Shifting urban mobility patterns due to COVID-19: comparative analysis of implemented urban policies and travel behaviour changes with an assessment of overall GHG emissions implications

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Abstract
COVID-19-induced confinements rapidly change behavioural patterns and social norms of street space use worldwide. In the following study we compile data to assess shifting urban mobility during confinement (phase 1), and in reaction to COVID-19 induced physical distancing policies (phase 2). In a comparative analysis of 16 cities, we show that public transit decreased by 80% during confinement, but individual motorized transport only by 64%. Cycling modal share increased in some cities. COVID-19 and sustainability are intertwined via risks, susceptiblility, and positive and negative outcomes, in particular via sustainable development goal 3 (SDG3) (health), SDG5 (gender equality), SDG11 (sustainable cities) and SDG13 (climate action).

Confinement-induced social gains are realized in reduced congestion, improved air quality, and less accidents, partially compensated by unhealthy eating, and domestic violence. Our analysis reveals that cities around the world provided more space for cyclist and pedestrians as part of pandemic-related measures, pedestrianizing streets, implementing 550 km ad-hoc bicycle infrastructure and planning additional 1500 km. Our computation indicates that GHG emissions savings due to increased uptake of cycling in the EU reduced urban land transport GHG emissions by 0.3% (1 Mt CO₂), while GHG emission savings were larger in cities with pop-up bicycle lanes (between 0.43% and 1.87%). Our findings also demonstrate that proactive cities had already plans in their drawers and demonstrated institutional alignment of vocal civil society, administrations and politicians. We argue that long-term sustainability trajectories of cities will depend on transformation of both physical and digital infrastructures.

COVID-19 is the first global pandemic in the century of urbanization, digitalization and climate change. Global confinements at different stringencies [1] may lead to lower global infection and death rates as compared to the Great Influenza of 1918. However, the impact on both the global economy and the environment are unprecedented and are hard to extrapolate from the Great Influenza, which caused a decline of about 6% in global gross domestic product (GDP) [2]. In addition, the COVID-19 pandemic encounters a simultaneous global sustainability crisis, which operates at slower time scales but is of even more dire consequences for humanity [3]. It is an open but important question of how societies react to the conjoint crisis and challenge, and nowhere can this better be observed than in cities.

Cities are a focal point of these combined dynamics, as high population densities foster infectious diseases like COVID-19; infection rates correlate with population density and social vulnerability [4, 5] and in the case of COVID-19 are exacerbated by long-term exposure to air pollution [6]. In turn, confinement directly impacts urban life, as strongly reduced physical interactions result in modified mobility patterns and
calmer, quieter cities with improved air quality. However, life in confined spaces and job uncertainty also induces stark psychological and physiological costs. Lifestyles in rural areas, including both agricultural societies and commuters in industrial societies, experience less change in their daily routines, corresponding to higher space availability, and, in some countries, higher dependence on individual modes of transport.

City administrations around the world aspire to compensate for lack in global cooperation on climate change and other sustainability challenges by taking a lead on climate action [7–9]. Cities use COVID-19 as an opportunity to test out street-use changes. In the US, 30 out of the largest 55 cities have expanded their efforts to experiment with walking-friendly street space; such changes may lay the foundation for a sustainable transformation [10].

In our study we investigate the impact of COVID-19 policies on urban mobility, their implications on CO$_2$-emissions, air pollution, accidents, and other public health dimensions, and impromptu policy action that encounters these dynamics for 16 cities world-wide. We first give an overview on the various relationships between COVID-19 and the UN Sustainable Development Goals (SDGs) in the arena of urban mobility. In the subsequent section, we elaborate on the descriptive observations, asking how COVID-19 changed urban mobility patterns, focussing on case study cities with notable modal share in cycling and cycling infrastructure. In the analysis section, we investigate the question of what institutional conditions were important that enabled some cities to rapidly adapt to COVID-19 by providing pop-up infrastructures (PUIs). We conclude with scenarios highlighting long-term implications on urban sustainability trajectories as induced by the COVID-19 crisis.

1. Overview

1.1. Urban lifestyles, sustainability, and COVID-19

The global pandemic is reinforced by human influence, and feeds back into urban lifestyles, wellbeing, and environmental quality (figure 1). While the 20th century witnessed three zoonotic pandemics, the young 21st century already experienced four of them, fostered by a rapidly growing and mobile world population connected by global transport networks; urbanization trends and the concentration of people; industrialized food production and growing consumption of meat [11, 12]. The rapid development of the Anthropocene and its impacts on ecosystems over the last 70 years have increased risk factors for zoonotic diseases (figure 1), as cultural practices that amplify contact between humans, wildlife, and livestock are key preconditions [13]. Air travel accelerates the global spread of infectious coronaviruses [14].

The susceptibility to COVID-19 is intensified by other anthropogenic environmental changes and by lifestyles of modern societies (figure 1). Studies suggest that long-term exposure to air pollution, specifically of PM2.5, increase susceptibility to COVID-19 in the US [6]. Long-term exposure to NO$_2$, associated with lung diseases, appears to increase mortality rates of COVID-19: 78% of all fatality cases appeared in 5 out 66 European regions analysed, coinciding with the 5 regions with the highest NO$_2$ pollution [15]. As non-communicable disease prevalent in modern societies, obesity also increases the susceptibility to COVID-19: the odds ratio of hospitalization is 4 with a body-mass-index (BMI) > 30, and 6 with a BMI > 40 [16].

The social reaction to COVID-19—mediated via confinement and physical distancing—produces novel social practices, in particular rapidly changing mobility patterns. Reduced road transport results in an estimated 7.5 Mt CO$_2$ emission reduction (corresponding to a 36% of all CO$_2$ emission of road transport) for 4 April 2020, as evaluated by computing daily emission patterns [17] (figure 1). This is a steeper reduction of CO$_2$ emissions than in any other sector [17].

As a positive effect of confinement, air quality improved in many cities (figure 1). A striking example is Milan in Northern Italy’s pollution-prone flatlands, where NO$_2$ levels dropped from more than 65 µg m$^{-1}$ [3] in January 2020 down to 15 µg m$^{-1}$ [3] towards the end of the lockdown period. One month of reduced air pollution over Europe, induced by lockdown and curtailed coal and oil consumption, result into 11 000 [7000–21 000] avoided deaths (27% of expected deaths from air pollution), and about 6000 fewer cases of asthma in children [18]. Monthly avoided death, resulting from confinement, are estimated at 50 000 in China or 21% of otherwise expected deaths [19]. However, a study of Beijing identified imbalanced reduction in air pollutants, which resulted in increased oxidants and secondary aerosols [20]. Hence, realizing air quality benefits may include additional mitigation efforts on volatile organic compounds [20].

Fatal traffic accidents are proportionally even more reduced, with 50% reduction observed in California [21], 60% in Washington state [22] and 67% in Germany [23]. This is about 10%–20% of the rate of life saved compared to better air quality (figure 1, Supplementary Data).

As negative effects of confinement, sedentary behaviour and domestic enclosure appears to amplify consumption of unhealthy diets and increase domestic violence. Preliminary results of a survey of more than 1000 participants in seven countries indicate a 30% reduction in physical activity, and 20% increase in unhealthy diets during confinement [24]. In an Italian case study of obese children and adolescents, sport
Figure 1. Unsustainable human systems foster COVID-19, and COVID-19 has positive and negative effects on sustainability dimensions. The figure summarizes susceptibility factors for morbidity and mortality from COVID-19, positive sustainability outcomes from the restrictions, and negative sustainability outcomes. Active mobility supports positive sustainability outcomes and combats negative ones. Indirectly it also helps reducing air pollution and obesity, two key risk factors for severe outcome of COVID-19 infections. Relationship with the sustainable development goals (SDGs) is presented in table 1.

activity was reduced by 60% during confinement, while intake of sugary drinks and red meat doubled, and consumption of potato chips grew eightfold [25]. Domestic violence may be another severe effect of confinement with long-term consequences. Intimate (male) partners subjected 18% of all women and girls (243 million cases), aged 15–49, to sexual and/or physical violence in 2018 [26]. During COVID-19 confinement, domestic violence may increase by 25%–33% as measured by indirect metrics, such as helpline calls [27].

The analysis demonstrates that COVID-19 also strongly interacts with key components of the SDGs (table 1) [28]. COVID-19 induced restrictions improve some and worsen other SDG-related metrics. Importantly, SDG 11—Sustainable Cities and Communities—is involved in most instances analysed here, particularly in the positive aspects of COVID-19 confinement. SDG 13 is considerably touched both by immediate CO₂ reductions and likely more importantly by how economic stimulus programmes may be designed to shape future carbon emissions.

Most effects, in particular air pollution and congestion relief, are more short-term and will end with the end of lockdowns. However, physical distancing rules likely remain active for months to years and will profoundly reshape cities. Especially transport mode choice interacts simultaneously with climate change (and other environmental concerns), COVID-19, and public health (table 2). This leads to the question of how COVID-19 relates to urban sustainability trajectories, and how urban governments can leverage these changes to long-term desirable outcomes.

2. Descriptive observations

2.1. Confinement-induced slump in urban mobility

We take a sample of 16 cities, some of which have responded to COVID-19 with PUI for bicycles and pedestrians and which have bicycle counter data available. We also included cities that did not respond in this way but which are of similar size and importance, aiming at a large geographical coverage. For these cities, we first perform a qualitative research on their actions taken with regards to (a) opening up new bike lanes and pedestrianize streets including the length of existing and planned projects, and (b) existing plans and long-term endeavours in regards to sustainable urban transportation. We also acquire bicycle data count from these cities either through the publicly available bicycle counter data or by request from relevant authorities (Copenhagen, Houston). We also extract changing mobility patterns for a set of 16 cities worldwide from Apple route query data [34].

Among all sectors, land transport was impacted the most by COVID-19 confinement in terms of total emissions reduction [17] (figure S1), while aviation had the largest relative decline in activity. In Wuhan, the epicentre of the crisis, urban transport collapsed nearly completely in spring 2020 (figure 1). Cities that were hit subsequently, such as Milan, New York, and Paris, also saw a strong decline (80%–90%, figure 2). Other
Table 1. Qualitative links between COVID-19 risk factors, COVID-19 susceptibility factors, positive and negative outcomes of lockdown measures. We also list the related sustainable development goals, as enumerated by into goals (1–17) and their specific targets (sdgs.un.org/goals).

| Susceptibility | Related sustainable development goals |
|----------------|---------------------------------------|
| **COVID-19 Risk factors** | |
| Urban population: Economical inequalities increase COVID susceptibility, e.g. in the case of overcrowding [29] | SDG 11.1 By 2030, ensure universal access to adequate, safe and affordable housing |
| International aviation: Aviation helps rapid intercontinental spread of COVID [14] | SDG 13 Climate action |
| Meat demand: Consumption of game meat underlies the animal-human interface (zoonotic disease risk factor) | SDG 13 Climate action (see the role of meat consumption in inducing GHG emissions) [30]. |
| **Positive lockdown outcomes** | |
| Air quality is improving due to less motorized transport [18]. | SDG 11.2 By 2030, provide access to safe, affordable, accessible and sustainable transport systems for all |
| **Negative lockdown outcomes** | |
| Less accidents is improving due to less motorized transport [23]. | SDG 3.6 By 2020, halve the number of global deaths and injuries from road traffic accidents. |
| Less GHG emissions [17]. | SDG 13 Climate action → see UNFCCC process |
| Overeating and inactivity: Lockdown increased overeating [25] and reduced healthy activity [24]. | SDG 3.4 By 2030, reduce by one-third premature mortality from NCDs through prevention and treatment and promote mental health and well-being (also SDG 2.3 and SDG 3.8) |
| Domestic violence: Lockdown increased domestic violence [26, 27]. | SDG 5.2 Eliminate all forms of violence against all women and girls in the public and private spheres, including trafficking and sexual and other types of exploitation |

Table 2. COVID-19, GHG emissions, and health effects of different transport modes. For GHG emissions reference values are from [31] (in practice there is large variation mostly due to occupancy level).

| COVID-19 exposure | Specific GHG emissions | Health |
|-------------------|------------------------|--------|
| **Cars** | Physical distancing possible | 160–170 gCO₂ km⁻¹ | Hazard ratio = 1.00 [32] |
| **Cycling** | Physical distancing possible | 0 gCO₂ km⁻¹ | Hazard ratio = 0.80 [32] |
| **Walking** | Physical distancing possible | 0 gCO₂ km⁻¹ | Hazard ratio = 0.93 [32] |
| **Public transit** | Physical distancing not always possible | 30 gCO₂ km⁻¹ | Hazard ratio = 0.90 [32] |
| **Teleworking** | Physical distancing possible | 0 gCO₂ km⁻¹ | Less movement, but in balance positive [33] |

Legend | |
|---|---|
| | Negative outcome |
| | Slightly positive outcome |
| | Desirable outcome |

cities, with fewer restrictions, such as Berlin and Houston, witnessed a more moderate reduction in urban mobility (40%–80%, figure 2).

The statistics show that all transport modal use was reduced significantly (figures S2 and S3). However, public transport lost most users and is the slowest to recover. In Houston, car traffic was reduced by 51% compared to reference week 3 levels (transit 60%), and by the week of 18th May significant reduction were only seen for transit (41%). Copenhagen, in contrast, had a reduction of only 39% in car use but a 75% decline in transit, with May 18th–24th reductions at 9% for cars but 53% for transit. Overall, week-15 car traffic was down 64% and transit 80% compared to pre-lockdown levels. Altogether, peak decline in public transit was 80% [91%–60%]. Cars and walking were less affected, with declines 64% and 69% [85%–47%; 50%–91%], respectively. This observation aligns with detailed data from Santander, Spain, where mobility activity was reduced by 76% during lockdown. The share of cars became more dominant (77% modal share within confinement, compared to 48% before) [35].

Cycling is not contained in the Apple mobility data. We hence extracted changing bicycle patterns from bicycle counters in ten cities (see Methods). In spring 2020, cycling plummeted to zero in Spanish, Italian,
and French cities, which banned cycling altogether. In contrast, cities with less draconian lockdowns or even outspoken support of cycling as a ‘pandemic-resilient’ means of transport have seen cycling numbers less affected or even increase, for example Berlin or New York. Shared bicycle schemes play a key role in safe transportation. In New York they have retained near-normal ridership numbers [36] with service areas expanded due to COVID-19 [37]. Berlin’s bike sharing system was free of charge [38] and its pooled mobility were reserved exclusively for care workers [39]. Our data show that by end-of-confinement, cycling was relatively more popular compared to pre-confinement and compared to car use in London, Berlin, New York, Sao Paolo, and Paris. This is aligning with a review on cycling in reaction to the COVID-19 pandemic [40].

Altogether, urban transport declined by 50% under strict confinement (confinement level 3 in [17]), with best estimates ranging from 40% to 65% activity reduction [17].

3. Analysis

3.1. New bike lanes as the response to a pandemic
Urban design responds to pandemics. In the 19th century, an improved understanding of infectious diseases dominated urban planning [41]. Urban reformers aimed to broaden Paris’ streets and open up squares to fight cholera with sunlight and fresh air [42]. Similarly, New York’s Central Park was motivated, at least partially, by public health workers arguing for open green space to improve health conditions [43].
In 2020, the COVID-19 crisis occurs on top of an emerging climate and sustainability crisis and the tentative restructuring of economies towards low-carbon technologies. Questions of urban street space allocation are newly asked by practitioners and ethicists [44, 45]. The historical experience of urban transformations and a bike boom raises the question of whether the confluence of health and environmental concerns could lead to another, possibly sustained transition to healthy, low-carbon cities.

To answer this question, we aggregate existing evidence on rapid urban space transformation, labelled PUI, as instigated by COVID-19 (figure 3). We distinguish between implemented and planned infrastructure, and between pop-up bicycle lanes and open streets (opening street space in particular for the slower modes) (see Methods and table S1). While bike lanes serve primarily a transportation purpose, we judge that ‘Open Streets’ provide space for exercise, socialising and leisure in otherwise crowded and stressful cities, a concept labelled as ‘streets as a place’ [44]. We find that on a per-capita basis, Oakland and Brussels dedicated most space for pedestrians and cyclists (about 80 km open streets per 1 million population), with specifics for London still pending. Île-de-France, the Paris metropolitan region, is implementing the largest overall bicycle network (680 km, or about 56 km per 1 million inhabitants) [46]. Bogotá made its Ciclovía Sunday cycling paths available permanently and added 80 km of protected bicycle lanes to its existing network of 550 km, resulting in a total of 88 km per 1 million inhabitants [47]. Hotspots of COVID-19, such as Milan [48] and New York [49], allocate relevant proportions of street space to active modes (25 km and 14 km per 1M residents respectively). Pop-up bicycle lanes, most of them intended to stay, in Berlin and Tirana correspond to 5 km and 10 km per 1M population, respectively.

Altogether, according to our sources, we calculate a total of 550 km of implemented PUI (320 km bike lanes, 220 km open streets) as response to COVID-19 considering all studied cases, and further 1500 km planned (1200 km bike lanes, 300 km open streets).

3.2. Shifting transportation to cycling benefits the climate and public health
For perspective, the bulk of European cities has a cycling network length between 0 km and 1000 km per million inhabitants [50]. Most of these networks comprise narrow cycle lanes, not equivalent to 2–3 m broad cycle lanes that are now increasingly implemented and which already exist in the Netherlands: Most Dutch cities have a cycle lane network from 1000 to 2000 km per million inhabitants. Cities like Berlin, Manchester and Beijing are planning for 400 km, 2900 km, and 3200 km long networks respectively, in agreement with
cycling cities. The acute crisis alone hence does not lead to bicycle friendly cities. Instead, only the next years will reveal whether the current action is a blip in fostering bicycle infrastructures or a stepping-stone for a longer lasting active travel revolution.

Cyclists have significantly lower CO$_2$ emissions than non-cyclists, every trip shifted from car or public transport to cycling significantly reduces per-trip emissions. Using the bicycle as the main mode of transport has been shown to reduce lifecycle emissions by 7.1 kg CO$_2$ day$^{-1}$ [51]. In the same study, shifting one trip from car to bicycle decreased emissions by 3.2 kg CO$_2$ day$^{-1}$ and from public transport to bicycle by 2.3 kg CO$_2$ day$^{-1}$.

The effect of pop-up bicycle infrastructure on bike traffic is substantial. A recent study documented an increase of cycling by 11%–48% [52] on average in cities which installed pop-up bike infrastructure, compared to those which did not expand cycling infrastructure. Similar dynamics can be observed in figure 2, where cities such as Berlin or New York show much increased cycling rates from weeks 10 to 19, with all other transport modes decreasing and only slowly recovering.

We here connect the climate effect of pop-up bicycle infrastructure together with the increased ridership as observed during COVID-19 and/or from new bike lanes to estimate an order of magnitude of greenhouse gas savings, taking the EU as an example. Assuming conservatively an 8% modal share baseline of cycling (2014 data for EU) [53] and an 8% increase in cycling due to COVID-19 in EU cities [40]; and given that 270 million Europeans older than 14 years live in cities, in average making 3.47 trips per day [54]; and observing that one additional bicycle trip reduces greenhouse gas (GHG) emissions compared to baseline (in average 3.2 kg day$^{-1}$) by 14% [54], then the 8% additional bike trips (2.2 billion), translate into 0.98 Mt CO$_2$ saving per year, which is 0.31% of annual land transport GHG emissions of the 270 million European urbanities. In cities, where in average 115 km pop-up bicycle lanes were provided [52], GHG emission savings were between 0.43% and 187%. Extrapolated, this indicates that if cities built >100 km bicycle networks, GHG emission savings at the order of 4%–19% are feasible. These numbers are only indicative and outcomes depend on additional city-specific variables, such as pre-existing modal shares, network effects, and policy packages.

3.3. Harvesting the fruits of sustainability planning

It is important to understand why these cities acted and why others did not. London, Paris, Berlin, New York, Bogota, Rome, Milan, Madrid and Barcelona all have in common that they are their countries’ largest or second largest cities. As large and dense cities suffer more from congestion and air pollution [55, 56], both political pressure and motivation are higher to provide support for zero-emission and space efficient modes of transport. Some cities, like Milan and New York, were also hotspots of COVID-19.

Cities whose COVID-19 response includes adding infrastructure for cyclists and pedestrians have two features in common. First, they had plans underway (table 3): in 2018, the Berlin government ratified a so-called mobility law, mandating 100 km of novel bicycle highways, and segregated safe and broad bike lanes along all major throughways. In 2017, Manchester’s cycling and walking commissioner, Chris Boardman, had drafted a proposal for 2900 km bicycle network for Greater Manchester, including a 15-step program to get there. In cities like Bogota, Milan, Brussels, New York or London, municipalities have been already previously engaged in providing space for pedestrians and cyclists and limiting congestion and air pollution in inner cities. Preparedness turned out to be a precondition for rapidly setting up PUI.

3.4. Institutional alignment matters

Second, successful cities witness an alignment of institutions encompassing support by civil society, administrations, and political leaders (table 3) alike. In Berlin, a 2016 campaign (‘Volksentscheid Fahrrad’) collected more than 100,000 signatures in 3 weeks and thus initiated a legislative process which obliged the city administration to build state of the art bicycle infrastructure. The Berlin district setting up most PUI, Friedrichshain-Kreuzberg, is led by deft and ample transport planners who found methods and procedures to rapidly implement PUI. The importance of local administrative support is also evidenced by those cities that lack engagement in PUI, as some districts fail to follow through with plans for bicycle infrastructure, with processes stuck in unwilling bureaucracy.

In Seattle, the opening up of 32 km of roads for pedestrians and cyclists was supported equally by the mayor, the director of Seattle Department of Transportation, and activist groups like Seattle Neighbourhood Greenways. The New York perspective is more complicated. The transport administration has grown accustomed to the idea of bicycle infrastructure and pedestrian area in the tenure of Janette Sadik-Khan and Michael Bloomberg. Several activist groups, from Transportation Alternatives to Families for Safe Streets actively pushed for opening streets, mirroring the challenge of crowded houses in the US’ most compact city. The mayor was more reluctant and had to be persuaded by the City Council to commit to opening up 160 km of streets. This reluctance may be grounded in opposition by taxi drivers and other constituents.
Table 3. Pop-up infrastructure in selected cities worldwide, and details of political preconditions. The information in this table has been compiled using publicly available information as published by the city administrations themselves, also taking guidance from local newspaper information which is available online.

| City                      | Action                                                                 | Preparedness                                                                                     | Institutional alignment                                                                 |
|---------------------------|------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------|
| Pop-up bicycle lanes      |                                                                        |                                                                                                |                                                                                        |
| Berlin                    | Pop-up bike lanes on former parking lanes in several inner-city districts | ‘Mobility Law’ (2017), promoted by civil society and activists, obliges city administration to provide safe cycling infrastructure. | Regine Günther, Berlin Senator for Transportation, Head of Roads and Green Spaces Department of Friedrichshain-Kreuzberg district Felix Weisbrich, and NGO Changing Cities working conjointly. |
| Bogotá                    | 75-mile network of streets usually turned over to bicycles one day a week to be traffic-free all week; further 47 miles of bike lanes are being opened. | Previous mayors, in particular Mockus and Penelosa, fostered civil society, social trust, implemented BRT and segregated bicycle lanes, winning prices for their engagement in urban mobility. | Green Party Mayor Claudia López and, from civil society foundation Ciudad Humana, Ricardo Montezuma advancing participatory processes for sustainable cities and implementing street space reallocation. |
| Manchester (Greater Manchester) | Councils encouraged to provide pop-up bicycle lanes and safe street infrastructure. Extra funding provided to townhalls by government. A section in Manchester city centre already opened up for pedestrians and cyclists. | Local officials already advancing bicycle plans (1800 miles of protected routes) and other recently implemented measures before COVID-19. Adhesion to the ‘Open Streets’ program in 2019. | Mayor Burnham supports the plan. The Cycling and Walking Commissioner Chris Boardman outlined a 700 mile, 1.5 billion pound cost cycling network in report ‘Made to Move’, to achieve Dutch levels of cycling. Civil society organization support (Walk Ride Greater Manchester and Bee Network). |
| Paris (Île-de-France)     | Projet RER velo: 650 km of cycleways are being built, ensuring cycling access from Île-de-France to Paris. Subsidies offered for bicycle repair and service. 116 French towns and cities plan to build temporary cycleways. | The city and its surrounding region build on two decades of successful integrated low-carbon urban transport planning (Halpern and Gales, 2019) and strong pro-bicycle policies by the Paris mayor. | Région Île-de-France President Valérie Pécresse, organised funding of 300,000,000€. This is further supported by Ministre de la Transition Écologique et Solidaire, Elisabeth Borne. Collectif Vélo Île-de-France comprises 30 organizations demanding this network. |
| Tirana                    | Tirana build over-night pop-up bicycle lanes.                          | Since 2014, there are plans to make Tirana more bicycle friendly. Since 2018, it has the Balkan’s first bike sharing offer. | Tirana’s mayor sees the provision of PUI as key policy strategy and also as way to gain international recognition. |
| Open streets              |                                                                        |                                                                                                |                                                                                        |
| Brussels                  | Inner city declared ‘zone de rencontre’, with pedestrian and cyclist priority, and speed limit of 20 km h\(^{-1}\) from May to August 2020. Installation of 40 km new bicycle paths. | 2019 mobility plan prepared some of the actions taken now, but COVID presented an opportunity for speeding up its implementation. | The Green Party city government has developed the mobility plan as immediate crisis response, aiming to make Brussels more attractive for active travel in the long term, according to city government representative Elke Van den Brandt. |

(Continued.)
| City     | Action                                                                                                                             | Preparedness                                                                                                                                                                                                 | Institutional alignment                                                                                                                                                                                                 |
|----------|-----------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| London   | Inner city to become ‘one of the world’s largest car-free zones’ to enable physical distancing, reduce public health impacts from air pollution. By May 2020, 5000 sqm of street pedestrianized. Congestion charge reinstated and increased. | In the past decade, London has worked to reintroduce bicycles into the city’s modal share, most notably through its bike share system and protected bike lanes.                                                                 | The Mayor’s Office and Transport for London recommend boroughs how to implement the proposed measures. These are aligned and supported by the United Kingdom’s government providing extra funding for all townhalls. |
| Milan    | Ambitious plan to encourage active travel and a speed limit of 30 km h$^{-1}$ (which is typically 50 km h$^{-1}$ in Italian cities). Installation of 35 km ‘emergency bike lanes’ by December 2020. | ‘Milan 2020 Adaptation Strategy’ prepared changes, used as starting point for COVID measures. The strategy builds on experience gathered during ‘Piazze Aperte’ interventions in 2018 and 2019.    | Deputy Mayors Marco Granelli and Pierfrancesco Maran both strongly argue for the Open Street implementation. An online petition, initiated by Federico Paralotto and named ‘Emergency Covid 19—More space for pedestrians and bicycles in Milan for Phase 2’ developed additional pressure for implementation. |
| New York City | Closing 40 miles (to be expanded to 100 miles) of residential streets to car through traffic with the purpose of creating free space for active modes. | Michael Bloomberg’s administration and NYC’s Transportation Commissioner Janette Sadik-Khan introduced principles of street space reallocation from cars to pedestrians, and the installation of protected bike lanes. | The city council and New York State Governor Cuomo support the opening of streets, while Mayor De Blasio was originally more reluctant. Organisation such as Riders Alliance Policy and Families for Safe Streets argued for PUI. |
| Oakland  | The Oakland Slow Streets program closes streets for through traffic to open them up for pedestrians, and cyclists. Residential drivers are urged to drive extremely carefully. | The Slow Streets program was established on April 2020 as a reaction to COVID-19, building on the 2019 Bicycle Plan ‘let us Bike Oakland’ which engaged over 3500 Oaklanders to propose street network changes. | The Mayor’s Office, in coordination with and support of OakDOT leadership and local transportation advocates, developed the plans. |
| Seattle  | The Stay Healthy Streets program transforms streets for cyclists and pedestrians has been applied to 20 miles. Seattle Neighborhood Greenways demands 130 miles in total. | The response to COVID-19 builds on a framework of administrative and legal support for neighbourhood initiatives wishing to implement ‘play streets’ which has existed since 2017. | Mayor Jenny Durkan, Seattle Department of Transportation (SDOT) with its director Sam Zimbabwe, and street-safety advocacy group Seattle Neighborhood Greenways all supported the measures. |
| Tel Aviv | Tel Aviv converts 11 city centre street segments (totalling 2 km) into pedestrian zones until August 31st, 2020. | The project has been envisaged before and is now implemented to enable physical distancing, and includes activities to reactivate businesses battered by the crisis. | Left-green mayoral party and administration central for implementation. Active bicycle association in Tel Aviv. |
In all successful cities we found evidence of broad political support. The relative role of institutional agents varies, and sometimes civil society takes the lead, such as in Berlin, and sometimes it can be the head of bureaucracy, such as in Manchester. Nonetheless, all cases demonstrate the importance of alignment across political, administrative, and civil society institutions.

Another notable development is international connectedness. Local newspapers and blogs regularly report road reallocation and new PUI in other cities worldwide, cross-referencing measures as positive examples. Urban transport planners are calling each other, asking for guidance, beyond the works of transport consultancies. Tentatively, a global bottom-up network of local street space modification for sustainability is emerging.

4. Discussion

4.1. Post COVID-19 trajectories: transforming physical and digital infrastructures

COVID-19 merges with both urbanization and climate change challenges in the arena of urban street space. It lays bare the challenges of urban sustainability transitions, but also provides a window of opportunity where entrenched habits and political dogmas are questioned, social practices dissolve, and new patterns emerge. In lockdown, established travel patterns were history at least temporarily and new questions about the sense or nonsense of travel modes were asked. But sustainable trajectories are not guaranteed. In Beijing, the end of the first lockdown in 2020 coincided with an increase of car use and a congestion level 15% above normal [57]. The slump in public transport is worrisome, and shift to teleworking and cycling will be of little use if car traffic increases, too, endangering and compromising the sustainable modes of transport. In fact, research does not support a clear answer whether working from home indeed reduces overall miles travelled [58].

We argue that trajectories to long-term sustainability involve politically guided transformation of physical and digital urban infrastructures (figure 4). A potential COVID-19 induced transition involves three phases: (a) confinement (typically 1–3 months); (b) smart physical distancing (3–24 months); (c) post-COVID-19.
COVID-19 cities. In physical infrastructures and mobility, confinement equates to a breaking of existing mobility patterns. The observations reveal that where civil society and administrative and political institutions align, PUI emerge at the end of confinement and as means to ensure physical distancing. A change in mobility is also dictated by both public health and transportation concerns: Physical distancing drastically reduces capacity of public transport, and with the road network being clogged by private cars, an extension of cycling capacity seems one of the few ways forward to keep cities moving. With vision and political stamina, walking and cycling infrastructures will be enlarged to form coherent networks and made permanent and safe in the long run.

Digitization and its institutional management play a complementary role to physical infrastructures. In the confinement phase, internet-based telework suddenly substituted for office presence [59]. The availability of web-based communication and videoconferencing is a precondition for this instantaneous shift. In a next phase, COVID-19 is likely to accelerate the transition to contactless digital payment (even though transmission risk via cash is low).

The true potential of digitization may be in agile transport and urban planning, matching latent demand for low-carbon and active transport with novel infrastructures, and even planning new districts accordingly [60]. For public transit this could entail opportunities for shifting peak demand [61] and thus limiting high-risk periods of public transit use. Big data and artificial intelligence, in turn, can be used to optimize electric bike and car fleets [62, 63]. Mobility-as-a-Service, matching variable demand and supply at low transaction costs, can offer flexible services [64]. To reach this goal, municipal governments need to take an active role in managing big urban mobility and planning data, while keeping them algorithmically safe, e.g. with trusted data governance [65].

5. Conclusions

Our analysis investigates the pull side for making sustainable modes of transport more attractive, especially PUI as response to COVID-19. While these measures will be effective at the margin, higher levels of modal shift towards sustainable modes of transport will require a combination of push and pull and thus equally involve measures that make car driving less attractive [66]. The short-term measures introduced during COVID-19 lockdowns to improve cycling and pedestrian access have led to a surge in these means of transport, but for keeping this momentum it is necessary to make such provisions more permanent. A pull approach delivers a positive narrative with novel bike and pedestrian centric infrastructures that offer safe transport and sustainable lifestyles for a broader part of the population. At the same time, redesigning cities towards more sustainable transport also translates into a major economic stimulus, which may be desirable also for combatting a recession. If value generation systematically shifts to shared mobility and mobility services, urban transport sustainability can be reached by effective governance.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

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Conflict of interest

The authors declare no conflicts of interest.

Codes

All coding and data analysis have been performed with R and Python. Codes can be made available upon request.
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