City mobility patterns during the COVID-19 pandemic: analysis of a global natural experiment

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Summary

Background During the COVID-19 pandemic, changes were seen in city mobility patterns around the world, including in active transportation (walking, cycling, micromobility, and public transit use), creating a unique opportunity for global public health lessons and action. We aimed to analyse a global natural experiment exploring city mobility patterns during the pandemic and how they related to the implementation of COVID-19-related policies.

Methods We obtained data from Apple's Mobility Trends Reports on city mobility indexes for 296 cities from Jan 13, 2020 to Feb 4, 2022. Mobility indexes represented the frequency of Apple Maps queries for driving, walking, and public transit journeys relative to a baseline value of 100 for the pre-pandemic period (defined as Jan 13, 2020). City mobility index trajectories were plotted with stratification by country income level, transportation-related city type, population density, and COVID-19 pandemic severity (SARS-CoV-2 infection rate). We also synthesised global pandemic policies and recovery actions that promoted or restricted city mobility and active transportation (walking, cycling and micromobility, and public transit) using the Shifting Streets dataset. Additionally, a natural experiment on a global scale evaluated the effects of new active transportation policies on walking and public transit use in cities around the world. We used multivariable regression with a difference-in-difference (DID) analysis to explore whether the implementation of walking or public transit promotion policies affected mobility indexes, comparing cities with and without implementation of these policies in the pre-intervention period (Jan 27 to April 12, 2020) and post-intervention period (April 13 to June 28, 2020).

Findings Based on city mobility index trajectories, we observed an overall decline in mobility indexes for walking, driving, and public transit at the beginning of the pandemic, but these values began to increase in April, 2020. Cities with lower population densities generally had higher driving and walking indexes than cities with higher population density, while cities with higher population densities had higher public transit indexes. Cities with higher pandemic severity generally had higher driving and walking indexes than cities with lower pandemic severity, while cities with lower pandemic severity had higher public transit indexes than other cities. We identified 587 policies in the dataset that had known implementation dates and were relevant to active transportation, which included 305 policies on walking, 321 on cycling and micromobility, and 143 on public transit, across 230 cities within 33 countries (19 high-income, 11 middle-income, and three low-income countries). In the global natural experiment (including 39 cities), implementation of policy interventions promoting walking was significantly associated with a higher absolute value of the walking index (DID coefficient 20·675 [95% CI 8·778–32·572]), whereas no such effect was seen for public transit-promoting policies (0·600 [–13·293 to 14·494]).

Interpretation Our results suggest that the policies implemented to mitigate the COVID-19 pandemic were effective in changing city mobility patterns, especially increasing active transportation. Given the known benefits of active transportation, such policies could be maintained, expanded, and evaluated post pandemic. The discrepancy in the interventions between countries of different incomes highlights that changes to the infrastructure to prioritise safe walking, cycling, and easy access to public transit use could help with the future-proofing of cities in low-income and middle-income countries.

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Introduction

The COVID-19 pandemic has affected lives across the globe in unprecedented ways, and pandemic recovery responses and actions have led to various health, economic, social, and environmental impacts.[1–13] During the pandemic period, all communities had to rapidly react, adapt, and operate in ways that have inextricably changed city mobility, including active transportation. The combination of these rapid, large-scale alterations and the level of global connectivity and integration we live in created a global natural experiment on city mobility policy patterns. We witnessed determined and swift actions of

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Research in context

Evidence before this study

A systematic review was conducted in December, 2021, using subject headings and keywords related to COVID-19, policy responses, active transportation, and travel behaviour, in Scopus, Web of Science, Worldwide Political Science Abstracts, PubMed Central, and the WHO COVID-19 Research Database. As a result of this search, we identified previously published studies that evaluated the health, economic, social, and environmental impact of the COVID-19 pandemic recovery responses and actions. Two systematic reviews explored the impact of non-pharmaceutical interventions on air quality and greenhouse gas emissions and reported a reduction in primary air pollutants and emissions of greenhouse gases in a majority of observed cities. Several reviews investigated how public responses to the COVID-19 crisis affected city transportation patterns during the early stage of the pandemic. Their results suggested that the pandemic produced a short and temporary reduction in city mobility consistent with government restrictions, reduction of industrial activities, and self-imposed curtailment of regular social activities among individuals.

Added value of this study

We evaluated the effect of city-based active transport policy actions implemented during the COVID-19 pandemic on walking behaviour and public transit use in cities, and assessed the extent of equity consideration in these policies. We included various cities around the globe in our analysis, among which many reported high SARS-CoV-2 infection rates, with wide variations in existing active travel infrastructure, pre-pandemic walking behaviours, and public transit use. We use mobility data from hundreds of thousands of people to, for the first time, track and analyse changes in walking behaviour and public transit use that appeared in response to active transport policy and infrastructure interventions deliberately enacted across these cities during the pandemic. Our analyses include real-time data captured on an unprecedented scale that enabled a global natural experiment.

Implications of all the available evidence

COVID-19 recovery policies in some instances led to increased use of active transportation, especially walking. These findings show that positive change for public health can be achieved when political will and needs align. There is potential for cities to adopt or expand policies to promote or sustain rates of active transport, which could additionally benefit associated goals of public health equity and climate action.

local and national governments to the public health threat from COVID-19. For example, the pandemic response measures in Milan, Paris, London, and Bogotá included pedestrianising streets and expanding cycle lanes, thereby facilitating COVID-19-safe transport during the crisis and enhancing economic activity and quality of life afterwards.[14] Typically, cities with city planning, design, and transportation systems favouring active modes of transportation were able to react and adapt their systems faster, building upon a solid foundation of previous experience and current capacity (eg, cycling and walking infrastructure and policies) and alignment of local, regional, and national policies and politics.[14]

However, there were disparities in response to COVID-19 recovery actions both within and between countries. Within-city disparities emerged among populations as not everyone could benefit from the enacted urban public health responses (eg, access to pedestrian and cycling facilities). Compared with higher-income areas, policy implementation (or lack of implementation) in response to COVID-19 was vastly different in cities in middle-income countries and low-income countries, where similar capacity and experiences were not evident.[15,16] Cities with low funding capacity, underdeveloped health-care and transport infrastructure, and limited technological capacity had less comprehensive and coordinated policy responses than higher-income cities and countries with greater availability of funding and more developed infrastructure.[17]

See Online for appendix

Pandemic response measures primarily focused on restrictions on public transit systems to increase adherence to physical distancing requirements, but governments in many settings have indicated that these changes will be permanent.[18] If made permanent (and well implemented), these interventions provide an opportunity to improve population health and wellbeing (including physical activity),[19] to reduce air and noise pollution and greenhouse gas emissions, to reduce risk of traffic collisions and casualties, to reduce risk of non-communicable and airborne diseases, to promote social equity, to reduce the demand on health services, and to contribute considerably to the UN Sustainable Development Goals.

Studies have investigated the effects of COVID-19 on transportation and pedestrian mobility. However, these studies did not focus specifically on active transportation modes and did not evaluate differences in policy responses across countries with varying income levels (see appendix p 2 for an overview). Furthermore, there has been little evaluation of the equity impacts of the policies adopted globally.

The necessary non-pharmaceutical responses to the COVID-19 pandemic designed to reduce risk of interpersonal disease transmission provided a unique opportunity to study changes in city mobility, including active transportation globally.

Understanding how pandemic response measures have affected city mobility patterns, including active transportation and related co-benefits, is important to help devise strategies to prevent the potential health and societal impacts of declining walking and cycling levels and to future-proof our cities against the impacts of impending disease outbreaks and subsequent inequities. We need robust, evidence-based policies that both improve active transportation opportunities and mitigate or reduce health-related, social, and environmental inequities. Advances in remote sensing and mobility tracking at scale mean that this is the first time we can track and analyse changes in city mobility patterns, including walking and public transit use, using data from hundreds of thousands of people, facilitating a global natural experiment. The findings could help us to greatly advance global public health actions by designing and informing policies and actions that promote healthier and more equitable communities, city planning and design, and active transportation, as well as future-proofing our cities and communities against the effects of impending disease outbreaks.

This study had three main objectives: (1) to investigate global changes in population city mobility patterns during the COVID-19 pandemic; (2) to synthesise global policies and recovery actions for city mobility (walking, cycling, micromobility use, and public transit use) during the COVID-19 pandemic, and assess whether health inequities were considered in such policies; and (3) to evaluate the effects of pandemic response policies on walking behaviour and public transit use in cities in a global natural experiment.

Methods

Overview

We used a multianalytical approach to address the objectives, including spatial analysis, policy analysis, and difference-in-difference (DID) analysis.

Ethical approval or consent was not required for this study as it analysed secondary data sources.

Global analysis of city mobility during the COVID-19 pandemic

For objective 1, we investigated global changes in population trends in city mobility patterns, including the spatial distributions of walking behaviour and public transit use, stratified by different groups (including country income level, severity of the pandemic, transportation-related city type, and population density; see appendix p 3 for further details). We aggregated daily mobility data for each city at the weekly, monthly, and yearly levels, using Apple's Mobility Trends Reports data.[20] These data show how queries in Apple Maps for driving, public transit use, and walking journeys changed compared with a baseline timepoint of Jan 13, 2020. The mobility index has a baseline value of 100, with values greater than 100 indicating increased mobility and values less than 100 indicating decreased mobility compared with the start of the pandemic. Data for 296 cities (all those with available data) from Jan 13, 2020 until Feb 4, 2022 were used. The justification for the use of Apple's Mobility Trends Reports data is detailed in the appendix (p 4).

Exploratory spatial and trajectory data analyses were done to explore how city mobility patterns varied globally and changed over time during the COVID-19 pandemic. First, we displayed the spatial distribution of different city mobility indexes for driving, walking, and public transit use in 2020, 2021, and 2022, using geographical information systems data. Second, local Moran's *I* statistics[21] (equations 1 to 9 in appendix p 18) were used to reflect the spatial patterns of mobility index in each city and its neighbours; these statistics show the degree of spatial difference and significance between the mobility index of each city and its surrounding cities. This information was used to develop four types of mobility clusters: high–high (cities with higher levels of a specific mobility index cluster with each other), low–low (cities with low levels of a specific mobility index cluster with each other), high–low (cities with higher levels of a specific mobility index cluster with cities with a lower level of a specific mobility index), and low–high (cities with lower level of a specific mobility index cluster with cities with higher level of a specific mobility index). Third, to understand the inequities in trajectories of different city mobility indexes over time, we stratified the sampled cities by country income level (ie, high *vs* upper-middle *vs* lower-middle), transportation-related city type based on Thompson and colleagues'[22] definitions (ie, motor city, high transit, chequerboard, informal, cul-de-sac, large block, irregular, intense; appendix p 3), population density (grouped into quartiles), and severity of the COVID-19 pandemic (ie, SARS-CoV-2 infection rate, grouped into quartiles), and presented the monthly trajectories of different mobility indexes (appendix p 3).

Mapping of policies and response actions to address city mobility

For objective 2, we synthesised global policies and recovery actions for city mobility (walking behaviour, cycling behaviour, use of micromobility [eg, e-bikes, e-scooters], and public transit use) during the COVID-19 pandemic and assessed the possible effects of these actions to address public health inequities that are influenced by multifactorial contributors, including disparities in city mobility and accessibility.[23,24] Data on country-level lockdown restrictions and closure measures that could plausibly have affected city mobility behaviour were obtained from the Oxford COVID-19 Government Response Tracker.[25] The dataset comprised systematically collected data on the response policies from Jan 21, 2020, to Aug 31, 2022 for over 180 countries. It contained 21 indicators grouped into four categories, including containment and closure policies, economic policies, health-system policies, and vaccine policies. We focused on the containment and closure policies. In the initial policy search, the objective was to collect all policies that could potentially influence city mobility behaviour. We captured policies broadly categorised into two groups: national-level policies sourced from the Oxford COVID-19 Government Response Tracker and spatial policy responses at the city level (from the Shifting Streets dataset).[26] As the focus was on policies influencing city mobility, we focused only on containment and closure policies, which included school closures, workplace closures, cancellation of public events, restrictions on gatherings, closure of public transit, and stay-at-home requirements. The stringency index (a composite measure based on nine indicators, including school closures, workplace closures, cancellation of public events, restrictions on public gatherings, closures of public transport, stay-at-home requirements, public information campaigns, restrictions on internal movements, and international travel controls)[25] for these measures was calculated.

For city-level response policies, we used the Shifting Streets dataset,[26] which collated data from three sources: local actions to support walking and cycling, COVID-19 Liveable Streets Response Strategies, and the COVID Mobility Network. The dataset contained over 1000 policies and included information such as the announcement and implementation date of each policy, policy descriptions, and whether the response was temporary or permanent.

First, policy descriptions were screened and categorised into four domains: walking, cycling, micromobility, and public transit use. We excluded policies without a known implementation date, with limited descriptions (ie, insufficient detail provided to facilitate further analysis), and not related to active transportation modes. Second, the four domains were categorised into key themes and labelled to indicate promotion or restriction of the respective domain activity. Third, the extent of equity consideration of policies was analysed using the PROGRESS-plus framework (appendix p 25).[27] This framework consists of factors that can potentially disadvantage health opportunities outcomes: place of residence; race, ethnicity, culture, and language; occupation; gender and sex; religion; education; socioeconomic status; and social capital; as well as the “plus” factors, which include disability (see O’Neill and colleagues’ study[27] for further descriptions). Policies were reviewed to identify if and how each policy incorporated equity factors into their approach.

Global natural experiment on the impact of the response policies and actions on active transportation

For objective 3, we evaluated the effect of response policies on walking behaviour and public transit use in a global natural experiment. We defined an intervention group and control group according to whether a particular city did or did not implement the specified intervention. Eligibility criteria for cities are described in the appendix (pp 6–8). Briefly, cities in the intervention group had to have an intervention date in April or May, and we excluded cities with missing information on covariates and without policy implementation information. For the control group, cities had to have intervention information within the policy dataset (to ensure that the cities had been screened) and an intervention date after the target period. The target period was defined as Jan 27 to Aug 23, 2020, to ensure the numbers of observations before and after the intervention date were equal. Due to the lack of data from Apple Mobility Trends Reports, we were not able to include analyses that investigated the effectiveness of the policy interventions on cycling behaviour.

We assessed the effect of policies on active transportation (including walking and public transit use) in the early phase of the COVID-19 pandemic. The analysis of active transportation policies suggested that most walking and public transit promotion policies were implemented in April or May, 2020. Therefore, the intervention point was set as mid-April, 2020 (and mid-May, 2020 in a sensitivity analysis). We excluded cities with missing information on covariates (appendix pp 6–13) and without policy implementation information.

Based on the analysis of active transportation policies, any policy defined as promoting walking was included in the intervention for walking index, and any policy defined as promoting public transit use was included in the intervention for public transit use index. To further understand the effect of specific policies, we investigated the effects of two policy approaches to promoting walking (road closures to motor vehicles and road space reallocation for pedestrians) and three policy approaches to promoting public transit use (COVID-19 control measures, financial support, and service improvement). Policy descriptions are provided in the appendix (pp 19–20). Changes in different mobility indexes between the pre-intervention period (Jan 27 to April 12, 2020) and post-intervention period (April 13 to June 28, 2020) were investigated. We used weekly city mobility indexes and multivariable linear regression with a DID study design (equation 10 in the appendix [p 10]) to calculate the mean difference between the intervention and control groups before the intervention point compared with after the intervention point, after adjusting for covariates (appendix p 10). We investigated differences in both the absolute value of the walking or public transit use index, and the change in value of the walking or public transit use index (eg, value in week 3=index in week 3 – index in week 2).

In a sensitivity analysis, the intervention point was set as mid-May (pre-intervention period Jan 27 to May 16, 2020; post-intervention period May 17 to Aug 23, 2020) and the above analysis repeated. Justification for the global natural experiment analysis design and other study designs considered are detailed in the appendix (pp 6–13).

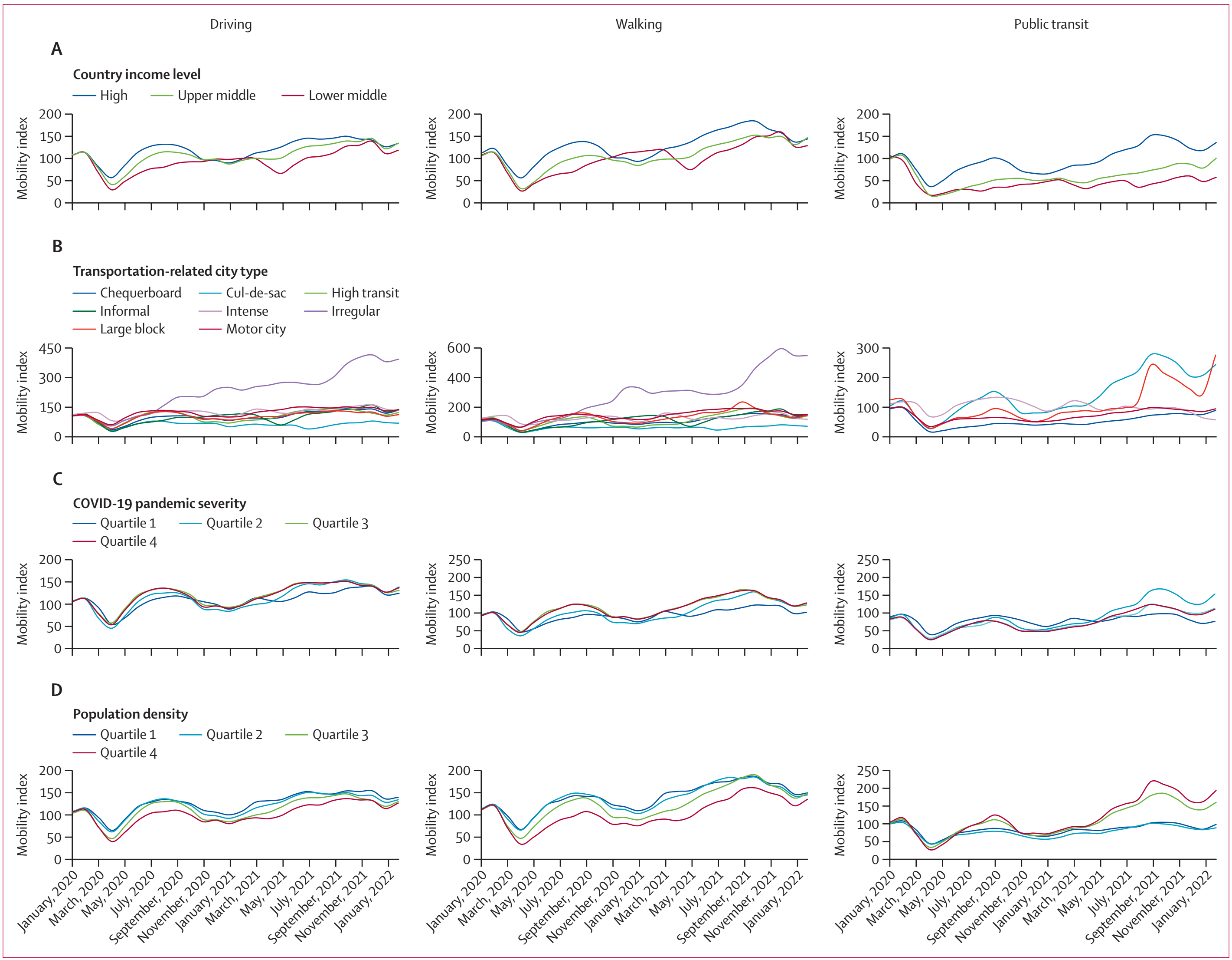


Figure 1: **Stratified trajectories of Apple Mobility Trends Reports data from Jan 13, 2020, to Feb 4, 2022**

Driving, walking, and public transit mobility indexes by month over time are shown with stratification by country income level (A), transportation-related city type (B), severity of COVID-19 pandemic (C), and population density (D). Mobility index has a baseline value of 100, with baseline defined as the start of the pandemic (Jan 13, 2020); values greater than 100 indicate increased mobility and values less than 100 indicate decreased mobility. Income level was based on the UN classification of countries. Transportation-related city type categories were based on Thompson and colleagues'[22] definitions. Severity of the COVID-19 pandemic was classified into quartiles of SARS-CoV-2 infection rate: 0–4% (quartile 1), 5–12% (quartile 2), 13–17% (quartile 3), and 18–31% (quartile 4). Population density was classified into quartiles: 31–1180 people per km² (quartile 1), 1195–2031 people per km² (quartile 2), 2047–4521 people per km² (quartile 3), and 4522–75 714 people per km² (quartile 4). Note: y-axis scales differ between graphs.

Role of the funding source

There was no funding source for this study.

Results

Objective 1 was to investigate city mobility during the COVID-19 pandemic. The spatial distributions of the aggregated mobility indexes (ie, driving, walking, and public transit use) in 2020, 2021, and 2022 are shown in the appendix (p 14). Generally, driving and walking indexes were high in North America, some parts of Europe (eg, western Europe), and Japan, but low in South America, Oceania, Africa, and most parts of Asia. The public transit use index was high in Europe, but low in North America, South America, Asia, and Oceania. The spatial distributions of sampled cities and transportation-based city type, developmental level, income level, population density, and COVID-19 pandemic severity are shown in the appendix (pp 16–17). Based on local Moran's *I* values in relation to the three types of aggregated city mobility indexes, high–high and low–low clusters comprised the majority of clusters (appendix p 15). High–high clusters of driving index and walking index were mainly in North America, whereas low–low clusters were in the rest of the world, similar to the results from the spatial distribution analysis.

Figure 1 shows the trajectories of mobility indexes for driving, walking, and public transit use separately for 296 cities between Jan 13, 2020, and Feb 4, 2022, stratified by country income level, transportation-related city type, severity of the pandemic, and population density (see appendix p 18 for details on statistical methods).

Overall, we observed a decline in the value of all three mobility indexes at the beginning of the pandemic, but the values began to increase in April, 2020. Stratified analysis indicated heterogeneity in the trajectories of mobility indexes between different groups. First, cities in high-income countries generally had higher mobility indexes than cities in upper-middle-income and lower-middle-income countries. Second, the driving and walking indexes were much higher in cities classified as having an irregular transportation-related type; however, there were only two cities, (Dubai [United Arab Emirates] and Victorville-Hesperia [CA, USA]) of this type. Additionally, the public transit use index was much higher in cities classified as high transit or large block transportation-related types than in cities of other types for most of the time period. Third, cities in quartiles 1 and 2 of population density (ie, population density ranges 31–1180 people per km² and 1195–2031 people per km², respectively) had higher driving and walking indexes than cities in quartiles 3 and 4 (2047–4521 people per km² and 4522–75 714 people per km²), while cities in quartiles 3 and 4 of population density had higher public transit index than cities in quartiles 1 and 2. Finally, cities in quartiles 3 and 4 of pandemic severity (ie, SARS-CoV-2 infection rate ranges of 13–17% and 18–31%, respectively) had higher driving and walking indexes than cities in quartiles 1 and 2 (0–4% and 5–12%, respectively), while cities in quartile 2 had a higher public transit use index than cities in other quartiles (appendix p 17).

Objective 2 was to map policies and response actions addressing city mobility. The Shifting Streets dataset (last updated in September, 2022) contained 1472 city mobility-related policies from 536 cities within 62 countries. After excluding 794 policies without a known implementation date and 91 unrelated to active transportation modes, we included 587 policies in our analysis. These policies were from 230 cities within 33 countries (19 high-income, six upper-middle-income, five lower-middle-income, and three low-income).

Figure 2 presents the distribution of active transportation policy types by country income group. Additional details and distributions, including the number of policies for each mode across different country income groups, are presented in the appendix (pp 21–24).

Of the 269 policies that promoted walking, nine themes were identified: road closures to motor vehicles, reduced speed limitations for motor vehicles, reduced waiting times for pedestrians at crossings, implementation of automated crossing signals, reallocation of road space to prioritise pedestrians, reallocation of road space to facilitate dining, provision of information for pedestrians, creation or revitalisation of public spaces, and establishment of designated walking directions (appendix pp 19–20). Conversely, 36 policies across two policy themes restricted walking behaviour: closure of pedestrian paths and reduced parking fees for motor vehicles. The most frequently implemented policies to support walking across countries were road closures to motor vehicles and reallocation of road or parking space (appendix pp 21–24).

Most walking policies (292 [96%] of 305) were implemented in high-income countries, while only nine policies (3%) were implemented in lower-middle and three policies (1%) in higher-middle-income countries such as Brazil, India, and Pakistan. Within these countries, policy themes included the reallocation of road space for pedestrian activity, closure of pedestrian paths, and revitalisation of public spaces (appendix pp 21–24). Only one walking policy was identified in a low-income country (Uganda); this policy, implemented in Jinja in May, 2020, aimed to modify the market design and traffic flow in the central market area to promote safe walkability.

Among the 299 policies promoting cycling and micromobility, ten themes were identified: new cycle lanes, road closure to motor vehicles, reallocation of road space for cyclists, reallocation of road space for dining, provision of cycle parking, reduced speed limitation for motor vehicles, financial support, providing information, training, and cycling direction (appendix pp 19–20). Policies that had a restrictive effect on cycling and micromobility (22 in total) included the closure of cycle lanes and the reduction of parking fees specifically for motor vehicles. Road closure, financial support, and the reallocation of road or parking spaces were the most commonly implemented measures to promote cycling and micromobility.

Similar to walking policies, cycling and micromobility policies were most frequently enacted in high-income countries (303 [94%] of 321 policies). Fewer policies (18 [6%]) were implemented in lower-middle-income and higher-middle-income countries, including Brazil, Turkiye, and Colombia. These policies fell under various themes, including the reallocation of road and parking space, provision of training and financial support, and reduction of motor vehicle speeds, all of which aim to promote safer cycling experiences. No policies were identified in low-income countries (appendix pp 22–23).

We identified 143 public transit-related policies. Three themes across 123 policies promoted the use of public transit: implementing COVID-19 control measures, provision of financial support, and improvement of services. By contrast, the 20 restrictive policies included reducing service frequency and lowering parking fees for motor vehicles. Detailed descriptions and examples of policy themes are provided in the appendix (pp 19–20).

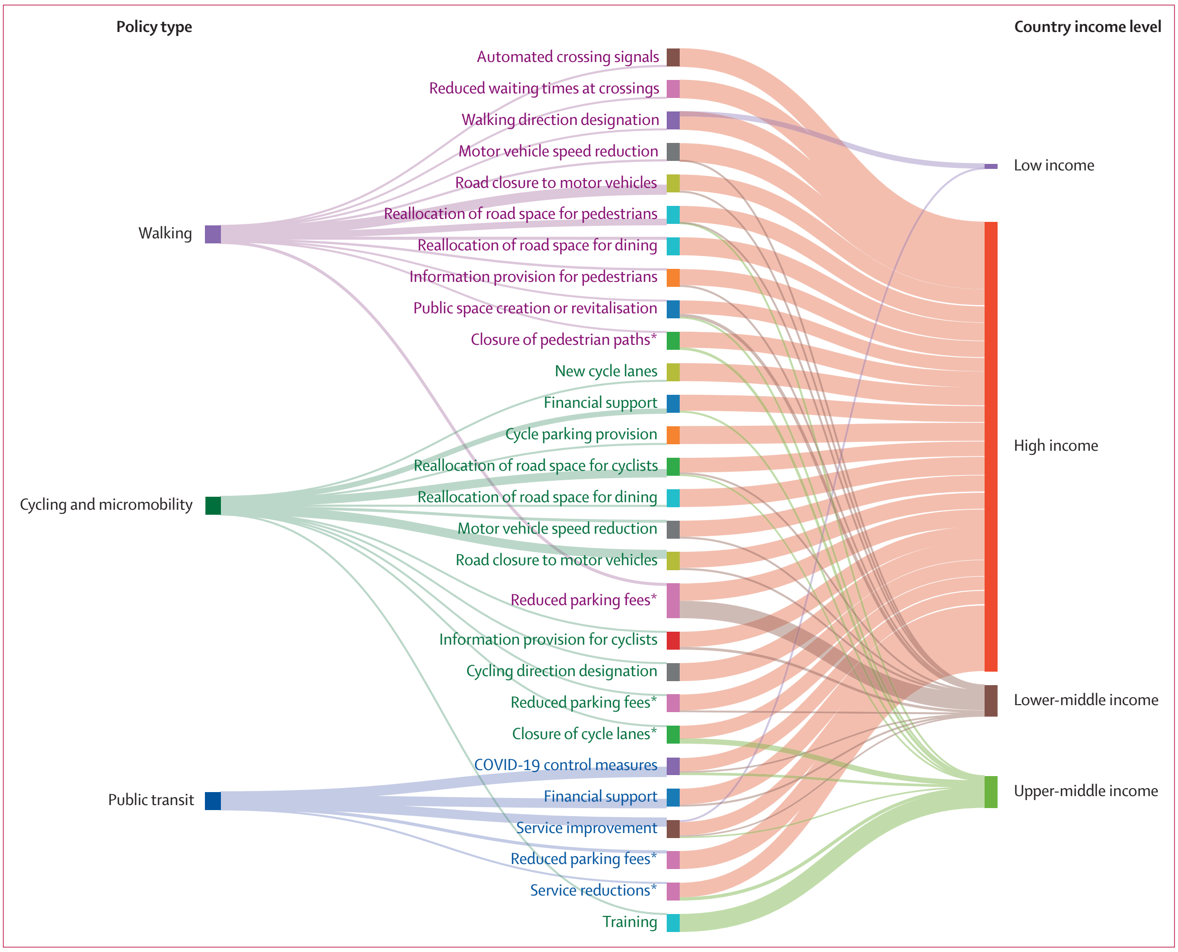


Figure 2: **Sankey plot showing the distribution of active transportation policy types by country income level**
As some policies were categorised into more than one theme, the total across policy themes is greater than the total number of policies analysed. *Policies considered to restrict (rather than promote) active transportation.

Few public transit policies were identified in lower-middle-income and higher-middle-income countries (ten [7%] of 143), and low-income countries (three [2%]). Implementation of COVID-19 control measures and service improvement emerged as the most prevalent themes in these locations. Only three policies were identified in low-income countries (Rwanda and the Republic of the Congo). In March, 2020, Rwandan authorities set up handwashing basins at a bus station in Kigali, prioritising public health and hygiene. In the Republic of the Congo, a contact-tracing programme was implemented in April, 2020, which used an SMS system to trace the chain of contamination (appendix pp 19–20).

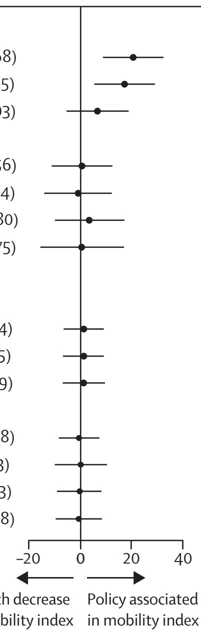
Of the 587 policy documents analysed, 423 (72%) included policies specifically targeting at least one PROGRESS-plus component. The place component was the most prevalent (345 policies), with specific focus on geographical considerations, aiming to benefit the entire city or accessible locations. 124 policies focused on specific occupational groups (ie, health-care workers, recognising the significance of addressing their unique needs and challenges). Additionally, 90 policies targeted socioeconomic status, highlighting the importance of addressing public health equities based on economic factors.

Objective 3 was to investigate the impact of response policies and actions on active transportation. We included 39 cities in the analysis: for the analysis of walking, 36 cities were included in intervention group and three in the control group; for the analysis of public transit use, 23 cities were included in intervention group and two in the control group. Descriptive statistics for all variables are presented in the appendix (p 26). Figure 3 shows the effects of policies on active transportation (walking and public transit use) in the early phase of the COVID-19 pandemic.

When the intervention point was set as mid-April, 2020, implementation of policies promoting walking was significantly associated with an increased absolute value of the walking index (DID coefficient 20·675 [95% CI 8·778 to 32·572]), while there was no evidence that such policy implementations were associated with the change in value of the walking index (1·233 [–6·592 to 9·059). When the intervention point was set as mid-May, 2020, the results were similar (21·336 [11·389 to 31·283] for absolute value of walking index; 0·118 [–6·581 to 6·817] for change in value of walking index). The results for specific active transportation policy interventions showed that road closures to motor vehicles were significantly

A Mid-April intervention point

	Number of cities: With intervention	Number of cities: Without intervention	Mean difference (SD): Pre-intervention	Mean difference (SD): Post-intervention	DID coefficient (95% CI)	p value
Walking mobility index*						
All policies	36	3	2·467 (7·766)	26·646 (7·068)	20·675 (8·778 to 32·572)	0·00065
Road closure to motor vehicles	18	3	3·342 (7·997)	23·954 (6·565)	17·371 (5·533 to 29·210)	0·0039
Road space reallocation	13	3	–0·494 (8·982)	9·162 (6·603)	6·821 (–5·341 to 18·984)	0·271
Public transit mobility index*						
All policies	23	2	1·579 (9·615)	1·446 (4·956)	0·600 (–13·293 to 14·494)	0·932
COVID-19 control measures	8	2	2·968 (10·487)	3·253 (6·064)	–0·842 (–14·209 to 12·525)	0·901
Financial support	7	2	1·672 (9·658)	4·980 (4·680)	3·596 (–10·197 to 17·389)	0·607
Service improvement	7	2	6·740 (12·259)	4·064 (6·075)	0·692 (–15·753 to 17·137)	0·934
Change in walking mobility index†						
All policies	36	3	1·048 (4·211)	1·870 (1·244)	1·233 (–6·592 to 9·059)	0·757
Road closure to motor vehicles	18	3	0·940 (3·992)	1·472 (1·245)	1·116 (–6·924 to 9·155)	0·785
Road space reallocation	13	3	–0·218 (4·225)	0·407 (1·259)	1·233 (–7·089 to 9·555)	0·771
Change in public transport mobility index†						
All policies	23	2	0·129 (5·323)	0·505 (0·948)	–0·605 (–8·671 to 7·461)	0·883
COVID-19 control measures	8	2	–0·105 (6·966)	0·233 (1·133)	0·120 (–10·308 to 10·549)	0·982
Financial support	7	2	0·202 (5·026)	–0·230 (1·133)	–0·447 (–9·325 to 8·430)	0·921
Service improvement	7	2	0·265 (5·675)	–0·164 (1·058)	–0·680 (–9·915 to 8·555)	0·885



B Mid-May intervention point

	Number of cities: With intervention	Number of cities: Without intervention	Mean difference (SD): Pre-intervention	Mean difference (SD): Post-intervention	DID coefficient (95% CI)	p value
Walking mobility index*						
All policies	36	3	7·948 (6·551)	31·721 (6·753)	21·336 (11·389 to 31·283)	<0·0001
Road closure to motor vehicles	18	3	7·895 (6·808)	29·594 (6·327)	20·089 (10·216 to 29·962)	<0·0001
Road space reallocation	13	3	1·614 (7·736)	8·269 (6·383)	4·183 (–6·092 to 28·209)	0·424
Public transit mobility index*						
All policies	23	2	2·154 (8·111)	6·018 (13·128)	10·714 (–6·781 to 6·817)	0·229
COVID-19 control measures	8	2	3·472 (8·860)	6·032 (8·434)	2·849 (–8·782 to 14·481)	0·630
Financial support	7	2	2·891 (8·250)	24·291 (21·184)	36·338 (11·330 to 61·346)	0·0045
Service improvement	7	2	6·459 (9·957)	5·494 (8·912)	8·581 (–4·783 to 21·945)	0·207
Change in walking mobility index†						
All policies	36	3	2·643 (2·960)	1·073 (1·232)	0·118 (–6·581 to 6·817)	0·972
Road closure to motor vehicles	18	3	1·302 (3·370)	1·221 (1·184)	0·210 (–6·846 to 7·266)	0·953
Road space reallocation	13	3	1·483 (3·627)	0·942 (1·510)	0·136 (–7·345 to 7·617)	0·971
Change in public transport mobility index†						
All policies	23	2	–0·190 (3·653)	1·401 (2·469)	1·949 (–5·104 to 9·002)	0·588
COVID-19 control measures	8	2	0·230 (3·675)	1·104 (1·382)	0·422 (–6·901 to 7·745)	0·910
Financial support	7	2	–0·268 (3·578)	3·710 (4·133)	5·918 (–3·366 to 15·204)	0·210
Service improvement	7	2	–0·090 (5·075)	0·645 (1·317)	0·584 (–8·004 to 9·171)	0·894

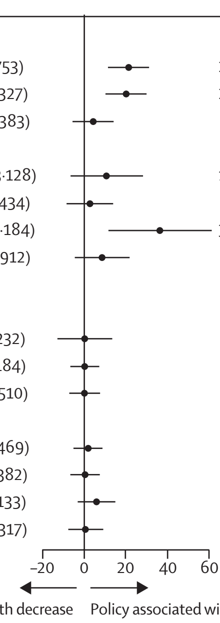


Figure 3: **Difference-in-difference results for walking and public transit use indexes before and after the intervention point**
Graphs show the regression results from multivariable linear models examining walking and public transit use indexes before and after the intervention. DID coefficients represent the intervention effect of the policy on mobility indexes. (A) Results when the intervention point was set as mid-April, 2020, with pre-intervention samples from Jan 27 to April 12, 2020, and post-intervention samples from April 13 to June 28, 2020. (B) Results when the intervention point was set as mid-May, 2020, with pre-intervention samples from Jan 27 to May 16, 2020, and post-intervention samples from May 17 to Aug 23, 2020. Error bars are 95% CIs. "All policies" indicates that samples with any of the walking promotion policies or public transit promotion policies, respectively, mentioned in figure 2 were included in the model. Analyses of specific policies (eg, road closure to motor vehicles) included only samples with the implementation of that policy. All models were adjusted for transportation-based city type, gross domestic product, night light value, human development index, average annual level of particulate matter with a diameter of <2·5 μm, stringency index, population density, and SARS-CoV-2 infection rate. The definitions of these covariates can be found in the appendix (p 3). *The dependent variable is the absolute average value of the specified mobility index in a given week. †The dependent variable is the change in the mobility index (eg, value in week 3=walking index week 3–walking index week 2).

associated with a higher absolute value of the walking index after the intervention, while there was no evidence of such an effect for road space reallocation (figure 3).

Setting the intervention point in mid-April, 2020, there was no evidence that the public transit use index was different after versus before policy interventions promoting public transit compared with cities without such policy interventions (DID coefficient 0·600 [95% CI –13·293 to 14·494]), nor of a difference in the change in public transit use index (–0·605 [–8·671 to 7·461]). Setting the intervention point as mid-May, 2020, the results remained similar (10·714 [–6·781 to 28·209] and 1·949 [–5·104 to 9·002]). Financial support policies were significantly associated with a higher absolute value of the public transit use index after the intervention when analysing the mid-May intervention point, whereas there was no evidence that COVID-19 control measures or service improvements were related to the absolute value or change in value of the public transit use index. Further details of the models and results are provided in the appendix (pp 27–35).

Discussion

We evaluated the impacts of COVID-19 recovery actions and policies on city mobility patterns including active transportation, and on public health equity. Findings from our analysis of the global natural experiment showed that rapidly implementable, low-cost policies could influence city mobility patterns at scale. In particular, we showed that an increase in walking mobility index was associated with response policies such as road closure to motor vehicles, which are inherently less costly than large-scale, physical infrastructure investments, as they do not require new physical infrastructure but instead deprioritise motor vehicle traffic. We also showed the impact of policy responses such as financial support, which increased the affordability and attractiveness of public transit use. This is particularly true for cities in high-income countries, which accounted for most cities included in the DID analysis due to data availability for policy implementation and city mobility data. These findings suggest the potential for active transportation to be changed at scale through effective urban policy interventions. Generally, it has been suggested that policies focusing on promoting active transportation, deprioritising motor vehicles, and making public transit more affordable and attractive, can be crucial in mitigating health inequities, especially in lower-middle-income and low-income countries.[18] However, the limited data and policies in our analyses indicated insufficient preparedness or capacity to act in cities in low-income and middle-income countries. The discrepancy in the number of policies identified between country income groups might suggest the need for increased attention and policy implementation in cities from lower-income countries. Given that low-income and middle-income countries face the most severe effects of climate change,[28] there are additional climate-related benefits associated with transport system interventions, as described in the appendix (p 36). Active transportation modes contribute to social justice and equity, which are among core aspects of climate-resilient development, and reduce land pollution, water pollution, congestion, and energy consumption.[29] Low-cost, scalable, and effective policies for city mobility, such as some of the policies examined in this study, can also have impacts on climate mitigation and adaptation, for which resources need to be increased dramatically.[30]

Our findings on mobility index and SARS-CoV-2 infection rates seem somewhat counterintuitive (objective 1), but we offer the following explanations. Cities with higher public transit use and lower SARS-CoV-2 infection rates might be those with better infection control measures on public transit. Cities with a higher driving index and higher infection rate might be those with a higher population density and motor-city designs, forcing higher driving rates coupled with higher infection rates.

A strength of our study was the use of a series of global cities, including those with some of the highest numbers of COVID-19 deaths globally, with variations in existing active transportation infrastructure and pre-pandemic walking behaviours and public transit use, and stark inequities in physical activity and health outcomes, which should be explicitly considered within the COVID-19 response. Our analyses include real-time data captured on an unprecedented scale. Scientific advances meant that this is the first time we could track and analyse changes in walking and cycling behaviour using city mobility data from hundreds of thousands of people.

As highlighted previously, we have scarce data from low-income and middle-income countries compared with high-income countries. Such data limitations also meant that we were not able to conduct a disaggregated analysis by country income level or policy type or intensity.

Additionally, there were limitations associated with the use of Apple Mobility Trends Reports, as detailed in the appendix (p 4). For example, these data were only collected from users of Apple technology, who might be biased in terms of socioeconomic and sociodemographic characteristics, and the smartphone penetration rate is substantially different between and within countries.[31] Due to the anonymous nature of these data, we were not able to investigate the effectiveness of policy interventions by sociodemographic groups. It is unclear how detailed mass mobility tracking data might become in the future, or whether the risks associated with obtaining such granular data outweigh potential privacy concerns for the purposes of public health planning. Examples of other limitations include individuals using other platforms for mapping trips, and that more familiar trips will not be captured via the map function.

Justification and trade-offs made in the design of our analysis for the global natural experiment are detailed in the appendix (pp 6–13). This includes key decisions we made regarding the use of comparator groups and intervention definitions. Trial designs with less bias, such as randomised controlled trials, were not possible during the pandemic. Our study design solutions provide an example of working in real-world conditions during a pandemic focused on public health needs rather than experimental study designs, which are not feasible to implement in many real-world situations.

The study focuses on city mobility, defined by the World Bank as "moving people from one location to another location within or between urban areas".[32] City mobility is based on two principles: people need to access housing, jobs, and other urban services; and people display a preference for motorised city mobility due to its cost efficiency. Across our analyses in this study, we considered walking, cycling, micromobility, public transit use, and driving. However, due to the lack of data from Apple Mobility Trends Reports, we were not able to include analyses that investigated the effectiveness of the policy interventions on cycling behaviour, either within our global trends analyses or our global natural experiment. This lack of cycling data is an important limitation to acknowledge.

For the policy data, policies targeting active transportation were obtained from the Shifting Streets dataset, which contains over 1400 mobility-related COVID-19 responses from jurisdictions worldwide. The dataset has a global focus and provides policy descriptions in English. Our study focused on policies and recovery actions implemented to influence city mobility. Lockdown and stay-at-home orders were not regarded as recovery actions or policies, as they were largely in place during the peak of the pandemic to stop transmission of the virus. These data are collected via crowdsourcing and updated regularly by volunteers, which has the advantage of enabling the collection of extensive data within a short time. However, the dataset has several limitations, including unknown implementation dates for a large proportion of policies, and the potential for bias due to the data collection process, as it could be influenced by several factors including the availability and motivation of participants to report policies. Additionally, there might be variations in the accuracy and completeness of the reported policies due to the absence of standardisation in the data collection process. Furthermore, this dataset does not provide an exhaustive list of policies; thus, if a policy was not present in the dataset, it does not mean that the policy did not exist. By only including policies provided in English, the findings might also be biased towards including policies in high-income countries and urban areas. Similar reporting errors might have led to biases or omissions in the reporting of relevant PROGRESS-plus indicators. Although the dataset provides links to actual policy documents and information, language barriers preclude obtaining further contextual information about specific policies in some cases. However, we addressed some of these limitations by cross-checking the policy information through the main sources (ie, government websites) and focusing on policies with given implementation dates.

Care should be taken when interpreting the results from the policy analysis. Although some policies might fall under the same theme of COVID-19 control measures, it is important to recognise that the scope of one policy can vary substantially from that of another. For example, although one policy could involve implementing multiple wash basins in a bus terminal, another policy could have a broader scope, encompassing comprehensive hygiene measures, including the provision of hand sanitisers. Both these policies are grouped under the theme of control measures, highlighting the diverse approaches taken to ensure public health and safety.

The COVID-19 pandemic, which resulted in almost 7 million deaths globally,[33] provided a unique opportunity to study the effect of active transport policy interventions on active transport rates and broader city mobility patterns that are central to population health and wellbeing. Our results show that some of these active transportation policies and interventions were associated with a difference in mobility patterns, providing evidence that positive change for public health can be achieved when political will and social needs align. The results also have implications beyond pandemic times, showing that government policies such as reallocation of road space could produce increased active transportation rates in cities. This evidence can help to inform the evolution of city mobility policies to meet health and environmental goals, reduce global health inequities, and enhance pandemic preparedness and mitigation. It also highlights the complementary roles that multiple sectors (eg, transport planning, urban design, and health care) can play in responding to both existing and novel public health concerns. Our findings could serve as a stimulus to advance policies and actions that promote healthy urban planning (including active transportation), reduce global inequities, and build capacity to future-proof cities against the impacts of pandemics.

Contributors

All authors contributed to the study design, interpretation of results, and critical revision of the manuscript for scientific content. RFH, SA, and RW drafted the article. RW and SA led the data analysis. RFH, SA, RW, and EM had full access to all the study data, and accessed and verified the data. All authors had access to the analysed data, had final responsibility for the decision to submit the manuscript for publication, and saw and approved the final text.

Declaration of interests

JT reports grant payments from the National Health and Medical Research Council (NHMRC) and the Australian Research Council (ARC) for projects unrelated to the current manuscript. All other authors declare no competing interests.

Data sharing

This study uses publicly available data sources. Processed data used in the analyses in this study can be made available by the corresponding author upon reasonable request.

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