Future-proofing cities against negative city mobility and public health impacts of impending natural hazards: a system dynamics modelling study

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Summary

Background The world faces increasing risk from more frequent and larger scale natural hazards, including infectious disease outbreaks (IDOs) and climate change-related extreme weather events (EWEs). These natural hazards are expected to have adverse mobility and public health impacts, with people living in cities especially vulnerable. Little is known about how transport systems can be optimally designed to make cities more resilient to these hazards. Our aim was to investigate how cities' transport systems, and their resulting mobility patterns, affect their capabilities to mitigate mobility and health impacts of future large-scale IDOs and EWEs.

Methods System dynamics modelling was used to investigate how different city mobility scenarios can affect the health and mobility impacts of four plausible future IDO and EWE (flooding) shocks in three cities: Belfast, UK; Belo Horizonte, Brazil; and Delhi, India. Three city mobility scenarios with incremental degrees of modal shift towards active travel (private motor vehicle volume reduced to 50% and 20% of total road trip volume in vision 1 and 2, and motor vehicle volume [including buses] reduced to 20% of total road trip volume in vision 3) were tested. For each city and each IDO and EWE shock, we estimated the percentage of deaths prevented in visions 1, 2, and 3, relative to the reference scenario, as well as changes in mode share over time.

Findings In all scenarios, all cities showed reduced susceptibility to flooding, with 4–50% of deaths potentially prevented, depending on case city, city mobility, and EWE scenario. The more ambitious the transition towards healthier city mobility patterns, the greater the resilience against flooding. Only vision 3 (the most ambitious transition) showed reduced vulnerability to IDOs, with 6–19% of deaths potentially prevented. Evolution of mode shares varied greatly across cities and mobility scenarios under the IDO shocks.

Interpretation Our results emphasise the importance of well designed, forward-thinking urban transport systems that make cities more resilient and reduce the impact of future public health-related and climate-related threats.

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Introduction

As the world emerges from the COVID-19 pandemic, it faces increasing risk of more frequent and larger scale natural hazards, including infectious disease outbreaks (IDOs) and climate change-related extreme weather events (EWEs), such as flooding, storms, heatwaves, and droughts, and combined events.[1–3] Data indicate that climate-related events, including EWEs, increased from 3656 in 1980–99 to 6681 in 2000–19.[3] Between 2000 and 2019, the number of major floods globally doubled, from 1389 to 3254, and the number of storms leapt from 1457 to 2034. The Intergovernmental Panel on Climate Change's 2023 report estimates that the frequency of EWEs will increase in the near term due to climate change.[4] Some estimates also indicate that the yearly probability of extreme IDOs (ie, whose death rate is at least 0·001‰ of the global population per year) could increase up to three-fold in the coming decades.[5] Climate change and the risk of IDOs are connected, as many emerging IDOs are facilitated by changes in environmental conditions; population growth; urban ecosystems; and global transport modes, patterns, and connectivity associated with climate change.[6]

The proportion of the world's population living in urban areas is projected to increase from 56% today to nearly 70% in 2050.[7] The growing number of people living in urban areas globally make cities especially vulnerable to the negative health impacts of IDOs and EWEs. In particular, cities in low-income and middle-income countries (LMICs) are highly vulnerable to

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Research in context

Evidence before this study

Between 2000 and 2019, the UN reported 7348 major disaster events including wildfires, floods, landslides, and a host of associated climate-related crises. These events affected 4·2 billion people, claimed 1·23 million lives, and contributed to economic losses of US$3 trillion. The COVID-19 pandemic was responsible for 7 million confirmed deaths worldwide by November, 2023. Since 2020, including the period dominated by the COVID-19 pandemic, there has been a continuation of these trends. As climate change, population growth, and global interconnectivity progress, there is evidence to suggest that the frequency, scale, and magnitude of crises—including extreme weather events and infectious disease outbreaks—will continue to grow.

Added value of this study

This study is one of the first to model city resilience in response to crises that might be typical in the future. The study introduces a model for understanding the potential city mobility and public health effects of crises, covering infectious disease outbreaks and climate change-related extreme weather and identifying city and transport system designs that are resilient (or otherwise) to envisaged hazards they might face. Consistent with empirical evidence gathered during the COVID-19 pandemic, our study shows that modelled cities with compact design and characteristics that support a balance of active and public transit are less likely to experience secondary adverse city mobility and public health impacts than those whose designs emphasise or prioritise private car use. Our study provides a framework for cities and city planners to consider healthy design choices and planning directions.

Implications of all the available evidence

The evidence to date suggests that there is likely to be little short-term to medium-term reprieve in the accelerating risk that cities face in relation to climate change and infectious disease outbreaks. In fact, these events are likely to occur at an increasing rate, magnitude, and scale, meaning that the timing of hazards could overlap and their negative city mobility and public health effects compound. It is in the best interest of cities and their populations to remain resilient to the impacts of such contemporaneous hazards. One way to remain resilient is ensuring that city designs become more compact and that transportation networks facilitate easy adaptation and switching between modes when likely disasters occur, guaranteeing that citizens are not locked to one way of accessing services and supports in times of need. Cities are complex systems and modelling of the type described here can provide insight into the futures that we might face and the actions we can take to maximise public health in challenging times.

climate and environmental changes, exacerbated by factors such as socioeconomic and gender inequalities and lack of adequate public policies to mitigate and adapt to the impacts of impeding natural hazards.[8,9] In the face of rapid urbanisation, uncontrolled expansion, and exposure to climate-related hazards, cities are important environments for disease transmission during IDOs due to frequent interactions between people in multiple settings (eg, education, transport, recreation, and commerce). During the COVID-19 pandemic, transmission was higher in urban settings where public transit and households were overcrowded.[10,11] Additionally, the health impacts of EWEs concentrate in cities, where population growth has been unmatched by growth in vital urban infrastructure and where systems expansion and capacity are not supported by climate resiliency planning. Many cities, especially those in LMICs, are not planned or designed to protect residents against EWEs, leading to infrastructure and systems that are not climate-change resilient. For example, housing and workplaces lack temperature insulation materials, water drainage systems are unprepared for higher rain volumes, road transport infrastructure is vulnerable to flooding, and rail infrastructure is vulnerable to periods of extreme heat. Continued urban population growth projected for the coming decades will further increase the vulnerability of cities to EWEs and IDOs. This vulnerability will be greater among populations living in peri-urban areas (ie, transitional spaces between urban and rural areas),[12] informal settlements, and LMICs.[7]

Active, healthy, sustainable mobility (eg, walking, cycling, and public transit) is enhanced or inhibited by how the transport systems are designed, implemented, and sustained. In a linked paper, Nice and colleagues[13] illustrate the importance of urban design constraints on transport systems in mediating the indirect health impacts of the COVID-19 pandemic. Findings indicate that short-term reductions in driving, air pollution, and road traffic injuries resulting from COVID-19 lockdown measures rebounded quickly in the recovery phases of the pandemic, but this was most pronounced in cities whose designs facilitated a mode shift from public transit to private car use. These findings show that the COVID-19 pandemic was a missed opportunity to reduce car dependence, and might have exacerbated it in many locations. Although not addressed directly, these findings also add weight to arguments that radical transformation towards compact cities could build resilience and protect city mobility and public health during future IDOs. Compact cities can better accommodate the range of human access needs (eg, travel to work, shops, schools, health care, and entertainment through all transportation modes), including walking and cycling, while also enabling easier implementation of physical distancing requirements and other mitigating actions (eg, health communication and face masking) during IDOs.[10,14,15]

Findings from Hunter and colleagues[16] indicate that many cities in high-income countries invested in developing more active transport infrastructure during the COVID-19 pandemic, such as expanding cycling lanes and pedestrianising streets, which showed some short-term benefits. However, these changes were generally modest in nature and often temporary (eg, pop-up bicycle lanes), and were less frequently adopted in cities with limited active travel infrastructure and in LMICs. For instance, most African cities did not make any major structural changes to their transport and mobility infrastructure during the COVID-19 pandemic,[17] with existing transport services restricted to reduced passenger capacities, without any changes to infrastructure for pedestrian activities and intermediate transport services.

Although we have some information about the effects of EWEs on transport use,[18] we know less about how transport systems can be designed to protect city mobility and public health during EWEs and subsequent recovery. We present a summary of some design features of urban transport systems needed to protect city mobility and public health during IDOs and EWEs in the appendix (pp 2–3).[19–29] These actions need to be coupled with an active health communication strategy to the public, including early warning systems to advise against travel or how to travel safely during IDOs and EWEs.

Cities are complex systems encompassing intricate networks of interdependent elements, whose dynamic and interconnected nature shapes their overall resilience.[30,31]

	Description	Inputs from other modules
Population dynamics	Estimates city's population size over time	It considers deaths from road emissions of $PM_{2.5}$, road collisions, flooding, and disease outbreaks
City mobility	Estimates volume of intracity trips per mode (motorcycle, car, bus, walking, and cycling) over time and cumulative deaths from the road transport modes (road emissions of $PM_{2.5}$ and road collisions)	Volume of trips considers whether and when restrictions on interpersonal contacts due to disease outbreaks are in place, changes in population size, and frequency of heavy rainfall; deaths from road collisions consider the frequency of heavy rainfall
Disease outbreaks	Estimates the fraction of the population that is susceptible, exposed, infectious, or recovered during a disease outbreak, as well as the cumulative deaths from the outbreak	Number of susceptible people depends on population size and birth rates; disease transmission rate depends on changes in bus trip volume and whether restrictions on interpersonal contacts due to disease outbreaks are in place; deaths from the outbreak include those that happen because of ICU beds
Health-care infrastructure capacity	Estimates the number of infected people needing ICU beds (as a proxy of the health-care system capacity more widely) and cumulative deaths due to insufficient ICU beds during a disease outbreak; tracks ICU beds occupancy rate, which triggers restrictions on interpersonal contacts	Infected people needing ICU beds is a function of the number of new infected people at each time step and the severity of the disease; whether restrictions on interpersonal contacts are in place or not also considers the effective reproduction number
Flooding and heavy rainfalls due to climate change	Estimates the number, frequency, and population at risk and affected by moderate and severe floodings, as well as the cumulative immediate and long-term deaths from flooding and its disruptions; estimates the yearly number of heavy rainfall days	Population at risk and affected by floodings depends on population size; the number of long-term deaths considers the effect of different city mobility scenarios on the permanent recovery of people affected by and rescued from flooding

ICU=intensive care unit.

Table 1: **Summary description of the modules in the system dynamics model**

Methods

Model overview

We used system dynamics modelling to investigate how different city mobility scenarios can affect the health and city mobility of populations during plausible future IDOs and EWEs. System dynamics is a computational modelling approach for analysing and understanding complex temporal systems that leverages feedback loops within a system to identify and understand the system's behaviour and evolution.[32] A strength of system dynamics is its ability to incorporate non-linearities and information feedback loops that occur within separate but connected components or modules of an overall system.[32] System dynamics is, therefore, well suited to tackling the challenge of overlapping or compound hazards.

Model development followed the sequence suggested by Sterman[32] and Maani and Cavana[33] (appendix pp 6–7). In summary, we initiated with qualitative modelling from the problem statement (appendix p 8). Next, we proceeded to quantitative modelling, developing, testing, and verifying the system dynamics model. Finally, we conducted a series of scenario-based analyses. The structure of our system dynamics model is informed by the causal loop diagram (appendix p 8). The model consists of five interrelated modules: population dynamics, city mobility, disease outbreaks, health-care infrastructure capacity, and flooding and heavy rainfalls due to climate change (table 1; appendix pp 9–20).

See Online for appendix

Contextual factors, including socioeconomic disparities between cities, can play an important role in determining cities' resilience to natural hazards. We therefore decided to model three cities with contrasting socioeconomic conditions: Belfast (UK), Belo Horizonte (Brazil), and Delhi (India). These cities were selected because they are located in different continents and in countries with different levels of income (Belfast: high income, Belo Horizonte: high-middle income, Delhi: low-middle income); have different health-care systems and infrastructure; have different social and health inequality levels; have different city mobility patterns (although all have very low active travel levels); implemented new (albeit sometimes temporary) active travel infrastructure to control and mitigate the effects of the COVID-19 pandemic; and have sufficient data on key aspects of city infrastructure and mobility to parameterise the system dynamics model. By studying these case cities, we aimed to understand what works in different settings while also highlighting broader generic or global principles.

	Reference scenario	Vision 1	Vision 2	Vision 3
Belfast, UK				
Motorcycle	0·5%	0·3%	0·13%	0·1%
Car	75·6%	49·7%	19·9%	7·9%
Bus	16·3%	29·3%	33·1%	12·0%
Cycling	1·8%	12·2%	24·2%	45·2%
Walking	5·9%	8·5%	22·7%	34·8%
Belo Horizonte, Brazil				
Motorcycle	5·4%	4·3%	2·9%	1·0%
Car	32·4%	25·7%	17·1%	7·0%
Bus	25·1%	29·0%	30·4%	12·0%
Cycling	1·2%	4·3%	8·3%	27·0%
Walking	35·9%	36·7%	41·2%	53·0%
Delhi, India				
Motorcycle	49·8%	34·5%	13·8%	6·0%
Car	22·5%	15·5%	6·2%	3·0%
Bus	20·8%	31·9%	36·5%	11·0%
Cycling	2·0%	10·9%	22·9%	45·8%
Walking	4·9%	7·2%	20·6%	34·2%

Percentages only consider on-road passenger modes (ie, trains, subways, goods-delivery vehicles, and similar are excluded). Vision 1 refers to a mild shift in patterns, vision 2 refers to medium shift, and vision 3 refers to a major shift.

Table 2: **Percentage of trip volume per mode by city mobility scenario and case city**

Mobility scenarios

For each city, we decided to model four mobility scenarios with incremental degrees of modal shift towards active travel resulting from investments in designing more compact cities (appendix p 4).

For the **model data spreadsheet** see https://doi.org/10.17605/OSF.IO/AG8Z2

The reference scenario refers to city mobility patterns (trip volume per mode) as observed in 2019 (ie, pre-pandemic). Vision 1 refers to a mild shift in patterns: some long trips by car are switched to bus and cycling trips; investments are made in cycling infrastructure, but with little investment in designing compact cities that further incentivise walking and cycling; private motor vehicle volume is reduced to 50% of the initial total road trip volume (30% in Belo Horizonte, whose private motor vehicle volume in the reference scenario is below 50%); and the difference in trip volume in relation to the reference scenario is distributed 50% to bus trips, 40% to cycling trips, and 10% to walking trips. Vision 2 refers to a medium shift in patterns: a substantial proportion of long trips by car are switched to bus trips and some to cycling trips, and there is moderate investment in designing compact cities that incentivise walking and cycling; private motor vehicle volume is reduced to 20% of the initial total road trip volume; and the difference in trip volume in relation to the reference scenario is distributed 30% to bus trips, 40% to cycling trips, and 30% to walking trips. Vision 3 refers to a major shift in patterns: there is substantial investment in designing compact cities that incentivise walking and cycling, substantially reducing long trips and the need for cars, and slightly reducing the need for bus trips; motor vehicle volume (including buses) is reduced to 20% of initial total road trip volume, 60% of which is in car trips; and the difference in trip volume in relation to the reference is distributed 60% to cycling trips and 40% to walking trips (table 2).

Total trip volume was kept equal at the beginning across all scenarios. The three vision scenarios also considered the extent to which trips by each mode were affected by, and recovered from, restrictions on interpersonal contacts during disease outbreaks, in accordance with the envisioned investments in compact cities (appendix pp 20–21).

IDO and EWE shocks

Four plausible future IDO and EWE shocks were modelled, all applied to each mobility scenario and city (ie, 48 experiments in total). We modelled two disease outbreaks with similar probability of transmission (1·5% and 1·0%). However, to consider diseases with different population impacts over time, one model (IDO 1, based on COVID-19) had lower case severity (0·15%) and case-fatality rates (1·00%), whereas the second model (IDO 2, more lethal, but less transmissible) had higher case severity (0·45%) and case-fatality rates (2·00%). In both outbreaks, the diseases were introduced at the beginning of modelled year 2, with a reinfection wave (eg, a different variant) occurring 1 year later. All parameters and assumptions can be viewed in the appendix (pp 9–20) and model data spreadsheet.

For EWEs, we modelled floods, as they were the most frequent of the climate-related disasters between 2000 and 2019 (3254 recorded events, 44% of the events recorded during the period), affected most people (1·65 billion, 41% of the people affected), and caused more than 100 000 deaths (9% of total). Flooding also imposes substantial current and future risk to the three case cities (panel). Climate-related variations for the case cities were projected based on representative concentration pathways (RCPs)—greenhouse gas concentration trajectory and future climate change scenarios introduced by the Intergovernmental Panel on Climate Change.[42] To cover the full spectrum of projected extreme weather events, we used RCP 2·6 (low-emission scenario that assumes a rapid and ambitious mitigation of greenhouse emissions—ie, the best-case scenario) and RCP 8·5 (high-emission scenario that assumes a continuation of current trends—ie, the worst-case scenario) in our model to generate moderate and severe flooding events over the period of observation. The model also considers the number of heavy rainfall days per year forecasted under each of the two RCP trajectories.

Model parameterisation and estimation of impacts

We parametrised and calibrated the models using data from the case cities. When data were not available for a given city or scenario, we used the next best data available (eg, from a location or event with similar characteristics or mean values and pooled estimates from systematic reviews) and calibrated inputs based on plausibility and alignment with the historical data available (appendix pp 9–20).

For each city and IDO and EWE shock, we estimated the percentage of deaths potentially preventable in the vision 1, 2, and 3 scenarios in comparison to the reference scenario. We looked at cause-specific deaths over time to estimate cumulative deaths due to the shocks (ie, flooding and moderate and heavy rainfall or disease outbreaks) directly, and changes in air pollution and road collisions because of changes in city mobility patterns during and outside the shocks. Two different timescales were used to account for the differences in timescales of the shocks: 5 years for the IDOs and 30 years for the EWEs. In all cases, each time step in the model represents a single day.

We also estimated the changes in mode share over time under the disease outbreaks and lasting changes in travel behaviour. Both disease outbreaks prompt very similar changes in travel behaviour. We therefore present the results for IDO 2 (higher case severity and case-fatality rates).

Role of the funding source

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

Results

The vision 1 (mild shift) scenario showed increased susceptibility to the two IDO shocks at varied degrees across the three case cities (figure 1). Compared with the reference city mobility scenarios, the 5-year accumulated deaths resulting from IDO 1 were 62% higher in Belfast, 4% higher in Belo Horizonte, and 29% higher in Delhi. Similar estimates were observed for IDO 2 in Belo Horizonte (6%) and Delhi (37%), but fewer additional deaths in relation to IDO 1 were estimated for Belfast (49%).

Reduced susceptibility to flooding relative to the reference city mobility scenario was observed for the three cities. In Belfast, 6% of deaths could potentially be prevented under RCP 2·6 and 8·5 trajectories (8% in Belo Horizonte and Delhi).

Transport-related deaths were estimated to decrease across all case cities and shocks in comparison to the reference scenario, with 4–11% of deaths potentially prevented.

Net prevented deaths were observed only for floods, with slightly better results for Belfast (6%) than Belo Horizonte and Delhi (4–5%). The relative net increase in deaths under IDO shocks varied greatly across cities, with estimates of 6% for Belo Horizonte, 39–41% for Delhi, and 49–65% for Belfast.

***Panel*: Flooding in the selected case cities**

There is a clear consensus that the risk of urban flood frequency and magnitude is increasing across the world due to the combined impacts of climate change, the associated rainfall intensities, and rapid urban development.[34]

Belfast is exposed to all four major sources of flooding: fluvial, coastal, pluvial, and from reservoirs. The Climate Change Risk Assessment report on Northern Ireland identified flooding as potentially the most substantial and urgent climate-induced risk to Belfast.[35] According to the Northern Ireland Flood Risk Assessment,[36] aggregated annual average damages of £16·18 million are predicted for flooding risk areas in Belfast only, which is substantially higher than the rest of Northern Ireland.

In Belo Horizonte, in southeastern Brazil, the devastating impact of severe flooding can be directly attributed to global climate change, which has caused an unprecedented increase in heavy rainfall.[37] Belo Horizonte is situated on the basin of the tributaries of the São Francisco river, including the das Velhas and Paraopeba rivers. Between 1979 and 2014, a total of 104 flooding events were reported in the city of Belo Horizonte, with a high potential to increase over the next decades due to increasing precipitation trends, the region's geographical features, increasing impermeability of the urban lands, and increased soil erosion.[38,39]

Delhi, one of India's most urbanised areas, is at high risk of flooding due to its rapid urbanisation without flood management infrastructure, inefficient urban drainage, and increased urban devegetation and impermeability rate.[40] In addition, the climate change-induced increase in precipitation over the National Capital Territory and Yamuna River National Capital Territory, which runs through Delhi, has made the area highly susceptible to extreme flooding events.[41] In the past decades, the water level reached more than 200 m, causing the worst flood ever in the whole region.

Thus, in all three case cities, flooding emerged as the foremost climatic threat, posing both direct and indirect effects on communities and individuals. The impacts range from death and mental health disorders to homelessness, increased traffic incidents, and residents' displacement.

The vision 2 scenario (medium shift) showed results in the same direction of the estimates for vision 1, but with larger effect sizes (figure 1). The increment in the effect sizes was more pronounced for Belo Horizonte and Delhi than for Belfast.

Increased susceptibility to the two IDO shocks was observed, with more cumulative deaths estimated for IDO 1 than IDO 2 in Belfast (89% *vs* 63%) and Delhi (78% *vs* 52%) relative to the reference city mobility scenario, and 9% more in Belo Horizonte for both IDOs.

Reduced susceptibility to flooding relative to the reference city mobility scenario was observed, with

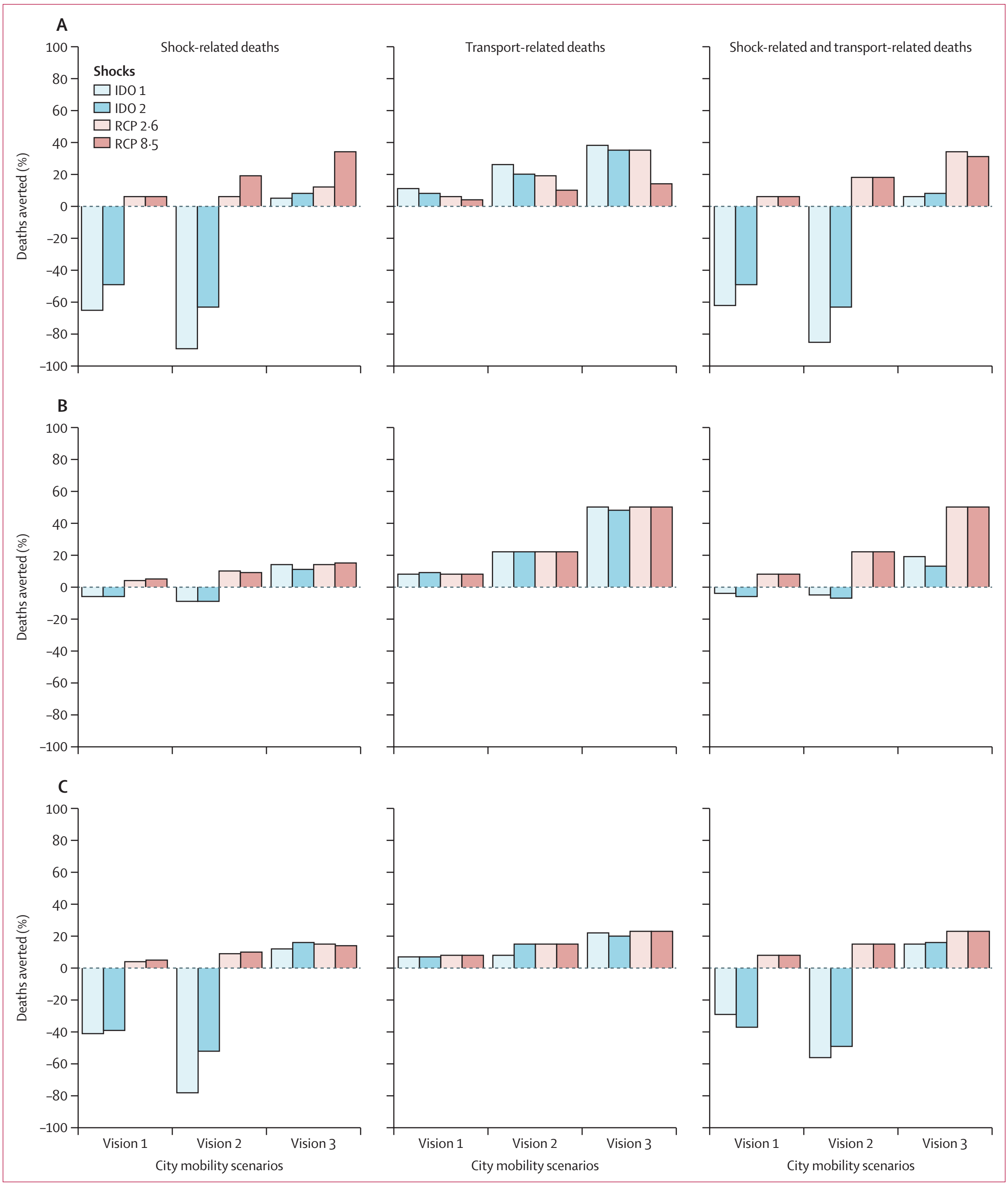

Figure 1: **Percentage of deaths prevented in Belfast, UK (A), Belo Horizonte, Brazil (B), and Delhi, India (C), by city mobility and shock scenario**
IDO=infectious disease outbreak. RCP=representative concentration pathway.

9–10% of deaths potentially prevented for Belo Horizonte and Delhi, and 6–19% for Belfast.

Transport-related deaths were estimated to decrease across all case cities and shocks. Deaths prevented relative to the reference city mobility scenario were generally around 20% across cities and shocks, ranging from 8% for Delhi under IDO 1, to 26% for Belfast under IDO 1.

Net prevented deaths were observed only for floodings, with 9–10% for Belo Horizonte and Delhi under RCP 2·6 and 8·5 trajectories, and 6% (RCP 2·6) and 19% (RCP 8·5) for Belfast. The relative net increase in deaths under IDO shocks differed substantially across cities, with estimates of 9% for Belo Horizonte, 52–78% for Delhi, and 63–89% for Belfast.

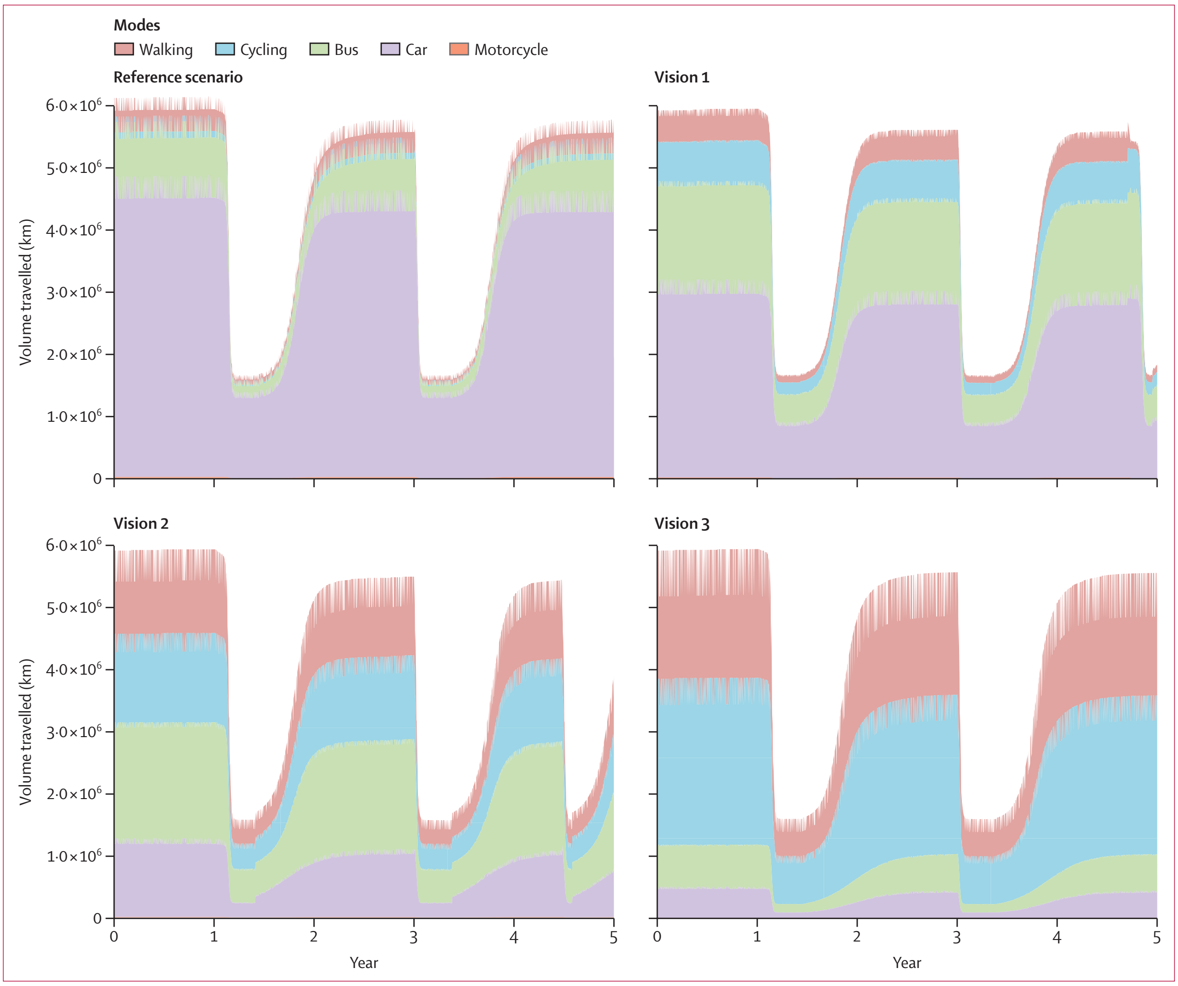

Figure 2: **Changes in mode share in Belfast, UK, under IDO 2, by city mobility scenario**
IDO 2 refers to the more lethal but less transmissible IDO scenario. IDO=infectious disease outbreak.

The vision 3 scenario (major shift) was the only scenario under which estimated reductions in deaths (in comparison to the reference city mobility scenario) were observed irrespective of the shock that impacted the cities (figure 1).

Decreased susceptibility to the two IDO shocks was observed for the three case cities. In Belfast, 5% (IDO 1) and 8% (IDO 2) of the 5-year cumulative deaths could potentially be prevented; in Belo Horizonte, 14% (IDO 1) and 11% (IDO 2) of the deaths could be prevented; and in Delhi, 12% (IDO 1) and 16% (IDO 2) could be prevented.

Reduced susceptibility to flooding relative to the reference city mobility scenario was also observed, with 12–15% of deaths potentially prevented for all cities and RCP trajectories, except for Belfast under RCP 8·5 (34% reduction in deaths).

Transport-related deaths were estimated to decrease relative to the reference scenario, but at different magnitudes across the case cities. In Belfast, 14–38% of these deaths could be potentially prevented; in Belo Horizonte, 48–50% could be potentially prevented; and in Delhi, 20–23% could be potentially prevented.

Net prevented deaths were observed for all shocks and cities, with better results estimated for Belo Horizonte (13–19% under IDO shocks, and 50% in both RCP trajectories) than Belfast (6–8% under IDO shocks, 31–34% in RCP trajectories) and Delhi (15–16% under IDO shocks, 23% in both RCP trajectories).

As for changes in city mobility patterns, under the IDO 2 shock, the absolute volume of trips decreases for all modes and mobility scenarios during the periods of restriction on interpersonal contacts, with the volume of trips per mode never returning to pre-IDO shock afterwards (figures 2–4). However, evolution of mode shares (ie, the relative volume of trips per mode) varied greatly across cities and mobility scenarios.

In the reference scenario, an increase in the share of private motor vehicle trips during the restrictions was estimated for all case cities, with a small (1–2 percentage

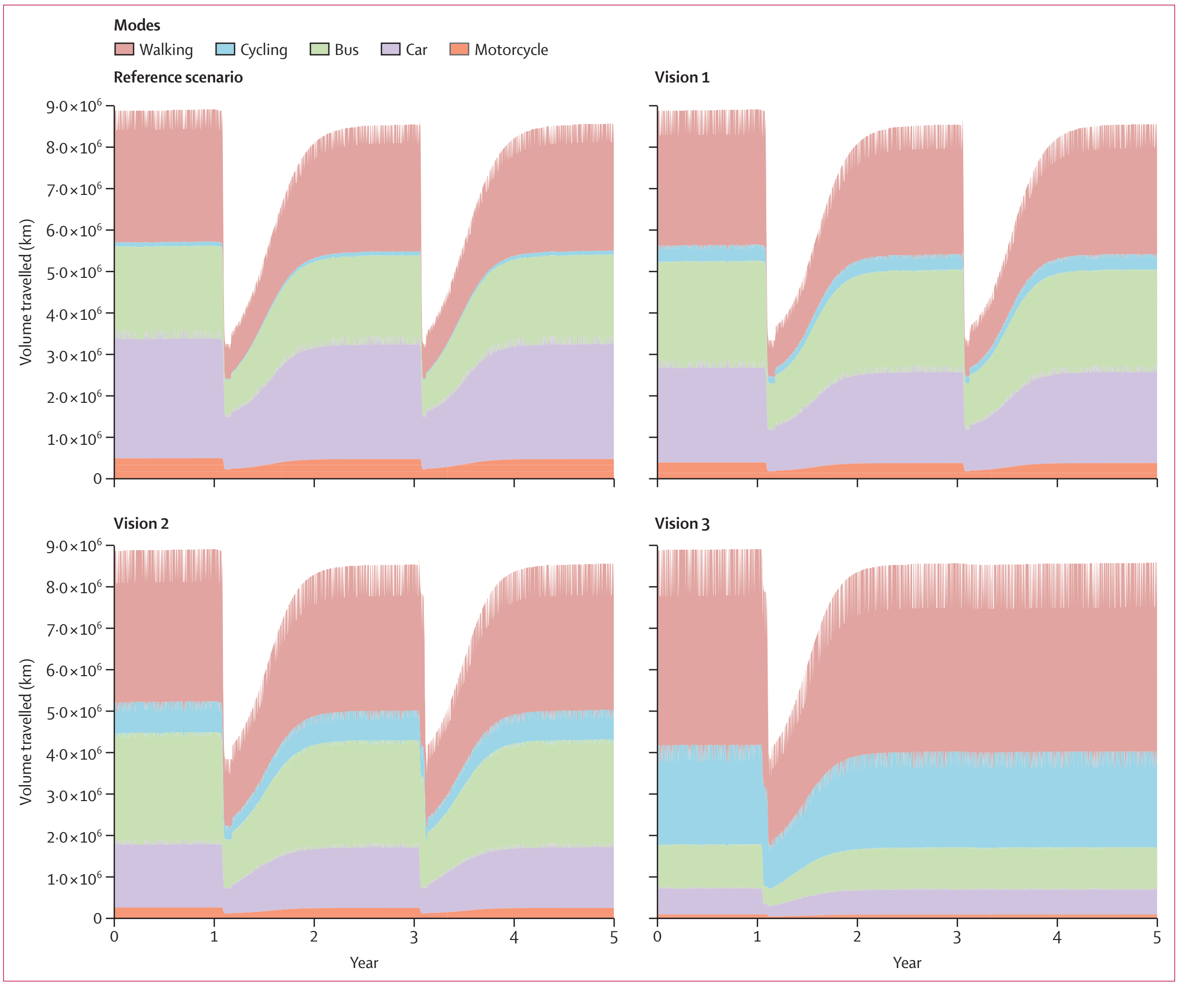

Figure 3: **Changes in mode share in Belo Horizonte, Brazil, under IDO 2, by city mobility scenario**
IDO 2 refers to the more lethal but less transmissible IDO scenario. IDO=infectious disease outbreak.

points) but lasting increment in their share at the end of the modelled period.

Under vision 1, mode shares did not change significantly between the start and end of the modelled period for the three cities. However, the dynamics were different during the restriction periods. Belfast was the only city to have three periods of restriction under this vision. In each restriction period, there was a small reduction in the share of walking trips, largely replaced by an increase in the share of car trips. In Belo Horizonte, there was a reduction in the share of walking trips, with an equivalent increase in the share of bus and car trips during the restrictions. The opposite occurred in Delhi, with an increase in the share of walking trips and a corresponding decrease in the share of all other modes.

Mode shares also did not change significantly in vision 2 between the start and end of the modelled period. However, the number of restriction periods varied between cities; Belfast and Delhi had three restriction periods, whereas Belo Horizonte only had two. All cities had more total days under restriction in this scenario relative to the reference one: 40% more in Belfast, 14% more in Belo Horizonte, and 2% more in Delhi. In all the case cities, there was a reduction in the share of car trips (most pronounced in Belfast) during the restrictions, with a corresponding increase in the share of all other modes.

Under vision 3, there was a small (1–2 percentage points) but lasting increment in the share of active travel at the end of the modelling period for Belfast and Delhi. Belo Horizonte did not have any significant change in mode share during the modelling period; however, it only had one restriction period and 88% fewer total restriction days relative to the other two cities.

Discussion

Transitioning away from private motor vehicle use is needed to reduce the overall environmental and health burden of transport systems. However, most evidence about the benefits of healthier and safer city mobility

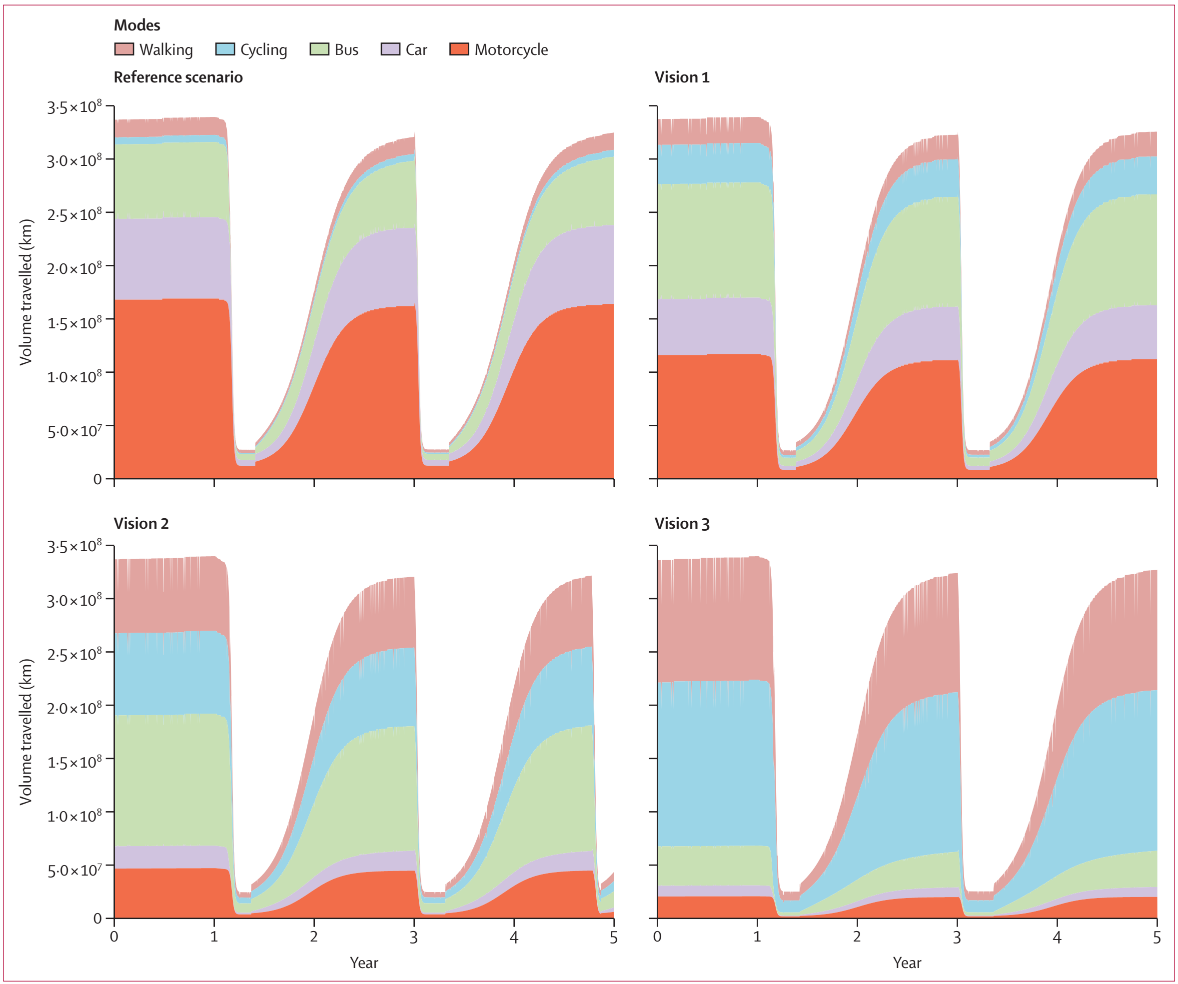

Figure 4: **Changes in mode share in Delhi, India, under IDO 2, by city mobility scenario**
IDO 2 refers to the more lethal but less transmissible IDO scenario. IDO=infectious disease outbreak.

patterns is limited to improvements in air pollution, road safety, and physical activity.[43,44] The results presented here add to this evidence base by showing the crucial role that urban transport planning will play in shaping the resilience of cities and in protecting city mobility and public health during natural hazards, which are projected to increase in frequency and magnitude.[2,4,5] Past studies have shown the importance of healthier and safer transport systems for climate change mitigation.[15,18] Our findings build on that, showing their importance for cities' capacity to adapt and respond to impeding IDOs and EWEs (appendix p 5).

Our results show that not every means of transitioning away from private motor vehicle use necessarily reduces the vulnerability of urban areas to all natural hazards and their city mobility and public health consequences. Our findings suggest that across all case cities, all envisioned scenarios could potentially reduce vulnerability against flooding, with greater contribution to city resilience the more ambitious the transition towards healthier city mobility patterns. Vision 3, the most ambitious scenario, is strongly coupled with the design of a compact city, with urban and transport design grounded on place-based, equity, and sustainability principles.[45,46] Beyond the expected health, environmental, and equity benefits (appendix p 4), this more ambitious vision performed best across all IDO and EWE shocks tested. However, realistically, few global cities have reached or are on track to reach city mobility infrastructure and patterns akin to those in vision 3, which requires a substantial investment in and commitment to prioritising healthy city redesign. Vision 3 is an ambition that should be encouraged and supported; however, incremental progresses (eg, visions 1 and 2) are welcomed and, for many cities, more achievable, at least in the near term. This notion is particularly true for cities in LMICs, where healthy city redesign is constrained by informal planning and the limited resources to implement more radical urban changes.[46] Available evidence (appendix p 4) also shows that more compact cities are probably associated with more sustainable mobility patterns (with implications for carbon emissions and climate change), better population health profiles (eg, fewer cases of obesity, type 2 diabetes, hypertension, cardiovascular diseases, and poor mental health), and less pronounced intra-city social, economic, and health inequalities. These additional benefits should also be considered when analysing the potential return in investing in more compact cities.

Visions 1 and 2 relied more heavily on public transit than vision 3. Public transit drove a large proportion of the differences in deaths prevented between scenarios, particularly in IDO shocks. These findings should not discourage the investment in public transit as a means of transitioning away from private motor vehicle use; rather, they should strengthen the case for well designed transit systems that reduce risk exposure and vulnerability in urban areas.[47] For instance, improved air ventilation and filtration, temperature and humidity control within buses, contactless payment and boarding, enhanced protocols for cleaning and disinfection of high-touch surfaces, hand sanitising stations at bus stops and within buses, and demand-responsive transport systems are some strategies and countermeasures that could be implemented to reduce the transmissibility of infectious diseases within public transit.

This study is the first to model city resilience in response to compound shocks across different cities and city mobility scenarios, setting a novel pathway for urban resilience research. We modelled three case study cities of different sizes, locations, and income levels on different continents, each with unique mobility patterns, health care, and transportation infrastructure. Although the three case study cities might not be representative of other cities in the same countries, and of cities in high-income, high-middle-income, and low-middle-income countries more broadly, they provide examples and insights from diverse contexts.

Our Article presents unique contributions and findings that are particularly relevant for those considering how to future-proof cities against impeding natural hazards. First, we show that different mobility scenarios have varying trade-offs in terms of resilience to potential IDOs and EWEs. Second, beyond estimating deaths directly attributable to IDOs and EWEs, we considered deaths attributable to road collisions and air pollution, two substantial health impacts from changes in urban form and mobility patterns. Third, our study includes a diverse set of case cities (including two from LMICs), mobility patterns scenarios, and IDOs and EWEs shocks, totalling 48 experiments covering a range of possible conditions. Lastly, we use four mobility pattern scenarios with incremental degrees of modal shift towards active travel. This approach allowed us to analyse their health implications using a dose–response perspective, thereby strengthening the confidence in our results.

We used system dynamics modelling to enhance the comprehension of the non-linear behaviour of urban complex systems and their associated temporal dynamics. Although system dynamics is a powerful causal-descriptive approach capable of modelling feedback, delays, and non-linear effects within a dynamic system, it is not considered as effective in the treatment of modelling uncertainties.[48] Our embedded modelling uncertainties are mainly due to the imperfect knowledge about the socioeconomic and climate change trajectories in the future. To overcome this limitation, multiple city mobility scenarios under different climatic scenarios were used. Scenarios were developed for case-specific analysis coupled with climate change-related EWE scenarios based on the outcomes of available local-based downscaled models of global climate change impact evaluations.

Our model has some limitations. First, we did not have the resources within the study to engage stakeholders from the three case cities in the model and scenario development process, which might lead to model misspecification.

Second, by expanding the scope of the model, we needed to balance the complexity and data requirements of the five modules across the three city cases. For instance, some models that focus on disease outbreaks or transport system performance can be more sophisticated on these specific domains, but with the caveat of having to reduce the scope of the model. It is also possible that by focusing on one city or natural hazard type, we could have addressed more of the contextual aspects that are unique to a given city, potentially resulting in a model less prone to misspecification.

Third, the population dynamics module did not consider population groups (eg, gender, age, cultural background, or deprivation level), as the data and information needed to parametrise the models at this level of disaggregation were not always available. This limitation constrained our capacity to model the scenarios and shock impacts by population groups, and prevented us from applying an equity lens to our analysis. For instance, urban and transport design that caters to the needs of diverse cultural and gender groups is necessary for equitable public transit and cycling uptake. We incorporated an equity lens by considering cities located across different continents and levels of income. Our findings suggest that investing in urban transport infrastructure that supports and promotes active transportation can help reduce global health inequalities that arise from EWEs and IDOs.

Fourth, we modelled shocks in isolation and considered only one type of major EWE—flooding events. Cities can be exposed to a spectrum of natural hazards, which can overlap in time or space, leading to non-linear interactions and effects. To account for the uncertainties in the forecast of floods and heavy rainfall days in each case city, we used two RCP pathways: 2·6 (best-case pathway) and 8·5 (worst-case pathway). Future flooding return periods or annual exceedance probabilities were assumed based on the available analysis by considering the probable impacts of climate change scenarios according to national climate risk reports.

Fifth, travel behaviour when restrictions on interpersonal contacts are put in place or lifted was modelled based on data from Apple Mobility Trends Reports and Google Community Mobility Reports. These data might be biased towards specific population groups and mobility behaviours. However, data were collected in a standardised way across the globe from millions of people, and previous studies have found strong correlations with survey-based transit and walking behaviour data.[49]

Sixth, despite being modelled as complex dynamic systems, the case cities were represented here as closed systems. As such, they do not include external influences such as immigration and emigration, links of the transport system to other places (eg, air transport, metropolitan buses, and trains), or a health-care system that acts as a hub for smaller surrounding cities. Furthermore, we purposefully did not consider possible demographic and technological transitions, such as changes in immigration and emigration rates and the uptake of electric cars. Technological advances that alter transport and urban planning, such as intelligent transport systems[50] and real-time monitoring of key infrastructure,[51] can drastically affect the trajectory and resilience of cities. However, these simplifications are required in models of this nature and should not detrimentally affect the interpretation of results, as these advances are likely to be equally implemented across all tested scenarios.

Lastly, in a few instances, input data were not available for a given case city (eg, $PM_{2·5}$ emission factor for motorcycles in Belo Horizonte), in which case we used data from a city with a similar context (eg, Sao Paulo). All these assumptions are described in the appendix (pp 9–20).

This paper highlights the role of transport system design in building resilience against the adverse impacts of climate change and IDOs across the globe. Our cities need well designed transport systems that can help them adapt to and withstand disruptions, facilitate access to essential services, support continuity of economic activities, and reduce the likelihood that already disadvantaged groups are not disproportionately affected by hazards. This study shows the need for forward-thinking urban transport planning that acknowledges and embraces its role in creating cities that are more resilient to future public health-related and climate-related threats, while promoting and sustaining healthier, safer, and more equitable city mobility patterns. Hunter and colleagues[16] showed that urgent changes in city mobility are possible. However, Nice and colleagues[13] showed that sustained modal shifts are only possible when coupled with city designs that avoid sustained mode shift towards private vehicle transit. Multisectoral approaches and solutions are urgently needed to fulfil the important cross-sectoral role that urban transport systems have, including for public health and the environment.

Contributors

All authors contributed to the study design. LG, MH, LL, CM, and JT drafted the article. LG, MH, and LL led the model development, with the support of JT and RG. LG, MH, and LL performed data analysis. LG, MH, LL, RW, SA, and RG accessed and verified the data. All authors interpreted the results and critically revised the manuscript for scientific content. All authors have access to the analysed data. All authors accepted responsibility for submitting the article for publication.

Declaration of interests

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Data sharing

This study uses publicly available data sources, all listed in the appendix and the model data spreadsheet (https://doi.org/10.17605/OSF.IO/AG8Z2). Processed data and analytical code used in the analyses in this study are available through https://doi.org/10.17605/OSF.IO/AG8Z2 and from the corresponding authors on reasonable request, immediately following publication, with no end date, for anyone who wishes to access them, and for any purpose.

References

1 Zscheischler J, Martius O, Westra S, et al. A typology of compound weather and climate events. *Nat Rev Earth Environ* 2020; **1:** 333–47.

2 Romanello M, Napoli CD, Green C, et al. The 2023 report of the *Lancet* Countdown on health and climate change: the imperative for a health-centred response in a world facing irreversible harms. *Lancet* 2023; **402:** 2346–94.

3 Centre for Research on the Epidemiology of Disasters, United Nations Office for Disaster Risk Reduction. The human cost of disasters: an overview of the last 20 years (2000–2019). United Nations Office for Disaster Risk Reduction, 2020.

4 Intergovernmental Panel on Climate Change. Climate change 2023: synthesis report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate Change, 2023.

5 Marani M, Katul GG, Pan WK, Parolari AJ. Intensity and frequency of extreme novel epidemics. *Proc Natl Acad Sci USA* 2021; **118:** e2105482118.

6 Baker RE, Mahmud AS, Miller IF, et al. Infectious disease in an era of global change. *Nat Rev Microbiol* 2022; **20:** 193–205.

7 World Bank. Urban development. https://www.worldbank.org/en/topic/urbandevelopment/overview (accessed Nov 2, 2023).

8 Ngcamu BS. Climate change effects on vulnerable populations in the Global South: a systematic review. *Nat Hazards* 2023; **118:** 977–91.

9 United Nations Environment Programme. Keeping the promise—annual report 2023. United Nations Environment Programme, 2024.

10 Khavarian-Garmsir AR, Sharifi A, Moradpour N. Are high-density districts more vulnerable to the COVID-19 pandemic? *Sustain Cities Soc* 2021; **70:** 102911.

11 Jinjarak Y, Ahmed R, Nair-Desai S, Xin W, Aizenman J. Accounting for global COVID-19 diffusion patterns, January–April 2020. *Econ Disaster Clim Chang* 2020; **4:** 515–59.

12 Sahana M, Ravetz J, Patel PP, Dadashpoor H, Follmann A. Where is the peri-urban? A systematic review of peri-urban research and approaches for its identification and demarcation worldwide. *Remote Sens (Basel)* 2023; **15:** 1316.

13 Nice KA, Thompson J, Zhao H, et al. City designs affect transport mode choice and exposure to health risks during and after a crisis: a global observational study. *Lancet Planetary Health* (in press).

14 Sharifi A. Urban form resilience: a meso-scale analysis. *Cities* 2019; **93:** 238–52.

15 Giles-Corti B, Foster S, Lynch B, Lowe M. What are the lessons from COVID-19 for creating healthy, sustainable, resilient future cities? *NPJ Urban Sustain* 2023; **3:** 29.

16 Hunter RF, Akaraci S, Wang R, et al. City mobility patterns during the COIVD-19 pandemic: analysis of a global natural experiment. *Lancet Public Health* 2024; **9:** e896–906.

17 Amoako C, Adarkwa KK, Poku-Boansi M. Effects of COVID-19 on urban mobility and public space use in Kumasi, Ghana. In: Brunn SD, Gilbreath D, eds. COVID-19 and a world of ad hoc geographies. Springer International Publishing, 2022: 987–1007.

18 Gössling S, Neger C, Steiger R, Bell R. Weather, climate change, and transport: a review. *Nat Hazards* 2023; **118:** 1–20.

19 Zukowska J, Gobis A, Krajewski P, et al. Which transport policies increase physical activity of the whole of society? A systematic review. *J Transp Health* 2022; **27:** 101488.

20 Zhang M, Wang S, Hu T, et al. Human mobility and COVID-19 transmission: a systematic review and future directions. *Ann GIS* 2022; **28:** 501–14.

21 Filip R, Gheorghita Puscaselu R, Anchidin-Norocel L, Dimian M, Savage WK. Global challenges to public health care systems during the COVID-19 pandemic: a review of pandemic measures and problems. *J Pers Med* 2022; **12:** 1295.

22 Newton PW, Rogers BC. Transforming built environments: towards carbon neutral and blue-green cities. *Sustainability (Basel)* 2020; **12:** 4745.

23 Munro A, Kovats RS, Rubin GJ, et al. Effect of evacuation and displacement on the association between flooding and mental health outcomes: a cross-sectional analysis of UK survey data. *Lancet Planet Health* 2017; **1:** e134–41.

24 Iungman T, Cirach M, Marando F, et al. Cooling cities through urban green infrastructure: a health impact assessment of European cities. *Lancet* 2023; **401:** 577–89.

25 Silveira IH, Cortes TR, Bell ML, Junger WL. Effects of heat waves on cardiovascular and respiratory mortality in Rio de Janeiro, Brazil. *PLoS One* 2023; **18:** e0283899.

26 Mills B, Andrey J, Doberstein B, Doherty S, Yessis J. Changing patterns of motor vehicle collision risk during winter storms: a new look at a pervasive problem. *Accid Anal Prev* 2019; **127:** 186–97.

27 Hanchey A, Jiva S, Bayleyegn T, Schnall A. Mortality surveillance during winter storm Uri, United States—2021. *Disaster Med Public Health Prep* 2023; **17:** e530.

28 Markolf SA, Hoehne C, Fraser A, Chester MV, Underwood BS. Transportation resilience to climate change and extreme weather events—beyond risk and robustness. *Transp Policy* 2019; **74:** 174–86.

29 Testa AC, Furtado MN, Alipour A. Resilience of coastal transportation networks faced with extreme climatic events. *Transp Res Rec* 2015; **2532:** 29–36.

30 Ortman SG, Lobo J, Smith ME. Cities: complexity, theory and history. *PLoS One* 2020; **15:** e0243621.

31 Giles-Corti B, Moudon AV, Lowe M, et al. What next? Expanding our view of city planning and global health, and implementing and monitoring evidence-informed policy. *Lancet Glob Health* 2022; **10:** e919–26.

32 Sterman J. Business dynamics: systems thinking for a complex world. Irwin–McGraw-Hill, 2000.

33 Maani KE, Cavana RY. Systems thinking, system dynamics: managing change and complexity. Pearson Education New Zealand, 2007.

34 Miller JD, Hutchins M. The impacts of urbanisation and climate change on urban flooding and urban water quality: a review of the evidence concerning the United Kingdom. *J Hydrol Reg Stud* 2017; **12:** 345–62.

35 NI.GOV.UK. North Eastern flood risk management plan. Department of Agriculture and Rural Development, 2015.

36 NI.GOV.UK. Northern Ireland flood risk assessment 2018. Department for Infrastructure, 2018.

37 Dalagnol R, Gramcianinov CB, Crespo NM, et al. Extreme rainfall and its impacts in the Brazilian Minas Gerais state in January 2020: can we blame climate change? *Clim Resil Sustain 2022;* **1:** e15.

38 Nunes AA, Pinto EJA, Baptista MB. Detection of trends for extreme events of precipitation in the Metropolitan Region of Belo Horizonte through statistical methods. *RBRH* 2018; **23:** e9.

39 Drumond RAS, Almeida RP, Nascimento NO. Climate change and master plan: flood mitigation in Belo Horizonte. *Cad Metrop* 2023; **25:** 899–922.

40 Tomar P, Singh SK, Kanga S, et al. GIS-based urban flood risk assessment and management—a case study of Delhi National Capital Territory (NCT), India. *Sustainability (Basel)* 2021; **13:** 12850.

41 Gupta S. Report on impact of floods in Delhi. Climatrans, 2017.

42 Intergovernmental Panel on Climate Change. Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate Change, 2014.

43 Stankov I, Garcia LMT, Mascolli MA, et al. A systematic review of empirical and simulation studies evaluating the health impact of transportation interventions. *Environ Res* 2020; **186:** 109519.

44 Mueller N, Rojas-Rueda D, Cole-Hunter T, et al. Health impact assessment of active transportation: a systematic review. *Prev Med* 2015; **76:** 103–14.

45 Giles-Corti B, Vernez-Moudon A, Reis R, et al. City planning and population health: a global challenge. *Lancet* 2016; **388:** 2912–24.

46 Guzman LA, Arellana J, Oviedo D, Aristizábal CAM. COVID-19, activity and mobility patterns in Bogotá. Are we ready for a '15-minute city'? *Travel Behav Soc* 2021; **24:** 245–56.

47 Gutiérrez A, Miravet D, Domènech A. COVID-19 and urban public transport services: emerging challenges and research agenda. *Cities Health* 2021; **5** (suppl 1)**:** S177–80.

48 Hafezi M, Stewart RA, Sahin O, Giffin AL, Mackey B. Evaluating coral reef ecosystem services outcomes from climate change adaptation strategies using integrative system dynamics. *J Environ Manage* 2021; **285:** 112082.

49 Hunter RF, Garcia L, de Sa TH, et al. Effect of COVID-19 response policies on walking behavior in US cities. *Nat Commun* 2021; **12:** 3652.

50 Tran CNN, Tat TTH, Tam VWY, Tran DH. Factors affecting intelligent transport systems towards a smart city: a critical review. *Int J Constr Manag* 2023; **23:** 1982–98.

51 Yereseme AK, Surendra HJ, Kuntoji G. Sustainable integrated urban flood management strategies for planning of smart cities: a review. *Sustain Water Resour Manag* 2022; 8: 85.