carlo approach to estimate quanta
- 810 m3 room
- Breathing rate 10.8-23 l/min
- Ventilation rate 0.3-1.0 ACH
- Deposition 0.3-1.5, inactivation 0-0.63

Skagit Choir





Considering multiple routes

- Close range (< 2m)
  - Exposure to all sizes of particles
  - Inhalation (up to 100 micron) plus direct droplet
  - Influenced by emission rate/type, distance, orientation, mask wearing
  - Viral decay likely to be less important factor – transmission quick
  - Complex physics – hard to predict detail of flow

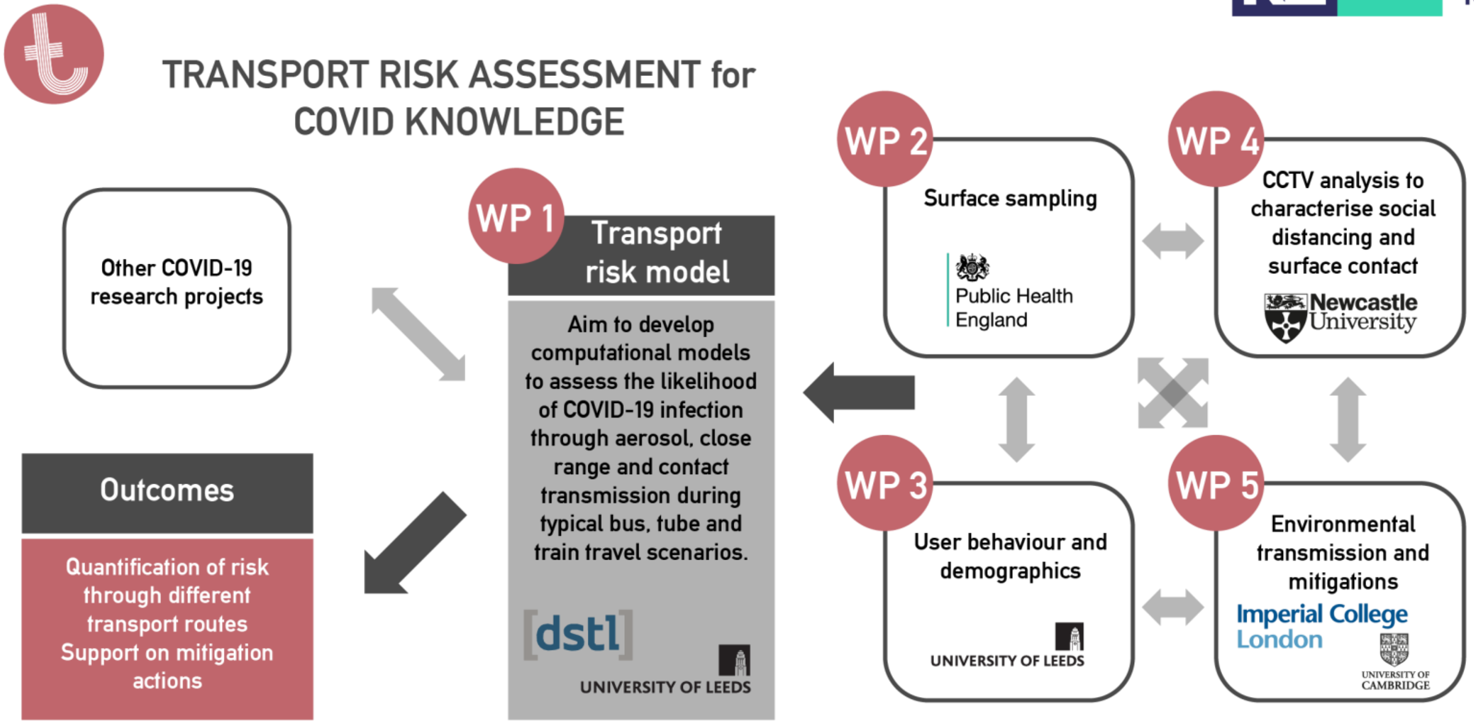
- Simple gradient or zonal model
- Modified gradient model with “cone” for exhalation
- Physics of particle trajectories
- Empirical model from experimental data
- Computational Fluid Dynamics

Considering multiple routes

- Fomites
  - Contamination of surfaces through deposition of droplets and contaminated hands
  - Exposure depends on surface touch frequency AND face (peri-oral) touch frequency
  - Influenced by emission, distance, mask wearing, surface properties, touch behaviours, viral decay, cleaning, hand hygiene
  - Highly stochastic, human behaviour essential part of model
  - Models need to consider multiple surfaces and multiple touches – compartmental, markov chain

TRACK project

Engineering and Physical Sciences Research Council



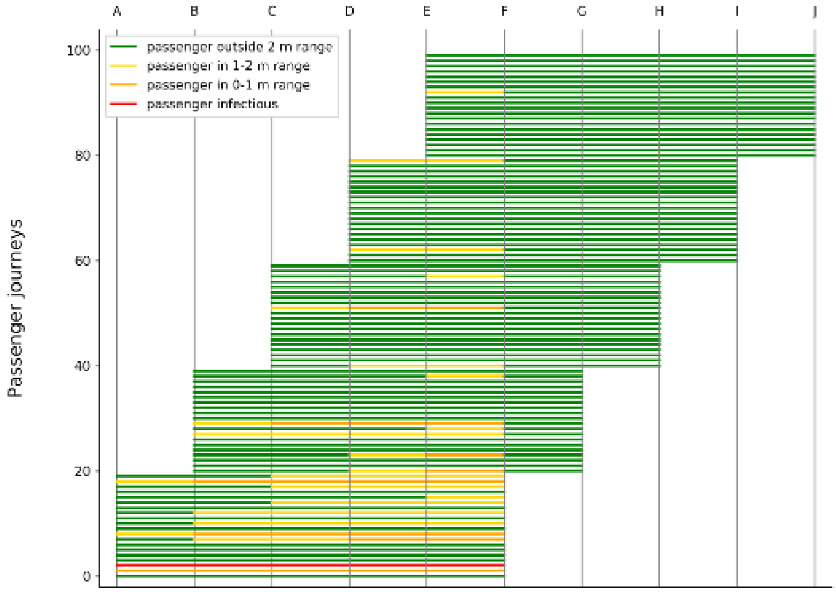
Transmission of Virus in Carriages (TVC) model

Lei et al. (2018) "Routes of transmission of influenza A H1N1, SARS CoV, and norovirus in air cabin: Comparative analyses" Indoor Air. 28(3):394-403.
https://doi.org/10.1111/ina.12445

- Stochastic Quantitative Microbial Risk Assessment model based on Lei et al. (2018)
- Source term for respiratory activity + fixed viral load
- Airborne transmission
  - Small aerosols, <5 micron dry diameter
  - Well mixed zone, max ventilation based on design occupancy (10 L/s/person)
- Fomite transmission
  - Initial hand contamination + optional coughing,
  - Passengers touch fixed number of surfaces (e.g.handrails,seat rests) during boarding and alighting
  - Transfer based on surface contamination, hand area and transfer efficiencies
- Close range transmission for passengers within 2 m of an infectious passenger
  - Exposure to small and larger aerosols
  - Zones defined at 0-1m and 1-2m, proximity estimated based on passenger density

Passengers

- Individual entities that board or alight at any station - input data based on scaled pre-pandemic demand data
- Passenger position in carriage is not explicitly tracked but specific passengers are allocated to be within 2m of an infectious passenger (IP)
- Area of the carriage within 2m of an infectious passenger calculated via a probabilistic distribution
- Cumulative dose by each potential route of infection is calculated and, optionally, risk of infection
- Mask wearing based on adherence probability

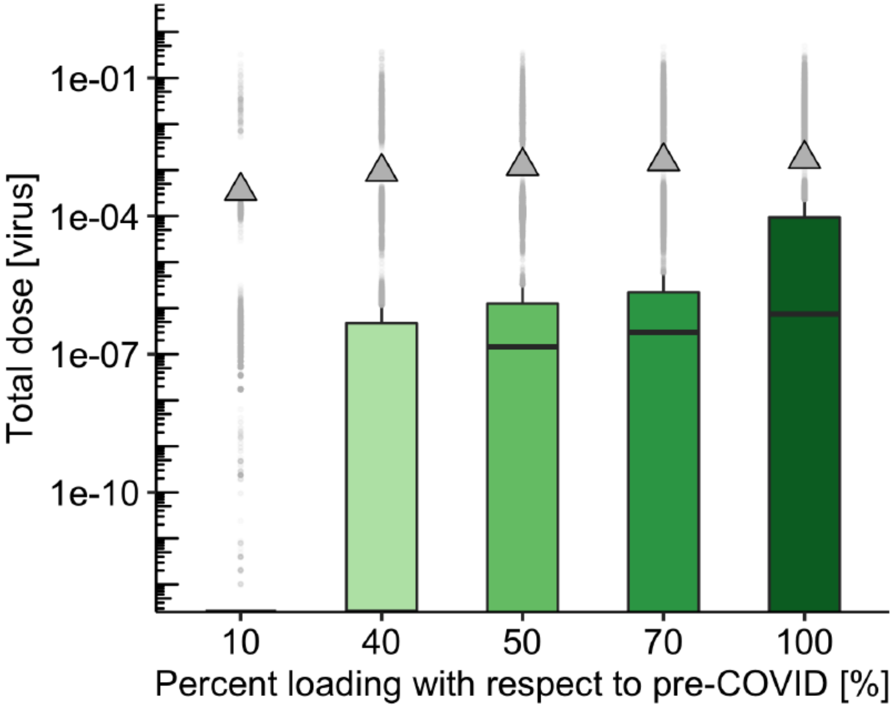


LIFD Leeds Institute for Fluid Dynamics

[dstl] The Science Inside

UNIVERSITY OF LEEDS

Effect of loading

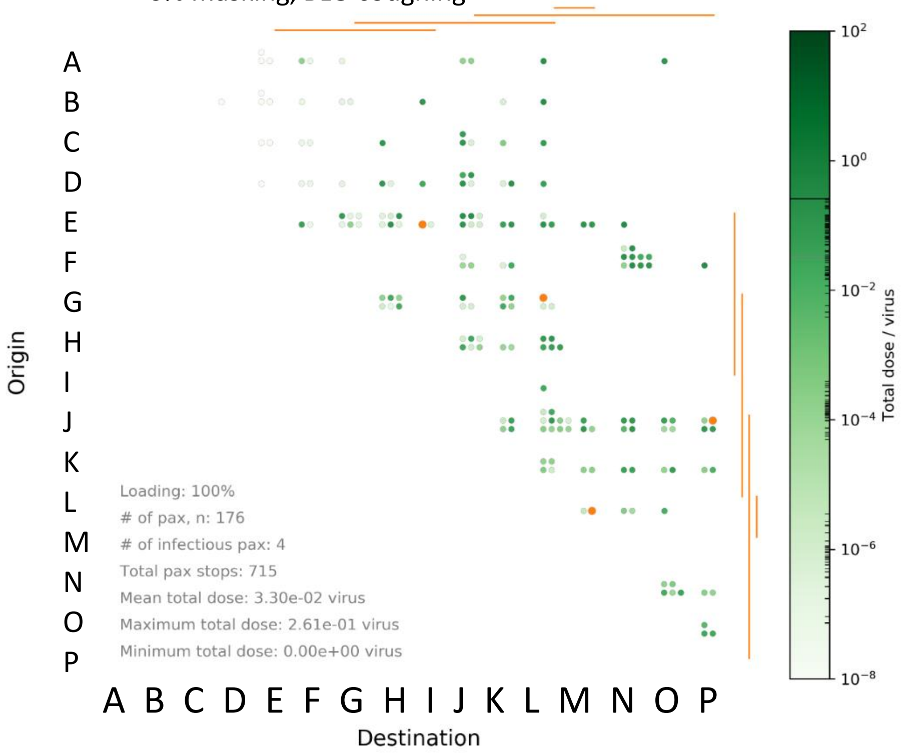


- Distribution of passenger doses under five system loading levels (10%, 40%, 50%, 70% and 90% of pre-pandemic levels) with 500 stochastic repeats
- Triangles show mean values
- Line shows median values while the box represents the interquartile range (IQR) and whiskers show 1.5 x IQR, while points show outliers outside of this range

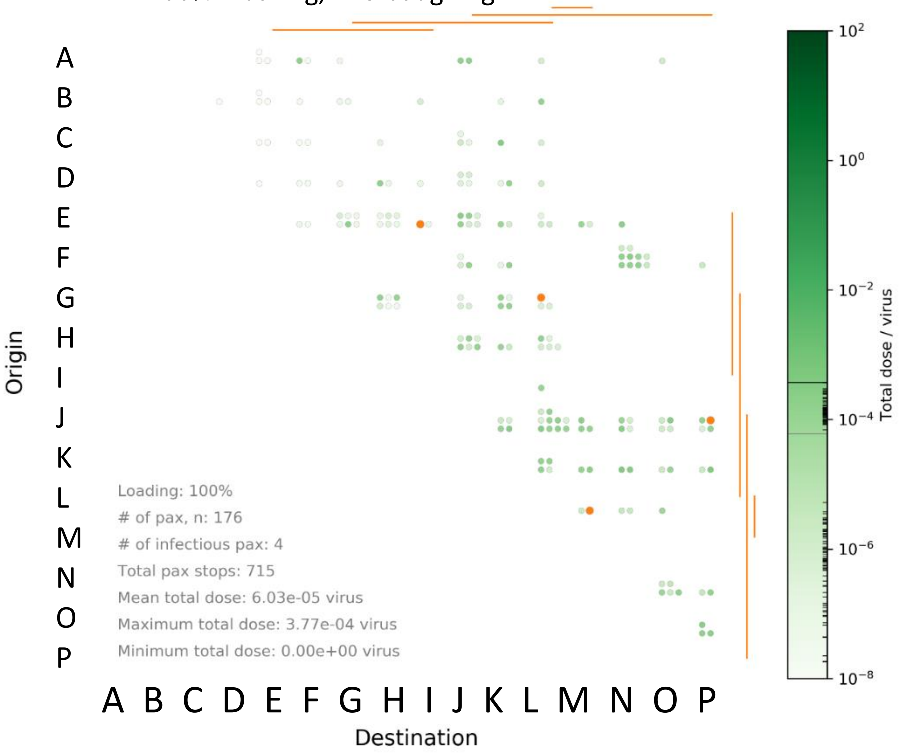
Prevalence percentage [0-100]	0.02%	0.1%	1%	2%
Median dose	0	0	3.64E-08	5.47E-07
Mean dose	3.20E-05	1.73E-04	1.30E-03	2.45E-03
Total non-infectious passengers	55988	55929	55408	54844
Total non-zero doses	1133	5752	32867	44501
% non-zero doses	2	10	59	81

Effect of mask wearing – total dose

100% loading
2% prevalence
0% masking, BLO coughing

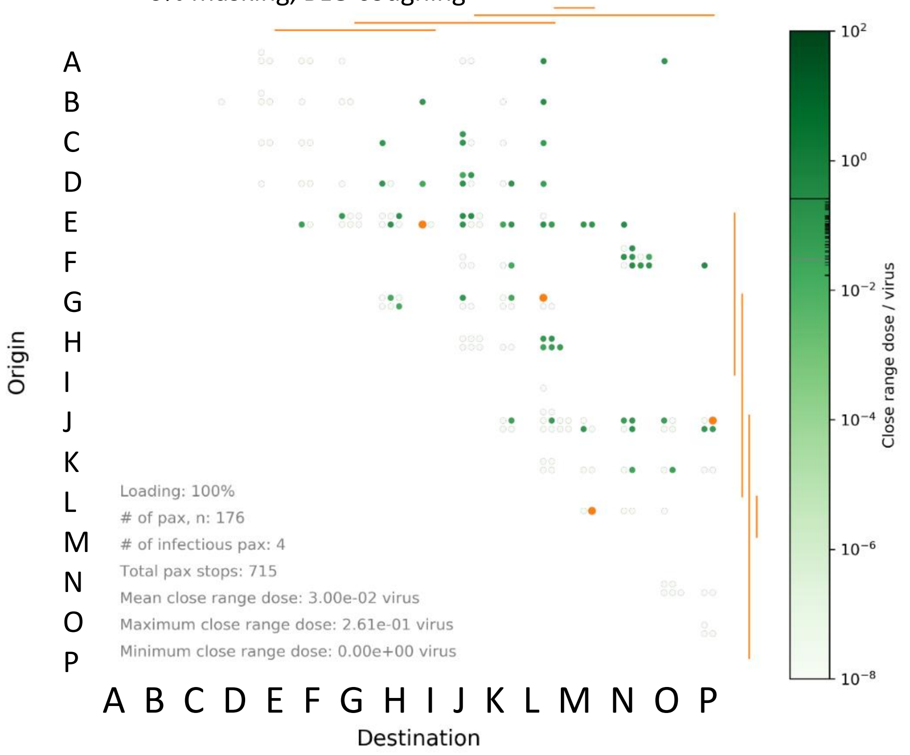


100% loading
2% prevalence
100% masking, BLO coughing

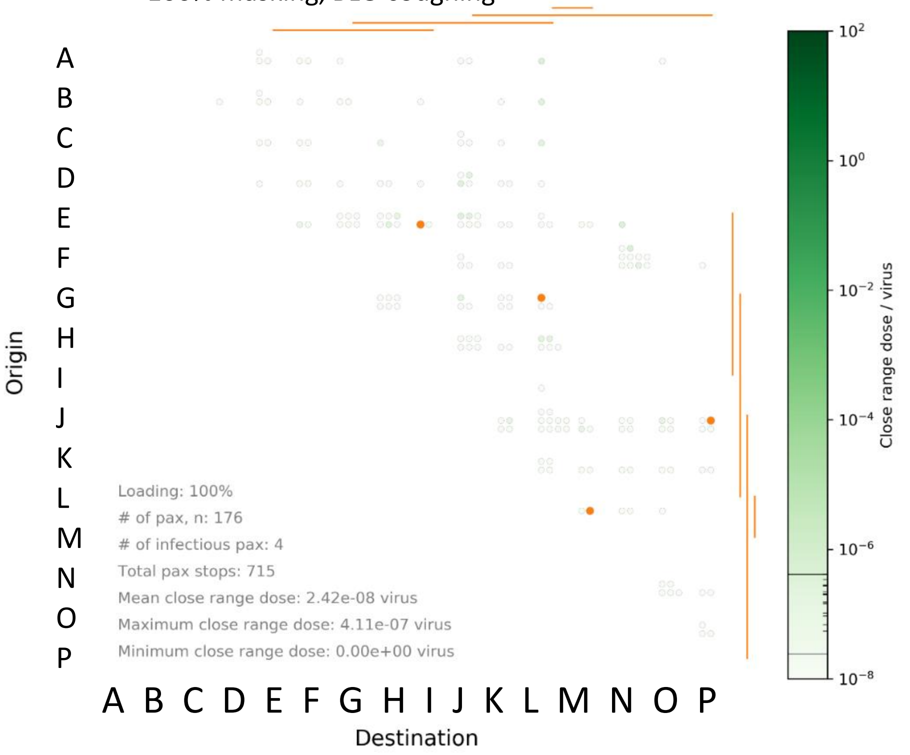


Effect of mask wearing – close range dose

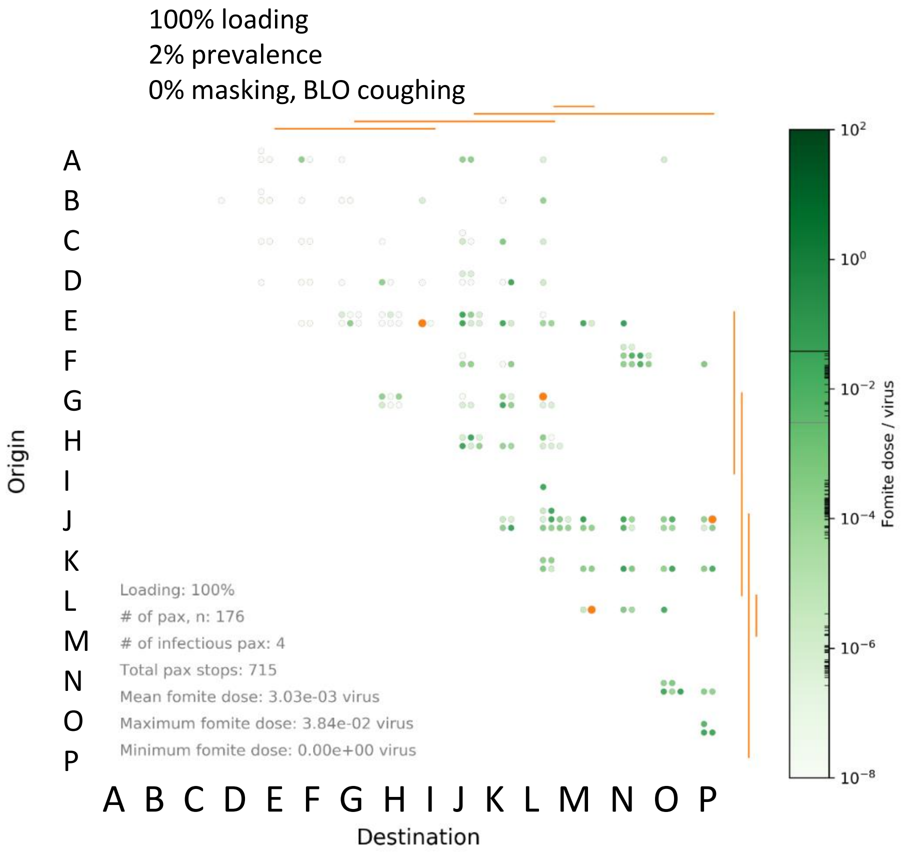
100% loading
2% prevalence
0% masking, BLO coughing

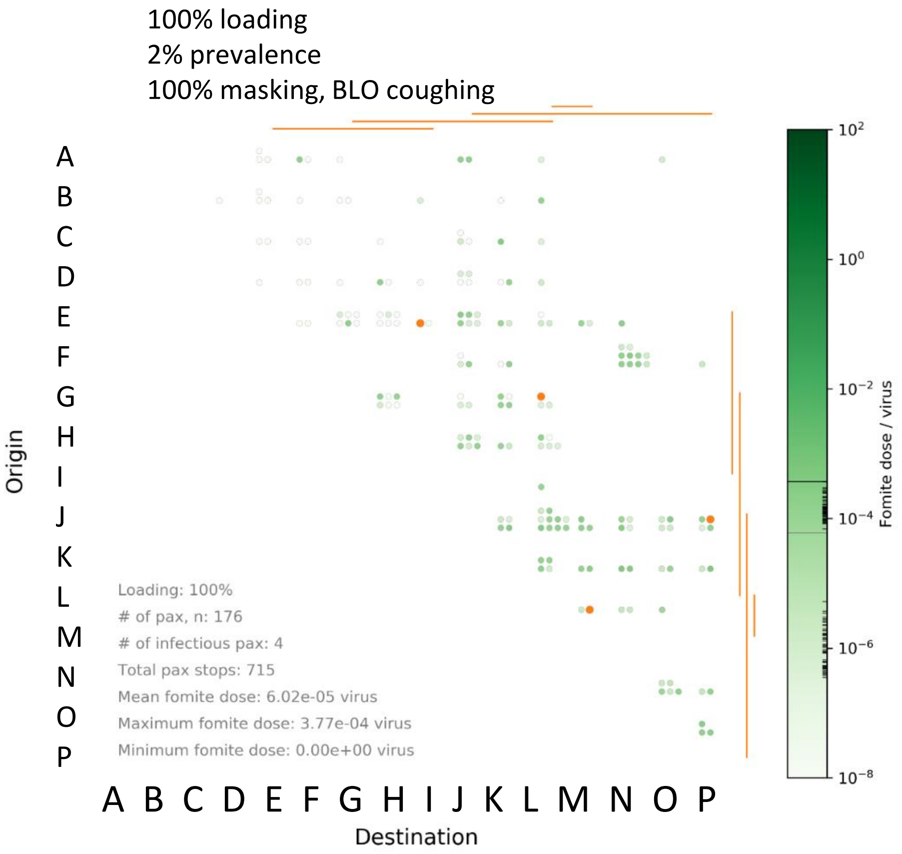


100% loading
2% prevalence
100% masking, BLO coughing



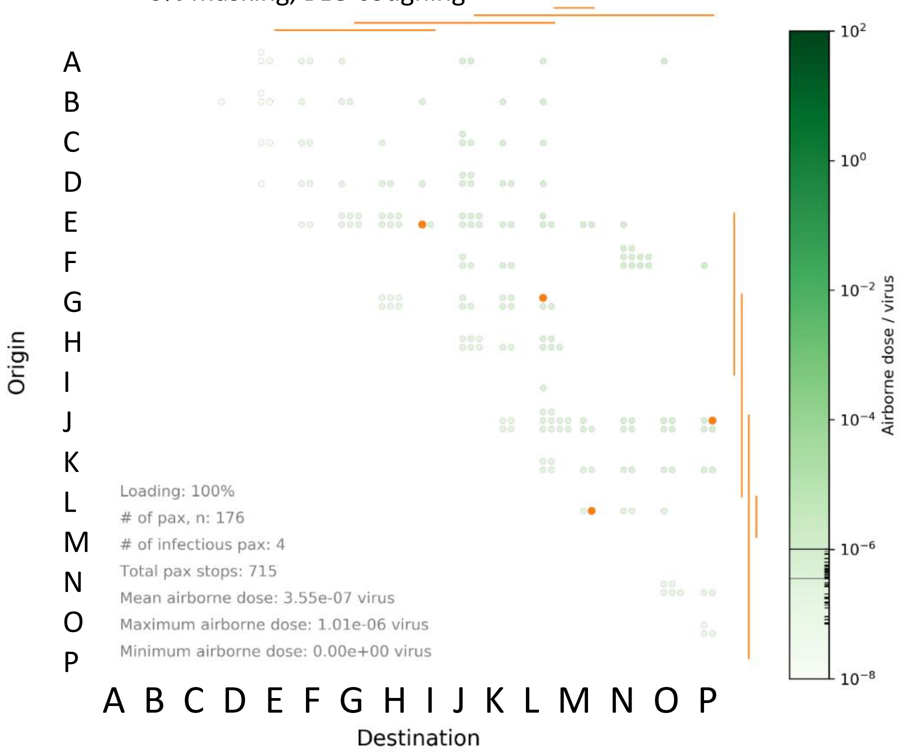
Effect of mask wearing – fomite dose



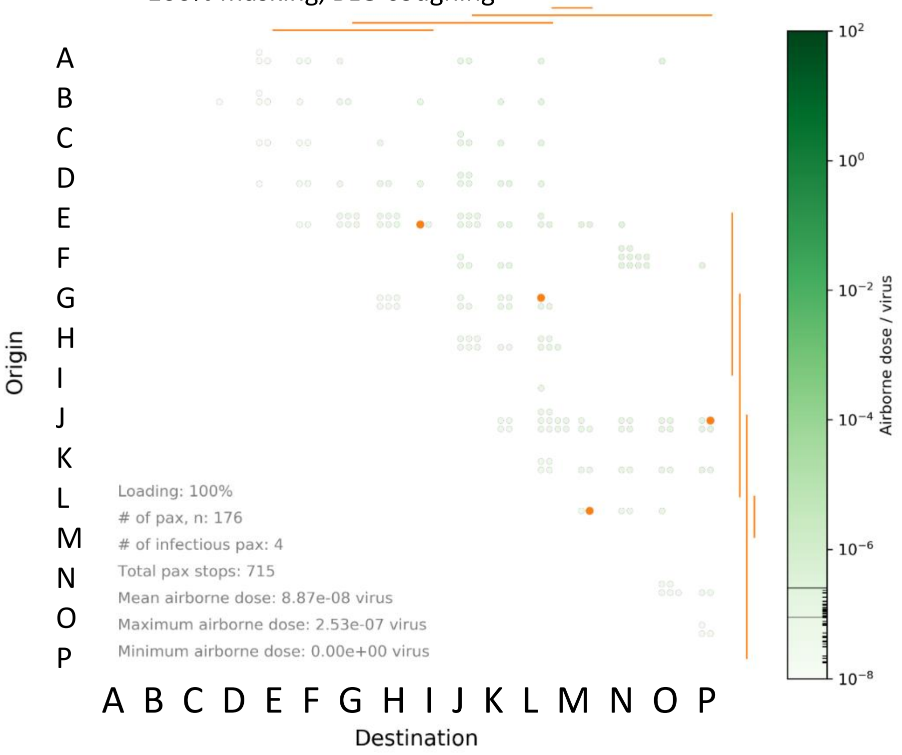


Effect of mask wearing – airborne dose

100% loading
2% prevalence
0% masking, BLO coughing



100% loading
2% prevalence
100% masking, BLO coughing



Ventilation and epidemics

Susceptible → **Exposed** → **Infectious** → **Removed**

β $1/\alpha$ γ

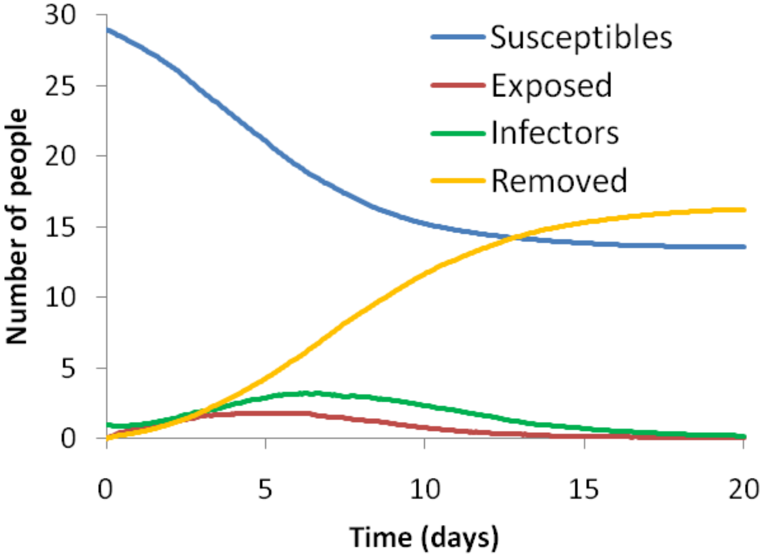
Model contact rate through Wells-Riley assumptions

- Breathing rate
- Emission rate (quanta)
- Ventilation rate

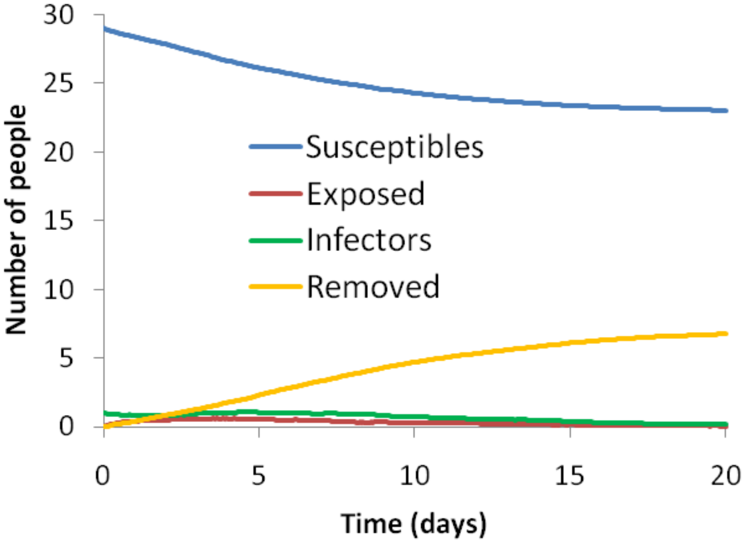
$$\beta = \frac{pq}{Q}$$

Hospital scenario

3 AC/h



6 AC/h

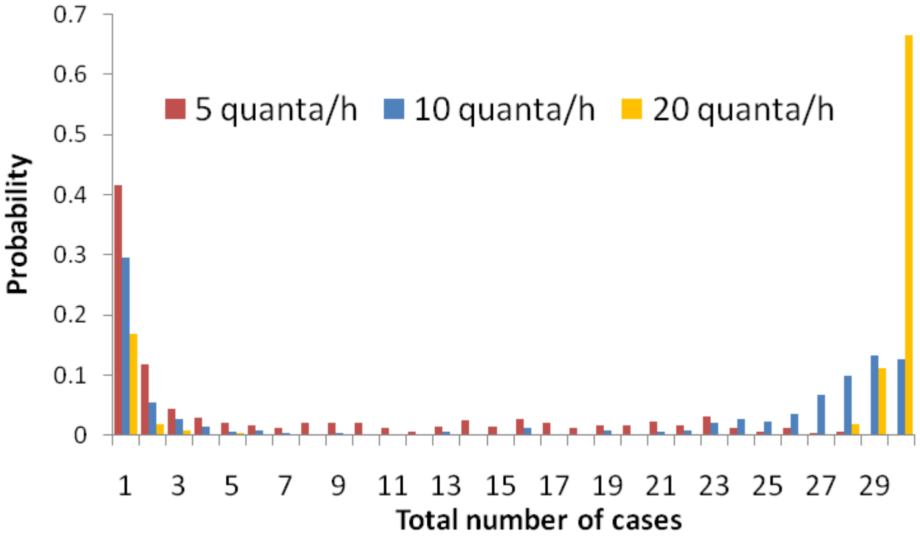


1 Infector, 30 Susceptibles, 1000 m^3 α=1 day, γ= 2 days

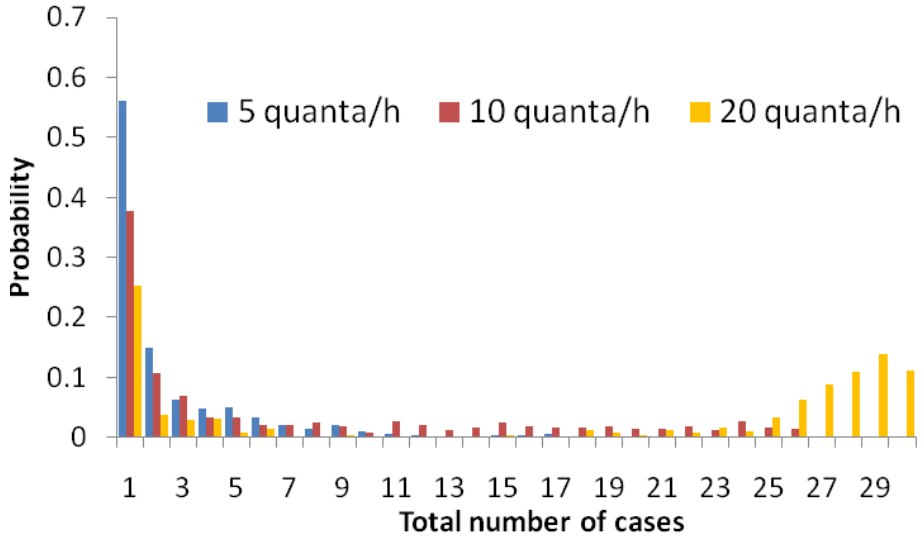
Mean of 500 simulations

Hospital scenario

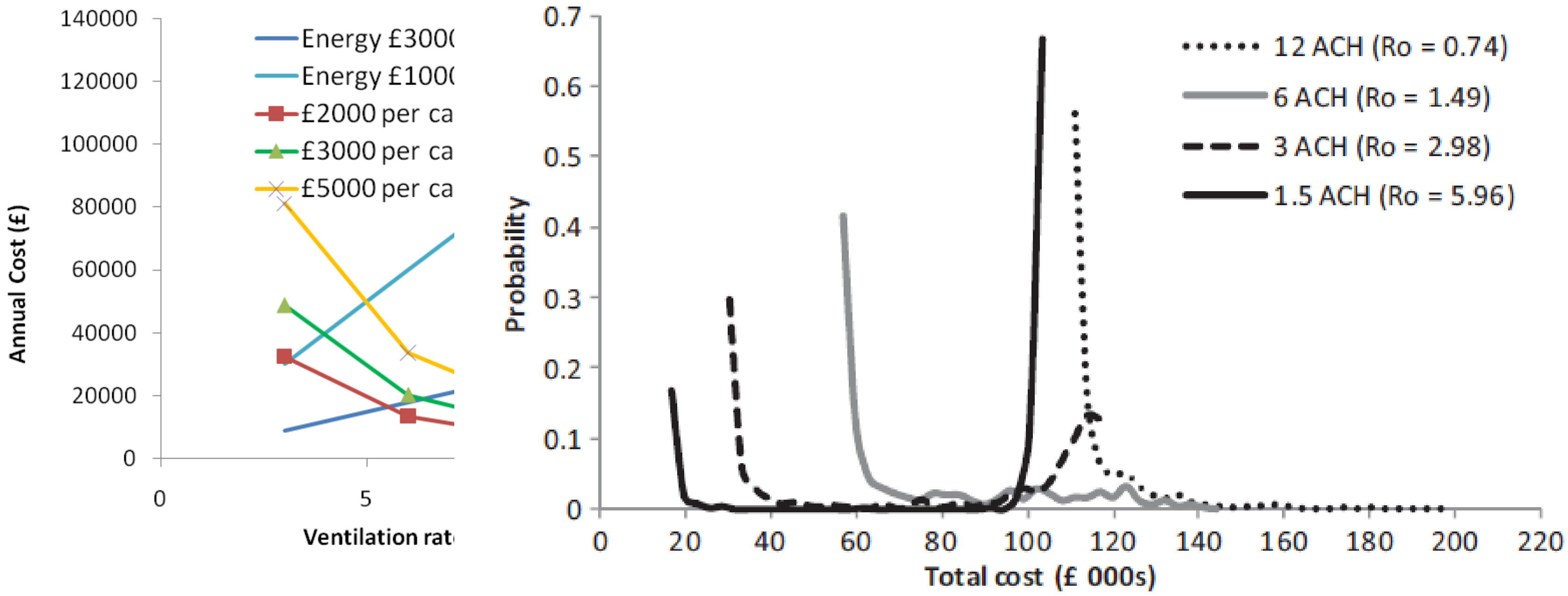
3 AC/h



6 AC/h

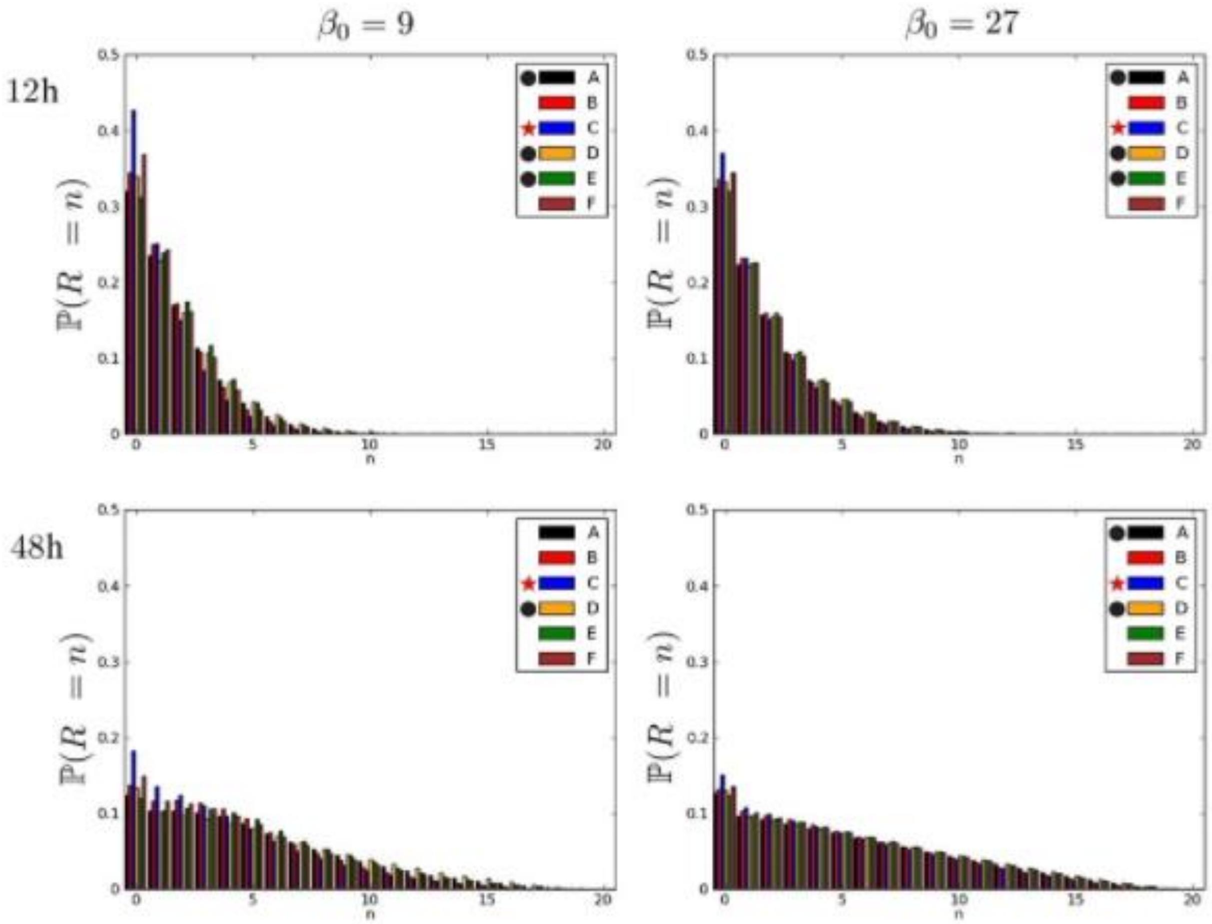


Trade offs


Annual Cost (£)
140000
120000
100000
80000
60000
40000
20000
0
0
5
Ventilation rat
Energy £300
Energy £100
£2000 per ca
£3000 per ca
£5000 per ca
Probability
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
120
140
160
180
200
220
Total cost (£ 000s)
12 ACH (Ro = 0.74)
6 ACH (Ro = 1.49)
3 ACH (Ro = 2.98)
1.5 ACH (Ro = 5.96)

Multi-zone SIS-WR model

- 3 bay ward, 18 patients
- Overall vent rate 3 ACH
- 30 quanta/hr
- Variation in ventilation distribution (A-F) and mixing between bays (βo)
- Time to symptoms 12/48 hrs



Key points

- Environment can influence all modes of transmission –greater impact on air and fomite
- Biggest impact on ongoing transmission through airborne – 1 to many transmission
- Ventilation rates could affect generation time, especially in regularly attended settings – schools, workplaces, prisons, care homes, hospitals
- National level of ventilation rates could affect progression?
- Need models to incorporate differential spaces and other transmission modes

Thank you

Leeds:

Marco-Felipe King

Amir Khan

Martin Lopez-Garcia

Andy Sleigh

Lee Benson

Andrew Bate

Engineering and Physical Sciences Research Council

Collaborators:

Ben Jones, Patrick Sharpe, Chris Iddon, Abigail Hathway, Shaun Fitzgerald

Shelly Miller + Skagit Choir group

All of TRACK team especially Simon Parker, Daniel Miller, Joseph Drodge, Henry Cooper, James Nally, Ursula Dalrymple, Gary Reeves, Ian Hall

All of SAGE EMG, aerosol and ventilation colleagues worldwide

Any Questions?

C.J.Noakes@leeds.ac.uk

@CathNoakes