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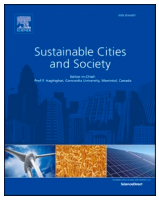

Pop-up cycling infrastructure as a niche innovation for sustainable transportation in European cities: An inter- and transdisciplinary case study of Berlin

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ABSTRACT

Mobility behavior changes due to the COVID-19 pandemic have opened a window of opportunity for an accelerated transition towards sustainable mobility. Many European cities installed temporary cycling infrastructure which can be considered a niche innovation in the Multi-Level-Perspective of transitions (Geels, 2002). We empirically assess the effects of such temporary infrastructure in terms of air quality, behaviour, and acceptance, with a focus on the city of Berlin, Germany. The numerous pop-up bike lanes installed serve as an inter- and transdisciplinary case study to systematically capture these effects. We conducted a survey among Berlin citizens (n= 1,661), analysed cycling usage data, and measured the exposure of cyclists to air quality before and after the implementation of one pop-up bike lane during the first wave of COVID-19. Results show that pop-up bike lanes receive high levels of acceptance, increase cycling usage on the respective street, and reduce cyclists' exposure to nitrogen dioxide. Their implementation fosters an innovative mind-set of transport planning: to temporarily try out new street designs, learn from these practical experiences, improve the designs, and then permanently implement the ones best proven in practice. We conclude that PUBL can accelerate the regime shift from car-oriented to bicycle-friendly cities because of its many demonstrated positive impacts.

1. Introduction

Most European cities face the challenge of climate change mitigation and adaption. As a part of the necessary transition, the transport sector plays a crucial role but mobility routines and practices are generally stable and resistant to change. In contrast, the COVID-19 pandemic has swiftly and unexpectedly changed the way people move (Benita, 2021). Temporarily, mobility demand was disruptively reduced (Ghanim, Muley, & Kharbeche, 2022). As a result, positive environmental effects of this decreased demand have been observed (e.g., Gkatzelis et al., 2021). With these shifts, carbon dioxide (CO_2) emission reduction targets and better air quality seem more achievable than before the pandemic (Forster et al., 2020). Moreover, the pandemic changes might facilitate a transition to sustainable mobility (Kanda & Kivimaa, 2020). To analyse transition processes, the multi-level perspective of transitions (MLP) is a well-established theoretical perspective (Geels, 2002, 2011; Schot & Geels, 2008) and has been successfully applied to the field of urban mobility studies (e.g. Geels, 2005; Geels, 2012). The MLP assumes that transitions develop over time, when interactions among three different levels occur. These levels include dynamic niche innovations on the micro-level, a relatively stable socio-technical regime on the meso-level, and broader overarching developments on the landscape level.

Within the MLP, the current changes due to the pandemic can be seen as a landscape shock and a window of opportunity for an accelerated transition towards sustainable development (Geels & Schot, 2007; Rosenbloom & Markard, 2020; Wells, Abouarghoub, Pettit, & Beresford, 2020). Cities have used this opportunity to implement a variety of measures that reallocate street space in an effort to explore sustainable mobility options, such as walking and cycling or to create public spaces where distancing is possible (Glaser & Krizek, 2021; Shirgaokar, Reynard, & Collins, 2021; Vecchio, Tiznado-Aitken, & Mora-Vega, 2021). A number of European cities have tried to use this window of opportunity by implementing temporary infrastructure for cycling and

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walking which can be considered “niche innovations” in the MLP. For example, Paris (France) and Berlin (Germany) have installed pop-up bike lanes (PUBLs) to enable more and safer cycling. Infrastructural changes for healthy and sustainable active modes of transport that previously took years to implement became rapidly achievable. These cities used the window of opportunity, opened by the pandemic, to push the transition to sustainable mobility forward. However, many of these have been ad-hoc policy decisions rather than long-term strategic planning. That said, research has identified non-motorized travel, and specifically the rapidly implementable PUBLs, as an ideal adaptation to existing urban transport plans given the COVID-19 pandemic (Simić, Ivanović, Đorić, & Torkayesh, 2022). Thus, it is not clear if the temporary niche innovation of PUBL will truly have an impact on the “socio-technical regime” that is still a car-oriented regime in many European cities.

The aim of this paper is to investigate the potential of temporary infrastructure as a niche innovation, in particular PUBLs, for accelerating regime change from car-dominated to bicycle-friendly cities and to answer the research question whether temporary infrastructure - in the form of PUBLs - can contribute to a faster implementation of the transport transition and under which conditions it effectively contributes to more sustainable cities. Transition research acknowledges the importance of temporary policies and emphasizes that such "transition experiments" and their effects should be studied more systematically (Köhler et al., 2019; Sengers, Wieczorek, & Raven, 2019). At the same time, another research gap in transition research is that the focus is usually on socio-political processes, while the natural science effects of transition experiments are ignored. We address these two research gaps with the present work in the form of a more holistic approach and evaluate the PUBLs in Berlin as an inter- and transdisciplinary case study. In doing so, we consider not only the socio-political dynamics, but also the environmental effects (e.g., air quality) of PUBLs.

2. Timeline of the first wave lockdown

In reaction to the first wave of the COVID-19 pandemic, lockdown measures were implemented in countries across the world. While these measures differed in their severity, generally, schools and non-essential businesses were closed, and travel was restricted. The timing of the lockdown measures varied based on local spread of the virus and how quickly countries implemented these restrictive measures. Some of the earliest lockdown measures were implemented in Wuhan, China (where the pandemic originated) as early as January of 2020. In Europe, lockdown measures were implemented in northern Italy from March 8 and in the rest of the country on March 10, 2020. Spain, France, and Germany followed suit in mid-March (Sicard et al., 2020). In Berlin, as in many other locations, the lockdown progressed in phases, with school closings and progressively more businesses being closed as of the 14th of March, with the most severe lockdown measures in place as of the 22nd of March. These measures remained in place in Berlin until the 22nd of April, at which point contact restrictions remained in place but some smaller businesses were allowed to reopen with safety measures in place. As of June 22nd, 2020, businesses, restaurants, day cares and schools were reopened, however, with safety measures (e.g., face masks & distance of 1.5 m) in place.

3. Assessing the first wave: what were the effects of COVID-19 containment policies on air quality and transport behavior?

Lockdown and social distancing policies due to the first wave of the COVID-19 pandemic severely restricted people’s mobility behavior and daily life. The goal of these restrictions was to contain the virus’ spread. Subsequently, economic activities and transportation of goods were drastically reduced. This had substantial effects on the environment in terms of air quality and (to a lesser extent) CO_2-emissions. Especially in high population density urban areas, many local governments created new policies to support active mobility (walking & cycling) and to improve quality of life of their residents (lack of exercise), in response to COVID-19. The main goal of these policies was not to contain the virus but to alleviate the negative side-effects of the COVID-19 containment policies or to help people adapt their behavior accordingly.

3.1. Air quality effects

In response to the COVID-19 pandemic, limitations were placed on a variety of activities, including mobility and travel. This resulted in a dramatic change in air pollutant and, to a lesser extent, greenhouse gas emissions, especially in the transport sector (Wang & Li, 2021).

Owing to air pollutants’ relatively short atmospheric lifetime (days to weeks, rather than years to a century, as is the case for CO_2), the effects of COVID-19 policies on changes in air quality were much more immediate and had a noticeable impact locally and regionally. An increasing number of papers are providing insight into these effects (e.g. Barré et al., 2020; Goldberg et al., 2020; Grange et al., 2021; Steinbrecht et al., 2021). Briefly, substantial decreases in nitrogen dioxide (NO_2), limited decreases in particulate matter (PM), and in many cases, increases in ozone (O_3) were observed during the pandemic shut-downs in urban areas (Baldasano, 2020; Menut et al., 2020; Naethe, Delaney, & Julitta, 2020; Ordóñez, Garrido-Perez, & García-Herrera, 2020; Sicard et al., 2020; Wang & Li, 2021).

(Baldasano, 2020)Ordóñez et al.(2020)(Menut et al., 2020)Overall, the reductions in NO_2 were largely attributed to changes in emissions from the transport sector, while changes in PM2.5 differed more strongly by region owing to a greater diversity of biogenic and anthropogenic sources, including agriculture and energy production (Guevara et al., 2021; Venter, Aunan, Chowdhury, & Lelieveld, 2020). Increases in ozone are generally attributed to the substantial NOx reductions, which because of the non-linear chemistry, can counter-intuitively lead to an increase in ozone (e.g., Jiang et al., 2021; Wang et al., 2022). As with greenhouse gas reductions, the concern that post-lockdown emissions will return to the prior status quo, is also relevant. Indeed, at this point, some work has already shown a return to normal air pollution levels after the first lockdown (Ding et al., 2020).

Emission reduction studies quantifying the effect of COVID-19 on mobility have clearly demonstrated that traffic emissions still contribute substantially to poor air quality in urban areas (Baldasano, 2020; Menut et al., 2020; Sicard et al., 2020). Research has also demonstrated the link between COVID-19 morbidity and mortality and the level of air pollution, with higher air pollution exposure leading to worse outcomes (Bourdrel, Annesi-Maesano, Alahmad, Maesano, & Bind, 2021; Cazzolla Gatti et al., 2020; Cole, Ozgen, & Strobl, 2020; Koch et al., 2022). To increase our resilience and preparedness for potential future pandemics, and take concrete steps in a transition to sustainability, a transport transition is called for. City governments are key players in this undertaking and policies that reduce air pollution and especially exposure will be critical. It is unclear in how far PUBLs can contribute to this. In this case study we evaluate the niche innovation of PUBLs to quantify what their effect on air quality and air pollution exposure for cyclists is.

3.2. The effects of COVID-19 distancing policies on mobility behavior

In general, individual mobility behavior is strongly shaped by fixed routines (Schwanen, Banister, & Anable, 2012; Verplanken, Aarts, & van Knippenberg, 1997). These routines determine not only the individual choice of transport mode for daily mobility, but also preferences for certain destinations for leisure which are usually combined with a corresponding means of transport (e.g., air travel for a summer vacation in a foreign country). The pandemic has disrupted mobility users’ routines on practically all dimensions of mobility: means of transport, number of trips, timing, distance and choice of destinations. These changes occurred in all segments of personal transportation – daily travel, business travel, and leisure travel have been affected by this

unprecedented collective behavior change.

Environmental psychology literature generally considers the breaking of individual routines as a window of opportunity for more sustainable behavior (e.g. Matthies, Klockner, & Preissner, 2006; Thøgersen, 2012; Verplanken & Roy, 2016). This behavior change can be stimulated by a change of attitude, by individual life events, such as moving house or having a child (Verplanken, Walker, Davis, & Jurasek, 2008), as well as by contextual factors such as infrastructural changes or transport-pricing changes (Fujii, Gärling, & Kitamura, 2001; Fujii & Kitamura, 2003; Pucher, Dill, & Handy, 2010). The COVID-19 pandemic is a form of collective life event that has changed mobility patterns. However, given the duration, it is an ongoing crisis rather than a short-term event where old routines are replaced by new *stable* routines, as is usually the case after an individual life event.

Traffic estimations for different European cities show that a dramatic reduction in demand for public transit, cycling and walking occurred during the second half of March 2020 (below 20% of normal demand), remaining extremely low during April 2020 (IEA, 2020) (Fig. 1). During the second half of May, mobility demand for these modes slowly increased again, back to a level of about 65% of the normal activity level by June 2020. In Paris (France), mobility demand reached 80% of the pre-COVID-19 activities in September, in Lyon (France) even 100%. As Fig. 1 illustrates, the second COVID-19 wave in autumn 2020 and the associated lockdown again considerably suppressed mobility demand to levels lower than experienced prior to the 1st wave.

Similar to the lower demand for transit and active modes during the first lockdown, car travel was also suppressed in many European cities (Fig. 2). However, car travel remained between 20% and 40% of pre-pandemic times between mid-March and end of April 2020. Moreover, at the end of the first lockdown, car travel demand reached around 80% of normal demand in various European cities, see Fig. 2. Thus, car travel routines seem to recover more easily than mobility demand for transit and active modes. Moreover, COVID-19 has led to a revival of car-centered cultural patterns in several cities, such as the drive-in cinema, but also new car-dependent practices directly related to the pandemic, such as drive-in testing centers.

At the same time, multimodal use behavior has declined, as is illustrated in Fig. 3. In summer 2020, users stuck more to one main mode of transport and have become less flexible than before. In the mobility tracking study by Follmer and Schelewsky (2020), the share of users who exclusively traveled by car has increased between the first measurement, before the pandemic (end of February until mid-March 2020), and the third measurement (mid-June 2020 until end of June 2020), see Fig. 3. In parallel, about half of those users that mainly use a car at the time of the second measurement, during the first lockdown (mid-March to mid-June 2020), had been multimodal users before the pandemic. The share of users who mainly use public transit has been cut in half between the first and the third measurement. A considerable part of those users ended up mainly traveling by bicycle at the third measurement. In total, this tracking study shows gains for bicycle use and car use, and losses for public transit and multimodal use behavior.

In summary, an unprecedented disruption of mobility routines has taken place in Europe which has temporarily led to a sharp decrease in transportation demand. Theoretically, this disruption of behavioral routines represents a window of opportunity for more sustainable mobility behavior in the future. However, car-centered mobility patterns displayed a strong tendency to return to normal, once the lockdown restrictions were eased. While there is a positive effect for bike use, the effects on public transit and multimodal mobility are negative. Thus, we conclude that the pandemic itself will not lead to a long-term behavior change that would be necessary to achieve a transition towards sustainable transportation in European cities.

4. European cities' reaction to the new mobility challenges: Overview on mobility-related COVID-19 policies

A number of European cities have engaged in innovative mobility policies as a reaction to the first wave of the COVID-19 pandemic in spring of 2020. These mobility policies have the potential to make use of the behavioral window of opportunity for an accelerated transition to a bike-friendly mobility regime in cities. They included a wide variety of mobility-related policy measures, spanning from expansion of special bus services or filtering traffic modes to providing free car parking or implementing speed limits, all aimed at safely enabling necessary mobility, in terms of reducing risk of infection but also road safety to minimize using hospital capacities for traffic accidents. Infrastructural measures, such as modal filters or physical barriers between car and bicycle lanes were also used to increase the ability to maintain distance. Other strategies included legal changes (e.g., officially allowing pedestrians on to roads which were already closed to motor traffic in Vienna), removing the necessity to touch a button for a green light at a pedestrian crossing, or reduced-fare or fare-free transit and bike-sharing (Combs, 2020). In this section, we present a brief overview of some of the more common COVID-19 policy responses that are directly related to traffic infrastructure (see Table 1). A common group of measures can be subsumed under the broad heading of 'spatial redistribution,' which

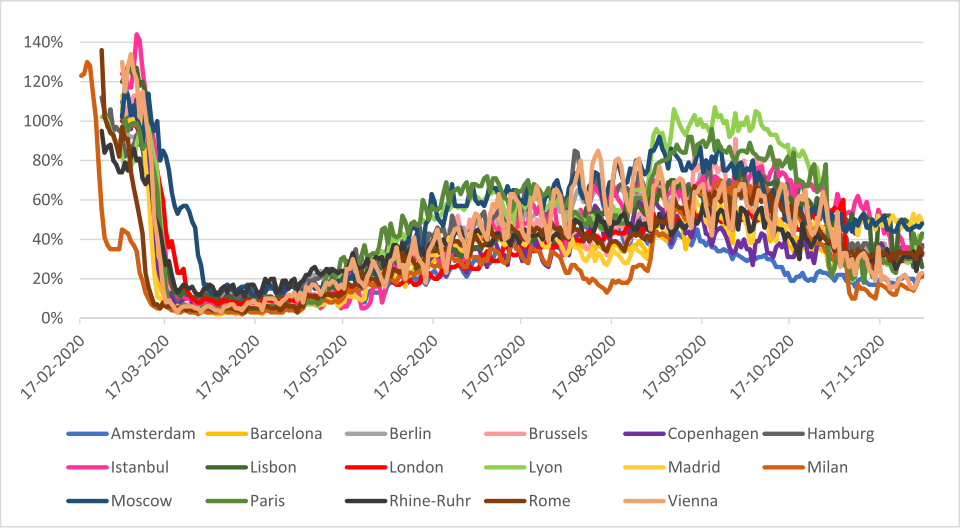

Fig. 1. Relative changes in mobility demand for transit, cycling and walking in various European cities from February to November 2020, compared to a "normal period" (Jan 6th and Feb 2nd, 2020; exception: Feb 3rd to March 1st in Paris). Data source: citymapper.com

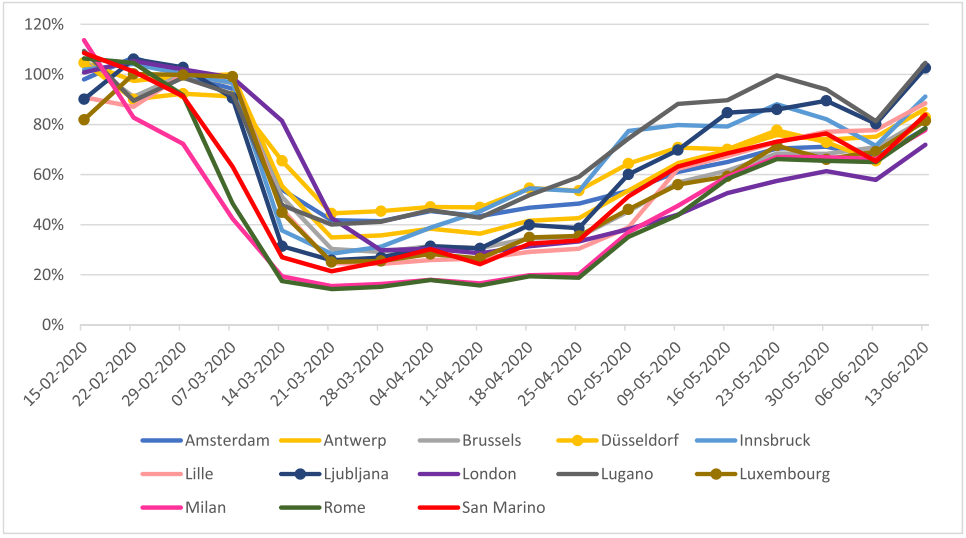

Fig. 2. Changes in mobility demand for car travel, displayed as the weekly average of trips by car in various European cities from February to June 2020, relative to their January averages. Data source: TOMTOM https://www.tomtom.com/blog/moving-world/covid-19-traffic-mobility/

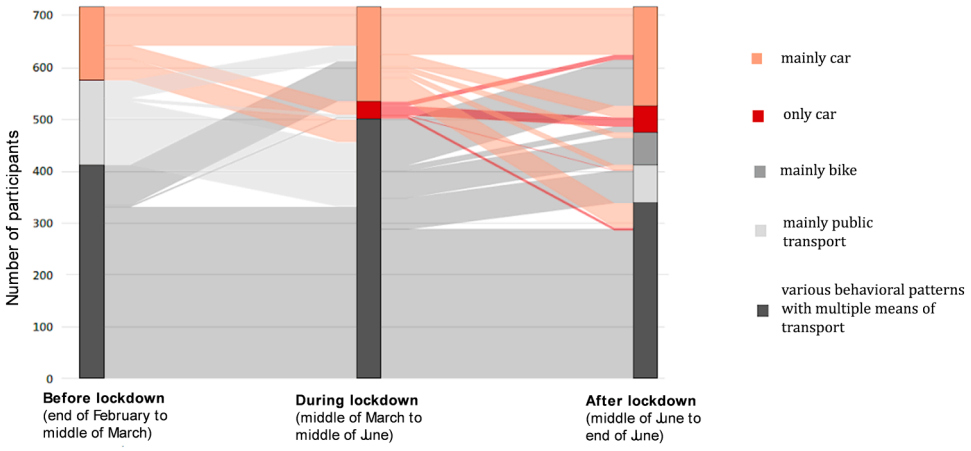

Fig. 3. Modal shift in different phases of lockdown policies in 2020. Data: Subsample (n = ca. 700) of a representative survey in Germany (first week of May to second week of June 2020); Based on approx. 700 participants without tracking interruption, tracking results in-house study MOTIONTAG; graph and source: Follmer & Schelewsky 2020, p.36; own translation from German.

Table 1
Overview of mobility-related COVID-19-measures in different European cities (source: own data/(Combs, 2020)).

City	Spatial Redistribution Measures		
	New Bike Lanes	Expanded Pedestrian Space	Space for Outdoor Dining
Berlin (Germany)	X	X	X
Barcelona (Spain)	X	X	
Brussels (Belgium)		X	X
Lisbon (Portugal)	X		X
London (England)	X		X
Milan (Italy)	X	X	X
Paris (France)	X		
Vienna (Austria)	X	X	X
Vilnius (Lithuania)			X

involves repurposing street space. These were typically aimed at increasing traffic safety and increasing space for pedestrians and cyclists to ensure the possibility for maintaining physical distance, but also to enable the use of road space for purposes other than transport to avoid crowding in parks and plazas.

The measures that possibly received the most attention were bicycle lanes. This measure, alternatively referred to as corona-lanes, pop-up bike lanes (PUBLs), or temporary bike lanes, was mostly carried out by repurposing street space – from motor traffic or car parking for use by bicycles. This measure was first implemented by the city of Bogotá (Columbia) at the end of March 2020 (Wray, 2020). Building on this example, more than 100 European cities followed suit, creating more than 2,000 km of new bike lanes by July 2020 (Kraus & Koch, 2021), with Berlin one of the first. These PUBLs are typically created by painting lines and bicycle pictograms onto the street (as in Milan), and can be supplemented with pylons or other physical barriers (as in Berlin, Lisbon, or Paris), see Fig. 4.

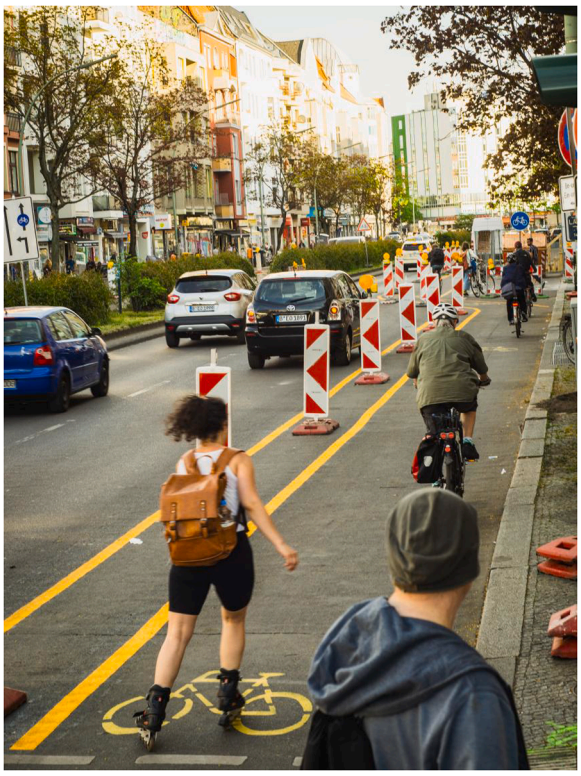

Fig. 4. Picture of a pop-up bike lane in Berlin (photo credit: P. Broytman)

5. Inter- and transdisciplinary case study: Berlin's pop-up infrastructure for cycling

To investigate COVID-19 temporary infrastructure and assess their potential for the overall regime shift to sustainable mobility, we conducted an inter- and transdisciplinary case study of the PUBLs in Berlin (Germany). A case study is "an in-depth exploration from multiple perspectives of the complexity and uniqueness of a particular project, policy, institution, programme or system in a 'real-life' context. It is research-based, inclusive of different methods and is evidence-led" (Helen Simmons, 2009, p. 21, cited after Thomas, 2015, p. 10). While the case study method is already well-suited for disciplinary research endeavors, we are convinced that the current case of PUBLs in Berlin calls for an inter- and transdisciplinary approach. Transdisciplinary research can produce and integrate different forms of knowledge, i.e. orientation knowledge, systems knowledge, and transformation knowledge (Pohl & Hirsch Hadorn, 2007). Here, we focus on the two latter forms of knowledge production in regard to the temporary infrastructures. New *systems knowledge* is needed because little is known about the environmental and health effects or the user reactions of the temporary COVID-19 infrastructure. For the present case study, perspectives from atmospheric science and psychology are brought together: we combine measurements of air quality with behavioral data on cycling usage, survey data on acceptance and perceived effects of the PUBLs. At the same time, the experiments with temporary infrastructure can be used to derive *transformation knowledge* about how sustainable transportation can be achieved more rapidly than before. Here, political science and practical knowledge are brought together to provide information about the political processes that enabled the implementation of the PUBLs in Berlin. The contextual background knowledge was gained through document research, a number of background talks and participation in discussion rounds with policy-makers and civil society organizations. This use of contextual process tracing is a specific benefit of the case study method (Flyvbjerg, 2011). Through our case study, we aim to provide evidence-based and policy-relevant knowledge on the implementation of temporary infrastructure in the present case study of PUBLs in Berlin. Further policy decisions on temporary infrastructure would benefit highly from knowledge about their effects and the lessons learned about the political implementation.

In section 5.1 we provide contextual information about the political situation in Berlin with regard to transport policy. In section 5.2 we provide a brief overview of the research design and data collection, organized by topic (see Table 2).

5.1. Political background in Berlin

As elsewhere in Germany (and also before COVID-19), there is a broad consensus across the political spectrum in the state of Berlin that a substantial part of motorized private transport should be shifted to public transport and the bicycle (von Schneidemesser, 2021). Despite this intention, Berlin remains a car-oriented city in terms of traffic design. Nearly 60% of the traffic areas in Berlin are dedicated to motorized traffic, although this only makes up about 25% of the routes – and the trend of car use is decreasing. Cycling, on the other hand, is allocated only 3% of the traffic areas, although it already accounts for 18% of the trips travelled - and the trend is rising (Agentur für clevere Städte, 2014; Gerike et al., 2019; Senatsverwaltung für Umwelt, Verkehr und Klimaschutz, 2019).

In 2016, a civil society initiative in Berlin began a campaign for a bicycle law. This led to Germany's first bicycle law being passed as part of the Berlin Mobility Act by Berlin's state parliament in 2018, indicating a paradigm shift in German traffic policy (Becker, Bögel, & Upham, 2021; von Schneidemesser, Herberg, & Stasiak, 2020), which otherwise focuses on motor traffic. As a city-state, the governmental structure of Berlin is such that there is the state-level government and administration as well as municipal district governments and administrations. The Mobility Act in Berlin requires the implementation of infrastructure projects (bike lanes, bicycle highways, bicycle parking) for which Berlin's 12 district administrations are largely responsible. This means that there are various levels of commitment and resources devoted to the implementation of the Mobility Act depending on the political and administrative situation in the respective district.

Such implementation is pursued with varying levels of commitment by the 12 districts. In the district of Friedrichshain-Kreuzberg, where Berlin's PUBLs were first implemented, the administrative and political leaders had long been working with civil society and scientific actors, bringing ideas and input together in a "Mobility-Transition Committee" (Bezirksamt Friedrichhain-Kreuzberg von Berlin, 2022) and other (ad-hoc) formats. An important difference between Friedrichshain-Kreuzberg and other districts was that this transdisciplinary cooperation was maintained (and even amplified during the beginnings of the COVID-19 pandemic) and approached constructively by all involved actors. Another key distinction was that there were already numerous concepts and impulses for the mobility transition and redistribution of

Table 2
Overview on data and methods

Topic	Variables	Data source	Methods
Air quality effects	Nitrogen dioxide (traffic-based air pollutant)	Air quality measurements	Quantitative analysis of before and after measurements
Behavioral effects	Cycling usage	STRAVA app (anonymous voluntary self-tracking by cyclists) with 479,954 measurement points	Descriptive statistical analysis of before and after measurements
User reactions and acceptance	Perceived advantages and disadvantages of PUBL; acceptance	Own user survey with n= 1,661 participants	Qualitative content analysis; statistical analysis

public space before the COVID-19 pandemic in the "first-adopter" district of Friedrichshain-Kreuzberg. Here, district-level political, administrative, and civil society actors had been (unknowingly) laying the foundations for quick action, both at the political and administrative levels. This coincided with a common vision at the state-level in the form of the 2018 Berlin Mobility Act. The common vision and the foundational work, however, were not sufficient until the window of opportunity presented itself in the form of the COVID-19 pandemic, requiring more space for pedestrians and cyclists. Important criteria from this cooperation that were key to facilitate the implementation of the PUBLs were:

1. *The idea for PUBLs was not new*: Civil society initiatives had brought in the notion of pop-up bicycle infrastructure *before* the COVID-19 pandemic arrived. Thus, at the very least there had been conceptual work done on the possibility of using temporary measures such as construction-zone materials to create bicycle infrastructure.
2. *The bike lanes were already officially identified as "projects"*: Civil society actors had suggested gathering the ongoing and planned projects related to bicycle infrastructure into a single list to be better able to maintain an overview. The administration took up the idea, and submitted a part of the result to the district parliament, who approved an initial list of 49 infrastructure projects in 2018 (Bezirksamt Friedrichhain-Kreuzberg von Berlin, 2018), providing political legitimacy for the bike lanes, again before the pandemic. Friedrichshain-Kreuzberg was the only district in Berlin to have such a list, and with few exceptions, the PUBLs implemented in Friedrichshain-Kreuzberg were already designated as future bike lanes on this list (Bezirksverordnetenversammlung Friedrichshain-Kreuzberg von Berlin, 2017). While such a procedure is not a prerequisite for implementing the bike lanes, it helps that plans for bike lanes on those particular streets were already underway, because the administration was familiar with and better prepared for the task of implementing bike lanes on these streets. Further, the approval through the district parliament made the bike lanes legitimate.
3. *Administrative competence*: Bicycle planning expertise was established to a greater degree in the administration of Friedrichshain-Kreuzberg than in any other district administration: the district was the only one with a bicycle planning position at the district level prior to the Berlin Mobility Act and had more bicycle planners than any other district.
4. *Political will paired with administrative competence*: A multi-actor constellation including various levels of the decision-making hierarchy aligned to enable the PUBLs. Both political and administrative leadership in Friedrichshain-Kreuzberg shared the aim of increasing cycling and safety for people on bicycles, explicitly through spatial redistribution away from motor traffic (Berliner Zeitung, 2020a; Bezirksamt Friedrichshain-Kreuzberg von Berlin, 2020). This conviction was shared by both the traffic minister and administrative leader at the state level (Berliner Zeitung, 2020b; Der Regierende Bürgermeister von Berlin. Senatskanzlei, 2019). This somewhat complex constellation is both rare and important for two reasons: 1) the administrative personnel at both levels remains beyond election periods while the political leadership changes. Due to high levels of job-security in Germany's civil service, administrative actors unwilling to follow certain positions of the political leadership can strongly influence priorities and enable or hinder infrastructure projects; 2) Because the majority of PUBLs are on main streets, the state level administration and the district administration must agree on orders (which they did).

While neither the Berlin Mobility Act nor the district's bicycle-infrastructure list were necessary for the district's response to the COVID-19 pandemic, both played an enabling role and paved the way for making the pop-up infrastructure permanent (Bezirksamt Friedrichshain-Kreuzberg von Berlin, 2021). The requirements of the Berlin Mobility Act helped to enable state- and district-level administrative actors to build capacities for active travel. This puts Berlin in a position to be more responsive, and ultimately leads to the creation of a more resilient city in terms of adaptation (Ribeiro et al., 2019).

The experience of the PUBLs in Berlin, however, also emphasizes the challenges facing new approaches to the implementation of sustainable mobility measures. A state parliamentarian from an extreme-right party filed a lawsuit against the implementation of the PUBLs claiming that they were unlawful and won in the first instance. The state-level administration appealed to the higher administrative court, and after an initial revision by that court, the lawsuit was withdrawn (Rbb24, 2021). As a result, the PUBL controversy ultimately resulted in a legal clarification showing that expedited implementation of bike lanes is legal.

5.2. Research design and data collection

The authors aligned their empirical measurements in time and space to obtain a multidimensional picture of the effects of PUBL at the street Kottbusser Damm in Berlin. The overview of the respective empirical measurements and data is given in Table 2. The claim here is not to integrate all three empirical levels with each other, since we are dealing with very different types of data. Rather, the aim is to obtain a multi-layered and comprehensive assessment of the effects of PUBL.

5.2.1. Air quality effects

To measure the impact of the bike lanes on air quality, measurements were done on Kottbusser Damm, the site of one PUBL in Friedrichshain-Kreuzberg, a district of Berlin. This included stationary measurements on lampposts and mobile measurements by bicycle. An air quality sensor was installed on the handlebars of a bicycle and a prescribed route, along Kottbusser Damm where the bike lane was later implemented, was cycled before and after implementation. The mobile measurements were designed to provide an indication of the change in air pollution exposure for cyclists before and after the implementation of the bike lane. For a more detailed description of the measurement instrumentation, measurement campaign, and analysis, see Schmitz, Caseiro, Kerschbaumer, and von Schneidemesser (2021). The analysis method accounted for the role of meteorology and other factors on air quality, including the larger context of changes in air quality in Berlin as a whole owing to the COVID-19 lockdown. Briefly, (Guevara et al., 2021)in Berlin, during the core lockdown period from 22 March – 21 April, 2020, traffic counts decreased by 36% on average relative to the previous four years, with greater reductions at the weekend (47%) relative to weekdays (32%) (von Schneidemesser et al., 2021). The subsequent changes in air quality measured at traffic stations were average reductions of 18 μg m^{-3} on weekdays and 17 μg m^{-3} on weekends, with standard deviations of 15 μg m^{-3} and 11 μg m^{-3}, respectively. These reduction values are weighted averages accounting for the prevalence of meteorological conditions during the 2020 period relative to the 2016-2019 period. The standard deviation reflects the variation across different stations in Berlin and is not a measure of uncertainty. These reductions correspond to ca. 40% and 50% reductions, respectively, relative to the previous period (von Schneidemesser et al., 2021). These city-wide effects were accounted for in the analysis, so that the air quality changes observed for cyclists could be isolated from these other factors. Further details on the overall changes in air quality in Berlin during the lockdown can be found in von Schneidemesser et al. (2021).

5.2.2. Behavioral effects

To investigate the behavioral effects of the PUBL at Kottbusser Damm, we analyzed cycling usage data before and after the implementation of the PUBL. The data is anonymized data from cyclists using the STRAVA app to track their cycling trips for health and fitness purposes. Thus, it is not representative data for all cyclists in a city but it

generally shows high correlations with official bicycle counts[1]. Before analysing the STRAVA cycling data for Kottbusser Damm (where no official bike counting stations are installed), we compared the STRAVA data for another street (Jannowitzbrücke) in Berlin that has a bike counting station, with the official bike counts[2]. The analysis reveals that STRAVA trips accounted for 1% of all cycling trips officially counted on this street and has a high correlation of r = 0.70. Thus, we deduce that the STRAVA data is useful to derive conclusions about the actual behavioral effects of the PUBL. For the relevant 24 months (April 2019 to March 2021), a total of n= 479,954 measurement points (trips per single edge per day) on Kottbusser Damm were available from STRAVA. The Kottbusser Damm consists of 42 "edges", i.e. single measurement sections of the STRAVA tracking app. The software package R was used to analyze the data.

5.2.3. User reactions and acceptance

To investigate Berlin residents' acceptance and perceived advantages and disadvantages with the new PUBLs, we conducted an exploratory survey shortly after the PUBLs had been implemented (from April 30th til May 8th 2020).

The survey contained 20 items (some of them are reported elsewhere) including perceived advantages, disadvantages, mobility behaviour, mobility-related identity, and socio-demographic questions. We measured the advantages and disadvantages with a free association task (e.g., Joffe and Elsey (2014)), so participants could freely name up to seven associations to the PUBL according to the questions which advantages and disadvantages they associate with the new PUBL. The other items were mostly measured in multiple-choice design.

Participants were recruited through local newspapers in Berlin. A total of 1,661 Berlin residents completed the online questionnaire. The sample includes a higher proportion of cyclists, voters of progressive parties, and people with a higher education level than Berlin residents on average (for further details of the sample see Götting and Becker (2020)). As this is a convenience sample, the results cannot be generalized for all residents in Berlin.

To deal with that, we analysed the results for users and non-users separately. While users are a very homogenous group with regard to their mobility behavior (cyclists or cargo bike cyclists), the non-users are very diverse. They include respondents who mainly identify themselves as pedestrians (8.4%), car drivers (25.4%), users of public transport (20.6%), users of other means of transport (9.1%), as well as cyclists (34.1%) who do not use the PUBLs, e.g., because they are not on their daily routes.

In total, there were four text corpora each containing either advantages or disadvantages for users' or non-users. As the text corpora are large, we firstly identified the most frequent words with a frequency analysis and used them as main categories for the qualitative content analysis (Waldherr et al., 2019).

Afterwards, we clustered the main categories with similar content and added more mentioned associations from the corpus to specify them. Besides, we investigated the respondents' acceptance regarding their mobility related identity.

5.3. Results

5.3.1. Air quality effects

For cyclists riding along Kottbusser Damm, the PUBL has reduced their exposure to NO_2. Fig. 5 shows boxplots of concentrations faced by cyclists before and after the implementation of the pop-up bike lane. The data are normalized to four stationary sensors attached to lampposts along Kottbusser Damm, to account for variations in meteorology and traffic conditions, including broader changes owing to any COVID-19 policies. As can be seen, NO_2 exposure for cyclists was higher without the PUBL before the lockdown than it was following the construction of the PUBL. The implementation of the bike lane reduced the NO_2 air pollution that cyclists were exposed to by 8.4 ± 7.4 μg m^{-3}, or 22%. Similar measurements along the side streets connecting to Kottbusser Damm did not exhibit evidence of a reduction in exposure. This indicates that the reductions in NO_2 seen on Kottbusser Damm can be attributed to local changes in emission patterns and do not result from a greater trend in Berlin. For more detail on this analysis, see (Schmitz et al., 2021).

5.3.2. Behavioral effects

An analysis of the cycling usage data on our case study street, Kottbusser Damm, reveals that cycling has substantially increased after the PUBL was implemented. With the PUBL, there is an average increase in cycling usage of 73% in the 12 months since the PUBL has been installed. For this analysis, we compared the amount of usage for each month of the year separately, to account for the seasonal differences. In May 2020, a maximum of 141% increase in cycling usage compared to May 2019 was observed (even though there were still lockdown policies in place at that time).

A second analysis of the cycling usage data shows the relative increase in cycling after the PUBL was installed, compared to a baseline level ("0% level") of the previous 12 months before the PUBL installation, and is shown in Fig. 6. Even though there is still the usual decline of cycling during the colder months of the year, the amount of cycling usage on Kottbusser Damm has reached a higher level overall in the 12 months since the PUBL has been installed.

5.3.3. User reactions and acceptance

User perspectives Many users highlight a higher level of (subjective) traffic safety due to the PUBLs. This could enable safer cycling for vulnerable groups such as children or elderly people, according to the users. In addition, they welcome the extra space, especially for overtaking or travelling by cargo bike. More space also helps to maintain distance with regard to infection prevention and allows for a safe distance to the motorized vehicle traffic according to the users. Some respondents appreciate the currently increased visibility of cyclists, and mention keywords such as justice, equal rights and distributional justice and see the PUBLs as a symbol of progress for the mobility transition. Furthermore, advantages for the environment, such as better air quality are mentioned. Many users also value the road quality of the new PUBLs

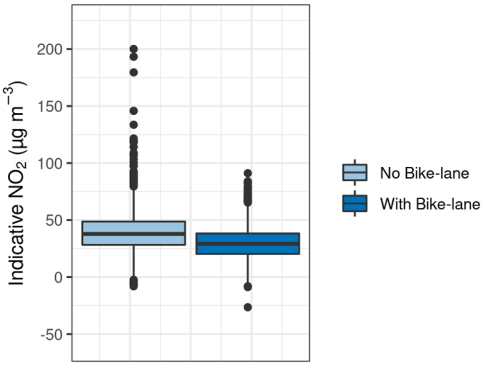

Fig. 5. The change in NO_2 concentration that cyclists were exposed to before and after the implementation of the bike lane. The concentrations are shown here as indicative NO_2 because the normalized concentrations were adjusted to reflect real-world concentrations by adding the median of all values that were normalized to (adapted from Schmitz et al. (2021)).

[1] In New York, STRAVA trips account for 6.5% of all cycling trips on average. An exemplary comparison with the official bike count data on the Manhattan Bridge (NY) shows a very strong interrelation of R^2 = 0.93. See https://stravametro.zendesk.com/hc/en-us/articles/360054069173 [accessed 2021/05/28]

[2] All data of Berlin's official bike counting stations is available online at https://www.berlin.de/sen/uvk/verkehr/verkehrsplanung/radverkehr/weitere-radinfrastruktur/zaehlstellen-und-fahrradbarometer/ [accessed 2021/05/28]

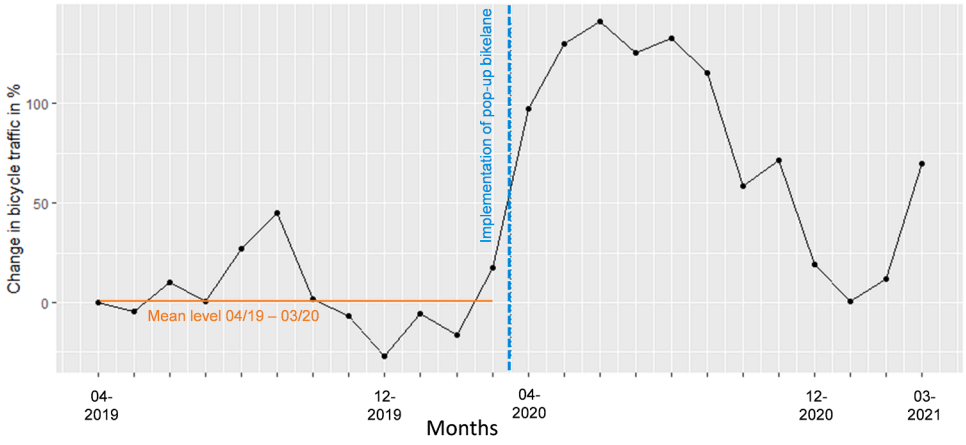

Fig. 6. Relative increase in cycling trips after the implementation of a pop-up bike lane on Kottbusser Damm (Berlin); based on aggregated and anonymized raw data of cycling trips tracked with the STRAVA app. The baseline level ("0%") on the y-axis represents the mean number of cycling trips in the 12 months before the PUBL was implemented (April 2019 - March 2020). The relative changes in cycling trips for all months displayed in the graph refer to this pre-PUBL baseline level (coloured in orange).

and describe the ride as more comfortable, pleasant and stress-free than before.

However, there are also users who criticize the quality of the new bike lanes. In some cases, they are perceived as too narrow (e.g. for overtaking), too short and rough or have been described to just stop abruptly. The latter might be dangerous, especially close to junctions, according to some respondents.

Besides, many users complain about stopping or parked cars, delivery vans or cabs on the bike lanes and about car drivers who don't take the barriers seriously or just ignore them. One explanation among the respondents is that car drivers are not used to the new bike lanes yet. Consequently, many users report negative reactions of car drivers such as aggressive behaviour, anger, frustration, irritation and rage.

In contrast, some users don't mention any disadvantages or just lament that the pop-up bike lanes seem to be temporary.

Non-user perspectives Some non-users mention the same benefits as the users, for example safety, (more) space, speed and environmental protection, whereas others, mostly car-drivers, do not see any advantages in the PUBLs. At the same time, some non-users criticise less space for cars, delivery vehicles, ambulances, and vehicles for nursing services. They associate the PUBLs with a waste of space and an unjust distribution of space. Additionally, they worry that PUBLs will exacerbate traffic jams and believe that the air pollution and CO_2 emissions will be increased by stop-and-go-traffic or by cars spending more time looking for parking. Moreover, some non-users question the increase in safety. They point out that crossing the bike lanes for pedestrians or car drivers on their way to a parking area is dangerous. Finally, they criticise that the bike lanes might not be used during bad weather.

Acceptance As expected, almost all cyclists accept the new PUBLs. Among the other transport users, the acceptance levels are heterogenous. Respondents who identify themselves as car drivers mostly reject the PUBLs, whereas respondents who identify themselves as pedestrians or users of public transport mostly support them. For more details see Table 3.

Table 3
Cross-table of attitude to the pop-up bike lanes and mobility group (source: Götting and Becker (2020)) In bold are the attitudes most common to each mobility group.

Mobility group ("I identify mainly as …")		Pedestrians	Cyclists	Users of public transport	Car drivers
Attitude to the pop-up bike lanes	Support	**75.2 %**	**94.1 %**	**79.2 %**	14.8 %
	Reject	21.1 %	3.3. %	15.1 %	**79.3 %**
	No opinion	3.7 %	1.8 %	4.7 %	5.9 %
	No information	0 %	0.8 %	1.1 %	0 %

6. Discussion

We found that the installation of PUBLs reduced the concentrations of NO_2 that cyclists are exposed to. This amounted to a reduction of 8.4 $\pm$ 7.4 μg m^{-3} or 22% following the implementation of the PUBL along Kottbusser Damm. These findings are in agreement with other limited studies which measured a reduction in cyclists' exposure to air pollution when switching from open-road cycling to a protected bike lane (Farrell, Weichenthal, Goldberg, & Hatzopoulou, 2015; Hernández, Ramírez, Benavides, & Franco, 2021). Other studies show that the further away a cyclist is from traffic emissions of air pollutants, particularly along main roads, the lower their total exposure will be (Jarjour et al., 2013; Shrestha, Mullins, Zhao, Selvey, & Rumchev, 2020).

While the temporary changes in traffic emissions and overall air quality in Berlin largely rebounded after the end of the 1st wave of the pandemic, the relative reduction in exposure measured along PUBLs is likely to be maintained with long-term implementation of the temporary infrastructure. Combined with a measured increase in cycling as a result of the PUBLs (see Fig. 6), these new bike lanes are likely to have substantial positive health effects for cyclists in Berlin. Moreover, the increased safety of protected bike-lanes will remain attractive for citizens and can facilitate a greater uptake of cycling across the city. On a city-scale, the most substantial health benefits come from the increase in physical activity associated with more cycling (Schepers et al., 2015).

The results of our survey show that most users of transit, cyclists, and pedestrians support the new PUBLs. A comparison with a large representative survey of the German population (n= 3,039) in autumn 2020 reveals that 70% of respondents have a positive attitude towards PUBLs. This high level of acceptance persists regardless of the respondents' age or the size of the city, and a majority of people favor the permanent preservation of such bike lanes (Jurczok et al., 2020). Furthermore, our survey showed that while users appreciate the space gained e.g., for passing other cyclists, using cargo bikes, etc., non-users, mostly car drivers, complain about the loss of space and worry about traffic jams or fewer parking spots. However, as the air quality analysis has shown, the apprehension expressed by some car drivers in the survey that the PUBL might exacerbate local air quality, is groundless.

Whereas users appreciate the increase in safety, some non-users question it. These results are in line with results from a survey concerning a PUBL in San José, California (Nixon, 2018). Ninety-five percent of the respondents emphasized aspects of increased safety as an advantage (ibid.). This is consistent with other studies highlighting that protected bike lanes generally increase the perceived safety (Dill, Goddard, Monsere, & McNeil, 2014). Moreover, the temporary bike infrastructure has been shown to increase cycling in many European cities (Kraus & Koch, 2021). On average, cycling increased by 42% in those cities that have implemented PUBLs compared to those cities that

have not, after controlling for a general growth effect in cycling through the pandemic (ibid.). In Berlin, official bike count data displays a 20 to 23 % increase in bike traffic for the year 2020[3], compared to the previous year, while we observed a 73% increase in bike traffic in our case study on Kottbusser Damm, based on STRAVA data. Thus, we conclude that part of the increase we observed is due to a change in routing behavior of cyclists preferring the new PUBL, and part of it is due to an increase in total cycling trips.

Our analysis of the political process behind the PUBLs in Berlin showed that the PUBLs were fast-tracked measures implemented in a temporary manner that are now beginning to be replaced by permanent infrastructure. The district that implemented these earliest and most extensively was also the only district with a district bicycle plan that included a list of infrastructural measures to be taken.

As Marsden and Docherty (2013) highlight, disruptions can have positive effects for a change towards sustainable transport policies. COVID-19 opened such a window of opportunity for a disruption and new mindsets of transport planning. Quick, "tactical urbanism"-style implementation of measures fosters an innovative mind-set for transport planning: to temporarily try out new street designs, learn from these practical experiences, improve the designs, and then permanently implement the one best proven in practice. As we observed for our case in Berlin's PUBL-pioneer district, neither administrative competence, nor the pandemic by itself were sufficient. The factors for success were: 1) a prepared administrative foundation; 2) a common vision shared amongst the proper constellation of administration and political leadership; 3) creative and popular support from civil society; and (4) the political leadership's will to persevere, even in conflicts over the PUBL in court. This latter conflictual dynamic fits with the MLP's theoretical assertions that the dominant regime has strong inertial forces (Fuenfschilling & Truffer, 2014; Geels et al., 2016; Geels & Schot, 2007; Kungl, 2015). In the concrete case, however, one can see that the innovation of PUBL also asserts itself legally and thus shifts the established regime a significant step in the direction of a more bicycle-friendly regime (Aldred & Goodman, 2020; Zografos et al., 2020).

7. Conclusion

Many European cities have established temporary cycling infrastructure during the first year of the COVID-19 pandemic. These PUBLs provided a valuable opportunity for researchers to gain empirical insights into the effects and significance of PUBLs. The goal of this study was to use PUBLs to explore the potential of COVID-19 temporary infrastructure as a niche innovation for the transport transition in European cities. To this end, we selected PUBLs in Berlin as an inter- and transdisciplinary case study and collected empirical data on their impact on air quality, cycling behavior, and user acceptance, and reflected on the policy processes around their implementation. The MLP (Geels, 2002) served as the broader theoretical framework to guide our study. The air quality measurements conducted here fill a research gap, as the effects of such infrastructure measures are rarely measured quantitatively. In parallel, the effects of infrastructure measures on behavior and attitudes are often difficult to measure empirically. Thus, we provide a scientific contribution to a better understanding of transition experiments (Köhler et al., 2019; Sengers et al., 2019).

The empirical results of our case study have shown that PUBLs have measurable environmental and health benefits as well as positive behavioral effects on cycling and are socially accepted. They are more likely to occur when there is already a well-prepared multi-actor constellation of politics, administration and civil society, and the political will is there to even go through legal disputes as well. Empirical evidence of the positive effects can help urban policy makers to support the introduction of cycle paths with well-founded arguments, because the benefits for people and the environment become demonstrable.

The inter- and transdisciplinary approach taken in this case study highlights the different facets that are important for a holistic understanding of mobility policy. In particular, the integration of natural science measurements into an MLP-based study has proven to be profitable. Not only social science but also natural science effect measures are important for policy evaluation and for the successful design and implementation of sustainable mobility infrastructures.

The routines in politics and administration, but also in individual behavior, that were broken by the first waves of the pandemic could enable a paradigm shift in approaches to urban planning and mobility change. More temporary and experimental approaches in urban planning would make it possible to first gain empirical knowledge about a temporarily implemented measure, to learn in the process, and only then to permanently implement the final configuration of a measure. Both the ongoing health crisis as well as the current energy crisis underline the need for cities to act flexibly in order to be sustainable and resilient.

Declaration of competing interest

The authors declare that they have no conflicts of interest.

Data Availability

The authors do not have permission to share data.
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[3] Depending on the consideration of temporary construction sites on several streets with bike counts in 2019 and 2020, slightly different results of relative change between the years occur. The raw data is available at: https://www.berlin.de/sen/uvk/verkehr/verkehrsplanung/radverkehr/weitere-radinfrastruktur/zaehlstellen-und-fahrradbarometer/ [accessed 2021/09/02]

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