Direct China/Hong Kong flights and Europe's first-wave COVID-19 excess mortality (2020): a EUROCONTROL ADRR coverage audit and exploratory analysis

Maximilian Elixhauser[a,*]

[a] *University of Salzburg,*

Abstract

We test whether direct long-haul exposure to China/Hong Kong just before Europe's COVID-19 shutdown helps explain first-wave excess mortality. Using EUROCONTROL's Aviation Data Repository for Research (ADRR), we count inbound IFR passenger flights from Mainland China and Hong Kong in December 2019 and March 2020 across 25 continental EUROCONTROL states ($F_{\mathrm{DEC}}, F_{\mathrm{MAR}}, F_{\mathrm{SUM}}$). Outcomes are excess deaths per million on 5 May in 2020–2023 (nearest value ± 7 days; Our World in Data / World Mortality Dataset). A coverage audit shows that community ADS-B (OpenSky) undercounts CN/HK $\rightarrow$ Europe-25 arrivals, so ADRR provides exposure while OpenSky is used only for QC. In 2020, exposure is positively associated with excess mortality (Spearman $\rho = 0.526$; 95% CI 0.177–0.771; $p = 0.007$); the top exposure quartile recorded ≈ 465 more deaths per million than the bottom quartile. The association weakens toward zero in 2021 and reverses in 2022 (negative and significant), remaining negative in 2023 with a 95% CI that includes zero. Limitations include the missing February ADRR snapshot, lack of passenger-load information ("ghost flights"), and unobserved multi-leg itineraries.

Keywords: COVID-19, Excess mortality, Air travel / international flights, EUROCONTROL ADRR, Europe, Spearman rank correlation

*Corresponding author
Email address: maximilian.elixhauser@stud.plus.ac.at (Maximilian Elixhauser)

1. Glossary

Table 1: Glossary of acronyms and symbols.

Acronym / symbol	Definition
ADEP / ADES	ICAO **Aerodrome** of **DEP**arture / **DES**tination
ADRR	*Aviation Data Repository for Research* (EUROCONTROL snapshot files)
ADS-B	*Automatic Dependent Surveillance–Broadcast* (aircraft position/velocity broadcasts; here observed via community receiver networks such as OpenSky)
ASK	*Available-Seat-Kilometre* (air-capacity metric)
CAAC	Civil Aviation Administration of China
CN/HK/MO	Mainland China, Hong Kong, Macao. (No Macao–Europe flights appear in Dec 2019 or Mar 2020; exposure figures and plots therefore refer to **CN/HK**.)
Europe-25	The 25 continental EUROCONTROL member states used in this study (includes non-EU members)
Effective distance	Network metric converting connection probabilities/flows into a distance scale
EUROCONTROL	European Organisation for the Safety of Air Navigation
FPM	Flights per million population (exposure normalised by country size)
GLEaM	*Global Epidemic and Mobility* metapopulation model
IFR (flight)	Flights operated under **Instrument Flight Rules**; in this study, those with **filed IFR flight plans** tracked by EUROCONTROL
IATA / ICAO	Code standards (IATA: airline & 3-letter airport; ICAO: airline, 4-letter airport, and aircraft-type)
LCC	Low-Cost Carrier
NPI	Non-Pharmaceutical Intervention (lockdown, mask mandate, etc.)
OWID	*Our World in Data* COVID-19 dataset
P-score	Percent excess mortality = (Observed − Expected)/Expected × 100 (a mortality outcome, not a significance measure)
ρ **(rho)**	Spearman rank-correlation coefficient (association between two ranked variables)
p (p-value)	Probability of observing the test statistic (here, for Spearman's ρ) under the null hypothesis; "n.s." means $p \geq 0.05$
Slot waiver	EU March 2020 rule suspending "use-it-or-lose-it" airport-slot requirement
WMD	*World Mortality Dataset* (source of excess-death figures)
WPP	UN *World Population Prospects* (population denominator)
n.s.	Not significant
Preighters	Passenger aircraft temporarily converted to carry cargo
HAQ	Healthcare Access and Quality Index (amenable mortality benchmark)
UHC	Universal Health Coverage – service coverage index

2. Introduction

2.1. Context & motivation

On **31 December 2019**, the Wuhan Municipal Health Commission reported a cluster of "viral pneumonia of unknown aetiology"; WHO issued its first Disease Outbreak News five days later (World Health Organization, 2022). Europe's first laboratory-confirmed SARS-CoV-2 infections were detected on **24 January 2020** in France (Spiteri et al., 2020). By **21–23 February 2020**, Italy had reported its **first COVID-19 death** and **rapidly expanding local-transmission clusters** centred on **Lombardy**, with additional cases in **Veneto, Piedmont, and Emilia-Romagna**; **ECDC** assessed the risk of **similar clusters elsewhere in the EU/EEA and UK** as **moderate to high** (European Centre for Disease Prevention and Control, 2020).

The six-week hop from Wuhan to Northern Italy shows how long-haul aviation can relocate a pathogen within a single generation interval. A global metapopulation model estimated that Wuhan's **23 January** cordon sanitaire delayed local growth by only **3–5 days**, yet reduced *international* exportations by roughly **78 %** through mid-February (Chinazzi et al., 2020). A **review of nearly 200** studies on COVID-19 and air transport concludes that dense pre-2020 flight networks **shrank** Europe, enabling rapid cross-border seeding before the March–April capacity collapse (Sun et al., 2022a).

Excess-mortality outcomes diverged sharply thereafter. A latent-class mixed-model analysis of **21 countries** found **COVID-19 incidence** (lagged) to be the strongest positive correlate of excess mortality, while **vaccination** and **policy stringency** (via interactions with incidence) were negatively associated with excess mortality (not always statistically significant across clusters). **Government revenue** and **government effectiveness** were among the most protective structural factors; the lower-mortality cluster also had higher **life expectancy/HAQ/UHC** (Rahmanian Haghighi et al., 2024).

This thesis asks how much of Europe's first-wave mortality spread is associated with a country's **direct-flight exposure to Mainland China and Hong Kong** just before lockdowns.

Provenance & scope. The project was initially conceived as a global, networked SIR exercise in the spirit of Brockmann and Helbing (2013) seeded in Wuhan and driven by early-2020 air-mobility data. After scoping, two constraints made that infeasible at bachelor scale—the commercial cost of global FR24 history and **East Asia** coverage gaps in community ADS-B (OpenSky). We therefore pivoted early to **EUROCONTROL ADRR** and built **Dec-2019 / Mar-2020** exposure measures for EUROCONTROL states, testing rank associations with **OWID/WMD** excess-mortality snapshots. The **February 2020** ADRR gap is noted as a limitation.

2.2. Research question

> Among the **continental EUROCONTROL states**, is a higher volume of **direct inbound flights** from Mainland China/Hong Kong in **Dec 2019** and **Mar 2020** associated with higher cumulative **excess mortality** on **5 May 2020**?[1]

2.3. Objectives

1. **Measure exposure:** Build a country-level index of inbound IFR flights (Dec 2019, Mar 2020, and their sum) from EUROCONTROL ADRR.
2. **Rank & correlate:** Compute Spearman ρ between exposure ranks and excess-mortality ranks on 5 May 2020; repeat for 2021–2023.
3. **Assess validity:** Discuss strengths and limitations of flight counts as a proxy for epidemic seeding.

The following chapter reviews prior research on mobility-driven epidemic seeding and macro-level determinants of excess mortality.

[1] Macao appears in the initial CN/HK/MO acronym but shows **zero** Europe-bound flights in the EUROCONTROL snapshots used here; analyses therefore refer to CN/HK. See Methods.

3. Literature Review

Recent syntheses—most recently Pizzato et al. (2024)—map socio-economic and vaccination gradients in Europe's excess mortality but give little attention to **importation pathways**. This thesis adds an early-mobility lens.

3.1. Excess mortality as benchmark

Official COVID-19 death tallies are sensitive to testing capacity and certification rules. In 35 countries, Kelly et al. (2021) contrasted reported COVID-19 deaths with excess-death estimates based on a *fixed 2020 population denominator* and showed large cross-country discrepancies, concluding that "published COVID-19 death data are **not directly comparable across countries**." This motivates excess mortality—scaled to a single mid-year population—as a more robust yardstick.

Because this thesis tracks excess mortality **at the same calendar cut-off (5 May) for four consecutive years**, each snapshot captures the tail of Europe's spring wave while avoiding later seasonal confounders (see Methods).

3.2. Mobility-driven seeding

Wuhan's **23 January 2020** cordon sanitaire delayed—but did not prevent—international spread: even a **90 %** air-traffic cut mainly *postponed* transmission unless local contact rates also fell (Chinazzi et al., 2020). This aligns with the "effective-distance" view that hub-and-spoke aviation collapses geography, allowing pathogens to traverse continents within a single incubation cycle (Brockmann and Helbing, 2013). A review of $\approx$ 200 studies confirms that the pre-2020 flight network enabled rapid intra-EU seeding before capacity fell **60–75 %** in March–April 2020 (Sun et al., 2022a).

This study tests whether the volume of direct Mainland-China/Hong-Kong flights just before the shutdown helps explain countries' first-wave excess deaths.

3.2.1. January–February 2020: long-haul seeding in practice

Passenger flows were quickly re-routed via non-Wuhan mainland hubs (e.g., PVG, PEK, CAN, KMG, SZX), so Europe's exposure was never limited to Wuhan alone (Chinazzi et al., 2020). In effective-distance terms, dense intercontinental links compressed travel times enough for seeding well inside a generation interval (Brockmann and Helbing, 2013), with the pre-2020 network doing the heavy lifting before the March collapse (Sun et al., 2022a).

3.2.2. Landmark air-traffic studies during COVID-19

Table 2: Key aviation studies motivating data choices and caveats.

Study	Data	Scope	Key insight
Chinazzi et al. (2020)	IATA/OAG pax matrix + GLEaM model	Global	Travel bans delay exports by days; multiple mainland hubs sustain residual risk.
Sun et al. (2022a)	Narrative review (≈200 papers)	Global/EU	Dense pre-2020 network enabled rapid seeding; travel bans work only when layered with domestic NPIs.
Sun et al. (2022b)	Sabre load-factor panel 2017–21	24 European airlines	Airline-level shares of statistically "abnormal" low-load flights spiked in **Mar–Apr 2020** and waned by late-2021; timing aligns with **EU slot-relief (30 Mar 2020)**.
Strohmeier et al. (2021)	OpenSky ADS-B (≈ 45% of FR24-tracked 2019 flights)	Global coverage audit	Global audit shows weaker East-Asia coverage; **therefore, for our Dec-2019/Mar-2020 CN/HK→Europe-25 counts**, OpenSky likely undercounts vs ADRR.
Warnock-Smith et al. (2021)	OAG seats + Sabre MIDT 2017–20	CN/HK EU/Asia; CN domestic	By **Dec 2020**, China–Europe seat capacity ≈ 7% of 2019 while China domestic ≈ **93%**; international markets lagged; Chinese domestic rebounded first.

3.2.3. Macro drivers of excess mortality

Large comparative studies converge on three protective clusters—**socio-economic advantage, resilient health systems, and fast-acting public-health measures**:

- Pizzato et al. (2024): Poverty/inequality raise, while GDP per capita, health spending, and vaccine coverage lower, age-standardised excess mortality (29 European countries).
- Rahmanian Haghighi et al. (2024): Low-mortality class combines government effectiveness, early stringent NPIs, and higher full-vaccination coverage (21 high-income countries, 2020–21).
- Matveeva and Shabalina (2023): During Delta, late vaccine roll-out plus limited ICU capacity amplified deaths.

These speak to **amplification after importation**. The present thesis steps one link earlier: did heavier **direct CN/HK flight volumes** give some countries a larger "ignition dose"?

3.2.4. Data-source considerations: EUROCONTROL vs OpenSky

Community ADS-B coverage is uneven. OpenSky's 2019 archive lists ≈ **31.0 million** flights—≈ **45%** of the **68.95 million** flights tracked by Flightradar24 that year—with much stronger reception over Western **Europe** than East Asia; because FR24 also uses non-ADS-B sources, **45%** is an **upper-bound** comparison. (Strohmeier et al., 2021)

For early-2020 **CN/HK → Europe-25** links (our 25 continental EUROCONTROL states), this matters: in our audit OpenSky records **zero** arrivals for five states and **undercounts** most others relative to EUROCONTROL. (See Appendix Table 14; Figure 7.)

By contrast, EUROCONTROL's *Aviation Data Repository for Research* (**ADRR**) contains **filed IFR flight plans in the EUROCONTROL Network Manager area**, independent of ADS-B reception. Public snapshots exist for **Mar | Jun | Sep | Dec**; **Dec 2019** and **Mar 2020** bracket the pre-lockdown seeding window used here.

4. Data & Methods

EUROCONTROL's public **ADRR** snapshots contain all filed **IFR** flight plans that touch **European Network Manager airspace**. We keep flights whose origin is any airport in **Mainland China (CN)** or **Hong Kong (HK)** and whose destination is one of **25 continental EUROCONTROL states**. (No Macao–Europe flights appear in either snapshot; exposure is effectively CN + HK. The full acronym *CN/HK/MO* is used only on first mention.)

Excess-mortality outcomes come from **Our World in Data's (OWID)** COVID-19 country-day series, which republishes the **World Mortality Dataset (WMD)**. For each of **2020–2023**, we take the observation **closest to 5 May** (±7 days).

Why 5 May? This date captures the tail of Europe's first epidemic wave and, for 2023, coincides with WHO's end-of-emergency announcement (World Health Organization, 2023).

4.1. Study design

Table 3: Study design choices.

Element	Choice	Rationale
Unit of analysis	Country (**n = 25** throughout; **Ukraine excluded ex ante**)	Islands/micro-states dropped for missing flight **or** mortality data; Ukraine removed for war-time breaks
Primary exposure	**Dec 2019** flights (F_{DEC}) and **Mar 2020** flights (F_{MAR}); sum F_{SUM}	Brackets Jan–Feb seeding window while preceding most EU lockdowns
Alt. exposure	$FPM = F_{\mathrm{SUM}}$/population	Population-scaled sensitivity check (size artefact)
Outcome	E_t = excess deaths per million on 5 May of year t (t = 2020–2023)	Uniform "first-wave" reference point; OWID/WMD snapshot
Statistic	Spearman's ρ with 95 % bootstrap CI (5,000 draws)	Rank test robust to skew/outliers; bootstrap stabilises CI in a small-n panel
Sensitivity tests	(i) **FPM** exposure; (ii) restrict to countries with complete 4-year E_t; (iii) partial ρ controlling % ≥65	Checks population scale, missing-data bias, and age confounding

4.1.1. Analytical variables

Table 4: Analytical variables.

Symbol	Definition	Transformation / note
F_{DEC}	Inbound CN/HK $\rightarrow$ Europe-25 flights, **Dec 2019**	raw count (ADRR)
F_{MAR}	Inbound flights, **Mar 2020**	raw count (ADRR)
F_{SUM}	$F_{\mathrm{DEC}} + F_{\mathrm{MAR}}$	main exposure metric
FPM	F_{SUM}/population	flights per million residents
E_t	excess deaths per million on 5 May of year t	$t \in \{2020, 2021, 2022, 2023\}$

4.1.2. Statistical approach

- **Association.** Spearman's ρ between each flight metric and E_t.
- **Uncertainty.** 95 % percentile-bootstrap CIs (5,000 draws; seed = 42). (DiCiccio and Efron, 1996)
- **Sensitivity.**
  1. replace F_{SUM} with FPM (population-scaled);
  2. restrict to countries with a **complete four-year E_t series**;
  3. compute **partial Spearman** controlling for the share of population ≥ 65 (rank-residualisation; see code).
- **Inference stance.** Two-sided tests; $\alpha = 0.05$. Given the exploratory aim, **no multiple-testing correction** is applied; emphasis is on effect sizes and CIs.

Software. Analyses were conducted in **R 4.4.0** (R Core Team, 2025); the full, reproducible pipeline is scripted in `R/`.

A confounder sanity-check showed that adjusting for age ≥ 65 changed ρ by $< \mathbf{0.02}$ in any year, so no further covariates were added (exploratory, correlation-focused study). We did **not** model vaccination, NPIs, GDP or other covariates; any mentions in the Discussion are descriptive context rather than part of the statistical tests.

4.2. Flight-exposure variable

4.2.1. Snapshot source

EUROCONTROL's **ADRR** publishes full **IFR** datasets for four "snapshot" months per year (**Mar | Jun | Sep | Dec**). Only **Dec 2019** and **Mar 2020** straddle the early-COVID seeding period; **February 2020 is not publicly available**. By mid-January, flows had already re-routed via non-Wuhan mainland hubs. (Chinazzi et al., 2020)

4.2.2. Filtering steps

Table 5: Filtering steps for ADRR snapshots.

Step / field	Rule	Rationale
Month slice	Keep **Dec 2019** and **Mar 2020**	Feb missing; Dec+Mar capture pre- and early-restriction traffic
Traffic type	Keep ICAO **S** (scheduled pax) and **N** (non-scheduled charter)	Exclude cargo-only **F**, military **M**, GA **G**, … (EUROCONTROL, 2025)
Origin (ADEP)	ADEP ISO-2 $\in$ {**CN**, **HK**}	Includes non-Wuhan mainland hubs after mid-Jan 2020 (Chinazzi et al., 2020).
Destination (ADES)	Destination in the **Europe-25** panel	Aligns exposure with the mortality panel
De-duplication	Collapse identical *callsign + off-block time* rows	Removes re-filed plans; yields unique movements
Metadata sanity	Drop rows with missing ADEP/ADES/type	Prevents merge errors and miscounts

*4.2.2.1. What **S** / **N** cover.*

Under **STATFOR 2022** rules (retro-applied to 2019), **S** (scheduled passenger) splits into **Regional** (scheduled flights on **19–120-seat** aircraft types) and **Mainline** (other scheduled, typically $>$ **120 seats**); **N** maps to **Charter** (helicopters moved to "Other"). Priority rules assign **Military** first, then **Business Aviation**, to avoid misclassification. (STATFOR, 2022)

4.2.2.2. Why ADRR over community ADS-B.

OpenSky captured $\approx$ **45%** of FR24's 2019 flights and is geographically skewed toward Western Europe, so raw ADS-B **undercounts CN/HK $\rightarrow$ Europe-25** exposure, including **zeros** for several states in our window. **ADRR** records **all filed IFR** in the EUROCONTROL NM area, recovering movements missed by ADS-B and providing a more reliable exposure baseline (Strohmeier et al., 2021). (See Coverage audit.)

4.2.2.3. Load-factor caveat (movement passengers).

A panel of **24 European airlines** shows **large shares of statistically "abnormal"** (low-load) flights in **Mar–Apr 2020**, receding through 2021; "abnormal" is defined **statistically** (IQR outliers), **not** as "$<$ 10% seats filled" (Sun et al., 2022b). **ADRR counts movements, not load**—a three-passenger A350 counts the same as a full one. At Frankfurt, passenger volume fell −73 in 2020, while **freighters carried** $\approx$**80%** of cargo tonnage (peaking $>$ **90%** in Apr–May) and airlines operated $\approx$ **8,600 preighter flights** ($>$ **150 kt**, $\approx$ **8%** of cargo tonnage). Treat F as **potential seeding capacity**, not realised traveller volume (Fraport AG, 2021).

$$
\begin{aligned}
F_{\text{DEC}} &= \text{CN/HK} \rightarrow \text{Europe-25 flights in Dec 2019}, \\
F_{\text{MAR}} &= \text{CN/HK} \rightarrow \text{Europe-25 flights in Mar 2020}, \\
F_{\text{SUM}} &= F_{\text{DEC}} + F_{\text{MAR}}
\end{aligned}
$$

Flights are assigned to destination countries using **OurAirports** (airport $\rightarrow$ ISO-2) and EUROCONTROL's ISO-2 $\rightarrow$ ISO-3 mapping.

4.2.3. Why fix exposure to Dec 2019 & Mar 2020?

Temporal precedence. Both snapshots precede the **5 May** outcome dates, limiting reverse causation (deaths → fewer flights). Later months mostly reflect domestic restrictions rather than initial import pressure. Extending exposure windows beyond 2020 is left for future work. **(Code in `R/`; processed tables in `data/processed/`.)**

4.3. Coverage audit — EUROCONTROL vs OpenSky

Purpose. Test whether community ADS-B (OpenSky) undercounts **direct CN/HK → Europe-25** arrivals in **Dec 2019 / Feb 2020 / Mar 2020**.

Finding. OpenSky is thin over **East Asia** and parts of **Eastern Europe** in early 2020:

- **Misses entirely:** `GEO`, `HRV`, `PRT`, `SVK`, `UKR` (no CN/HK arrivals recorded in our window).
- **Undercounts:** 14 of the remaining 21 states vs **ADRR** (typical shortfall ≈ **a dozen flights** in the Dec-2019 baseline).

(Full country-by-country comparisons in Appendix Table 14; see also Figure 7 for the erratic month-to-month pattern.)

How OpenSky defines a "flight." A "flight" is a derived ADS-B trajectory: ≥ **15 min** continuous contact; segments are **split after > 10 min** gaps unless a kinematic check reconnects them; origin/destination may be **NULL** if the last seen point is **> 2,500 m** altitude or **> 10 km** from any airport. These rules can miss oceanic/peripheral segments and sometimes misassign ADEP/ADES. (Strohmeier et al., 2021)

Consequence. Because crowdsourced ADS-B systematically understates exposure for peripheral markets, we use **ADRR** for all exposure metrics (filed IFR in the **EUROCONTROL NM area**) and **OpenSky only as a QC benchmark**. (Strohmeier et al., 2021)

Table 6: Coverage audit excerpt (first 20 rows). The full table appears in Appendix Table 14.

iso3	Dec 2019 (EU)	Dec 2019 (OS)	Feb 2020 (OS)	Mar 2020 (EU)	Mar 2020 (OS)
GBR	693	299	227	239	145
DEU	691	174	123	353	153
FRA	396	63	53	74	21
NLD	381	72	60	196	34
ITA	257	61	1	9	2
TUR	192	3	0	19	4
FIN	175	60	47	22	22
BEL	151	58	38	120	46
ESP	126	43	27	30	7
CHE	124	60	54	33	35
DNK	77	15	18	6	4
AUT	69	16	6	7	10
CZE	44	9	0	10	3
SWE	36	3	2	5	0
POL	28	1	1	2	0
HUN	27	9	5	1	10
GEO	14	0	0	0	0
GRC	14	2	0	3	1
PRT	11	0	0	4	0
LUX	8	25	6	0	37

4.4. Excess-mortality snapshots

Why $\pm$7 days? Most WMD series (as republished by OWID) are **weekly** (some **fortnightly** or **monthly**). Picking the observation **nearest to 5 May ($\pm$7 days)** keeps countries aligned within **one reporting interval** and avoids artefacts from different week cut-offs. For monthly reporters, the rule collapses to the same month snapshot. (Karlinsky and Kobak, 2021; Mathieu et al., 2021)

4.5. Population denominator — validation & choice

We use OWID's **mid-2020 population** (UN **WPP 2024** reprint), following the fixed-denominator convention in excess-mortality work (Karlinsky and Kobak, 2021; Kelly et al., 2021).

QC against raw UN WPP (via `wpp2024`):

- **38 / 41** country values differ by **< 5 %** (median **2 %**).
- Largest gaps: **CYP −31 %**, **UKR −11 %**, **MKD +11 %** (boundary/census updates).
- Re-running correlations with UN figures shifts Spearman ρ **by < 0.01**.

We therefore keep OWID's mid-2020 values for **consistency** with the excess-mortality numerator. (Details: `04_population_qc.R`.)

Table 7: EUROCONTROL member states where OWID vs UN WPP mid-2020 population differs by > 10 %.

ISO-3	OWID pop	WPP pop	Δ %
CYP	896,007	1,294,504	-30.8%
UKR	39,701,744	44,835,870	-11.5%

Table 7: EUROCONTROL member states where OWID vs UN WPP mid-2020 population differs by > 10 %.

ISO-3	OWID pop	WPP pop	Δ %
MKD	2,093,606	1,886,191	11.0%

4.6. Analysis workflow

1. **Define exposure metrics**

$$F_{\text{DEC}},\ F_{\text{MAR}},\quad F_{\text{SUM}} = F_{\text{DEC}} + F_{\text{MAR}}.$$

2. **Assemble outcome series**

$$E_t = \text{excess deaths per million on 5 May of year } t, \quad t \in \{2020, 2021, 2022, 2023\}.$$

3. **Main test** Spearman ρ with **95 % bootstrap CIs** (5 000 draws) for each $F_k \times E_t$.
4. **Sensitivity panel**

Label	Modification	Purpose
FPM	Scale exposure by population	Size artefact check
COMPLETE	Keep only countries with full 4-year E_t	Missing-data bias
AGE 65+	Partial Spearman (control % aged $\geq$ 65)	Confounder sanity-check

5. **Reproducibility** Code, data, and the Thesis are version-tracked; a single `build.sh` rebuilds everything from raw inputs.

4.6.1. Visual encoding & accessibility

All plots use the **Okabe–Ito** colour-universal palette (Okabe and Ito, 2008). Direct labels, clear axis titles, and dashed reference lines ensure legibility in greyscale and for common colour-vision deficiencies. We avoid high-valence hues (e.g., "alarming red") to limit framing bias.

4.7. Digital methods & reproducibility

Reproducibility. The analysis is fully scripted and rebuildable: from a clean clone (with required raw inputs), one command runs the data prep, analysis, and rendering end-to-end.

1. **Know the data infrastructure.** Two complementary sources are used: community ADS-B (**OpenSky**) with uneven East-Asian coverage and no load factors, and regulator-grade IFR plans (**EUROCONTROL ADRR**) with complete European coverage (also no passenger counts). Mapping each stream's blind spots (see Coverage audit) is part of the method.
2. **Single-command rebuild.** A Bash wrapper `build.sh` orchestrates the pipeline *raw CSV → cleaned RDS → Quarto → PDF/HTML*. A fresh clone plus the raw inputs reproduces every table and figure without manual edits.
3. **Versioned R environment.** The repository ships an `renv.lock` and `build.sh` runs `renv::restore()` automatically. If the lockfile is missing, `R/00_load_libs.R` can install any missing packages when `INSTALL_MISSING=1` is set.
4. **Path-robust, fail-fast code.** Paths use `here::here()`. The pipeline checks required inputs and stops with clear messages if something is missing.
5. **Licensing & data access.** Code and lightweight derived data are in Git (MIT licence on release). Large/restricted datasets (e.g., EUROCONTROL snapshots) are excluded; the README documents how to obtain them under the correct terms.

Transition. With data-quality checks, clear exposure/outcome definitions, and a reproducible build in place, we proceed to the empirical results.

5. Results

5.1. Panel completeness

Table 9: Completeness of the analysis panel (Dec-2019 & Mar-2020 exposure × 2020–2023 mortality snapshots).

Rows (panel)	Countries	Reference years	Rows with flights	Rows missing flights	% flight NA	Rows with mortality	Rows missing mortality	% mortality NA
100	25	4	100	0	0.0 %	100	0	0.0 %

Output confirms a fully balanced panel:

Completeness. All 25 EUROCONTROL states have flight-exposure and excess-mortality entries at each of the four reference years; no cells are missing.

5.2. Exposure landscape (Dec 2019 & Mar 2020)

Early exposure landscape. Direct CN/HK flights funnelled into a handful of Western European gateways. Figure 1 shows **Germany, the UK, and the Netherlands** handling a majority of arrivals in December 2019 and retaining that lead after the March collapse. Those same hubs also drew from the **widest mix** of Chinese origins—**LHR 15**, **CDG 13**, **FRA 12** (Figure 2). Volume and diversity rose in lock-step (airport-level Spearman $\rho \approx$ **0.86**; Figure 3). **Liège (LGG)** sits above the trend—high origin diversity for ~200 rotations—because many S/N movements there are **cargo charters** (see Limitations).

Together, the three plots show that both **how much** traffic and **how many** source cities concentrated in the same Western hubs, yielding a right-skewed exposure profile at country level.

5.2.1. Gateway concentration

Before the pandemic shock, direct CN/HK traffic into Europe was highly skewed. Figure 1 (Top-10 destination **countries**) shows **Germany, the UK, and the Netherlands** absorbing over half of all arrivals in December 2019 and still dominating after the March 2020 cliff-edge.

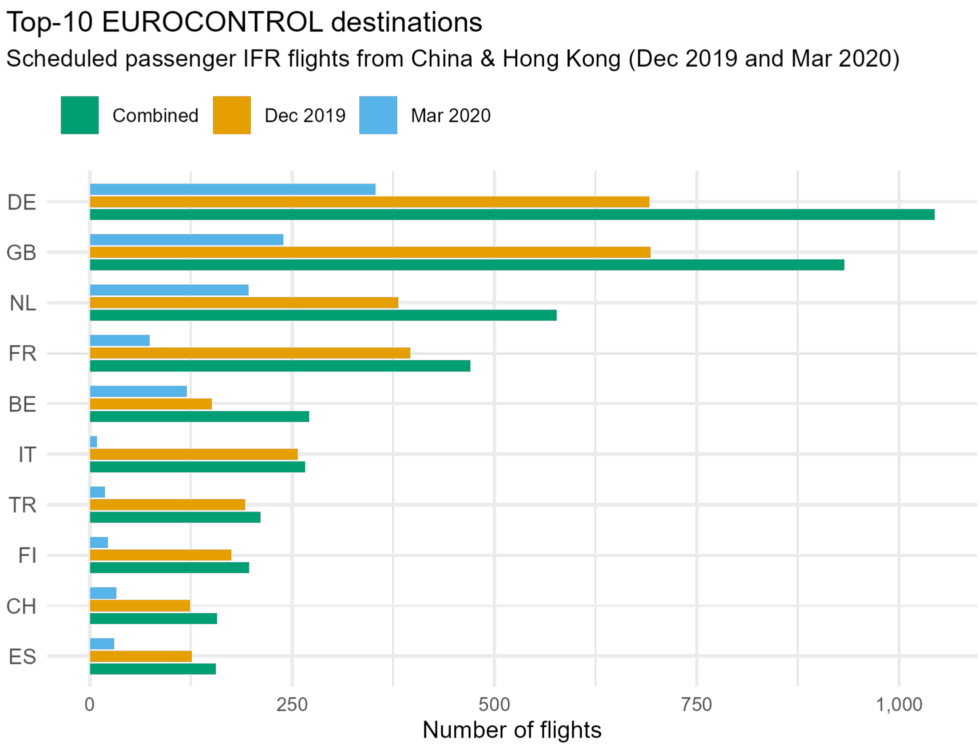

Figure 1: Top-10 European destination countries for direct CN/HK IFR S/N flights in December 2019 (orange), March 2020 (blue), and combined (green). Bars are counts of filed IFR scheduled/charter movements (cargo-only F excluded).

Take-away. Import pressure was not evenly distributed: a few Western gateways carried most movements in both study months, producing a right-skewed country-level exposure index.

5.2.2. *Route diversity vs. volume*

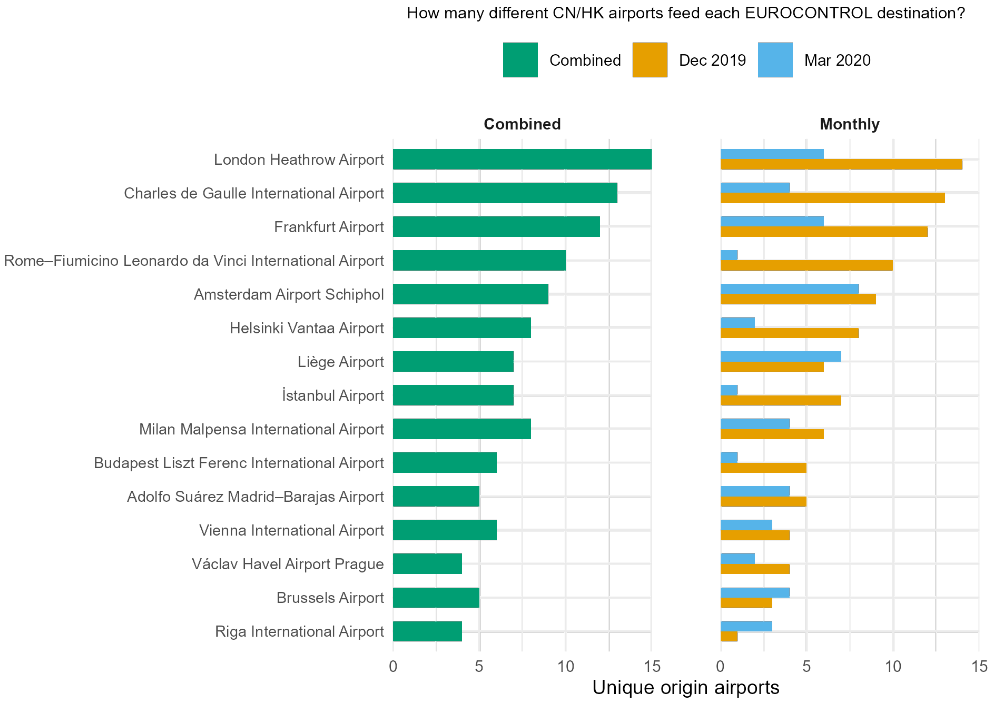

Figure 2: How many distinct CN/HK origin airports fed each EUROCONTROL destination? Left: combined Dec-2019 + Mar-2020; right: month-by-month. Western megahubs (**LHR 15**, **CDG 13**, **FRA 12**) top the list. **Liège (LGG)** ranks high on diversity despite modest volume because many **N** flights are cargo charters—illustrating how movement counts can overstate **passenger** exposure at freight-biased airports.

Volume and diversity move together. Each additional ~100 flights is associated with **1–2** extra Chinese origin airports ($\rho \approx \mathbf{0.86}$; $\boldsymbol{p < 0.001}$; $\boldsymbol{n = 47}$).

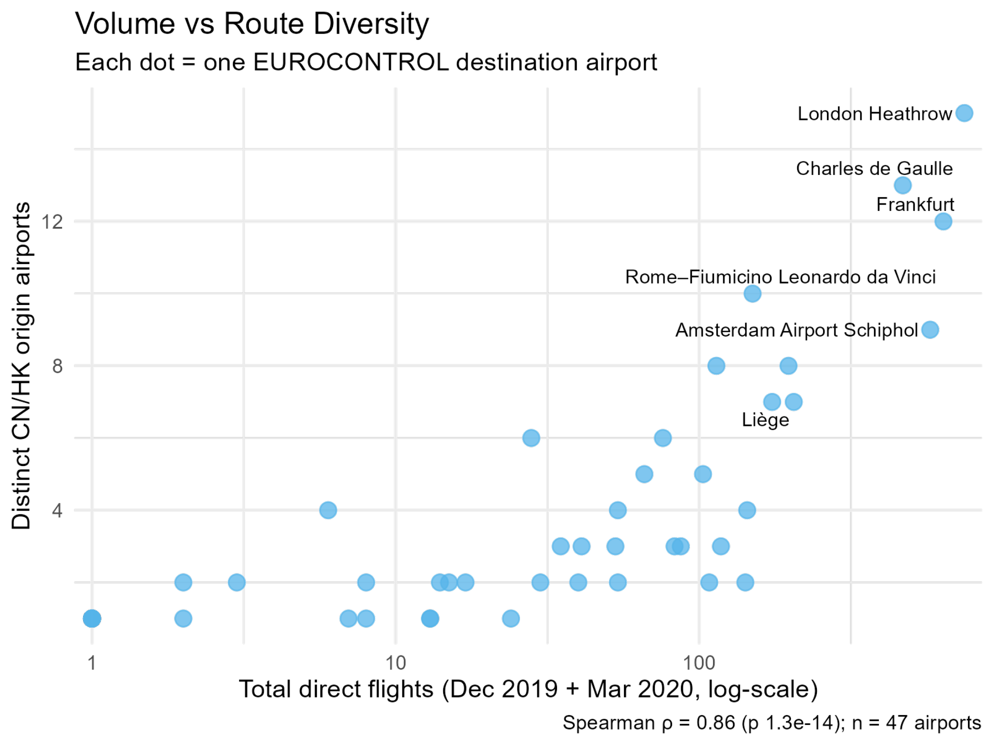

Figure 3: Each dot is one destination airport. X: combined Dec-2019 + Mar-2020 S/N flights (log-scale). Y: number of distinct CN/HK origin airports. Spearman $\rho \approx 0.86$ ($p < 0.001$; $n = 47$). **LGG** lies above the trend—high diversity for moderate volume—because many flights are cargo charters.

Interpretation. The slope is driven by large passenger hubs in the upper-right; most other airports remain low-volume/low-diversity. **LGG** is freight-biased and inflates "exposure" without adding many travellers (see Limitations).

5.2.3. March 2020 cliff-edge

We **plot only the 21 states** with $\geq$ **5** direct CN/HK flights in Dec-2019 to avoid visually noisy -100% bars from trivial baselines (e.g., single charters). The correlation analysis uses the full **25-country** panel.

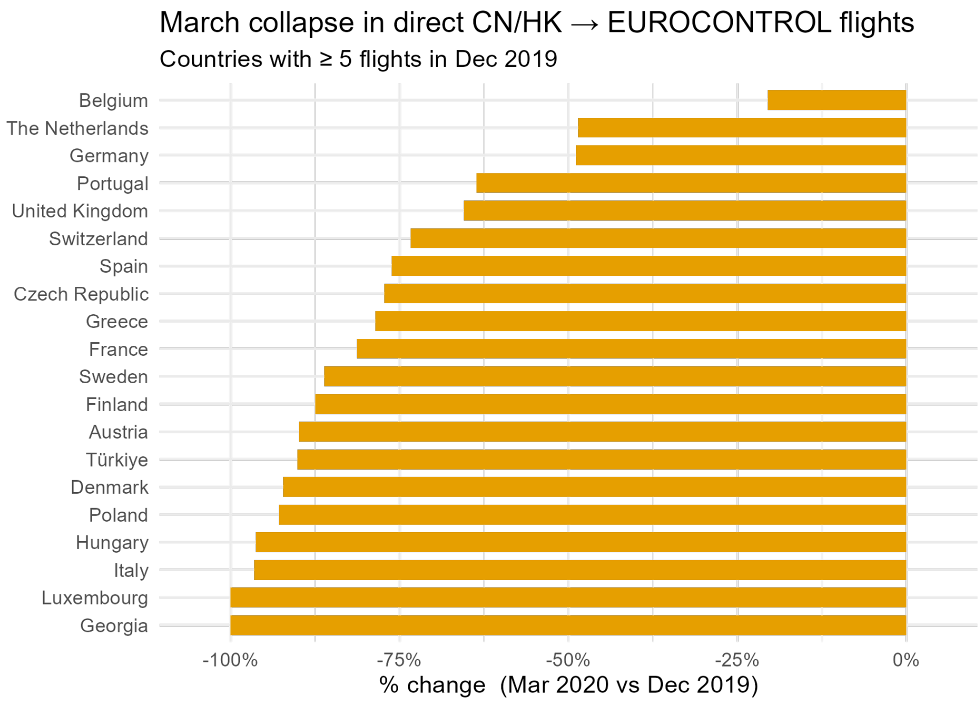

Figure 4: Percentage change in direct CN/HK S/N flights from Dec-2019 baseline to Mar-2020 for countries with ≥5 December flights ($n = 21$). All countries cut traffic by at least 50%; 7/21 reduced >90%, and 14/21 ≥75%. The Netherlands and Germany retained the largest residual shares; most others were near zero.

What the figure shows. Among the **21 ≥ 5-flight countries**, every one cut traffic by ≥ **50%** by late March 2020:

- **7 of 21** slashed > **90%** (bars pinned near −100%).
- **14 of 21** cut ≥ **75%** — a tightly synchronised shutdown.
- **The Netherlands and Germany** retained the largest **percentage** shares; several others, including **Belgium**, retained **lower percentage shares** but can still rank high in **absolute** counts.

Table 10: Signals at the March-2020 cliff-edge and their implications for analysis.

Signal	Take-away
Timing	The plunge aligns with EU actions restricting **non-essential travel to the EU** (Commission Communication, **16 Mar 2020**; later codified by **Council Recommendation (EU) 2020/912**, **30 Jun 2020**) and the CAAC **“Five-One”** policy (**26 Mar 2020**) limiting international passenger services to **one route per airline per country** with **at most one weekly flight**. (European Commission, 2020; Council of the European Union, 2020; Civil Aviation Administration of China, 2020)
Uniformity	Because the contraction is pan-European, any exposure–mortality link must be driven by traffic that occurred **before** the cliff.
Residual risk	Absolute counts still diverged after March: a few hubs kept ~**200–350** rotations, so a trickle of import potential remained (see Δ-flights in Table 15).

Data note (capacity vs movements). The OAG figures cited elsewhere report **scheduled passenger seat capacity** only; **charter** operations and **all-cargo** flights are excluded. Accordingly, these series should be **interpreted as a capacity baseline**, not as counts of movements or passengers. (Warnock-Smith et al., 2021)

With direct CN/HK traffic reduced to a trickle after late March, any variation in **first-wave** excess mortality must trace back to flights that arrived **before** the cliff-edge. The next subsection tests whether pre-collapse exposure leaves a statistical imprint in the **5 May 2020** snapshot.

5.3. Association with first-wave mortality

Table 11: Spearman ρ between early flight-exposure metrics and excess mortality on 5 May 2020 (95% bootstrap CI; n = 25). Significant results ($p < 0.05$) marked .

variable	rho	ci_lo	ci_hi	p	sig	n
Dec 2019	0.502	0.135	0.759	0.011		25
Mar 2020	0.573	0.228	0.796	0.003		25
Combined	0.526	0.177	0.771	0.007		25
Flights / M pop	0.303	-0.077	0.606	0.141	—	25

Reading the 2020 snapshot. All four exposure metrics are **positively** associated with first-wave excess mortality (Table 11). Three are statistically significant; the population-scaled metric is positive but not significant. Using the **Dec + Mar combined** count:

- Spearman $\rho = 0.526$ (95% CI **0.177–0.771**, $p = 0.007$; $n = 25$).
- Countries in the **top exposure quartile** recorded ≈ **465 excess deaths / million** more than those in the bottom quartile (median gap).
- Figure 5 shows an overall positive slope with **notable vertical outliers** (e.g., **ESP** with high mortality despite fewer direct flights; **DEU** with lower mortality given its volume).

Figure 5: Direct CN/HK S/N flights (Dec-2019 + Mar-2020, log-scale) versus excess deaths per million on 5 May 2020 (n = 25). Spearman $\rho \approx 0.53$ ($p < 0.01$). Several Western hubs anchor the right tail; **ESP** is a high-mortality outlier at moderate exposure.

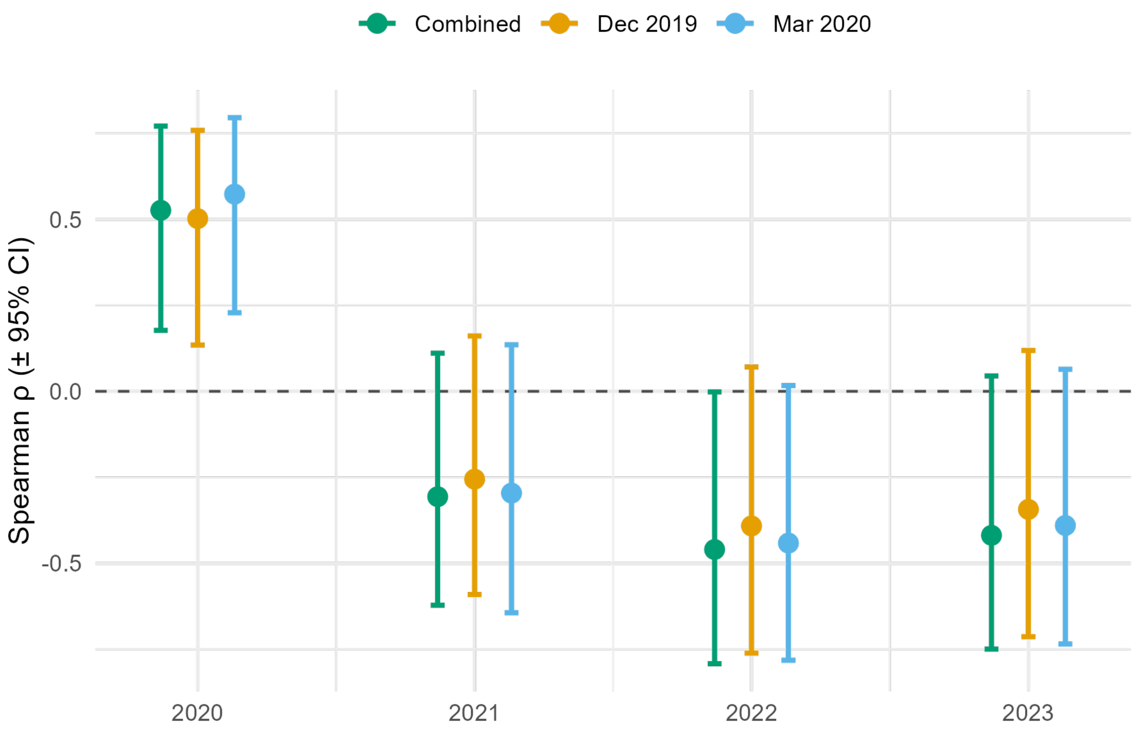

Figure 6: Spearman ρ (points) with 95% bootstrap CIs (bars) for Dec-2019, Mar-2020, and their sum. Estimates are positive in 2020. From 2021 onward they trend toward zero or below; in 2022 the Mar and Combined metrics are significantly negative. In 2023 they remain negative with CIs that touch or narrowly include zero.

Pattern. Estimates are **positive** in 2020, weaken toward **zero** in 2021, and turn **negative** in 2022–2023. For the **Combined** metric:

- **2020:** $\rho = \mathbf{0.526}$ (95% CI 0.177–0.771; $p = 0.007$)
- **2021:** $\rho = \mathbf{-0.306}$ (95% CI -0.622–0.111; n.s.)
- **2022:** $\rho = \mathbf{-0.460}$ (95% CI -0.792 to -0.001; $p \approx 0.02$)
- **2023:** $\rho = \mathbf{-0.419}$ (95% CI -0.749–0.045; **borderline**; CI grazes zero)

Table 12: Sensitivity: baseline vs partial Spearman controlling for population ≥ 65 y.

year	ρ baseline	ρ adj age 65+	p adj
2020	0.526	0.525	0.008
2021	-0.306	-0.289	0.171
2022	-0.460	-0.456	0.025
2023	-0.419	-0.424	0.039

Sensitivity & partial checks. Adjusting for the share aged ≥ 65 leaves effect sizes essentially unchanged ($|\boldsymbol{\Delta}\rho| \leq \mathbf{0.02}$) and does not alter any year's inference; age structure cannot explain the sign flip.

5.4.0.1. *Vaccination coverage by exposure quartile (May 2022).*

Table 13: Full-vaccination coverage on 5 May 2022 (±7 days) by flight-exposure quartile (baseline = Dec-2019 + Mar-2020 flights; OWID `people_fully_vaccinated_per_hundred`).

Exposure quartile	Median full-vax %	n
Q1	69.3 %	n = 7
Q2	65.5 %	n = 6
Q3	62.1 %	n = 6
Q4	78.0 %	n = 6

Gradient. Median full-vaccination rises from **Q3** $\approx$ **62%** and **Q1** $\approx$ **69%** to **Q4** $\approx$ **78%** (n per quartile in table), consistent with wealth/governance gradients and the weakening/negative ρ in 2021–2023.

5.5. *Results summary*

- **2020:** heavier direct CN/HK exposure **higher** first-wave excess mortality ($\rho \approx$ **0.53**).
- **2021:** association $\approx$ **zero**.
- **2022–2023:** association **negative** (significant in **2022**; **negative/borderline** in **2023**).
- **Population-scaled exposure** flips **earlier** (negative by **2021**).

6. Discussion

6.1. *Interpreting the reversal (2021–2023)*

- **Wealth & structural vulnerability.** Excess mortality tends to **fall with GDP per capita** and **rise with poverty/inequality**, which helps explain why the positive flight–mortality link **vanishes after 2020**: Europe's most connected hubs (Germany, the UK, the Netherlands, France) also sit in the top-GDP tercile and had more protective structural factors. (Ioannidis et al., 2023)

- **Vaccination rollout.** By **5 May 2022** (±7 days), the **highest-exposure quartile (Q4)** had **higher full-vaccination** than lower-exposure quartiles (see Table 13), aligning with OWID's series and helping explain the **post-2020 attenuation/flip**. (Mathieu et al., 2021)

- **Policy timing & capacity.** Comparative work shows **travel curbs mostly delay** spread unless paired with local measures. (Chinazzi et al., 2020) In Europe, the **slot-waiver** adopted in late March 2020 **removed the 80/20 "use-it-or-lose-it" incentive**, coinciding with a **drop in statistically abnormal low-load flights** documented for EU carriers. (Sun et al., 2022a,b) Together with vaccination and governance-capacity gradients (Rahmanian Haghighi et al., 2024), this helps rationalise the **2022–2023 sign-flip**.

6.2. *Strengths*

- **Regulator-grade exposure. ADRR** captures **every filed IFR passenger movement touching European airspace**, avoiding known East Asia **ADS-B gaps** and origin/destination ambiguities. (Strohmeier et al., 2021)
- **Lean, transparent cleaning. S/N** only; exact re-files de-duplicated; scripts and derived tables alongside the manuscript. (STATFOR, 2022)
- **Reproducibility.** End-to-end R + Quarto with `build.sh` and `renv.lock`; **5,000-draw bootstrap CIs** for every Spearman ρ.

6.3. Limitations

- **Load-factor bias.** Many EU carriers operated **statistically "abnormal" low-load** flights in **Mar–Apr 2020**, with shares receding through 2021; "abnormal" is defined **statistically** (IQR outliers vs 2017–2019 baselines), **not** by a fixed occupancy cut-off (e.g., *under 10% of seats filled*). Hence F_{SUM} measures **potential seeding capacity**, not realised traveller volumes. (Sun et al., 2022b) At a major hub like **Frankfurt**, passenger volumes collapsed while cargo shifted to freighters and "preighters." (Fraport AG, 2021)
- **February gap.** No public **ADRR** slice for **Feb 2020** → peak early-exposure may be **under-estimated**.
- **Indirect legs invisible.** Multi-leg routings (e.g., **PVG → DXB → VIE**) and non-air links aren't captured.
- **Ecological, small *n*.** A country-level panel (~25 units) can't resolve within-state heterogeneity; residual confounding remains possible.

6.4. Methodological reflections

The project was **initially envisioned** as a global effective-distance SIR exercise (Brockmann and Helbing, 2013), but we did not proceed beyond scoping. Two constraints drove an early pivot: (i) sparse **East Asia ADS-B coverage** (and OpenSky's flight-derivation quirks) (Strohmeier et al., 2021), and (ii) no **February** ADRR snapshot (public months are **Mar | Jun | Sep | Dec**). Given those constraints—and a BA time-box—we adopted an exploratory, fully reproducible **rank-correlation** design on **Dec 2019** and **Mar 2020** exposures against **four** annual excess-mortality snapshots.

6.5. Implications & directions for future research

What the results do say. Direct CN/HK flight volumes help explain cross-country differences in **spring 2020** excess mortality.

What they don't say. Ecological, rank-based associations do **not** identify causal effects or passenger-level transmission.

Future work (beyond the scope of this study).

1. **Passenger weighting.** Combine ADRR movements with IATA/OAG load factors to down-weight "ghost flights" and approximate imported passenger volumes.
2. **Multi-leg & multimodal import paths.** Reconstruct OD chains (air–air and air–land/sea) to capture indirect routes (e.g., PVG → DXB → VIE) and non-air entries.
3. **Sub-national resolution.** Build NUTS-2 or airport-catchment panels to reduce ecological bias and align exposure with local mortality.
4. **Integrated transmission models.** Embed exposure in network SEIR/SEnIR frameworks with NPIs, vaccination, and health-system capacity to move from association to mechanism.

6.6. Conclusion

Flight counts are a useful proxy for **initial import pressure**: they **correlate with first-wave excess mortality** but **not** with later outcomes, which align more with **vaccination**, **policy timing**, and **system capacity**.

7. References

Brockmann, D., Helbing, D., 2013. The hidden geometry of complex, network-driven contagion phenomena. Science 342, 1337–1342. doi:10.1126/science.1245200.

Chinazzi, M., Davis, J.T., Ajelli, M., Gioannini, C., Litvinova, M., Merler, S., y Piontti, A.P., Mu, K., Rossi, L., Sun, K., Viboud, C., Xiong, X., Yu, H., Halloran, M.E., Longini, I.M., Vespignani, A., 2020. The effect of travel restrictions on the spread of the 2019 novel coronavirus (covid-19) outbreak. Science 368, 395–400. URL: https://www.science.org/doi/abs/10.1126/science.aba9757, doi:10.1126/science.aba9757, arXiv:https://www.science.org/doi/pdf/10.1126/science.aba9757.

Civil Aviation Administration of China, 2020. Notice on further reducing international passenger flights during the epidemic prevention and control period. URL: https://www.caac.gov.cn/English/News/202305/t20230515_219440.html. unofficial English translation.

Council of the European Union, 2020. Council recommendation (eu) 2020/912 of 30 june 2020 on the temporary restriction on non-essential travel into the eu and the possible lifting of such restriction. URL: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32020H0912.

DiCiccio, T.J., Efron, B., 1996. Bootstrap confidence intervals. Statistical Science 11, 189–228. doi:10.1214/ss/1032280214.

EUROCONTROL, 2025. Aviation Data Repository for Research – Metadata (FNI Doc 25, v6). Technical Report. EUROCONTROL Network Manager. URL: https://www.eurocontrol.int/sites/default/files/2025-04/eurocontrol-aviation-data-repository-research-metadata.pdf.

European Centre for Disease Prevention and Control, 2020. Outbreak of Novel Coronavirus Disease 2019 (COVID-19): Situation in Italy. Threat Assessment Brief. ECDC. Stockholm. URL: https://www.ecdc.europa.eu/en/publications-data/outbreak-novel-coronavirus-disease-2019-covid-19-situation-italy.

European Commission, 2020. Communication from the commission to the european parliament, the european council and the council covid-19: Temporary restriction on non-essential travel to the eu. Communication COM(2020) 115 final. URL: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0115. communication to the European Parliament, the European Council and the Council.

Fraport AG, 2021. Air Traffic Statistics 2020. Statistical report. Fraport AG. URL: https://www.fraport.com/content/dam/fraport-company/documents/investoren/eng/aviation-statistics/Air_Traffic_Statistics_2020.pdf/_jcr_content/renditions/original.media_file.download_attachment.file/Air_Traffic_Statistics_2020.pdf.

Ioannidis, J.P.A., Zonta, F., Levitt, M., 2023. Variability in excess deaths across countries with different vulnerability during 2020–2023. Proceedings of the National Academy of Sciences 120, e2309557120. URL: https://www.pnas.org/doi/abs/10.1073/pnas.2309557120, doi:10.1073/pnas.2309557120, arXiv:https://www.pnas.org/doi/pdf/10.1073/pnas.2309557120.

Karlinsky, A., Kobak, D., 2021. Tracking excess mortality across countries during the COVID-19 pandemic with the world mortality dataset. eLife 10, e69336. URL: https://doi.org/10.7554/eLife.69336, doi:10.7554/eLife.69336.

Kelly, G., Petti, S., Noah, N., 2021. Covid-19, non-covid-19 and excess mortality rates not comparable across countries. Epidemiology and Infection 149, e176. doi:10.1017/S0950268821001850.

Mathieu, E., Ritchie, H., Ortiz-Ospina, E., Roser, M., Hasell, J., Appel, C., Giattino, C., Rodés-Guirao, L., 2021. A global database of covid-19 vaccinations. Nature Human Behaviour 5, 947–953. doi:10.1038/s41562-021-01122-8.

Matveeva, O., Shabalina, S.A., 2023. Comparison of vaccination and booster rates and their impact on excess mortality during the covid-19 pandemic in european countries. Frontiers in Immunology 14. URL: https://www.frontiersin.org/journals/immunology/articles/10.3389/fimmu.2023.1151311, doi:10.3389/fimmu.2023.1151311.

Okabe, M., Ito, K., 2008. Color universal design (CUD): How to make figures and presentations that are friendly to color-blind people. English translation on the JFly website. URL: https://jfly.uni-koeln.de/color/. originally published in Japanese, 2002. Accessed 2025-05-18.

Pizzato, M., Gerli, A.G., La Vecchia, C., Alicandro, G., 2024. Impact of covid-19 on total excess mortality and geographic disparities in europe, 2020–2023: a spatio-temporal analysis. The Lancet Regional Health – Europe 44. URL: https://doi.org/10.1016/j.lanepe.2024.100996, doi:10.1016/j.lanepe.2024.100996.

R Core Team, 2025. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing. Vienna, Austria. URL: https://www.R-project.org/.

Rahmanian Haghighi, M.R., Pallari, C.T., Achilleos, S., Quattrocchi, A., Gabel, J., Artemiou, A., Athanasiadou, M., Papatheodorou, S., Liu, T., Cernuda Martínez, J.A., et al., 2024. Excess mortality and its determinants during the covid-19 pandemic in 21 countries: an ecological study from the c-mor project, 2020 and 2021. Journal of Epidemiology and Global Health 14, 1650–1661. URL: https://doi.org/10.1007/s44197-024-00320-7, doi:10.1007/s44197-024-00320-7.

Spiteri, G., Fielding, J., Diercke, M., Campese, C., Enouf, V., Gaymard, A., Bella, A., Sognamiglio, P., Sierra Moros, M.J., Riutort, A.N., Demina, Y.V., Mahieu, R., Broas, M., Bengnér, M., Buda, S., Schilling, J., Filleul, L., Lepoutre, A., Saura, C., Mailles, A., Levy-Bruhl, D., Coignard, B., Bernard-Stoecklin, S., Behillil, S., van der Werf, S., Valette, M., Lina, B., Riccardo, F., Nicastri, E., Casas, I., Larrauri, A., Salom Castell, M., Pozo, F., Maksyutov, R.A., Martin, C., Van Ranst, M., Bossuyt, N., Siira, L., Sane, J., Tegmark-Wisell, K., Palmérus, M., Broberg, E.K., Beauté, J., Jorgensen, P., Bundle, N., Pereyaslov, D., Adlhoch, C., Pukkila, J., Pebody, R., Olsen, S., Ciancio, B.C., 2020. First cases of coronavirus disease 2019 (covid-19) in the who european region, 24 january to 21 february 2020. Eurosurveillance 25. URL: https://www.eurosurveillance.org/content/10.2807/1560-7917.ES.2020.25.9.2000178, doi:10.2807/1560-7917.ES.2020.25.9.2000178.

STATFOR, E., 2022. Market Segment 2022: Rules and Definitions. Technical Report. EUROCONTROL. URL: https://www.eurocontrol.int/sites/default/files/2022-05/eurocontrol-market-segment-update-2022-05.pdf.

Strohmeier, M., Olive, X., Lübbe, J., Schäfer, M., Lenders, V., 2021. Crowdsourced air traffic data from the opensky network 2019–2020. Earth System Science Data 13, 357–366. URL: https://essd.copernicus.org/articles/13/357/2021/, doi:10.5194/essd-13-357-2021.

Sun, X., Wandelt, S., Zhang, A., 2022a. Covid-19 pandemic and air transportation: Summary of recent research, policy consideration and future research directions. Transportation Research Interdisciplinary Perspectives 16, 100718. URL: https://www.sciencedirect.com/science/article/pii/S2590198222001786, doi:10.1016/j.trip.2022.100718.

Sun, X., Wandelt, S., Zhang, A., 2022b. Ghostbusters: Hunting abnormal flights in europe during covid-19. Transport Policy 127, 203–217. URL: https://www.sciencedirect.com/science/article/pii/S0967070X22002396, doi:10.1016/j.tranpol.2022.08.020.

Warnock-Smith, D., Graham, A., O'Connell, J.F., Efthymiou, M., 2021. Impact of covid-19 on air transport passenger markets: Examining evidence from the chinese market. Journal of Air Transport Management 94, 102085. URL: https://www.sciencedirect.com/science/article/pii/S0969699721000685, doi:10.1016/j.jairtraman.2021.102085.

World Health Organization, 2022. Timeline: WHO's COVID-19 response. URL: https://www.who.int/emergencies/diseases/novel-coronavirus-2019/interactive-timeline. dynamic page; data updated regularly.

World Health Organization, 2023. Statement on the fifteenth meeting of the IHR (2005) emergency committee on the COVID-19 pandemic. WHO website. URL: https://www.who.int/news/item/05-05-2023-statement-on-the-fifteenth-meeting-of-the-international-health-regulations-(2005)-emergency-committee-regarding-the-coronavirus-disease-(covid-19)-pandemic. accessed 2025-04-14.

8. Acknowledgments

This thesis uses the Aviation Data Repository for Research (ADRR) made available by EUROCONTROL © 2025. EUROCONTROL does not necessarily endorse the conclusions and shall not be liable for any direct, indirect, incidental or consequential damages arising out of or in connection with this work.

I would also like to thank my supervisor, Christian Neuwirth, for his trust, which allowed me to refine my skills and learn a great deal over the past years — with the guidance of a mentor, even if unofficial.

9. Appendix

9.1. Supplementary methods & figures

9.1.1. Coverage audit — EUROCONTROL vs OpenSky

OpenSky's community ADS-B coverage in early 2020 is uneven—**strong in Western Europe**, **thin over East Asia** and parts of **Eastern Europe** so it **undercounts** direct CN/HK arrivals relative to EUROCONTROL ADRR. In our audit, OpenSky **misses** five countries entirely and **undercounts** most others; we therefore treat OpenSky as a **QC benchmark only**. (Strohmeier et al., 2021)

Table 14: Direct CN/HK arrivals captured by EUROCONTROL ADRR (EU) vs OpenSky (OS). Rows sorted by ADRR Dec-2019 counts. OS reflects receiver coverage, not filed IFR (S/N passenger traffic only).

iso3	Dec 2019 (EU)	Mar 2020 (EU)	Dec 2019 (OS)	Feb 2020 (OS)	Mar 2020 (OS)	EU_only	OS_only
GBR	693	239	299	227	145	FALSE	FALSE
DEU	691	353	174	123	153	FALSE	FALSE
FRA	396	74	63	53	21	FALSE	FALSE
NLD	381	196	72	60	34	FALSE	FALSE
ITA	257	9	61	1	2	FALSE	FALSE
TUR	192	19	3	0	4	FALSE	FALSE
FIN	175	22	60	47	22	FALSE	FALSE
BEL	151	120	58	38	46	FALSE	FALSE
ESP	126	30	43	27	7	FALSE	FALSE
CHE	124	33	60	54	35	FALSE	FALSE
DNK	77	6	15	18	4	FALSE	FALSE
AUT	69	7	16	6	10	FALSE	FALSE

Table 14: Direct CN/HK arrivals captured by EUROCONTROL ADRR (EU) vs OpenSky (OS). Rows sorted by ADRR Dec-2019 counts. OS reflects receiver coverage, not filed IFR (S/N passenger traffic only).

iso3	Dec 2019 (EU)	Mar 2020 (EU)	Dec 2019 (OS)	Feb 2020 (OS)	Mar 2020 (OS)	EU_only	OS_only
CZE	44	10	9	0	3	FALSE	FALSE
SWE	36	5	3	2	0	FALSE	FALSE
POL	28	2	1	1	0	FALSE	FALSE
HUN	27	1	9	5	10	FALSE	FALSE
GEO	14	0	0	0	0	TRUE	FALSE
GRC	14	3	2	0	1	FALSE	FALSE
PRT	11	4	0	0	0	TRUE	FALSE
LUX	8	0	25	6	37	FALSE	FALSE
UKR	6	2	0	0	0	TRUE	FALSE
LTU	1	3	0	0	1	FALSE	FALSE
LVA	1	5	0	5	4	FALSE	FALSE
ALB	0	0	0	0	0	FALSE	FALSE
ARM	0	0	0	0	0	FALSE	FALSE
BGR	0	0	0	0	0	FALSE	FALSE
BIH	0	0	0	0	0	FALSE	FALSE
CYP	0	0	0	0	0	FALSE	FALSE
EST	0	0	0	0	0	FALSE	FALSE
HRV	0	1	0	0	0	TRUE	FALSE
IRL	0	7	0	1	0	FALSE	FALSE
MCO	0	0	0	0	0	FALSE	FALSE
MDA	0	0	0	0	0	FALSE	FALSE
MKD	0	0	0	0	0	FALSE	FALSE
MLT	0	0	0	0	0	FALSE	FALSE
MNE	0	0	0	0	0	FALSE	FALSE
NOR	0	0	0	0	0	FALSE	FALSE
ROU	0	0	0	0	0	FALSE	FALSE
SRB	0	0	0	0	0	FALSE	FALSE
SVK	0	1	0	0	0	TRUE	FALSE
SVN	0	0	0	0	0	FALSE	FALSE

9.1.2. Absolute change in flights, Mar-2020 vs Dec-2019

Table 15: Absolute change in direct CN/HK → Europe-25 flights between Dec-2019 and Mar-2020 (countries with ≥5 December flights). Residual March totals highlight hubs that still handled ~200–350 rotations post-cliff.

Country	Dec 2019	Mar 2020	Δ flights
Luxembourg	8	0	-8
Denmark	77	6	-71
Austria	69	7	-62
United Kingdom	693	239	-454
Germany	691	353	-338

9.1.3. OpenSky top-10 (illustrative)

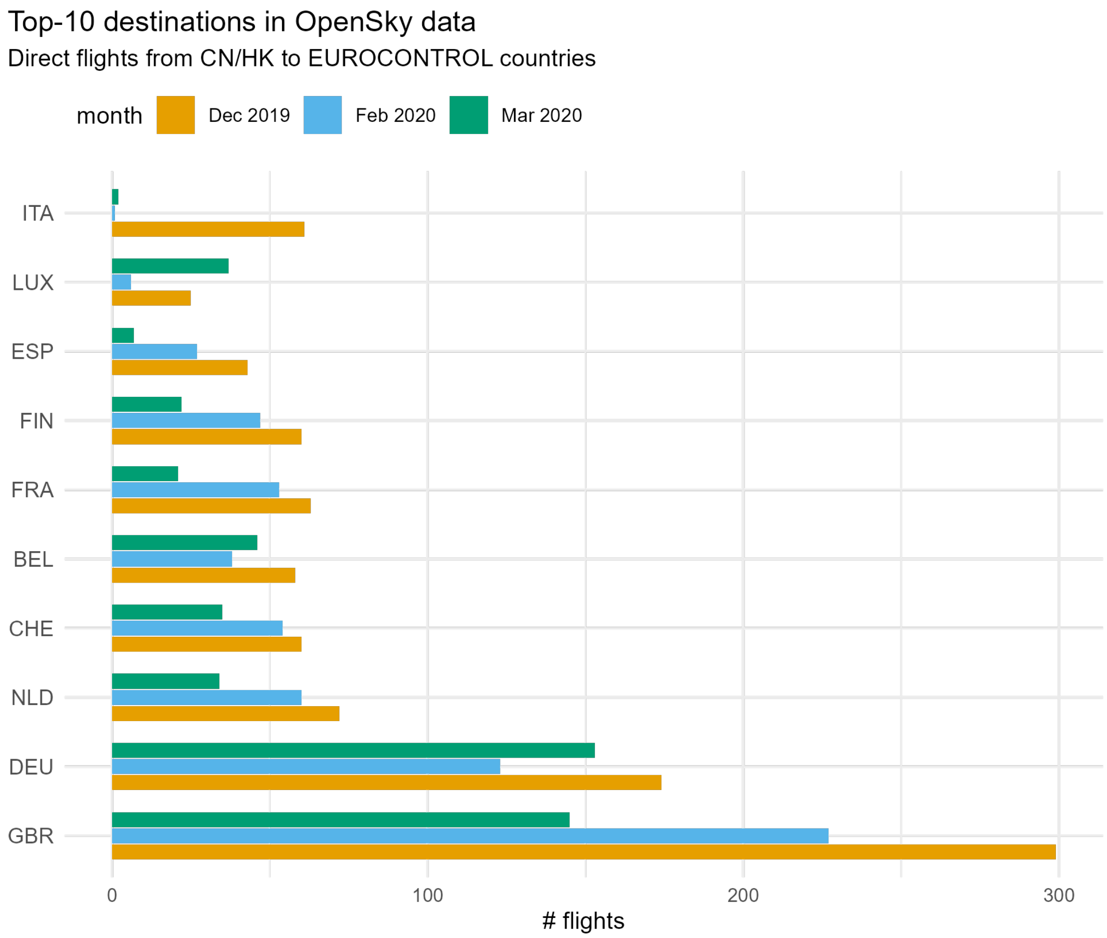

Figure 7: Top-10 destinations by number of direct CN/HK flights in OpenSky data (Dec-2019, Feb-2020, Mar-2020). OpenSky reflects community ADS-B coverage; patterns motivate prioritising EUROCONTROL ADRR for exposure measurement.

9.1.4. Vaccination by exposure quartile (May 2022)

Country membership of flight-exposure quartiles (baseline = **Dec-2019 + Mar-2020**; $n = 25$). Quartiles contain 6–7 countries.

Table 16: Country membership of flight-exposure quartiles (Dec-2019 + Mar-2020 baseline).

Q1 (low)	Q2	Q3	Q4 (high)
GEO, HRV, IRL, LTU, LUX, LVA, SVK	CZE, GRC, HUN, POL, PRT, SWE	AUT, CHE, DNK, ESP, FIN, TUR	BEL, DEU, FRA, GBR, ITA, NLD

For the descriptive comparison in the Discussion, `people_fully_vaccinated_per_hundred` was taken nearest to **5 May 2022 (±7 days)** for the same 25-country set (`01b_extract_vax.R` → `data/processed/vax_snapshot.{csv,rds}`). Vaccination figures are **not** used in any correlation/regression.