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Do new bike lanes impact air pollution exposure for cyclists?—a case study from Berlin

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Cities in the 21st century are dynamically changing in response to environmental and societal pressures, not least among which are climate change and air pollution. In some of these metropolises, such as Berlin, a transformation of mobility systems has already begun. Along a mid-sized street in Berlin, a measurement campaign was conducted in 2020 to accompany the construction of a bike lane and the implementation of a community space along one of the side-streets. Using the new technology of low-cost sensors, higher resolution measurements of local air quality were enabled. Stationary and mobile measurements were taken using EarthSense Zephyr sensor systems before and after the construction of the bike lane and during the timeframe when the community space was in place. It was found that the implementation of the bike lane led to a reduction in NO₂ exposure for cyclists. During periods when the community space was in place, a reduction in NO₂ concentrations was also measured. This study highlights not only the utility of low-cost sensors for the measurement of urban air quality, but also their value in a science-policy context. Measuring local air quality changes in response to traffic interventions will enhance understanding of the associated health benefits, especially in connection with measures promoting more sustainable modes of active travel. More research of this nature is needed to gain a clear understanding of the impacts of traffic interventions on local air quality for better protection of human health.

1. Introduction

Ambient air pollution was estimated to contribute to around 4.2 million deaths globally in 2015 [1]. Other studies using updated hazard risk ratios [2] and alternative risk and exposure assumptions [3, 4] suggest that this number might be twofold larger. The health effects of ambient air pollution are significant in Europe, with 74% and 99% of its urban population exposed to particulate matter less than 2.5 μm in diameter (PM_{2.5}) and ozone (O₃) concentrations, respectively, above WHO recommended limit-values in 2018 [5].

Urban air pollution is a major human health problem with substantial emissions from the transport sector. Consequently, participants in urban transportation (car-drivers, cyclists, pedestrians, etc) are exposed to high levels of air pollution. The level of exposure is driven by many factors, including, but not limited to, transport emissions, city

and transportation infrastructure, time spent commuting, and climate and meteorology. In Europe, car-drivers are exposed to the largest amount of air pollution, followed by cyclists and public transportation users, with pedestrians typically exposed to the least amount [6–8]. A systematic review found that commuters using motorized transport had increased exposure to air pollution due to their proximity to traffic and high air interchange whereas the increased inhalation rates and commuting time of active commuters caused them to have a higher inhaled dose [9]. The calculation of exposure varies across these studies, but an intercomparison of these methods reveals that there is no single best method, many are appropriate, and they should be selected based on the size and objectives of the study [10].

The direct health impacts of this air pollution exposure have been studied extensively, though most studies use PM and black carbon (BC) as proxies for all air pollutants, with less assessing the impact of

exposure to high levels of nitrogen dioxide (NO₂). One study found a significant relationship between exposure to NO₂ and heart rate variability in healthy adults [11], whereas previous studies identified this relationship only in elderly populations or subjects with pre-existing cardiovascular disease. A cohort study found similar results, with long-term exposure to NO₂ pollution associated with higher risk of heart failure [12]. Moreover, systematic reviews of studies assessing NO₂ exposure and mortality have consistently found evidence of NO₂ exposure associated with a higher risk of all-cause, cardiovascular, and respiratory mortality that might be independent of other common air pollutants [13–16]. This connection between NO₂ and health effects was also made by participants in a study across seven European cities, in which levels of pollution at their home addresses was significantly linked to their concern over the health effects of air pollution [17].

While studies show that the benefits of active travel outweigh the negative health effects of air pollution exposure [9, 18, 19], further reductions in exposure by choosing low-traffic routes can additionally reduce associated health effects [20, 21]. Research from Montréal and Bogotá revealed that cyclists' exposure to PM and BC was reduced when riding on separated, protected bike lanes as opposed to in-street facilities [22, 23]. In addition to the reduction in air pollution exposure gained from implementing dedicated cycling infrastructure in cities, the primary increase in health benefits at city-scale comes from the consequent increase in physical activity as more citizens switch to active transport [24].

Personal exposure measurements are limited, and regulatory monitoring stations are sparsely distributed throughout cities. This means that exposure to microenvironments, such as the transport environment, are poorly understood in the context of overall daily exposure. While urban background (UB) monitoring locations are often used in population exposure assessment, studies have shown poor agreement between measurements at these monitoring stations and personal exposure in transport environments [25–28]. To overcome these issues, new technologies such as low-cost sensors are being used to increase the spatial resolution of monitoring networks [29–33], to assess personal exposure [32, 34, 35], and in mobile monitoring [36–40]. While they are less accurate than reference-grade instruments, their low-cost and relatively small size make them more suitable for these applications. Furthermore, they can serve to increase our understanding of air pollution in urban environments, especially with regards to human health and exposure, providing valuable information not only for scientists, but also for citizens and policymakers.

For various reasons, European cities are starting to shift towards sustainable modes of transport. Some are focused on the win-win of achieving climate

goals by reducing emissions of greenhouse gases and reducing the health impacts of air pollution, while others are focused on making these modes safer and more attractive for their citizens. To achieve these goals, many of these cities need to enact policies to encourage greater uptake of cycling [41, 42], among other sustainable transport options. In cities like London, Barcelona, and Berlin, the shift towards more active transport has already begun [43–45]. Berlin became the first federal state in Germany to enact a Mobility Act in 2018, which was driven largely by a citizen-led bicycle referendum called the 'Volksentscheid Fahrrad,' [43]. As a result, new cycling infrastructure, such as protected bike lanes, has been built in the city, with more planned in the coming years. On one street, Kottbusser Damm (KD) in the district of Friedrichshain-Kreuzberg, a protected bike lane was initially planned to be built in the late summer of 2020. With the onset of the COVID-19 pandemic, plans for this were accelerated and it was built as a temporary pop-up bike lane to provide safer infrastructure for citizens seeking to switch away from public transport and towards cycling. A separate measure that was planned and executed according to plan involved the transformation of a portion of a side-street (Böckhstrasse) that is directly linked to KD into a *Spielstrasse* or 'community space', for which the street was closed to through-traffic, allowing for greater outdoor space for public use. In this study, we conducted a measurement campaign using low-cost sensors to assess changes in air quality on KD and on the Böckhstrasse in connection with the bike lane and the community space, respectively.

2. Methods

2.1. Small air quality sensors

This data used in this study were collected with small air quality sensors housed in the EarthSense Zephyr sensor system. Included in this sensor system are: (a) electrochemical (EC) sensors that provide a measure of NO₂ and O₃; (b) micro-optical sensors that count particles to provide a measure of PM; (c) a global positioning system (GPS) unit; (d) internal temperature and relative humidity monitors; (e) an internal fan for air intake and expulsion; (f) a lithium-ion battery; and (g) a Global System for Mobile Communications unit for sending logged data to an external database [46]. These sensor systems are part of a new generation of air quality measurement devices that are lower-cost, smaller, and easier to use in comparison to standard reference instrumentation. As a result, they are easily deployed for both stationary and mobile measurements with a potential for high spatial and temporal resolution in various environments.

The EC sensors housed within the Zephyrs react in the presence of atmospheric gas-phase pollutants such as NO₂ and O₃, as the molecules chemically interacting with the measurement nodes of the

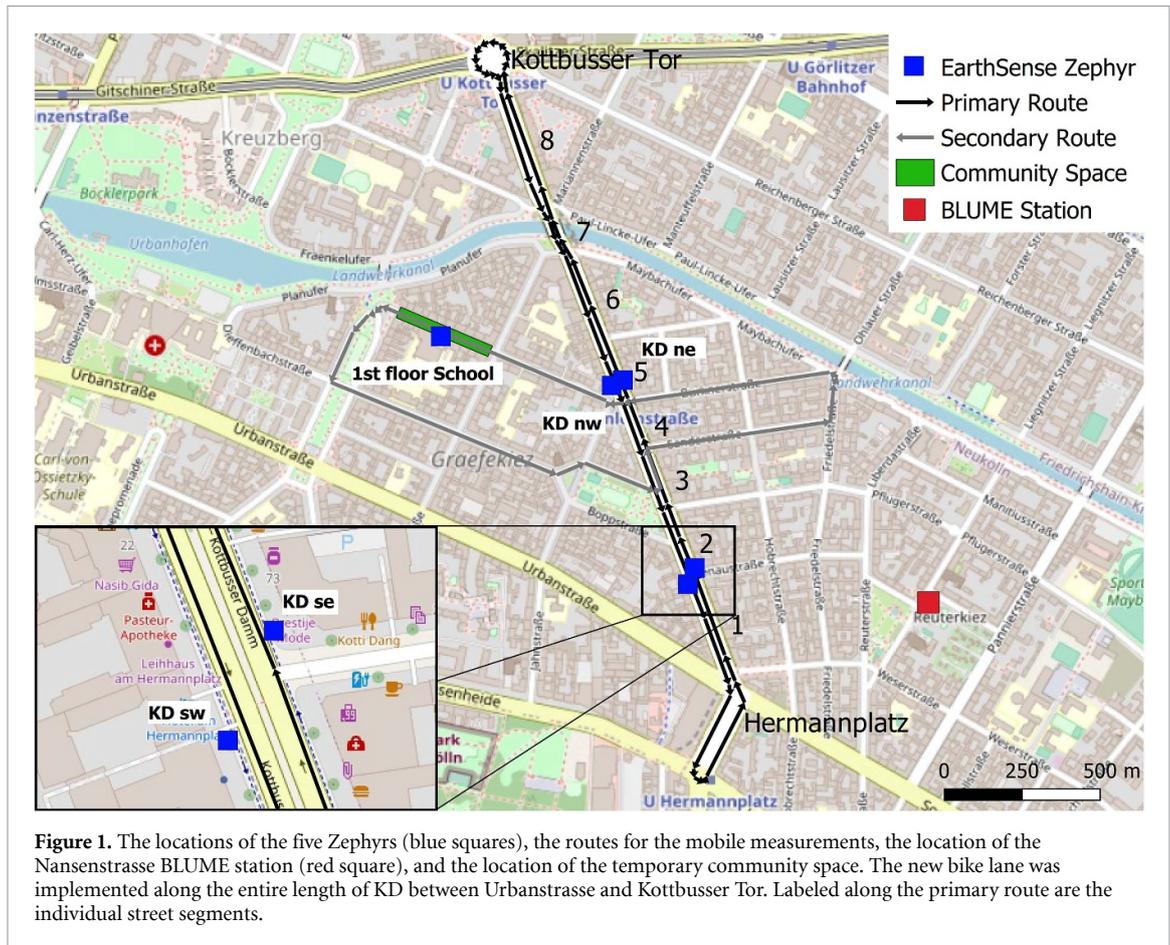


Figure 1. The locations of the five Zephyrs (blue squares), the routes for the mobile measurements, the location of the Nansenstrasse BLUME station (red square), and the location of the temporary community space. The new bike lane was implemented along the entire length of KD between Urbanstrasse and Kottbuser Tor. Labeled along the primary route are the individual street segments.

sensor. To transform this raw voltage signal into concentrations of each pollutant, the sensor system must be co-located and calibrated with reference-grade air quality sensors. Co-location in this context refers to physically installing the sensor systems at a location where they will receive samples from the same parcel of air as the reference instruments.

2.2. Co-locations and reference instrumentation

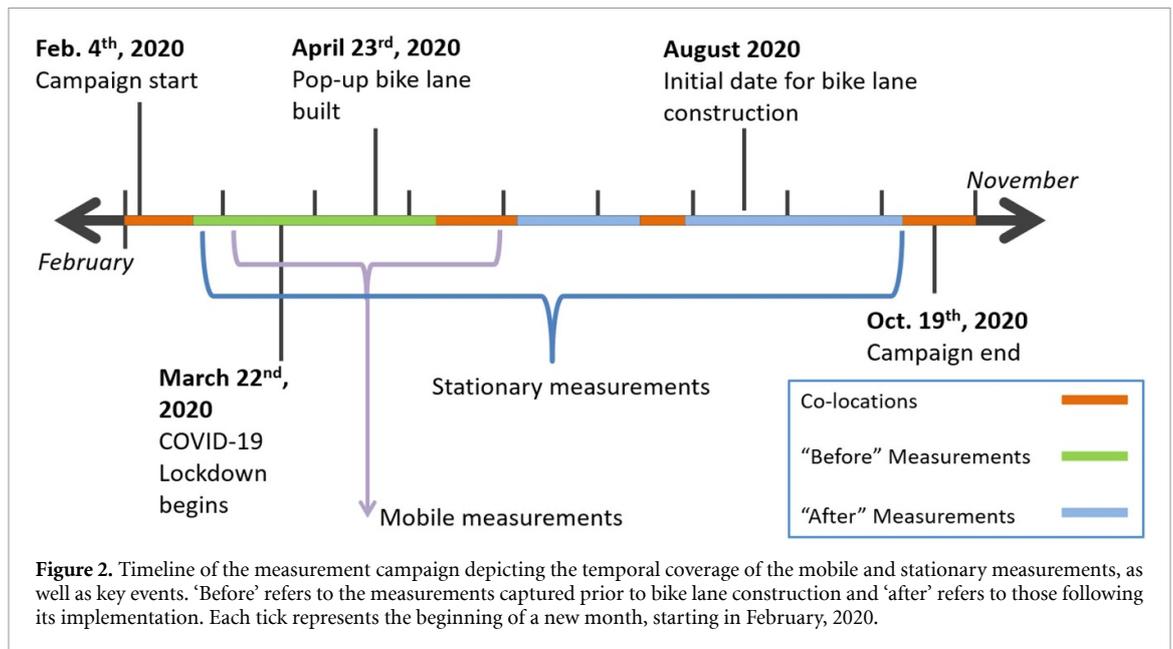
To co-locate the Zephyrs, measurement stations of the Berlin Air Quality Measurement Network (BLUME) were used. When co-locating small sensors, it is crucial that the calibration site experience environmental conditions (i.e. pollution levels, meteorological conditions) as similar to those of the experimental site as possible [47]. In this case, the Zephyrs that were installed on lampposts along KD in Neukölln, Berlin were co-located at a roadside-traffic station, MC117 in Steglitz, Berlin. While it is situated several kilometers away from the experimental site in a different part of the city, the shape of the street canyon and traffic levels are comparable to those of KD. The Zephyr that was installed on the 1st floor of the primary school on the Böckhstrasse was co-located at a UB station, MC042 in Neukölln, Berlin. This station is only a few blocks away from KD and since the side streets do not experience heavy traffic, it was selected as a more appropriate co-location site than MC117.

2.3. Sampling site and sampling strategies

As can be seen in figure 1, four Zephyrs were deployed on lampposts on KD and one was deployed on the 1st floor façade of a primary school on the side-street Böckhstrasse. The latter location was selected as the school lies along the stretch of Böckhstrasse that was converted to a community space. For the mobile measurements, two separate routes were designed to capture various changes in air pollution associated with the new bike-lane; the primary route covered the length of KD, whereas the second route covered side-streets, including along Böckhstrasse. A timeline of the measurement campaign can be seen in figure 2. In total, 9 sets and 11 sets of mobile measurements were conducted before and after the implementation of the bike lane, respectively, and were composed of three continuous loops along each route. These measurements were conducted during the morning, afternoon, and evening to capture the range of intra-day variability in NO_2 concentrations.

2.4. Statistical calibration and transformation

To calibrate the Zephyrs, data from the reference instruments was used to train statistical models that included as independent variables the raw sensor signal and meteorological conditions, such as temperature and relative humidity. To this end, the seven-step method was used to clean and flag the raw



data; build, train, and optimize the parameters of a multiple linear regression (MLR) model; and predict the final concentrations with an associated measure of uncertainty for each measurement [48]. A random forest model was also built, but this was determined to have no significant increase in accuracy over the MLR model and had more limitations. Further details on the seven-step methodology can be found in Schmitz *et al* [48]. The seven-step methodology has been developed and applied to gas-phase concentrations only at this point. For this reason, as well as the predominance of traffic emissions to total NO_x emissions in urban areas in Europe and Berlin, the analysis presented here is limited to NO₂.

To account for changes in meteorological conditions, traffic patterns, and other external forces such as the COVID-19 lockdowns that may have influenced variations in NO₂ concentrations on KD, all calibrated concentrations were normalized. In this case, hourly averaged concentrations from the five stationary Zephyrs along KD and on the side-streets were normalized to the hourly average of four UB stations by subtracting the UB hourly averaged concentrations from the Zephyr hourly averaged concentrations. Similarly, the mobile measurements along KD and the side-streets were normalized to the 5 min averages of the four lamppost Zephyrs on KD and the Nansenstrasse UB station, respectively. This higher resolution was necessary as each set of mobile measurements took roughly ~40 min for each route.

3. Results

3.1. Stationary measurements

As can be seen in figure 3, the stationary measurements along KD exhibit a similar diurnal pattern with good agreement. The side-street Zephyr on the

primary school agrees more closely with the average UB NO₂ across four stations. In all cases, the morning and evening peaks in NO₂ align, with the KD Zephyrs showing higher concentrations and a lower mid-day dip as a result of higher local emissions from the street. Using a Mann-Whitney U-test, the distributions of all stationary Zephyrs were compared (table 1). All KD Zephyrs were found to have significantly different distributions than the primary school Zephyr. Among the lamppost Zephyrs, the northern and southern Zephyrs form two distinct groups. Given these results, it was concluded that normalizing the mobile measurements along the primary route to the nearest pair of sensors was appropriate. For measurements along segments between the two pairs, a weighted average was used. However, using the simple average of all four Zephyrs produced similar results.

Analysis was conducted to assess the relative impact of the bike lane on the stationary measurements, which reflect the local air pollution conditions on KD. However, due to the significant impact of the COVID-19 pandemic and subsequent stringent measures in Berlin, potential effects from the bike lane on NO₂ concentrations for the general KD area, as represented by the stationary measurements on KD, could not be isolated. More data would be needed to establish this connection.

3.2. Mobile measurements

To assess the impact of the bike lane on cyclists' personal exposure, NO₂ concentrations from the primary and secondary route from before and after its construction were compared. Figure 4 shows these data in box-and-whisker plots, grouped according to the presence of the bike lane. As each measurement contained an associated uncertainty, error was propagated when comparing the before and

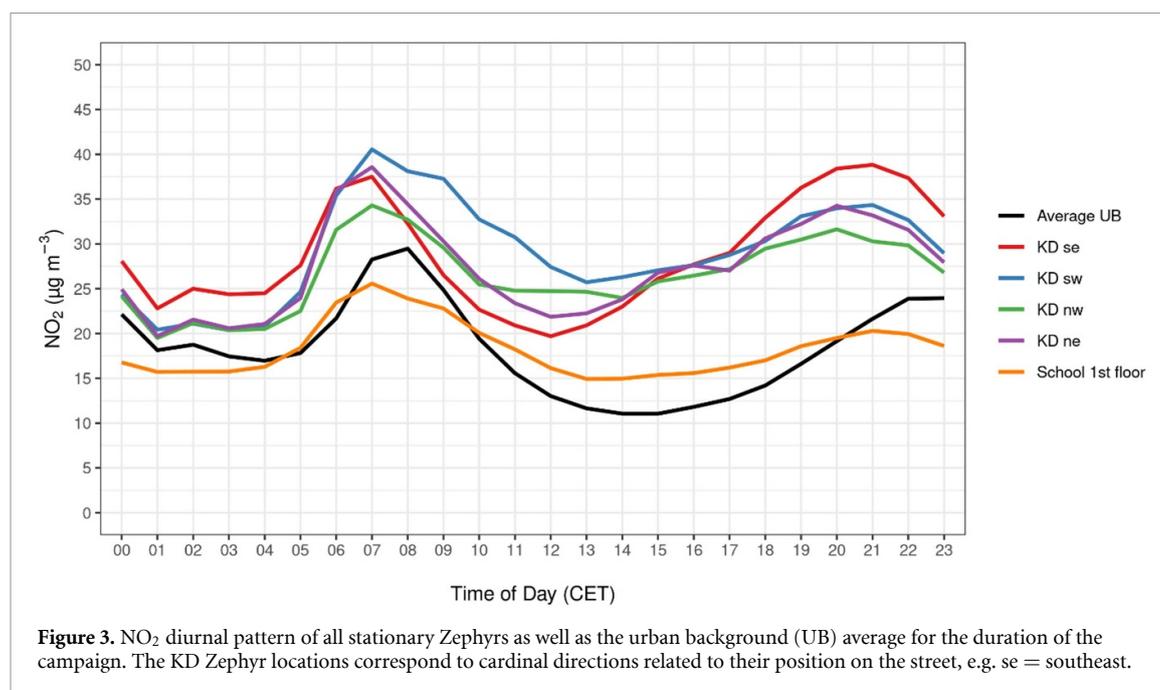


Figure 3. NO₂ diurnal pattern of all stationary Zephyrs as well as the urban background (UB) average for the duration of the campaign. The KD Zephyr locations correspond to cardinal directions related to their position on the street, e.g. se = southeast.

Table 1. Wilcoxon-Mann-Whitney U-tests of the difference in means between each of the stationary Zephyrs across the entire experiment. Reported in the table are *p*-values. Italicized and bolded are values below the Bonferroni-corrected *p*-value of 0.01, which indicate acceptance of the alternative hypothesis, that the distributions of the two sensors are NOT equal. Extremely low *p*-values are represented here as 0.

	KD SW	KD SE	KD NW	KD NE	School 1st floor
KD SW					
KD SE	0.48				
KD NW	0	0			
KD NE	0.0058	0.0003	0.053		
School 1st floor	0	0	0	0	

after samples³. For the primary route, a decrease in the median normalized NO₂ of $8.4 \pm 7.4 \mu\text{g m}^{-3}$ was measured whereas for the secondary route the decrease in the median normalized NO₂ was $2.5 \pm 7.4 \mu\text{g m}^{-3}$. In both cases, tests with the Mann-Whitney U-test were significant at a *p*-value of 0.05, indicating the distributions of the data from before and after the implementation of the bike lane are different. At the 95th percentile, the reduction in normalized NO₂ for the primary route was $14 \pm 7.4 \mu\text{g m}^{-3}$, whereas for the secondary route an increase of $2.4 \pm 7.4 \mu\text{g m}^{-3}$ was found.

To more closely inspect these results, the data from each route were broken down into smaller segments. For the primary route, the trend of decreasing concentrations was found in every segment and all were statistically significant. Two of the segments along the route, at Hermannplatz and Kottbusser Tor, showed the same trend in decreasing concentrations

even though no changes to cycling infrastructure were implemented at these sites. The same analysis for the secondary route was inconclusive, as only three of the twelve segments were statistically significant, with some segments showing no decrease or even a slight increase in NO₂ concentrations.

3.3. Community space measurements

Figure 5 shows box-and-whisker plots for the Zephyr located at the primary school, grouped according to whether the community space was in place or not. On Wednesdays between 14:00 and 18:00, when the community space was in place (April–September), the median normalized NO₂ was $3.7 \pm 11.2 \mu\text{g m}^{-3}$ less than when there was no community space in place (February, March, and October). A Mann-Whitney U-test indicated that these distributions are statistically different (*p* = 0.012). To confirm that the difference seen in figure 5(a) (the comparison of Wednesdays with and without the community space) was indeed owing to the community space, a parallel comparison for all other weekdays was also carried out (figure 5(b)). This difference in median normalized NO₂ from 14:00 to 18:00 was $0.42 \pm 11.2 \mu\text{g m}^{-3}$ under the same conditions and was not statistically

³ Propagation of error for differences between medians and the 95th percentile were calculated using the formula $Q = \sqrt{(e_1)^2 + (e_2)^2}$, where *Q* is the propagated error and *e*₁ and *e*₂ are the individual uncertainties of the two measurements being compared.

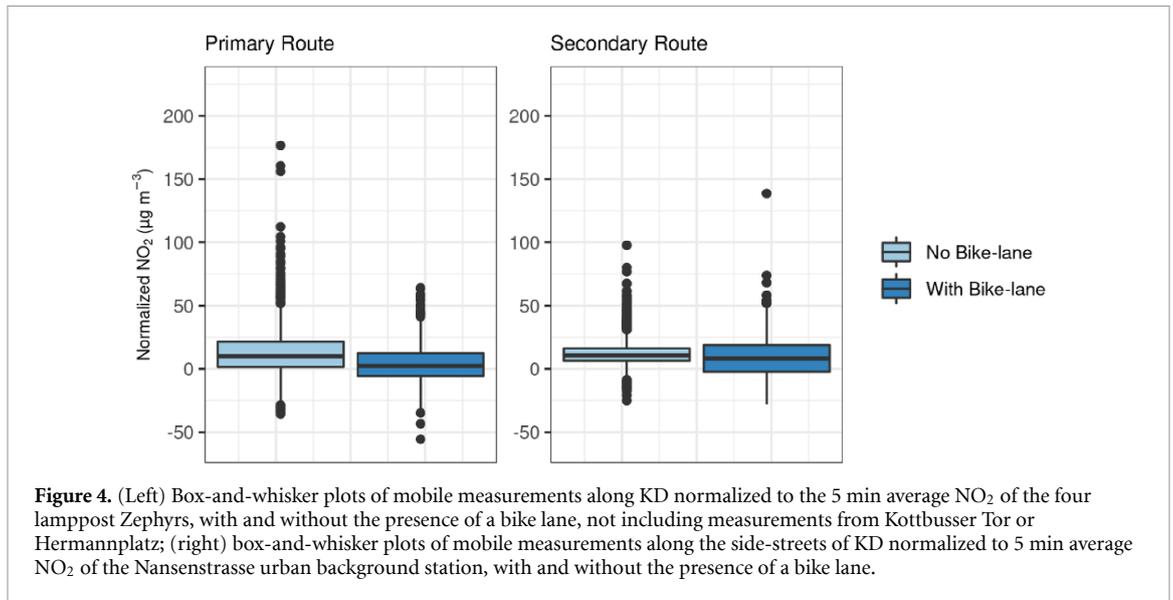


Figure 4. (Left) Box-and-whisker plots of mobile measurements along KD normalized to the 5 min average NO_2 of the four lamppost Zephyrs, with and without the presence of a bike lane, not including measurements from Kottbusser Tor or Hermannplatz; (right) box-and-whisker plots of mobile measurements along the side-streets of KD normalized to 5 min average NO_2 of the Nansenstrasse urban background station, with and without the presence of a bike lane.

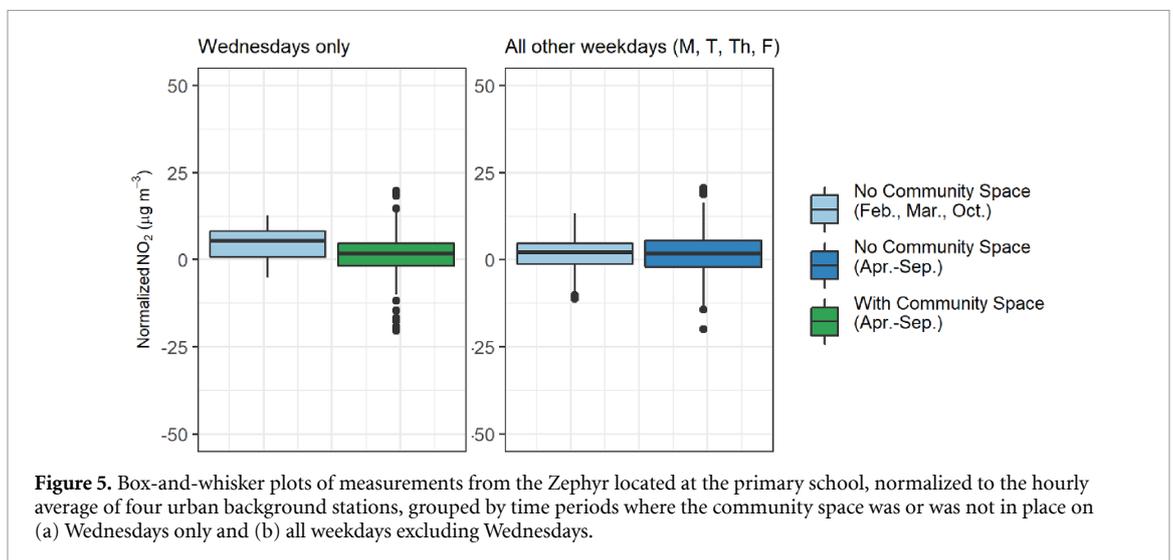


Figure 5. Box-and-whisker plots of measurements from the Zephyr located at the primary school, normalized to the hourly average of four urban background stations, grouped by time periods where the community space was or was not in place on (a) Wednesdays only and (b) all weekdays excluding Wednesdays.

significant ($p = 0.61$). With this analysis, it was assured that the changes measured on Wednesdays could be associated with the community space, as all other weekdays during the same time window did not exhibit any significant changes. A comparison to weekend concentrations was not made, as weekend NO_2 concentrations were significantly different than on weekdays and were not related to the street closures. Finally, an analysis to control for holiday days that fell on weekdays was done and showed that the effect was negligible.

4. Discussion

This study has successfully shown that low-cost sensors can be deployed to assess changes in air quality in connection with local transport measures. In general, the Zephyrs accurately captured the expected diurnal trends of NO_2 on KD as well as on the Böckstrasse, demonstrating their utility for such work. Despite the higher level of uncertainty in the

measurements, these low-cost sensors have proven their value in assessing small-scale spatial changes in air quality in cities, which has implications for future research aimed at understanding local changes in air quality, including before-after measurements in connection with transport measures. In the context of the mobility transition in Germany, these sensors can provide valuable information to policymakers with regards to the effect on air quality for the various measures they may implement.

Here, a reduction in exposure to NO_2 for cyclists following the implementation of the bike lane, after normalization to local conditions, was measured. Furthermore, the reduction in exposure along KD was higher at the 95th percentile, which suggests that cyclists were exposed to fewer extreme peaks in concentrations associated with proximity to tailpipe emissions from motor vehicles. These reductions were not seen along the side-streets, indicating that the effect is local in nature and can be associated with the construction of the bike lane. The exposure

to peak concentrations can be quite important; Dons *et al* found that only 5.5% of participants' daily exposure was attributed to peak concentrations, but these contributed to 21% of their total exposure [49]. As such, cyclists along KD appear to have profited from this measure, not only from the increased safety of a protected bike lane, but also from the reduction in exposure to both overall and peak NO₂ concentrations. An effect of the bike lane on overall air quality on KD could not be determined due to a lack of data representative of local conditions following the implementation of the bike lane that are free of effects from restrictive COVID-19 health measures. While no other studies exist in the literature that are directly comparable, related studies have shown that cycling infrastructure influences the particle number concentration cyclists are exposed to [39, 50], whereas others quantify the role of urban infrastructure on air pollution, such as green walls or low emission zones [51, 52], but these do not assess changes to cyclists' exposure to air pollution. Other studies that explicitly measured cyclists' exposure to air pollution did not explicitly connect their mobile measurements to specific transport measures [53]. Therefore, this study is one of the first to measure changes in cyclists' exposure to NO₂ in direct connection with changes in cycling infrastructure.

While quantifying the health benefits associated with this reduction is beyond the scope of this study, a reduction in NO₂ exposure is a positive influence on cyclists' health, given the established connections between NO₂ exposure and mortality [12–16]. In addition, recent research has shown that pop-up bike lanes increased cycling across European cities [54]. That study estimated that the associated health benefits in terms of kilometers of new bike lanes per square kilometer were estimated to be worth between \$1 and \$7 billion annually, or \$1.2–\$3.5 in terms of kilometers per capita, if the uptake in cycling is maintained [54]. This is in line with other research estimating the health benefits across 167 European cities, in which the expansion of cycling networks could lead to the avoidance of 10 000 premature deaths annually [55]. These findings indicate that a measured increase in cycling uptake along KD confers additional health benefits to Berlin cyclists alongside the reduction in NO₂ exposure associated with new bike lane infrastructure.

The implementation of the community space also led to a measured reduction in NO₂ concentrations. On other weekdays where the community space was not in place, there was no discernible difference in NO₂ concentrations. While this reduction was smaller than that on KD, it highlights the relationship between NO₂ and vehicle traffic. Böckhstrasse is already traffic-calmed, but if cars are no longer allowed to traverse the street, there will be further local reductions in NO₂ concentrations. The overall decrease, however, is constrained by UB levels of NO₂

pollution, which would require larger-scale changes in emissions sources to change.

4.1. Limitations

This study and its findings are subject to several key limitations. Primarily, the COVID-19 pandemic disrupted the plans for this measurement campaign. Due to restrictive lockdowns implemented in Berlin in response to the pandemic, traffic patterns and behaviors were substantially altered during the campaign. Furthermore, the bike lane was implemented as temporary cycling infrastructure months earlier than anticipated. These circumstances led to a substantial reduction in the amount of data collected before and after the bike lane was in place. In addition, this study would have benefited from additional measurements that quantitatively assessed traffic patterns, composition, and behavior along KD and its side-streets. This data would allow for a more detailed analysis of the impact of the bike lane on local traffic, individual transport decisions, and the concomitant influences on air quality. For this study, such data were unavailable. In addition, no tests on sensor performance pertaining to mobile deployment were conducted and therefore the potential influences of mobile use on the sensors (i.e. vibration) in this study are unknown. However, as the analysis focuses on gas-phase species (not PM) isokinetic sampling is a non-issue, and previous mobile deployments of measurement devices have not shown vibration to cause any interference. As there are few studies assessing low-cost sensor performance in mobile conditions, more research is needed to identify potential interferences on measurement quality. Last, it should be noted that the deployment of the sensors in this study did not follow regulatory guidelines for site selection, nor did the sensor go through any certification process for assessing their performance relative to regulatory standards. As such, the data should not be used to assess exceedances of air quality limit values. However, the results of this study still have a high relevance for human health in urban areas, and data are presented with associated uncertainties.

5. Conclusions

This study has demonstrated the utility of small sensors for both stationary and mobile measurements in an urban environment to measure small scale spatial changes in air quality. This is one of the first studies to implement such small sensors to accompany the implementation of a mobility policy to quantify the effect on air pollution, including exposure. Results showed that the implementation of a (pop-up) bike lane, in which cyclists went from cycling in the street with traffic, to a dedicated bike lane largely protected from motor vehicle traffic by a lane of parked cars, resulted in a reduction of $8.4 \pm 7.4 \mu\text{g m}^{-3}$ in NO₂ or

22% ± 19% that they were exposed to. This underlines the importance of infrastructure for the protection of human health in urban areas. Additional studies are needed to understand how representative and transferrable these results are. As the mobility transition in Berlin and across Europe proceeds, these types of measurements will prove invaluable for decision makers.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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