Effects of city design on transport mode choice and exposure to health risks during and after a crisis: a retrospective observational analysis

Kerry A Nice, Jason Thompson*, Haifeng Zhao, Sachith Seneviratne, Belen Zapata-Diomedi, Leandro Garcia, Ruth F Hunter, Rodrigo Siqueira Reis, Pedro C Hallal, Christopher Millett, Ruoyu Wang, Mark Stevenson*

Summary

Background Rapid declines in city mobility during the early stages of the COVID-19 pandemic in 2020 resulted in reductions in citizens' exposure to transport-related air pollution and associated health risks as many cities introduced non-pharmaceutical interventions designed to curb the spread of COVID-19. However, these benefits soon reversed during the pandemic's recovery phase (ie, from September, 2020, onwards), especially in cities with designs that afforded mode shifts away from public and active transport in favour of private motor vehicles. The aim of this study was to understand the association between global city designs, transport mode choices, and population-level risk exposure during 2020.

Methods In this retrospective observational analysis, we assembled and analysed spatial datasets (including historical and predicted pollution levels, mobility indicators, and measures of individual disease transmission) and clustered 507 global cities using a graph neural network approach based on measures of the structural dimensions of each individual city's design and network structures of urban transportation systems. We compared city types on the basis of transportation mode shifts, air pollution levels, and associated health outcomes (ie, cardiovascular disease, ischaemic heart disease, respiratory disease, asthma, and reported COVID-19 cases) throughout 2020. We estimated risk reductions for these health outcomes across four phases of the pandemic, which we defined as the pre-pandemic, entry, mid-crisis, and recovery phases. We also identified city designs showing sustained reductions at the end of 2020 in transport-related air pollution (fine particulate matter [$PM_{2·5}$] and nitrogen dioxide [NO_2]) associated with reduced estimated risk of acute and chronic disease outcomes (ie, all-cause mortality, ischaemic heart disease mortality, cardiovascular disease, respiratory disease, and asthma).

Findings The mean estimated reduction of global NO_2 concentrations across the observed cities from the beginning of the entry phase until the mid-crisis phase was 3·76 parts per billion (ppb), calculated as the difference between observed 2020 mean levels of 12·63 ppb and predicted mean levels (if the pandemic and mobility restrictions had not occurred) of 16·39 ppb. The mean estimated reduction of global $PM_{2·5}$ concentrations across the observed cities was 9·76 μg/m³ (the difference between observed 2020 mean levels [29·03 μg/m³] and predicted mean levels [38·79 μg/m³]). If maintained over the long term, the estimated NO_2 reduction could have a substantial effect on reducing health risks for both acute and chronic disease, equating to an estimated overall reduction in all-cause mortality risk of 1·5% (95% CI 2·2–3·0), a reduction in cardiovascular mortality risk of 4·1% (2·6–6·0), and a reduction in respiratory disease mortality risk of 1·9% (0·8–3·0). If the reduction in $PM_{2·5}$ concentration estimated in this period was maintained over the long term, all-cause mortality risk reductions of 18·9% (95% CI 13·2–25·0), asthma risk reductions of 46·8% (18·7–65·5), and ischaemic heart disease morbidity risk reductions of 0·25% (0·2–0·3) could be achieved. In the later stages of 2020, city designs (primarily in the Americas and Oceania) that afforded a mode shift away from public transit to private motor vehicles during the pandemic's recovery phase tended to show the poorest outcomes across all air pollution and health measures, even increasing risk levels above pre-pandemic baselines in some cases. By contrast, cities located in Japan and South Korea showed little change in pre-crisis and post-crisis transport mode choice, maintaining comparatively low levels of air pollution and associated disease risk, and reduced rates of infectious disease transmission throughout the 2020 observation period. Contrasting experiences of road injury in the post-pandemic phase (ie, post 2020) were also observed between these locations.

Interpretation Our results highlight the transient environmental and health benefits observed during the early stages of the COVID-19 pandemic, driven by substantial reductions in transport-related air pollution and associated health risks due to imposed non-pharmaceutical public health interventions. City design appears to have played a crucial role in observed pollution and health risk differences between cities, with those that afforded a shift away from public and active transport towards private vehicles witnessing a rapid erosion of pollution-related health benefits gained in the entry to mid-crisis phases of the pandemic. These negative effects appear to have also transferred through to increased rates of road trauma in these cities, with a resurgence in road injury above pre-pandemic levels, particularly within countries reliant on private motorised transport. Conversely, cities in Japan, South Korea, and some European regions, which did

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*Contributed equally

Transport, Health, and Urban Systems Research Lab, Faculty of Architecture, Building, and Planning, University of Melbourne, Melbourne, VIC, Australia (K A Nice PhD, H Zhao PhD, S Seneviratne PhD, Prof M Stevenson PhD); **Faculty of Engineering and Information Technology and the Melbourne School of Population and Global Health, University of Melbourne, Melbourne, VIC, Australia** (Prof M Stevenson); **Centre for Human Factors and Sociotechnical Systems, University of the Sunshine Coast, Buderim, QLD, Australia** Prof J Thompson PhD); **Department of Psychiatry, Faculty of Medicine, Dentistry and Health Sciences, The University of Melbourne, Melbourne, VIC, Australia** (Prof J Thompson); **Healthy Liveable Cities Lab, Centre for Urban Research, RMIT University, Melbourne, VIC, Australia** (B Zapata-Diomedi PhD); **Centre for Public Health, Institute of Clinical Sciences, Queen's University Belfast, Belfast, Northern Ireland, UK** (L Garcia PhD, Prof R F Hunter PhD, R Wang PhD); **People, Health and Place Unit, Prevention Research Center, School of Public Health, Washington University in St Louis, St Louis, MO, USA** (Prof R S Reis PhD); **Department of Kinesiology and Community Health, University of Illinois Urbana-Champaign, Champaign, IL, USA** (Prof P C Hallal PhD); **Public Health Policy Evaluation Unit, School of Public Health, Imperial College London, London, UK** (Prof C Millett PhD); **NOVA National School of Public Health, Public Health Research Centre,**

Comprehensive Health Research Center, NOVA University Lisbon, Lisbon, Portugal (Prof C Millett); **Instituto de Estudos para Polı´ticas de Saúde, São Paulo, Brazil** (Prof C Millett); **Postgraduate Program in Epidemiology, Federal University of Pelotas, Pelotas, Brazil** (Prof P C Hallal); **Physical Activity Epidemiology Group, University of São Paulo, São Paulo, Brazil** (L Garcia)

Correspondence to: Dr Kerry A Nice, Transport, Health, and Urban Systems Research Lab, Faculty of Architecture, Building, and Planning, University of Melbourne, Melbourne, VIC 3010, Australia **kerry.nice@unimelb.edu.au**

not experience modal shifts towards cars, sustained their reductions in air pollution and have continued along a trend of declining road transport injuries. These findings underscore city design as a key factor in navigating pandemic-related challenges and suggest that city designs with higher levels of public and mass transit show greater levels of resilience when confronted with infectious disease threats.

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Introduction

City designs can arise from strict top-down regimes[1] or via organic bottom-up processes.[2,3] Although some city designs foster movement and patterns of interaction that reduce exposure to notable health risks (including air pollution, injury, physical inactivity, and concomitant chronic diseases), others facilitate increased health risks.[4–7] Given that approximately 56% of the world's 8 billion people live in cities (with projections indicating this proportion will rise to 68% by 2050),[8] understanding the role city design plays in mitigating adverse health outcomes is key to implementing strategies to reduce the global burden of disease.

Research has highlighted that city designs are heavily influenced by the prevailing transport modes at the time of design,[9] whereas subsequent urbanisation is driven by dynamic, interactive processes.[10] Consequently, there is considerable variation between city designs, heavily influencing citizens' movement patterns and transport mode choices.[11] City design therefore both affords and constrains transport mode choices and substantially influences city mobility patterns, daily living activities, and exposure to health risks.[8]

Previous large-scale analysis of urban areas has identified nine global city design types that are associated with differing road injury burdens.[11] The per-capita burden of road transport injury for the poorest performing of these global city types (motor cities dominated by motorised transport modes) is estimated to be 2-times greater than the best performing city types (ie, intense and high transit cities), producing an estimated 9 million disability-adjusted life-years attributable to suboptimal urban design per year.[11] Similarly, differences in road and intersection design can produce considerable variation in risk exposure for residents within cities.[12,13] Such elevated risk is in addition to that generated by car-dependent urban design, which disproportionately forces car use and ownership on already disadvantaged households.[14,15] City planning—and transport system design—matters greatly for public health.

Although roads and other transportation infrastructure are fairly static, hazards and risks are not. Risk exposure can shift massively in response to unfolding crises (eg, extreme weather events or infectious disease outbreaks) and can be facilitated or inhibited by city design. For instance, cities with suitable housing stocks (eg, well constructed, large, or spacious housing), industrial profiles (eg, service economy), demographic profiles (eg, nuclear families), and associated digital and urban infrastructure (eg, fast and widespread internet connections) might adapt readily to population-wide, stay-in-place policies triggered by biological or natural hazards.[16] Although such

Research in context

Evidence before this study

Previous studies have highlighted reductions in transport and industrial-related air pollution and associated health risks for some locations during 2020, linked to reductions in city mobility during the COVID-19 pandemic. Studies have also observed subsequent resurgence in air pollution and road collision risk for some cities and locations post pandemic.

Added value of this study

This study adds a global perspective to the existing literature by analysing changes in health risks associated with levels of air pollution during 2020 across 507 cities and linking the findings of this analysis to previously established city design types. By including such a large sample of locations, this research enables comparison between city types and shows how differences in the initial reduction and then resurgence of air pollution and associated health risks over the course of 2020 were associated with urban design characteristics.

Implications of all the available evidence

Our results indicate that city designs that enable adaptation to crises through rapid transitions from public or active transport modes to private transport might ultimately endure worse public health outcomes across a syndemic of chronic disease, infectious disease, and road injury if these adapted patterns of behaviour become entrenched. Cities that offered a diversity of public, active, and private transport options and did not exchange public transport for private transport showed greater resilience during the public health crisis produced by the COVID-19 pandemic.

population-wide public health interventions might be effective in mitigating disease spread, they can also produce additional economic and health burdens for people who need to remain in manual work or in roles that cannot be performed remotely.[17,18] Such inequalities can heighten disadvantages for already vulnerable communities,[19] which can in turn foster resentment and broad-scale resistance towards observance of public health interventions.[20] When vulnerable groups or groups at high risk for public health risks reject public health guidance on the basis that they are disproportionately disadvantaged by the side-effects of policy intention, risk exposure for the entire population is also elevated, especially in relation to communicable disease.[21]

The COVID-19 pandemic led to 5·4 million deaths globally over 2020 and 2021[22] and prompted a range of non-pharmaceutical public health responses from local, regional, and national governments[23] designed to contain disease transmission through reducing opportunities for interpersonal contact. These policies, which often included movement restrictions such as stay-at-home orders, also produced marked declines in city mobility, resulting in reductions in transport-related air pollution.[24–27] Given the application of similar mobility restrictions internationally, the pandemic provided an opportunity to compare the impact of city design on the implementation of these measures and citizens' adaptation to the public health crisis. The availability of high-volume, high-frequency, broad-based, and standardised data sources (ie, big data) enables the exploration of city designs and associated trends in health risks both over time and at a global scale, dampening observed volatility at the individual country, regional, or city level. A present limitation of these standardised data, however, is that the majority of data at the city level come from high-income countries, whereas the majority of the world's urban population lives in low-income and middle-income countries.[28]

We aimed to describe how the design of cities influenced change in travel patterns, mode share, and concomitant changes in air pollution and public health risk during the first year of the COVID-19 pandemic (ie, 2020). With existing evidence on dose–response relationships between air pollution and disease outcomes, we set out to estimate the changes in transport-related air pollution levels (ie, fine particulate matter [$PM_{2·5}$] and nitrogen dioxide [NO_2]) associated with transport use across 507 cities and how these changes in mobility and pollution, if sustained, could potentially translate into estimated changes in risk associated with all-cause mortality, cardiovascular disease, respiratory disease, asthma, and infectious disease. We aimed to identify how different city designs might afford or constrain cities' abilities to adapt to and recover from the COVID-19 pandemic and to extend this analysis to identify which city designs might aid resilience against immediate and long-term adverse health outcomes in the context of chronic disease and road injury, with implications for future public health challenges (appendix p 2).

See Online for appendix

Methods

Study design

In this retrospective observational analysis, we assembled and analysed spatial datasets for 507 cities, including the network structures of urban transportation systems, historical and predicted pollution levels, mobility indicators, measures of individual disease transmission, and measures of the structural dimensions of each individual city's design. With these datasets, we trained a graph neural network to predict pollution levels over 2020, and used the underlying representation of the resulting network to cluster the cities into urban types by similarities and differences in urban characteristics.

Characterisation of city design

We first created a representation of global cities to accurately capture the features of city design related to city mobility and public health. Analysis of urban design centred around urban road networks has previously been done following several different approaches, including the generation of metrics of the three Ds (density, diversity, and design;[29] later updated to also include destination accessibility and distance to transit) and the use of graph networks to derive measures of betweenness centrality, closeness, and connectedness between nodes of network graphs.[30] We used a graph neural network (appendix p 3) constructed with OpenStreetMap (OSM) road network data[31] from a set of 1692 global cities with populations exceeding 300 000 people[32] previously identified by Thompson and colleagues.[11] We used the dataset generated by Wijnands and colleagues[4] of historic pollution observations (2015–19) and predicted pollution anomalies over 2020. We eliminated cities with incomplete 2015–20 timeseries of $PM_{2·5}$ and NO_2 (predominantly those in low-income countries), bringing the final set of cities in our analysis to 507 cities (appendix pp 9–11). The global city design types identified by Thompson and colleagues[11] for the 507 cities used in this study are shown in the appendix (p 7). We generated graphs for the graph neural network that consisted of nodes (intersections) and edges (roads). We attached annotations to these edges (including road types [such as residential, secondary, or arterial], speed limits, the length and shape of the roads, and additional characteristics such as one way traffic or the presence of footpaths or bike lanes) and nodes (including node locations in reference to other nodes and the number of intersecting roads and angles of these roads) to ensure the graph neural network could capture the topography of a city's transportation networks alongside broader characteristics such as the city's compactness versus sprawl or symmetry versus irregularity.

City-level air pollution data (appendix p 4) were used to validate the city representation learned by our graph neural network, confirming whether the neural network could capture the road networks of the modelled cities and approximate the relationship between this transport network and the behaviour of air pollutants within the city. We plotted a t-distributed stochastic neighbour embedded (t-SNE) representation (appendix p 3) of the 507 cities based on the underlying representation of the graph neural network model. We additionally validated the ability of the graph neural network to analyse the elements of urban design by plotting the t-SNE representation against previously calculated dimensions of urban design: city block size and block regularity (ie, the extent to which city blocks form parallelograms)[11] and the percentage of road and transit networks (ie, black and orange pixels in sampled maps)[33] observed in each city in previous studies.

Changes in city mobility, air pollution, and associated health outcomes during the COVID-19 pandemic

For the **2020 Google COVID-19 Community Mobility Reports** see https://www.google.com/covid19/mobility/

For the **2020 Apple Maps Mobility Trends Reports** see https://covid19-static.cdn-apple.com/mobility

For the **Google COVID-19 open data** see https://github.com/GoogleCloudPlatform/covid-19-open-data

City mobility measures were calculated as 7-day rolling mean aggregations of Google and Apple mobility indices (ie, from Google mobility workplaces and transit locations and Apple transit and driving map requests) across the 507 cities for which data were available (appendix p 4). Air pollution anomalies of NO_2 and $PM_{2·5}$ were calculated as percentage 7-day rolling mean differences relative to the baseline period of Jan 1–10, 2020 (appendix p 4). COVID-19 cases were calculated as the 7-day rolling mean number of cases per 100 000 population from Google (appendix p 4).

Much research has explored the association between air pollution (eg, NO_2, $PM_{2·5}$, ozone, and PM_{10}) and health outcomes. In general, this work has indicated that the dose–response relationship between pollutants and health outcomes (eg, disease incidence and hospital presentations) is generally linear, with no evidence of a threshold.[34] We estimated risk reductions within the the entry phase, mid-crisis phase, and recovery phase) both globally and across six different regions (Africa, Asia, Europe, North America, South America, and Oceania). The phases were defined as occurring between day 1 and day 46 of 2020 (ie, Jan 1 to Feb 15), between day 47 and day 83 (ie, Feb 16 to March 23), between day 84 and day 250 (ie, March 24 to Sept 6), and from day 251 (ie, Sept 7) onwards. Relationships between observed city-level NO_2 pollution and estimated health risk reductions were investigated for all-cause mortality, cardiovascular disease, and respiratory disease.[35] Changes in city-level $PM_{2·5}$ pollution were associated with estimated changes in relative health risk for all-cause mortality, ischaemic heart disease mortality, and asthma (consistent with contemporary estimates),[36–38] with the following equation:

$$RR = 1 + \frac{\text{risk coefficient} \times \text{anomaly}}{\textit{units of pollution variable}\ \text{(eg, 10)}},$$

where RR is relative risk.

Risk calculations for chronic conditions assumed that pollution reduction levels were sustained over the long term.

Role of the funding source

The funders of the study had no role in study design, data collection, data analysis, data interpretation, or in the submission or writing of the report.

Results

The t-SNE two-dimensional representation (appendix p 3) of the 507 cities obtained with our graph neural network is shown in figure 1. The graph is organised by cities' similarities across urban characteristics. For each city, our neural network could predict whether air pollution levels rose or fell compared with the previous year (ie, 2019) with an accuracy of 97%, underscoring the network's ability to not only capture the road network of the modelled cities, but also approximate the relationship between the transport network and the behaviour of air pollutants. Additional validation of the neural network comes from figure 2. Combined, the results in figure 1, figure 2, and the appendix (p 3) show that the urban morphology for the analysed cities follows gradual changes across dimensions. High-density cities, cities with small block size, and cities with relatively regular (eg, quadrilateral) blocks are depicted on the mid-left to upper-left of figure 1 (eg, in grid areas A2 and A3 and B1 and B2), whereas sparse cities, cities with large block size, and cities with little public transit infrastructure as a proportion of their transport networks cluster together in the bottom right (areas G7–H6).

Figure 1 also shows that cities from within countries and continents tend to cluster together. For example, Japanese cities tend to cluster tightly together across grid areas A3 and A4, whereas European cities cluster together in and around grid areas A2–C4. Asian cities across China, India, and Viet Nam extend in a regular pattern from grid areas B5 through to H6, as their designs differed along dimensions of block size and road network density. There are also visible clusters of Australasian, South American, and North American cities in grid areas C1–C3 and B1–B3. Urban designs in these areas tended to show regular, medium-sized blocks with medium-to-low levels of public transit. Cities in these locations were typically of chequerboard (ie, with square blocks) or motor city (ie, with large, oblong blocks) types, designed to facilitate the egress of motor vehicles.

Mean mobility, anomalies of NO_2 and $PM_{2·5}$ air pollution, and the total number of reported COVID-19 cases for all 507 cities across the pre-pandemic, entry, mid-crisis, and recovery phases of the COVID-19 pandemic in 2020 are shown in figure 3A–C. The effect on global city mobility that resulted from the introduction of movement restrictions, including stay-at-home orders, that were implemented across cities during the entry phase[16] of the

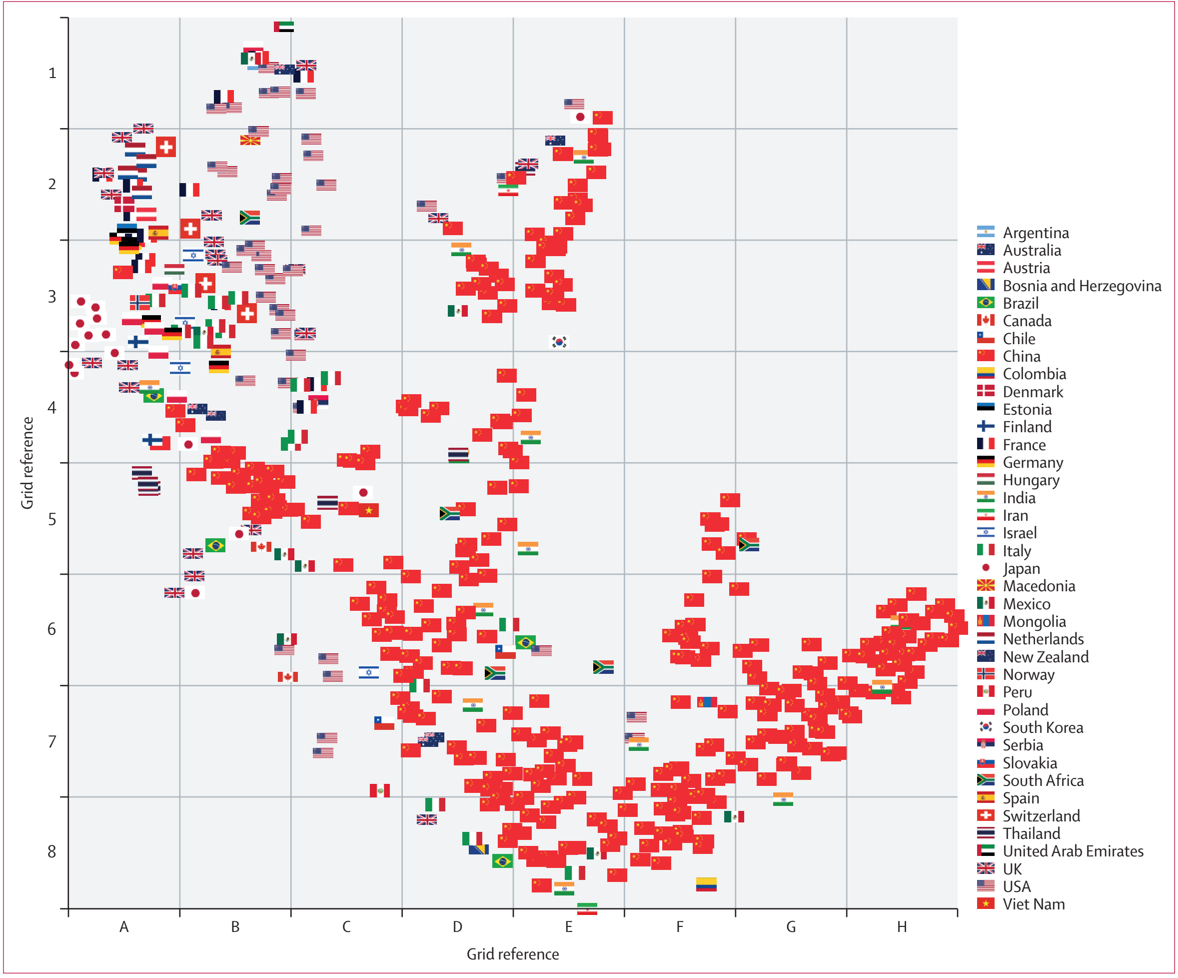

Figure 1: **t-SNE two-dimensional representation of 507 global cities from OpenStreetMap network graphs, organised by their similarities across urban characteristics**
The axes provide grid references (ie, A1), which are used in the main text to describe regions in the graph. t-SNE= t-distributed stochastic neighbour embedded.

pandemic can be seen. Although movement restrictions were designed as a public health measure to reduce person-to-person disease transmission, secondary effects were seen related to reductions in global road trauma[39] and substantial reductions in mean transport-related NO_2 and $PM_{2·5}$ concentrations.[40] Average city mobility declined across cities, reaching a nadir at approximately 45 days after the start of the entry phase (ie, around day 90 of 2020). This period also coincided with a plateau in global COVID-19 infections (figure 3C), not least because of the public observance of mobility restrictions and other non-pharmaceutical interventions implemented up to and including this time.[16]

The mean estimated reduction of global NO_2 concentrations across the observed cities from the beginning of the entry phase until the mid-crisis phase was 3·76 parts per billion (ppb), calculated as the difference between observed 2020 mean levels of 12·63 ppb and predicted mean levels (if the pandemic and mobility restrictions had not occurred) of 16·39 ppb. The mean estimated reduction of global $PM_{2·5}$ concentrations across the observed cities was 9·76 µg/m³ (the difference between observed 2020 mean levels [29·03 µg/m³] and predicted mean levels [38·79 µg/m³]). If maintained over the long term, the estimated NO_2 reductions could have a substantial effect on reducing health risks for both acute and chronic disease equating to an estimated overall reduction in all-cause mortality risk of 1·5% (95% CI 2·2–3·0), a reduction in cardiovascular mortality risk of 4·1% (2·6–6·0), and a reduction in respiratory disease mortality risk of 1·9% (0·8–3·0).[35] Similarly, if the reductions in $PM_{2·5}$ concentrations attained in this period were maintained over the long term, all-cause mortality risk reductions of 18·9% (95% CI 13·2–25·0),[37] asthma risk reductions of 46·8% (18·7–65·5), and ischaemic heart disease morbidity risk reductions of 0·25% (0·2–0·3)[36] could be achieved. These potential effects on relative health risks were continued into the mid-crisis period, when reductions in both city mobility and exposure to consequent transport-related air pollution

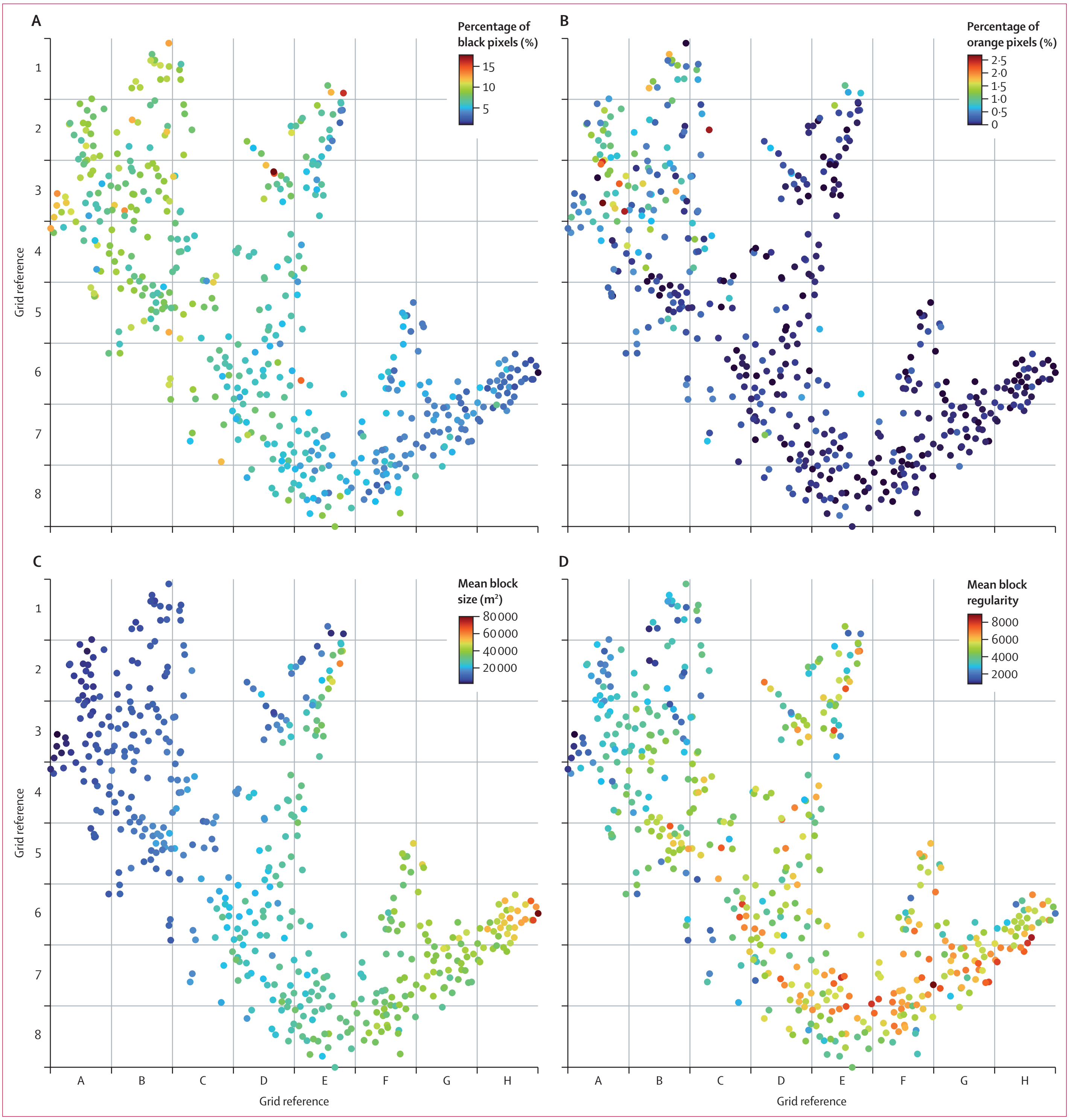

Figure 2: **t-SNE two-dimensional representation of 507 global cities showing various city characteristics**
City locations and grid references correspond to those in figure 1. (A) Percentage of black pixels reflecting amounts of road space from sampled maps in each city.[11] (B) Percentage of orange pixels reflecting public transport rail lines from sampled maps in each city.[11] (C) Mean block sizes (m^2).[33] (D) Mean block regularity.[33] Lower block regularity values reflect increasing block squareness. t-SNE= t-distributed stochastic neighbour embedded.

were greatest across regions outside Asia (appendix p 5). With identical means for calculating risk reduction in the mid-crisis phase, all-cause mortality estimates for NO_2 were consistently around 1·3 (95% CI 0·9–1·7) below baseline, remaining in this range through to the recovery phase (ie, day 250 onwards). Exceptions to this trend were generally found in cities located in the Americas, where air pollution-related risk across a range of chronic diseases returned to levels approximating the pre-pandemic baseline or above (figure 4). These locations have also seen a relative increase in road trauma beyond pre-pandemic levels, which is probably associated with an uptake of private vehicles in favour of public transport over the same period.[39,41,42] Estimated changes in relative risks associated with air pollution reductions across continents and phases for all-cause mortality, type 2 diabetes, asthma, and ischaemic heart disease mortality and morbidity for the entry, mid-crisis, and recovery phases of the pandemic converted from the percentage reductions are presented in figure 4 and the appendix (p 5).

Alongside private vehicle transport, public transit ridership declined by up to 90% in the pandemic's entry phase.[43] However, as city mobility restrictions eased in response to declining rates of COVID-19 transmission and populations began re-engaging with workplaces and social settings, citizens were faced with new factors that influenced their transportation choices including the risk of infection through the use of mass transit.[44] These concerns contributed to a global shift away from public transport towards private vehicle use (appendix p 6), with positive difference values indicating a proportional modal shift away from public transit and towards private vehicle use in comparison to pre-pandemic conditions. This trend, which was seen across most cities, was most evident during July and August, 2020 (appendix p 6), but continued until early 2021, with many cities later implementing incentive programmes to boost public transit ridership.[45] Global trends are summarised in the table.

The timing of the increase in private vehicle transport in mid-2020 (table) coincided with a substantial rebound of NO_2 and $PM_{2·5}$ concentrations back to concentrations that would be typically expected under non-crisis conditions (adjusting for weather, trends in seasonality, distinct topography, urban morphology, climate, and the atmospheric conditions of each city;[4] figure 3B). This rebound was particularly pronounced for NO_2, which consistently exceeded typical pre-pandemic concentrations across cities in the latter part of 2020 (figure 3B).

However, despite the global trend of transitioning from public transit to private motor vehicle use,[46] our results reveal that the extent of this shift was not uniform across all city types. Mode shifts were more pronounced in cities largely designed for motor vehicles,[11] which were represented in grid areas A3–A5 and B4–B6 in figure 1.

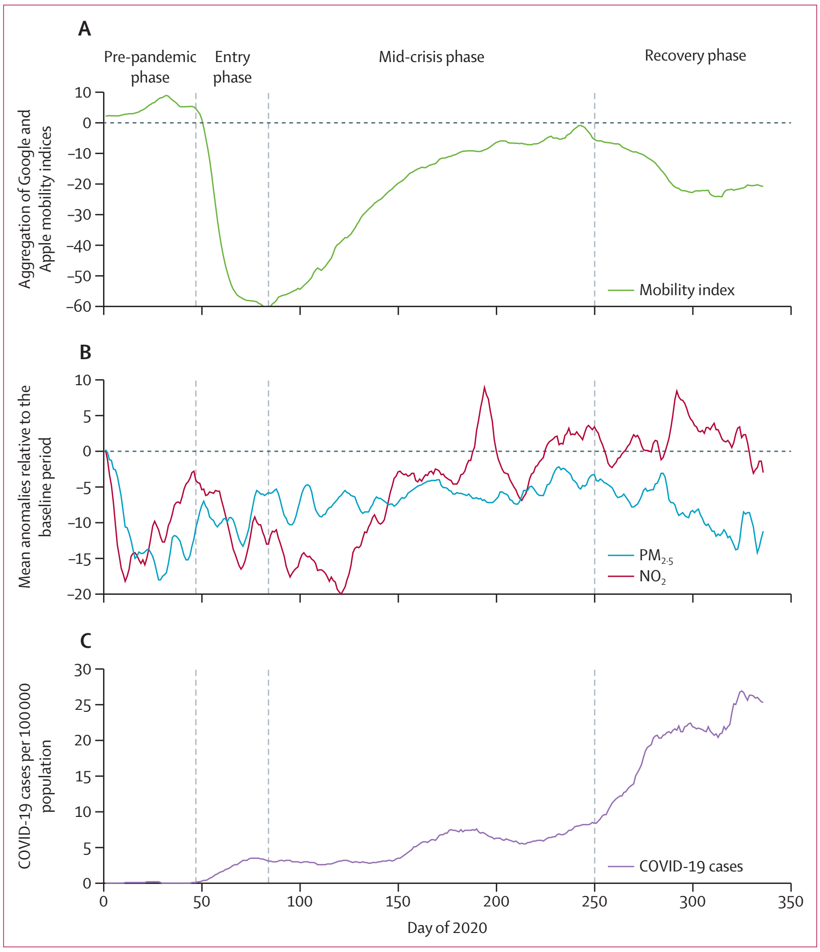

Figure 3: **Overview of the progression of the COVID-19 crisis across 507 global cities in 2020**
(A) 7-day rolling mean aggregations of Google and Apple mobility indices (ie, from Google mobility workplaces and transit locations and Apple transit and driving map requests). (B) 7-day rolling mean pollution percentage anomalies ($PM_{2·5}$ and NO_2) relative to the Jan 1–10, 2020, baseline. (C) 7-day rolling mean COVID-19 cases per 100 000 population. The entry phase begins mid-February, 2020, as mobility restrictions are quickly implemented globally, reaching maximum stringency levels in late March (ie, in the mid-crisis phase). In early September, 2020, the recovery stage corresponds to the end of widespread easing of restrictions and the beginning of a period of localised increases and decreases in stringencies. NO_2=nitrogen dioxide.

The effect of these mode shifts on transport-related pollution in the form of $PM_{2·5}$ and NO_2 concentrations is highlighted in figure 5, presenting mean anomalies for these pollutants for cities located in each grid reference tile. As mentioned earlier, cities in these grid locations (ie, A3–A5 and B4–B6) typically show regular, medium-sized blocks with medium to comparatively low levels of public transit.

The characteristic design of cities designed to promote the egress of motor vehicles is that they have planned layouts with regular blocks (eg, quadrilateral block patterns) and have medium-sized blocks in comparison with other global cities.[11] Such vehicle-centric city designs are predominantly found in countries such as the USA, Australia, Canada, New Zealand, and Argentina, which saw rapid urban expansion in the late 19th and early 20th centuries. During the COVID-19

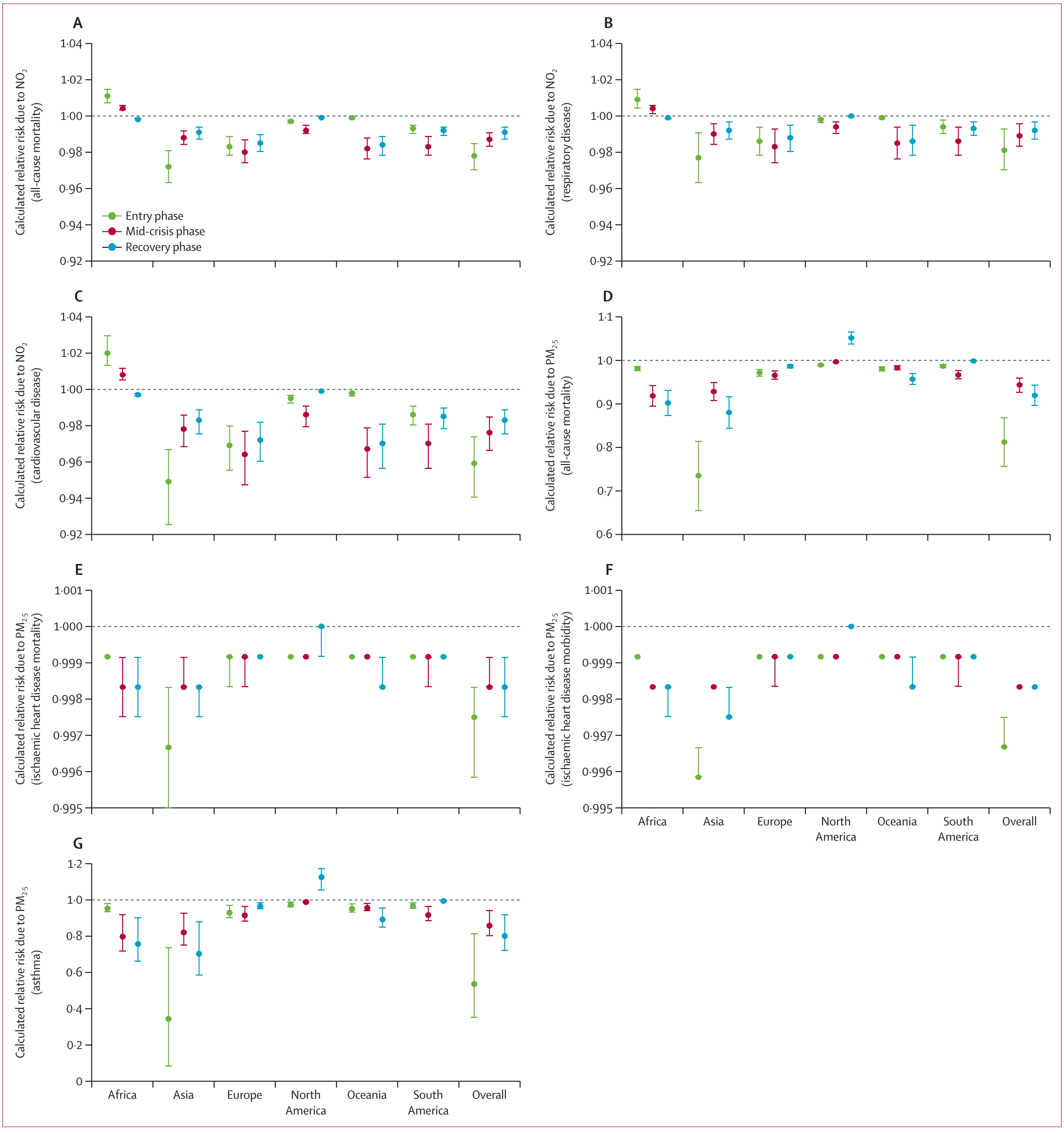

Figure 4: **Relative health risks associated with air pollution reductions across continents and pandemic phases due to NO_2 (A–C) and $PM_{2·5}$ (D–G)**
Values >1 indicate increased health risks. Bars indicate 95% CIs. NO_2=nitrogen dioxide.

pandemic's mid-crisis and recovery phases, cities optimised for private vehicle transport afforded citizens a choice between public transit and private vehicle use. Given the public's fear of potential infectious disease transmission on public transit,[46] citizens who had the option to avoid public transit in favour of private vehicles largely did so. In these cities, public transit ridership did not rebound to pre-pandemic levels within the observation period (table).

For example, an archetypal city with a regular, car-based network is Los Angeles, USA. Figure 6A shows the relative change in mode share between public transit and private vehicles for Los Angeles from a pre-pandemic baseline during 2020 alongside anomalies from expected levels of $PM_{2·5}$ pollution over the same period. Although observed patterns of city mobility for Los Angeles' residents largely returned to typical patterns in the second half of 2020, public transit remained well below baseline (figure 6A). The trade-off between public transit and private vehicle use during the recovery phase was also associated with a peak in $PM_{2·5}$ pollution. Although a proportion of this pollution peak on some days was probably attributable to active wildfires, this pattern of results was consistently observed across similarly organised cities in North America and other cities with designs that located them in grid areas C1–C3 and B1–B3 in figure 1 (ie, those with predominantly private car-based transport systems). In São Paulo, Brazil (figure 6B), similar mobility shifts are seen. However, although Los Angeles' transit rates stagnated at low levels across the remainder of 2020, transit use in São Paulo began recovery towards baseline levels, although at a much slower rate than in the earlier transition to private vehicle use.

For both North American and South American locations, the combination of increased air pollution levels, disease risk, and increased private vehicle transport also coincided with the highest mean reported per-capita COVID-19 cases per 100 000 population according to epidemiology data from the Google Health COVID-19 Open Data Repository (appendix p 8). Drawing direct causal relationships between these data is not possible, except perhaps to the extent that infection rates increased from already comparatively high global rates (especially in North America) once levels of mobility began increasing again (appendix p 8). This pattern was in contrast to some locations (eg, in Asia and Oceania) that had maintained comparatively low levels of COVID-19 in the mid-crisis phase. Of course, because these data relate to reported cases, they are also subject to some variation given differences in testing and reporting regimens between regions.

For example, the rebound in city mobility in the second half of 2020 in the city of Tokyo, Japan (figure 6C), did not result in a sustained modal transfer between public transit and private vehicles late in 2020. Similarly, neither did this rebound coincide with peaks in transport-related air pollution (figure 6C) nor widespread COVID-19 infections. This pattern of results was observed across Japanese cities, which are peculiar globally in that they combine very dense road networks and very small blocks with high levels of public transit alongside policies that restrict on-street vehicle parking.[47] Japanese cities' combination of city design and public policy shifts responsibility for parking provision onto individual vehicle owners rather than local government, shifting transport choice away from private means and disincentivising car ownership. Therefore, although car-centric city designs and associated policies in some countries afforded populations transport mode choice and a shift towards private vehicle use when concerns regarding infectious disease transmission on public transit were high, Japanese cities and their supporting policies constrained citizens' capacity to shift away from public transport quickly even if they wanted to, resulting in a relative return to typical patterns during the recovery phase of the pandemic.

	Entry phase	Mid-crisis phase	Recovery phase
Africa	12·87%	–48·88%	–2·78%
Asia	21·29%	–15·69%	7·16%
Europe	18·07%	–78·44%	45·25%
North America	13·49%	–54·71%	4·07%
Oceania	9·51%	–43·18%	–5·97%
South America	15·67%	–67·23%	9·04%

Values are percentage changes in driving and transit indices relative to the baseline period. Negative numbers indicate a reduction of private vehicle use.

Table: **Changes in private vehicle use across continents and pandemic phases relative to the baseline period (Jan 1–10, 2020)**

Discussion

Our results indicate that city designs afforded populations across the world different tools with which to adapt and deal with the threat posed by the COVID-19 pandemic as the public health crisis unfolded, and pandemic responses also had both beneficial and harmful consequences during progressive phases. If we consider resilience as the "ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions",[48] this led some city types to show greater defence against public health threats than others.

For the data from the **Google Health COVID-19 Open Data Repository** see https://github.com/GoogleCloudPlatform/covid-19-open-data/blob/main/docs/table-epidemiology.md

First, there appears to have been a demonstrable reduction in air pollution and related disease risk (mostly in the long term should these new levels of air pollution be maintained) in cities in which mobility restrictions were enforced by governments seeking to reduce person-to-person interaction and, therefore, infectious disease spread. Despite the threat posed by the COVID-19 pandemic to what was an unvaccinated population at the time, these secondary benefits were realised most acutely in the entry and mid-crisis phases of the pandemic, when city mobility was most greatly reduced. Although no globally consistent data sources on road trauma at daily city levels are available, evidence suggests

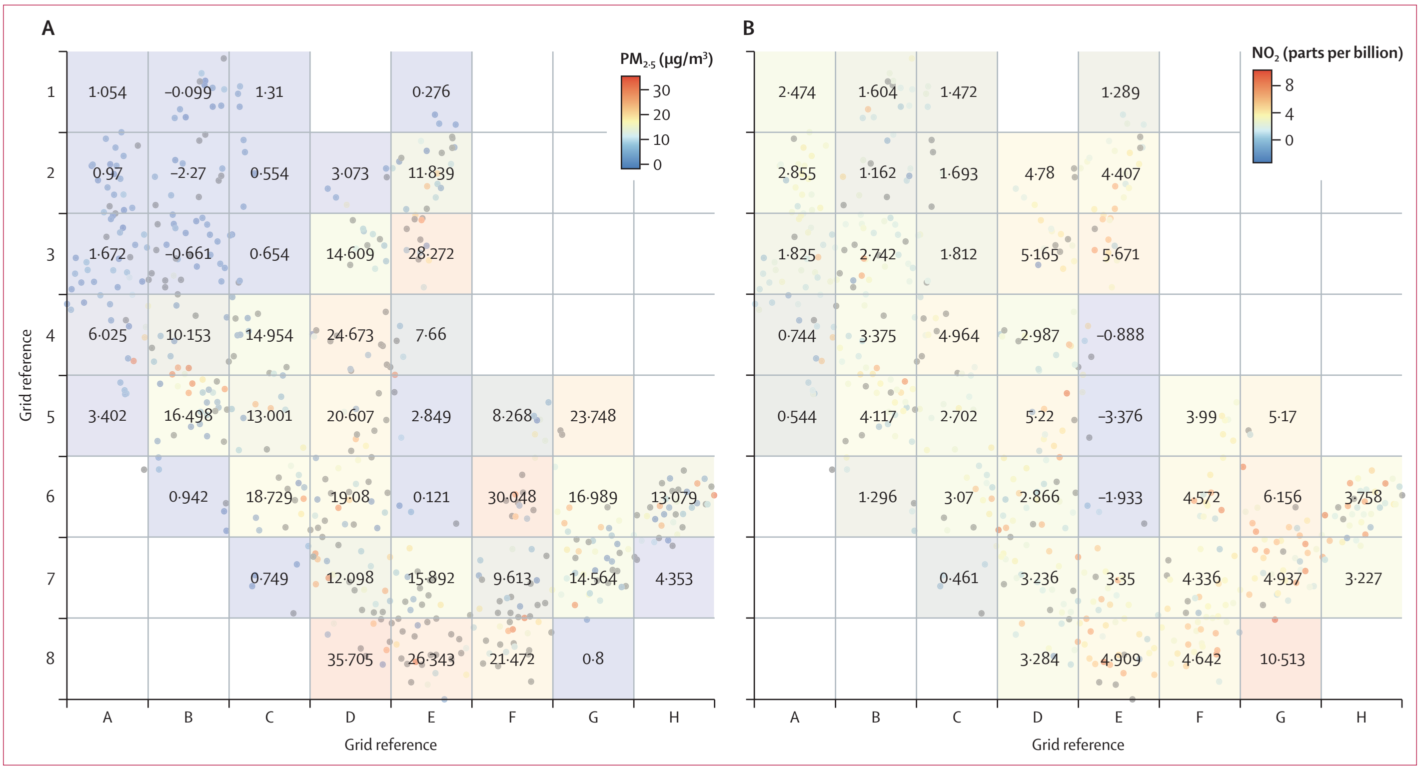

***Figure 5*: Mean anomalies of $PM_{2·5}$ (μg/m³; A) and NO_2 (parts per billion; B) across the period of days 84–250 in 2020 relative to the pre-pandemic baseline (ie, days 1–20 of 2020) for cities in each grid reference tile**

City locations and grid references correspond to those in figure 1. Driving and transit mode shifts were more pronounced in cities largely designed for motor vehicles (grid areas A3–A5 and B4–B6). NO_2=nitrogen dioxide.

that these phases also saw a considerable reduction in road trauma across the world in terms of both raw numbers of deaths and injuries.[39,41,49,50] However, this effect was short-lived.

Many of the early benefits accrued from reductions in air pollution were not sustained, even until the end of 2020. Furthermore, with the desire to rebound to previous levels of economic activity and mobility, many cities designed for private, car-based transport and in which private vehicles are favoured over public or active transit options[42] also rebounded to levels of air pollution (and associated chronic disease risk) that were equal to, if not greater than, pre-pandemic levels. Some of the few public health benefits of the pandemic era were also lost. Added to these trends were widely observed post-pandemic rebounds in global road trauma (appendix p 8). For example, in its 2023 report,[39] the International Traffic Safety Data and Analysis Group, which described 2020 and 2021 as “exceptional years”[39] in terms of reductions in road trauma among its member nations, laments that fatalities in many countries have now returned beyond their pre-pandemic levels. It highlights that countries including the USA (which saw a 27% increase), New Zealand (a 22% increase), Israel (a 21% increase), and Costa Rica (a 20% increase) appear to be witnessing even higher rates of road trauma than were experienced just a decade before. This pattern is in contrast to the notable road fatality declines in countries such as Japan (which saw a 39% decrease), Lithuania (a 60% decrease), South Korea (a 50% decrease), Poland (a 47% decrease), Greece (a 35% decrease), Belgium (a 35% decrease), Slovenia (a 34% decrease), and Austria (a 30% decrease).[39,49] Differences in post-pandemic road trauma patterns observed between regions are consistent with what might be expected given the dominant city and transport types housed within each country and explored within this study.

The results above show that the optimal city types for health are not static but change over time given the dynamic nature of health crises and concerns. This finding should come as little surprise given the role of cities and shared urban infrastructure in historical public health challenges. However, the performance of cities and their role in producing or preventing disease has previously tended to be considered over a period of centuries, decades, or multiple years. In this study, we show that optimal designs for health can change amid crises that occur over weeks and months.

Beyond infrastructure and design, we also acknowledge that embedded transport cultures[51] can influence whether rapid changes in transport mode share last or not. Exploring this relationship is a direction for future research. For example, the fact that so many locations around the world experienced substantial reductions in pollution, road trauma, and associated chronic disease health risks during 2020 and 2021 appears to have been insufficient incentive for more societies to seek a more permanent transition away from transport modes that contribute to such risks. In fact, in many locations, car culture has not only been resilient to change but has strengthened, especially in locations where city design has facilitated car culture, but even in locations where strategies have been attempted to prevent car culture or at least establish benefits from alternative, active, and sustainable transport modes.[52] In this sense, considering some instances of resilience (ie, preservation and restoration of essential basic structures and functions) as being counterproductive to progress on overall planetary or population health might be reasonable. This dilemma is pertinent when we consider that more than half of the world's greenhouse gas emissions have occurred in the period following the UN Framework Convention for Climate Change in 1992,[53] with road transport as one of the most substantial contributors. The societal challenge to subvert some elements of resilient city designs in efforts to transition to net zero by 2050[54] is considerable.

Some limitations of our study should be noted. The graph neural network clustering is based on OSM data. Assessments have found that although OSM data might have lower levels of completeness, their accuracy is generally high.[55,56] OSM data were gathered in March, 2023, and so might be slightly different from the study period (ie, 2020). However, road and transport networks do not change greatly over short periods[57] making it unlikely that major infrastructure changes took place that would affect the observed results in any material way. Furthermore, in comparison with the use of imagery or map data, a strength of this approach is that the analysed road networks of each city represent a direct, rather than inferred, data source. Use of the city and pollution dataset from Wijnands and colleagues[4] allowed for cross-city comparisons of individual, observed, city-level and ground-level pollution anomalies in 2020, generated through a consistent methodology and based on a single source of observations at a global level. A sample size of no more than 385 cities was required to achieve a confidence level of 95% and a margin of error of 5%. Of the 900 cities available from the study by Wijnands and colleagues,[4] we used the data from 507 cities that met the criteria of sufficiently complete datasets of both NO_2 and $PM_{2·5}$ (global coverage is shown in the appendix [pp 3, 9–11]). Some extreme outliers were removed from the relative health risk analysis when they represented known external sources of pollution (eg, a few days of extreme $PM_{2·5}$ levels during wildfires on the west coast of the USA in September, 2020). Finally, our health risk calculations for chronic conditions relied on epidemiological evidence that assumed pollution reduction levels were sustained.

Cities generate social and economic benefits for individuals and societies alike. Large cities generate substantial interaction, trade, and creativity, and promote efficiency by placing people and resources in close proximity to one another.[58] Because of this capacity, cities are also places where the majority of the world's population chooses to live. However, the design of cities also produces and facilitates unwanted and persistent problems, including disease, pollution, and injury. This observational analysis has shown that these disadvantages are not inherent to cities in general, but rather a consequence of their design. Our results highlight that city design affects the extent to which these negative aspects manifest, especially during crises. They also suggest the prestige and health (or ill-health) experienced by citizens in even the greatest or seemingly healthiest of cities might be ephemeral. The timing, circumstances, environments, and phases of unfolding crises can appear rapidly, exposing citizens and societies to new risks and public health challenges, some of which are based on our responses to those

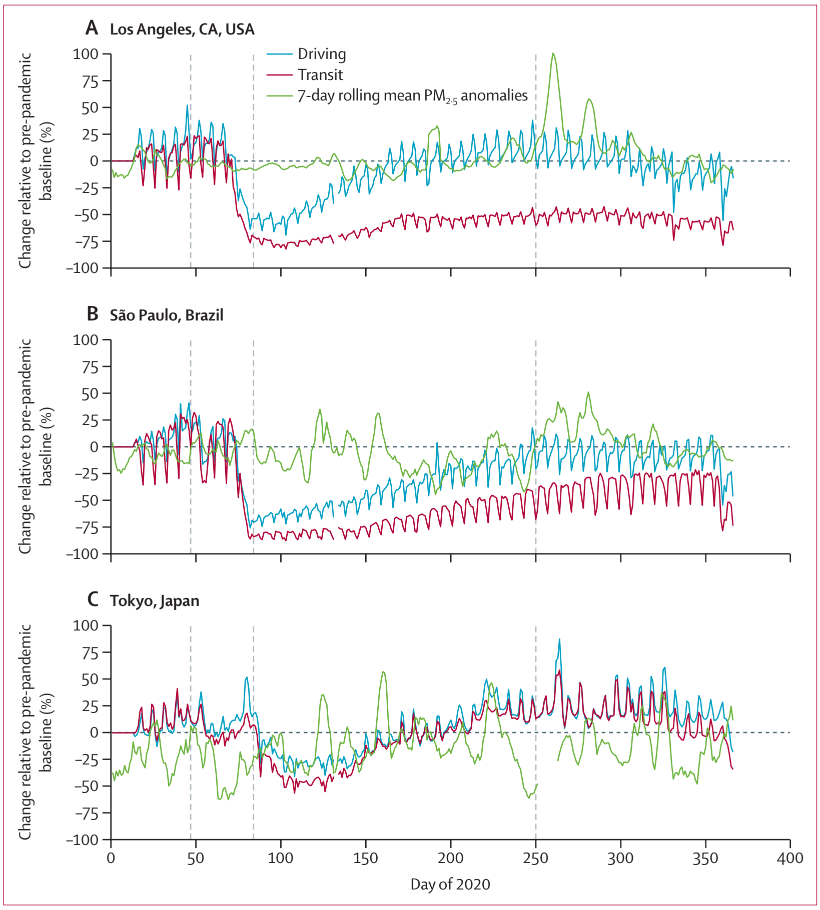

Figure 6: **An overview of the relative shifts in transportation mode preferences (daily Apple mobility indices for driving and transit modes) and 7-day rolling mean $PM_{2·5}$ anomalies over 2020 for Los Angeles, CA, USA (A), São Paulo, Brazil (B), and Tokyo, Japan (C)**

The baseline period is Jan 1–10, 2020.There was an increased reliance on private vehicle use over public transit during the course of the COVID-19 pandemic in Los Angeles and São Paulo, but minimal changes in transport mode share between public transit and private motor vehicles were seen in Tokyo. Extremes in $PM_{2·5}$ readings in Los Angeles might have been exacerbated by summer wildfires on some days. $PM_{2·5}$=fine particulate matter with particles 2·5 μm or less in diameter.

same crises.[52,59] City designs enable dynamism and the building of transport and urban systems that enable rapid adaptation when needs arise.

Contributors

KAN and JT conceived and designed this study and wrote the initial manuscript. KAN collected the mobility and pollution data and KAN and JT accessed, verified, and analysed the data. HZ and SS performed additional data analysis and helped develop the methods. All authors contributed to developing, writing, and editing the manuscript and interpreting the findings. All authors had full access to all the data in the study and had final responsibility for the decision to submit for publication.

Declaration of interests

We declare no competing interests.

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References

1 Mundigo AI, Crouch DP. The city planning ordinances of the laws of the indies revisited. Part I: their philosophy and implications. *Town Plan Rev* 1977; **48:** 247–68.

2 Batty M, Marshall S. Thinking organic, acting civic: the paradox of planning for cities in evolution. *Landsc Urban Plan* 2017; **166:** 4–14.

3 Dovey K, van Oostrum M, Shafique T, Chatterjee I, Pafka E. Atlas of informal settlement: understanding self-organized urban design. London: Bloomsbury Publishing, 2023.

4 Wijnands JS, Nice KA, Seneviratne S, Thompson J, Stevenson M. The impact of the COVID-19 pandemic on air pollution: a global assessment using machine learning techniques. *Atmos Pollut Res* 2022; **13:** 101438.

5 Stevenson M, Thompson J, de Sá TH, et al. Land use, transport, and population health: estimating the health benefits of compact cities. *Lancet* 2016; **388:** 2925–35.

6 Wang Z, Chen X, Qi Z, Cui C. Flood sensitivity assessment of super cities. *Sci Rep* 2023; **13:** 5582.

7 Stanley J, Young B. Managing the risk of wildfire where urban meets the natural environment. In: Brears RC, ed. The Palgrave encyclopedia of urban and regional futures. Springer, 2022: 1–6.

8 WHO. Urban health. World Health Organization, 2023. https://www.who.int/health-topics/urban-health\#tab=tab_1 (accessed Oct 12, 2024).

9 Knowles RD, Ferbrache F, Nikitas A. Transport's historical, contemporary and future role in shaping urban development: re-evaluating transit oriented development. *Cities* 2020; **99:** 102607.

10 Strano E, Nicosia V, Latora V, Porta S, Barthélemy M. Elementary processes governing the evolution of road networks. *Sci Rep* 2012; **2:** 296.

11 Thompson J, Stevenson M, Wijnands JS, et al. A global analysis of urban design types and road transport injury: an image processing study. *Lancet Planet Health* 2020; **4:** e32–42.

12 Wijnands JS, Zhao H, Nice KA, et al. Identifying safe intersection design through unsupervised feature extraction from satellite imagery. *Comput Aided Civ Infrastruct Eng* 2021; **36:** 346–61.

13 Morrison CN, Thompson J, Kondo MC, Beck B. On-road bicycle lane types, roadway characteristics, and risks for bicycle crashes. *Accid Anal Prev* 2019; **123:** 123–31.

14 Currie G, Delbosc A, Pavkova K. Alarming trends in the growth of forced car ownership in Melbourne. 40th Australasian Transport Research Forum; Oct 30–Nov 1, 2018. https://www.monash.edu/__data/assets/pdf_file/0004/1515676/ATRF2018_Paper_8_Forced-Car-Ownership-in-Melbourne-.pdf (accessed Oct 12, 2024).

15 Curl A, Clark J, Kearns A. Household car adoption and financial distress in deprived urban communities: a case of forced car ownership? *Transp Policy* 2018; **65:** 61–71.

16 Hale T, Angrist N, Goldszmidt R, et al. A global panel database of pandemic policies (Oxford COVID-19 Government Response Tracker). *Nat Hum Behav* 2021; **5:** 529–38.

17 Craig L, Churchill B. Working and caring at home: gender differences in the effects of COVID-19 on paid and unpaid labor in Australia. *Fem Econ* 2021; **27:** 310–26.

18 Vyas L, Butakhieo N. The impact of working from home during COVID-19 on work and life domains: an exploratory study on Hong Kong. *Policy Des Pract* 2021; **4:** 59–76.

19 Martin M, Lawson M, Abdo N, Waddock D, Walker J. Fighting inequality in the time of COVID-19: the commitment to reducing inequality index 2020. Oxfam International, 2020.

20 de Gooyert V, Rouwette E, van Kranenburg H, Freeman E, van Breen H. Sustainability transition dynamics: towards overcoming policy resistance. *Technol Forecast Soc Change* 2016; **111:** 135–45.

21 Koopman JS, Simon CP, Riolo CP. When to control endemic infections by focusing on high-risk groups. *Epidemiology* 2005; **16:** 621–27.

22 Taylor L. Covid-19: true global death toll from pandemic is almost 15 million, says WHO. *BMJ* 2022; **377:** o1144.

23 Hunter RF, Akaraci S, Wang R, et al. Investigating the urban mobility impact and public health equity of pandemic recovery actions: a global natural experiment. *Lancet Public Health* 2024; **9:** e896–906.

24 Forster PM, Forster HI, Evans MJ, et al. Current and future global climate impacts resulting from COVID-19. *Nat Clim Chang* 2020; **10:** 913–19.

25 He G, Pan Y, Tanaka T. The short-term impacts of COVID-19 lockdown on urban air pollution in China. *Nat Sustain* 2020; **3:** 1005–11.

26 Le Quéré C, Jackson RB, Jones MW, et al. Temporary reduction in daily global CO2 emissions during the COVID-19 forced confinement. *Nat Clim Chang* 2020; **10:** 647–54.

27 Venter ZS, Aunan K, Chowdhury S, Lelieveld J. COVID-19 lockdowns cause global air pollution declines. *Proc Natl Acad Sci USA* 2020; **117:** 18984–90.

28 Smit W. Urbanization in the Global South. In: Oxford research encyclopedia of global public health. Oxford University Press, 2021.

29 Ewing R, Cervero R. Travel and the built environment: a meta-analysis. *J Am Plann Assoc* 2010; **4363:** 265–94.

30 Barthélemy M. Spatial networks. *Phys Rep* 2011; **499:** 1–101.

31 Boeing G. OSMnx: new methods for acquiring, constructing, analyzing, and visualizing complex street networks. *Comput Environ Urban Syst* 2017; **65:** 126–39.

32 UN Department of Economic and Social Affairs. World urbanization prospects 2018. United Nations, 2019. https://population.un.org/wup/Publications/ (accessed Oct 12, 2024).

33 Nice KA, Aschwanden GDPA, Wijnands JS, Thompson J, Zhao H, Stevenson M. The nature of human settlement: building an understanding of high performance city design. *arXiv* 2019; published online Oct 8. https://arxiv.org/abs/1910.03219 (preprint).

34 Schwartz J, Laden F, Zanobetti A. The concentration-response relation between PM(2.5) and daily deaths. *Environ Health Perspect* 2002; **110:** 1025–29.

35 Huang S, Li H, Wang M, et al. Long-term exposure to nitrogen dioxide and mortality: a systematic review and meta-analysis. *Sci Total Environ* 2021; **776:** 145968.

36 Xie W, Li G, Zhao D, et al. Relationship between fine particulate air pollution and ischaemic heart disease morbidity and mortality. *Heart* 2015; **101:** 257–63.

37 Yu YAS, Guo Y, Shi L, Li S. The association between long-term exposure to low-level $PM_{2.5}$ and mortality in the state of Queensland, Australia: a modelling study with the difference-in-differences approach. *PLoS Med* 2020; **17:** 1–19.

38 Balti EV, Echouffo-Tcheugui JB, Yako YY, Kengne AP. Air pollution and risk of type 2 diabetes mellitus: a systematic review and meta-analysis. *Diabetes Res Clin Pract* 2014; **106:** 161–72.

39 International Traffic Safety Data and Analysis Group. Road safety annual report 2023. Organisation for Economic Co-operation and Development, 2023. https://www.itf-oecd.org/sites/default/files/docs/irtad-road-safety-annual-report-2023.pdf (accessed Oct 12, 2024).
40 Zhang Q, Mao X, Wang Z, et al. Impact of the emergency response to COVID-19 on air quality and its policy implications: evidence from 290 cities in China. *Environ Sci Policy* 2023; **145:** 50–59.
41 Saladié Ò, Domínguez-Mallafré M, Domènech A, Gutiérrez A. 'Back to the past': the decline and rebound in traffic accident numbers in Catalonia in the context of COVID-19 lockdown and post-lockdown. *Nor Geogr Tidsskr* 2023; **77:** 78–97.
42 Das S, Boruah A, Banerjee A, Raoniar R, Nama S, Maurya AK. Impact of COVID-19: a radical modal shift from public to private transport mode. *Transp Policy* 2021; **109:** 1–11.
43 Gkiotsalitis K, Cats O. Public transport planning adaption under the COVID-19 pandemic crisis: literature review of research needs and directions. *Transp Rev* 2021; **41:** 374–92.
44 Beck MJ, Hensher DA. Insights into the impact of COVID-19 on household travel and activities in Australia—the early days of easing restrictions. *Transp Policy* 2020; **99:** 95–119.
45 Dai J, Liu Z, Li R. Improving the subway attraction for the post-COVID-19 era: the role of fare-free public transport policy. *Transp Policy* 2021; **103:** 21–30.
46 International Transport Forum. Shaping post-COVID mobility in cities: summary and conclusions. ITF roundtable reports, no 190. International Transport Forum, 2023. https://www.itf-oecd.org/sites/default/files/docs/shaping-post-covid-mobility-cities.pdf (accessed Oct 12, 2024).
47 Clements R. Socialising parking: public opportunities via regulated market approaches. 9th State of Australian Cities National Conference; Nov 30–Dec 5, 2019. https://apo.org.au/node/305268 (accessed Oct 12, 2024).
48 UN Office for Disaster Risk Reduction. Terminology on disaster risk reduction. Geneva: United Nations, 2009.
49 International Traffic Safety Data and Analysis Group. Road safety annual report 2022. Organisation for Economic Co-operation and Development, 2022. https://www.itf-oecd.org/sites/default/files/docs/irtad-road-safety-annual-report-2022.pdf (accessed Oct 12, 2024).
50 Institute For Health Metrics and Evaluation. Global burden of disease study 2021. Institute For Health Metrics and Evaluation, 2022.
51 Paterson M. Car culture and global environmental politics. *Rev Int Stud* 2000; **26:** 253–70.
52 Hunter RF, Akaraci S, Wang R, et al. City mobility patterns during the COVID-19 pandemic: analysis of a global natural experiment. *Lancet Public Health* 2024; **9:** e896–906.
53 Intergovernmental Panel on Climate Change. In: Shukla PR, Skea J, Slade R, eds. Climate change 2022: mitigation of climate change. Contribution of Working Group III to the sixth assessment report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, NY, USA: Cambridge University Press, 2022.
54 Lynskey R, Graham S, Li M, Stock P. Moving to zero: accelerating the transition to zero-emissions transport. ClimateWorks Australia, 2020.
55 Zhou Q, Wang S, Liu Y. Exploring the accuracy and completeness patterns of global land-cover/land-use data in OpenStreetMap. *Appl Geogr* 2022; **145:** 102742.
56 Zhou Q, Zhang Y, Chang K, Brovelli MA. Assessing OSM building completeness for almost 13,000 cities globally. *Int J Digit Earth* 2022; **15:** 2400–21.
57 Taillanter E, Barthelemy M. Evolution of road infrastructure in large urban areas. *Phys Rev E* 2023; **107:** 034304.
58 Bettencourt LM. The origins of scaling in cities. *Science* 2013; **340:** 1438–41.
59 Garcia L, Hafezi M, Lima L, et al. Future-proofing cities against negative city mobility and public health impacts of impending natural hazards: a system dynamics modelling study. *Lancet Planet Health* 2025; **9:** e207–18.