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PAPER

Low-cost system application for policy assessment: a case study from Berlin

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Abstract

Local policies are part of the toolbox available to decision makers to improve air quality but their effectiveness is underevaluated and underreported. We evaluate the impact of the pedestrianization of a street in the city centre of Berlin on the local air pollution. Nitrogen dioxide (NO_2) was measured on the street where the policy was implemented and on two parallel streets using low-cost sensor systems supported by periodic calibrations against reference-grade instruments and constrained by passive samplers. Further measurements of NO_2 were conducted with a reference-grade instrument mounted on a mobile platform. The concentrations were evaluated against the urban background (UB) to isolate the policy-related signal from natural fluctuations, long-term trends and the COVID-19 lockdown. Our analysis shows that the most likely result of the intervention is a reduced NO_2 concentrations to the level of the UB on weekdays for the pedestrian zone. Kerbside NO_2 concentrations exhibited substantial differences to the concentrations measured at lampposts highlighting the difficulty for such measurements to capture personal exposure. The results have implications for policy, showing that an intervention on the local traffic patterns can possibly be effective in improving local air quality.

1. Introduction

Cities are hot spots of atmospheric emissions and urban populations. Worldwide, cities have struggled with air quality issues for decades (EEA 2007, Lelieveld *et al* 2015, Liu *et al* 2019). A vast majority (over 70%) of the population of the European Union (EU) lives in cities. Despite improvements, 77% of the EU-28 urban population was still exposed to $PM_{2.5}$ concentrations above the World Health Organization (WHO) Air Quality Guidelines value in 2019 (EEA 2019, 2020a, 2020b). Even low concentrations of air pollutants pose a threat to human health (GBD 2017 Risk Factor Collaborators 2018, Dominici *et al* 2019), and the WHO has recently recognized this research finding by updating its guidelines based on a systematic review of the body of literature (WHO, World Health Organization 2021). The presence of pollutants in the air impacts the population by means of increased incidence of diseases and years of life lost, mainly via cardiovascular diseases (Burnett *et al* 2018, HEI 2020). For instance, in 2018, 54 000 premature deaths in the EU-28 (of which 9200 in Germany) were attributed to NO_2 alone (EEA 2020a). In the context of the ongoing SARS-CoV-2 pandemic, previous exposure to air pollution was identified as a relevant factor increasing mortality risk from the COVID-19 disease (Pozzer *et al* 2020, von Schneidemesser *et al* 2021).

In 2013, relevant and ambitious goals were set in Europe to tackle the issue: (1) the long-term goal to reach the WHO guidelines, even upon update (European Commission 2013, WHO, World Health Organization 2021), (2) full compliance with existing legislation by 2020, and (3) the halving (in 2030 relative to the 2005 levels) of the premature deaths in the EU due to air pollution (EC 2013). Although achieving the objective for 2020 was deemed unlikely in all member states already in 2018 (EEA 2018), the adoption of novel instruments (e.g. the National Emission reduction Commitments Directive of 2016) allows some degree of optimism regarding the attainment of the long-term objectives, with significant disparities between member states, depending on if the member-states comply with the obligations laid out in their National Air Pollution Control Programmes (EC 2019, 2021, Sicard *et al* 2021).

Fossil fuel burning has been identified as a dominant source of air pollution-related health impacts (Lelieveld *et al* 2019). The role of road traffic in the concentration increase of air pollutants in urban areas with respect to background levels has long been acknowledged (e.g. Lenschow *et al* 2001, Oliveira *et al* 2010). For NO_2 in particular, exceedences of the standards in European cities is attributed mainly to the high levels of road traffic and domestic combustion (e.g. Dias *et al* 2018). This has spurred the emergence of a concept known as the mobility transition. Indeed, over half of the policies implemented by member states to reduce air pollution were traffic-related, targeting urban mobility either by addressing technological issues to lower end-of-pipe emissions or reducing traffic (urban road tolls, low emission zones (LEZ), and access regulation schemes) (EEA 2018).

Traffic reduction policies, technological measures and behavioral change are factors which have been recognized as having the potential to mitigate exposure to air pollution in an ever more urbanized anthropocene world (Fuglestvedt *et al* 2008, Shindell *et al* 2011, Yan *et al* 2014, Kelly and Zhu 2016, Gallardo *et al* 2018). The EU has evolved towards more stringent emission standards (e.g. Magueta *et al* 2018). Despite the technological advances prompted by the evolution of legislation, which have considerably decreased the fleet's emission factors, the increased use of personal motorized transportation has offset those gains (Kelly and Zhu 2016). European cities therefore find themselves in a situation where the reduction in per vehicle emissions has not been sufficient to alleviate the detrimental effects of traffic emissions on human health.

The policy treated in the present work goes along with strategies such as charging schemes, LEZs, vehicle speed management or the prohibition of circulation for highly polluting vehicles, which have been adopted by European cities in recent years (e.g. Rodriguez-Rey *et al* 2022). Such strategies are translated into policies and put in place in order to reduce the externalities related to traffic, such as congestion, noise, accident risk and air pollution. (De Borger and Proost 2013, Tretvik *et al* 2014, Sfendonis *et al* 2017, Morton *et al* 2021, Bernardo *et al* 2021a, 2021b). While charging schemes aim to reduce the flow of traffic within a city, LEZs are defined areas where access by more polluting vehicles is restricted or banned, in an attempt to control the technology mix of the emitters. There is indeed some evidence that freight transport and fleet composition are affected by the implementation of LEZs, but the change, relative to e.g. the national average, appears to be short-lived (Ellison *et al* 2013, André *et al* 2017, Settey *et al* 2019, Peters *et al* 2021, Ye *et al* 2021). LEZs have been implemented in over 250 European cities in the last decade and a half, with varying approaches and rules (Cruz and Montenon 2016, Aguayo *et al* 2021). In Berlin (the capital city of Germany, with 3.7 million people), some of the policies implemented to improve air quality over the past decade include a ban on older, high NO_2-emitting vehicles on eight highly polluted streets, the establishment of a LEZ and the fostering of clean transport modes ((e-)bikes and electric buses), among others, and can be understood as a part of the mobility transition, reinforced by the Berlin mobility Act of 2018. Although the situation for particulate matter has been improving over the last years (EEA 2018), NO_2 exposure is still a serious problem (EEA 2021).

LEZs and similar policies are underevaluated in the scientific literature. The study of the impact of LEZs may be conducted via modelling exercises, either *ex-ante* in the planning phase or after their implementation (e.g. Carslaw and Beevers 2002, Keuken *et al* 2012, Dias *et al* 2016, Host *et al* 2020, Börjesson *et al* 2021, Degraeuwe *et al* 2021, Poulhès and Proulhac 2021, Sánchez *et al* 2021). The number of studies which evaluate the impact of LEZs on air quality by means of measurements is limited and the conclusions are sometimes contradictory, e.g. Boogaard *et al* (2012) and Panteliadis *et al* (2014) (the Netherlands), Wood *et al* (2015) and Mudway *et al* (2019) (London), or Ferreira *et al* (2015) and Santos *et al* (2019) (Lisbon). Indeed, the effect on air pollutant concententrations, and public health indicators, appears to be of diminished importance relative to pre-LEZ levels (Jones *et al* 2012, Ellison *et al* 2013, Ferreira *et al* 2015, Wood *et al* 2015, Gu *et al* 2022). Therefore, results of such studies are largely affected by which sources of bias are taken into consideration and how they are controlled for (Holman *et al* 2015, Malina and Scheffler 2015a, 2015b, Morfeld *et al* 2015a, 2015b, Gehrsitz 2017). The heterogeneity of the nature of LEZs (e.g. which vehicles are affected or how large the LEZ is) further hinders drawing a general conclusion on their effectiveness (Holman *et al* 2015, Cyrys *et al* 2018, Lurkin *et al* 2021). For example, results from Germany, where light-duty vehicles (LDVs) have been affected by LEZs along with heavy-duty vehicles (HDVs), show a clearer effect than in places where only HDVs, and not LDVs, are the subject of policies (Holman *et al* 2015, Jiang *et al* 2017, Pestel and Wozny 2021). In the particular case of air pollution, most studies have evaluated the pre- and post-policy levels by means of data from monitoring stations (e.g. Ferreira *et al* 2015, Gehrsitz 2017). Although suitable for large inner-city areas, using monitoring data do not have the necessary spatial resolution which allows catching the fine nature of the impact of a local policy. Furthermore, confounders such as meteorology and pre-policy technological trends, influence the outcome of the before/after analysis and are only seldom accounted for in measurements-based assessments (e.g. Mudway *et al* 2019, Santos *et al* 2019, Tartakovsky *et al* 2020, Salas *et al* 2021).

In the present study, we attempt to overcome the limitations listed above by using localized, calibrated, NO_2 measurements (from reference instrumentation on a mobile platform and static, calibrated, low-cost systems (LCS) and passive samplers), normalized to the urban background (UB), to assess the impact of a street closure to motor vehicle traffic on air quality. Additionally, we investigate the relevance of sampling location at the micro-environment scale for exposure assessment. LCS are a popular new technology in the field of atmospheric chemistry, especially within the last 10–15 years. Much research has been done investigating their accuracy (Cross *et al* 2017, Rai *et al* 2017, Zimmerman *et al* 2018, Karagulian *et al* 2019, Malings *et al* 2019), potential applications (Castell *et al* 2017, McKercher *et al* 2017, Bigi *et al* 2018, Morawska *et al* 2018), and technological advancement (Fishbain *et al* 2017, Peterson *et al* 2017, Spandonidis *et al* 2020), but few studies deploy them in a policy evaluation context (Schmitz *et al* 2021b). Despite current accuracy and precision limitations, LCS are highly versatile and offer the possibility of a quick information return upon a flexible deployment.

The policy was implemented by the city of Berlin as a trial in the context of the mobility transition. The idea behind the policy was primarily to increase the attractiveness of the street, the Friedrichstrasse, thereby increasing the volume of visitors to the heavily commercial street. In addition, a new bike-lane would be implemented for cyclists traversing the street. This trial creating a pedestrian zone and closing the street to motor vehicle traffic was put in place in August 2020 and was planned through the end of January 2021. It was later extended until the end of October 2021. This study presents the results of that measurement campaign and discusses their implications. We show that LCS have the ability to quickly inform policy-makers about the change in ambient air quality produced by a policy. We further show that the sampling location must be chosen carefully if the measurements are to be used to assess human exposure to urban air pollution.

2. Methods

2.1. Policy description

In 2020, an important through-street in central Berlin, the Friedrichstrasse, was subject to a new policy implemented by the Berlin government. The goal was to redesign the street away from its focus on motorized vehicles and towards pedestrians and cyclists. The car-free Friedrichstrasse policy led to the closure of the street to car-traffic between Französische Strasse and Leipziger Strasse (5 blocks). Motorized traffic was allowed on Friedrichstrasse until 21 August 2020, followed by one week of public space adaptation to accomodate pedestrian and cycling friendly infrastructure. On 28 August 2020, the Friedrichstrasse was re-opened to the general public, without motorized traffic. On 16 December 2020, a stringent COVID-19 related lockdown was imposed. The stringent lockdown lasted until the end of the experiment on 1 February 2021. The end of the experiment meant the end of the air quality monitoring, which was started on 13 June 2020, about two months before the car-free policy was put in place.

Relevant dates for the experiment are given in table 1

The measurement site was located around the Friedrichstrasse in the Mitte city district of Berlin and covers a three by five city-block area (figure 1). Within this study area, passive samplers and EarthSense Zephyrs (see below) were installed on Glinkastrasse, Friedrichstrasse, and Charlottenstrasse. These locations were selected to assess the effect of the policy on the air quality on Friedrichstrasse itself, as well as on parallel streets associated with potential changes in traffic patterns. Also incorporated in this study were data collected from measurement stations that are a part of BLUME. Figure 1(upper panel) shows the location of four UB stations (MC 010, MC 018, MC 042, MC 171, which surround the measurement site and together were considered representative of UB conditions) and one roadside station (MC 117, used for the co-locations, see below), that are a part of the Berlin air quality measurement network (BLUME), that were selected for use in comparison to the study area.

2.2. Instrumentation

In the present study, a variety of instruments were used to gather data on air pollution at the study site and generally in Berlin. The focus of the analysis is the measurement of NO_2, owing to the substantial contribution of vehicle emissions to NO_2 concentrations in Berlin and urban areas generally.

2.2.1. EarthSense Zephyrs

To gather high-resolution data at multiple sites in the study area, three Zephyrs manufactured by EarthSense Systems Ltd were installed on lampposts at about 3 m height. These sensor systems contain a variety of components including: (1) electrochemical (EC) sensors that measure NO_2 and O_3; (2) micro-optical sensors for the measurement of PM; (3) a global positioning system unit; (4) internal temperature and

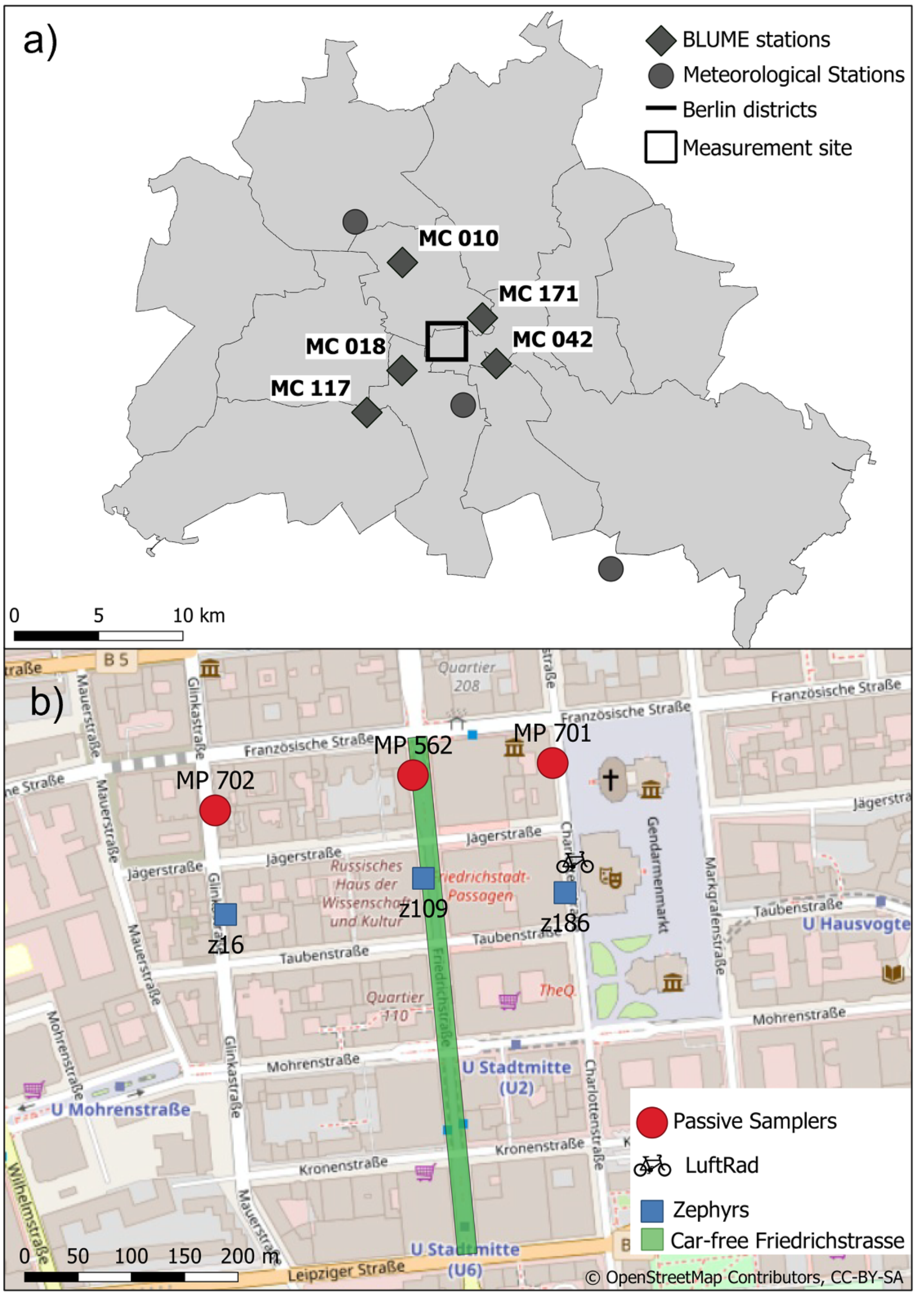

Figure 1. (a) Map of the city districts of Berlin, including the locations of the four urban background BLUME stations, three meteorological stations, one roadside BLUME station, and the location of the main measurement site; (b) map of the measurement site, including the location of the passive samplers, the EarthSense Zephyrs, and the LuftRad. Highlighted in green is the portion of Friedrichstrasse closed to car traffic for the policy.

relative humidity monitors; (5) an internal fan for air intake and expulsion; (6) a lithium-ion battery; and (7) a Global System for Mobile Communications unit for sending logged data to an external database (EarthSense 2021). 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. These were installed on Glinkastrasse, Friedrichstrasse, and Charlottenstrasse on 13 June 2020, and provided continuous measurements throughout the entire campaign (until 31 January 2021).

As the low-cost sensors within the Zephyrs do not directly measure concentrations of pollutants such as NO_2, they must be calibrated against reference-grade instrumentation. By doing so, statistical models can be trained using reference data and the raw data from the Zephyrs as response and predictor variables, respectively. To achieve this, the Zephyrs were physically removed from the measurement site and deployed at a BLUME roadside monitoring station (MC117) in Steglitz, Berlin. Over the course of the campaign, three of these co-locations were performed at the same site (co-locations 2–4, see table 1). These were spaced accordingly with seasonal variation, so as to cover as wide a range of meteorological conditions as possible.

Table 1. Relevant dates regarding the sampling campaign.

	Start	End
Policy-related events		
experiment start	13 June 2020	
motorized traffic allowed		21 August 2020
public space adaptation	21 August 2020	28 August 2020
reopening without motorized traffic	28 August 2020	
stringent lockdown	16 December 2020	
experiment end		1 February 2021
Sensors-related events		
co-location 1	5 February 2020	18 February 2020
co-location 2	14 May 2020	02 June 2020
co-location 3	22 July 2020	30 July 2020
co-location 4	6 November 2020	18 November 2020
co-location 5	04 March 2021	16 March 2021
co-location 6	24 June 2021	07 July 2021

Statistical models, in this case using multiple linear regression (MLR), were then built using the seven-step method (Schmitz *et al* 2021b) and were used to predict NO_2 concentrations throughout the measurement campaign.

2.2.1.1. Sensitivity analysis

In the process of obtaining NO_2 concentrations, an uncertainty range in the form of upper and lower bounds are also produced. In the present study, the ratio of the average upper (lower) bounds to the individual 5 min data are 1.31, 1.34 and 1.27 (0.69, 0.65 and 0.73) for Friedrichstrasse, Glinkastrasse and Charlottenstrasse. These bounds were calculated in the final step of the seven-step method, in which reference instrument error was combined with the prediction uncertainty of the statistical MLR models calculated during validation with co-location data. As low-cost sensors' field performance are affected by many factors, this calculation produces representatively large ranges of uncertainty. However, this uncertainty is associated with the magnitude of changes in concentrations, not with the direction of the changes, as the Zephyrs capture the diurnal patterns of NO_2 concentrations. A first sensitivity analysis was conducted using the upper and lower bounds of the individual 5 min data as input for the analysis and comparing its outcome to the that of the main analysis.

The seven-step methodology produces NO_2 concentrations based on co-location data. Co-locations within the sampling campaign (co-locations 2, 3 and 4, roughly between 13 June 2020 and 31 January 2021, see table 1) were used for the main analysis. Data from three other co-locations (co-locations 1, 5 and 6, see table 1) were added to the calibration process and the corresponding NO_2 concentrations used as input for the analysis for sensitivity analysis purposes.

To compare results using different methods, the seven-step methodology was used to produce NO_2 concentrations with MLR and the random forest machine-learning technique (RF). These produced consistent results, but MLR was selected as it more accurately captured extreme high and low concentrations, which the RF model did not. The analysis was repeated with the RF-based dataset as a third sensitivity analysis to check the robustness of the calibration.

2.2.2. Passive samplers

As a part of the test phase of the car-free Friedrichstrasse policy, the Berlin Senate Department for Urban Mobility, Transport, Climate Action and the Environment (SenMVKU) expanded their network of passive samplers to include more locations in the study area. Of these, three were located on lampposts at about 3 m height one block north of the EarthSense Zephyrs on each street and were therefore selected for comparison with the Zephyrs (figure 1(b)).

Passive samplers capture ambient NO_2 as the gas molecules adsorb to a reactive chemical on the surface of the tube. This mixture is then extracted and chemically analyzed to measure the total amount of NO_2 collected. All samplers were deployed for periods of two weeks, whereafter they were collected for analysis and replaced with new ones. In this case, an external lab provided the passive samplers and conducted the laboratory analysis. For samplers MP 701 and MP 702, these measurements began on the 16th of June 2020 and continued through the end of the campaign. Sampler MP 562 was already in place as part of the measurement network run by the SenMVKU and therefore has continuous data from well before the start and through the end of the campaign.

2.2.3. Cargo bike

In addition to the measurements with passive samplers and EarthSense Zephyrs, measurements with reference instruments were conducted on Charlottenstrasse. These took place on the same city block as the EarthSense Zephyr installed there. To achieve this, three reference-grade instruments were installed in a specially designed e-cargo bike (LuftRad) which was parked on the street, allowing for the instrument inlets to face the street at about 1–1.5 m height. A GRIMM 11-R mobile particulate matter (PM) monitor, a 2B-Technologies Ozone Monitor, and a Teledyne T-200 NOx monitor were used to this end. The devices were powered by a rechargeable Lithium-ion GreenPack ® battery from Ansmann AG. Each set of measurements lasted as long as the battery-life, which totaled roughly seven hours. In total, five days of 7 h measurements using this cargo bike were conducted on Charlottenstrasse.

2.2.4. BLUME

The five BLUME stations used in this analysis employ HORIBA APNA-370 NOx Monitors to measure NO_2 concentrations in ambient air in accordance with DIN EN 14211 (DIN 2012). For quality assurance, these NOx Monitors are subject to an automatic daily function check with NO_2 permeation test gas generators, a two-monthly calibration with NO and NO_2 test gas cylinders and an annual maintenance and adjustment in the BLUME test and calibration laboratory (TüV 2006). All test gases used are traceable to national standards of the German Environment Agency (*Umweltbundesamt*, UBA).

2.3. Meteorology

2.3.1. Meteorological stations

In the present study we have used the pressure and wind speed data measured at three stations within, or in the direct vicinity of, the city of Berlin (Berlin Brandenburg, Berlin-Tegel and Berlin-Tempelhof, see figure 1) and operated by the German Weather Service (*Deutscher Wetter Dienst*, DWD). The data were downloaded from the DWD Open Data Hub (https://opendata.dwd.de/), accessed on 10 August 2021. The vertical temperature profiles were retrieved from the DWD Open Data Hub for the Lindenberg station (52.2° N, 14.1° E).

2.3.2. Reanalysis

The boundary layer height (BLH) data was retrieved from the Copernicus Atmosphere Monitoring Service (CAMS) global greenhouse gas reanalysis (EGG4). The data were downloaded from the Copernicus Atmosphere Monitoring Service (CAMS) Atmosphere Data Store (ADS) (https://ads.atmosphere.copernicus.eu/cdsapp#!/dataset/cams-global-ghg-reanalysis-egg4), accessed on 10 August 2021.

2.4. Traffic counts

Traffic counters were installed at the intersections between Friedrichstrasse, Glinkastrasse and Charlottenstrasse and the perpendicular streets Französische Strasse, Jägerstrasse, Taubenstrasse, Mohrenstrasse, Kronenstrasse and Leipziger Strasse (see figure 1). This resulted in counts for five segments (a subsection of the street between two interections) for Friedrichstrasse and the parallel streets Glinkastrasse and Charlottenstrasse, from North to South: segment 1 (between Französische Strasse and Jägerstrasse), segment 2 (between Jägerstrasse and Taubenstrasse), segment 3 (between Taubenstrasse and Mohrenstrasse), segment 4 (between Mohrenstrasse and Kronenstrasse), segment 5 (between Kronenstrasse and Leipziger Strasse). The traffic counts were conducted on seven days throughout the experiment: 2 days before the closure of Friedrichstrasse (14 July 2020 and 13 August 2020, Tuesday and Thursday), 4 days after the closure and before the lockdown (10 September 2020, 6 October 2020, 5 November 2020 and 15 December 2020, Thursday, Tuesday, Wednesday and Tuesday) and one day after the closure and during the lockdown (21 January 2021, Thursday).

2.5. Experimental design

The measurements provided by the Zephyrs, combined with the UB average value, provide the basis for the analysis. Vehicles were allowed on the Friedrichstrasse until 21 August 2020 04:00:00, when construction started. The street reopened one week later on 28 August 2020 22:00:00, without vehicle traffic. In the following analysis, we subtract (on an hourly basis) the average UB concentration from the concentration measured at the experiment sites. UB sites are representative for several square kilometres, influenced by the integrated contribution from all sources upwind and not dominated by a single source (European Parliament and Council of the European Union 2008). The resulting variable is called the NO_2 roadside impact, and can be understood as normalized NO_2 concentration. The UB stations considered (figure 1) are: Wedding (MC 010) to the Northwest, Schöneberg (MC 018) to the Southwest, Mitte (MC 171) to the East, and Neukölln (MC 042) to the Southeast. With this approach we not only take into consideration the weather variability but also other phenomena which impacted the air quality within the city, in an effort to isolate the signal produced by the intervention. The effct of the intervention was isolated using the measurements relating to the period before the implementation of the stringent lockdown (until 16 December 2020). From there on, both the effect of the intervention and of the stringent lockdown are evaluated in a cumulative way. We first use statistical testing to assess the significance of the effects. In a second step, we propose a quantification of the effect, with uncertainties.

To test the hypothesis that local concentrations were reduced with respect to the UB levels and in order to disentangle the effects of the intervention and that of the stringent lockdown related to the COVID-19 pandemic, we compare the concentrations at the three experiment sites with the average of the 4 closest UB stations (see figure 1) by means of the Student's t-test, the Wilcoxon–Mann–Whitney U-test and the Kolmogorov–Smirnov test (K-S-test). The null hypothesis of the Student's t-test states that the true difference in means is equal to 0. The null hypothesis of the Wilcoxon–Mann–Whitney U-test and of the K-S-test (both two-sided) state that both the distributions are equal. If the p-value of the test is very low, the null hypothesis is rejected and dissimilitude between the concentration distributions is assumed. Table 2 shows the p-values of the statistical tests conducted to compare the concentrations at Friedrichstrasse, Glinkastrasse and Charlottenstrasse with those at the 4 closest UB stations. The tests were conducted for the time intervals before (16 June–21 August 2020), after the intervention without stringent COVID-19 lockdown policies (28 August–16 December 2020), and after the intervention with stringent COVID-19 lockdown policies (16 December 2020–1 February 2021), discriminated by weekdays and weekends. Our approach can be classified as difference-in-differences (DID). The Friedrichstrasse, where the intervention took place, is the treatment-like group, whereas the Glinkastrasse and the Charlottenstrasse, parallel streets without any intervention, are the control-like group, with matching. The DID approach was applied using the roadside increment as dependent (outcome or response) variable, which allows to quantify the effect of the policy in terms of roadside impact. By applying the DID approach to the variable roadside increment, computed hourly, we introduce, to some extent, control for variations in the traffic cycle or variations due to the meteorology (e.g. the effect of the mixing height), among others.

In order to confirm, beyond the calibration procedure, the reliability of the Zephyr data, we performed a comparison with the data from the passive samplers deployed one block away (see figure 1). The passive samplers have a temporal resolution of two weeks.

The traffic data is used to support evidence concerning the emissions from car traffic.

At Charlottenstrasse we also conducted measurements with reference-grade air quality monitoring equipment installed on a cargo bike (see section 2.2.3). The cargo bike measures NO_2 near exhaust height (1–1.5 m), closer to the breathing zone than the 3 m height at which the Zephyrs are deployed (on lampposts). This setting allowed for investigating the difference between the concentrations at those two heights.

3. Results

3.1. City centre nitrogen dioxide

Figures 2–4 show the time series of the Zephyr data at the city centre sites. The dashed vertical lines represent the closure and the reopening of the Friedrichstrasse, between which arrangements for the new, car-free, street space were implemented.

In the measurement period before the closure of the Friedrichstrasse, the NO_2 hourly concentrations measured by the Zephyrs were in the ranges (first and ninety-ninth percentiles) 0–56, 0–45 and 0–50 $\mu g \cdot m^{-3}$ at Friedrichstrasse, Glinkastrasse and Charlottenstrasse, respectively. The concentration ranges when the Friedrichstrasse was car-free were 2.7–57, 4.6–55 and 4.3–58 $\mu g\ m^{-3}$ at Friedrichstrasse, Glinkastrasse and Charlottenstrasse, respectively.

3.2. Comparison of the LCS data with the passive samplers

Figure S2 presents the comparison of the NO_2 concentrations from the passive samplers with the average NO_2 concentrations and the 10th, 25th, 75th and 90th from the Zephyrs during the same two weeks. The datasets compare well given the difference in measurement method and measurement location. The passive sampler measurements lie within the inter-quartile range of the Zephyr measurements except in three cases, where it is slightly outside this range.

3.3. Traffic data

Figure S1 shows the traffic counts at Friedrichstrasse and the two parallel streets Glinkastrasse and Charlottenstrasse. The first two days for which traffic data is available, both before the Friedrichstrasse closure, took place during the summer, a time of year where traffic intensity throughout the city is lower. The

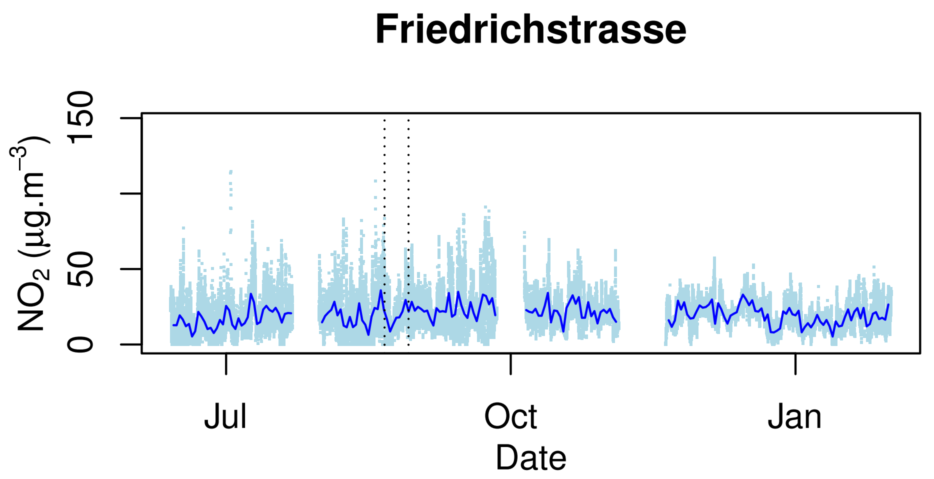

Figure 2. NO_2 concentration time series at the Friedrichstrasse site. The dots are the 5 min values, the line shows the daily averages. The dashed vertical lines represent the closure and the reopening of the Friedrichstrasse, after which the street was car-free. The periods without data are the times when the Zephyr instruments were taken for co-location, except for the period around the beginning of October, which corresponds to a data loss.

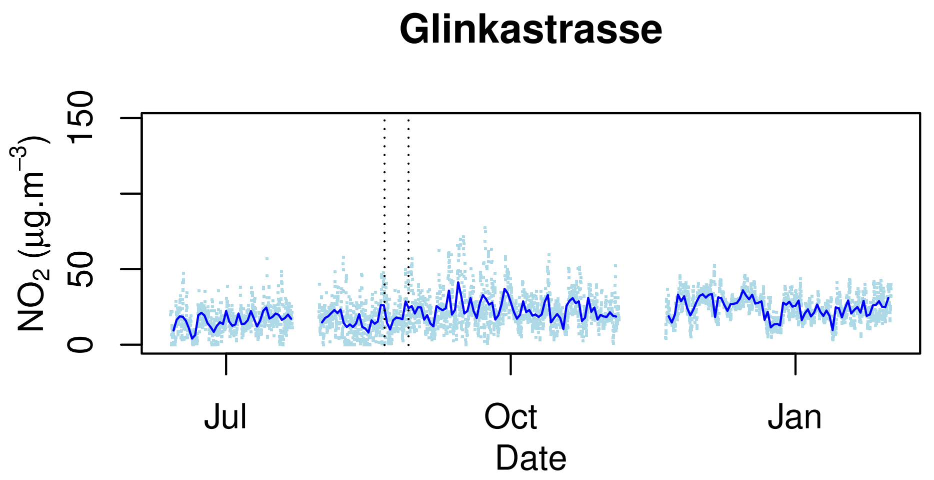

Figure 3. NO_2 concentration time series at the Glinkastrasse site. The dots are the 5 min values, the line shows the daily averages. The dashed vertical lines represent the closure and the reopening of the Friedrichstrasse, after which the street was car-free. The periods without data are the times when the Zephyr instruments were taken for co-location.

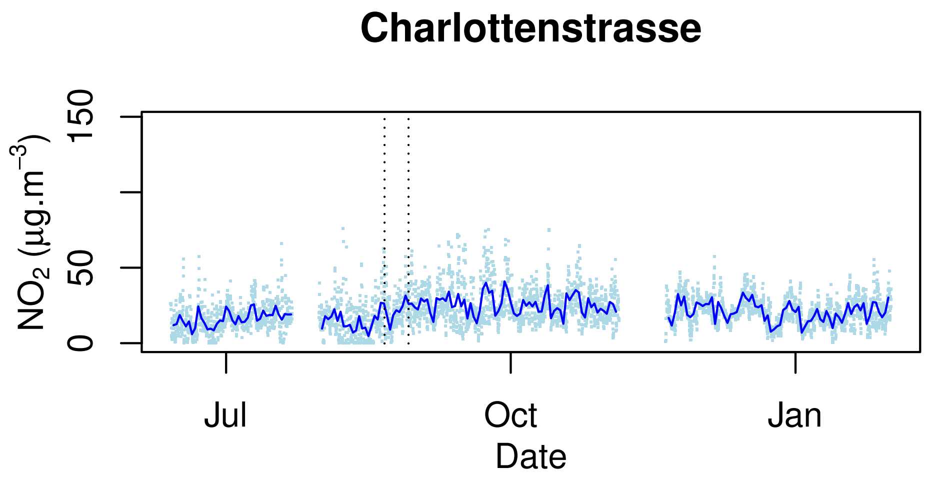

Figure 4. NO_2 concentration time series at the Charlottenstrasse site. The dots are the 5 min values, the line shows the daily averages. The dashed vertical lines represent the closure and the reopening of the Friedrichstrasse, after which the street was car-free. The periods without data are the times when the Zephyr instruments were taken for co-location.

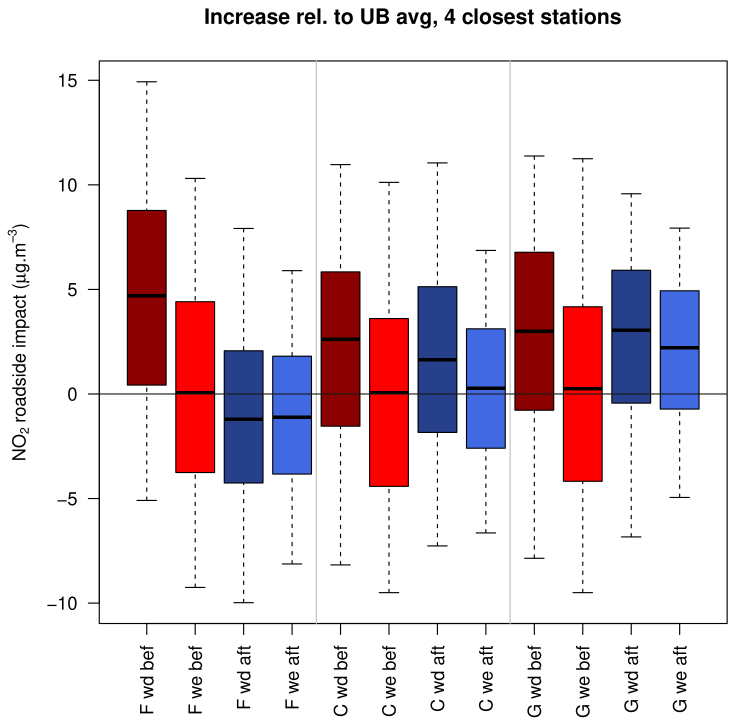

Figure 5. Normalized NO_2 concentration at Friedrichstrasse (F, left), Charlottenstrasse (C, middle) and Glinkastrasse (G, right). The whiskers extend to the 10th and the 90th percentiles. For each street, the data was separated by weekdays (wd, darker tones) and weekends (we, lighter tones), and for before (bef, left, red tones) and after (aft, right, blue tones) the intervention. The after period includes the whole experimental period after the intervention, i.e. also the period under lockdown.

Friedrichstrasse closure is clear in the data. The effect of the lockdown is also clear on the counts from 21 January 2021, clearly lower (by approximately one third) than the peaks on 10 September 2020, 6 October 2020, and 15 December 2020.

The sampling strategy for the traffic counts does not allow to evaluate if the closure of Friedrichstrasse had an impact on the traffic at the two parallel streets. The phenomena identified as the sources of the fluctuations at the three streets are expected to uniformly impact the city centre as a whole.

3.4. Comparison before and after the intervention

Figure 5 shows that before the intervention, NO_2 concentrations at the three streets were clearly above the UB on weekdays (Monday to Friday), but similar on weekends (Saturday–Sunday). After the intervention, the concentrations at Friedrichstrasse were clearly lower than before, relative to the UB, with little to no differentiation between weekdays and weekends. For Charlottenstrasse and Glinkastrasse the increment relative to the UB was maintained after the intervention (weekdays) or even increased (weekends, Glinkastrasse). Besides the closure to traffic, the introduction of stringent COVID-19 lockdown policies introduced in mid-December 2020 is another factor that could have strongly influenced local concentrations.

The density plots (figure S3) of the NO_2 concentrations show a difference at Friedrichstrasse: before the intervention (blue lines), the concentrations are clearly higher than at the UB sites on weekdays, but more similar on weekends. This is confirmed by the statistical tests (table 2): the means and the distribution are different before the intervention on weekdays, but similar on weekends. Following the intervention but before the hard lockdown was put in place (green lines on figure S3), Friedrichstrasse became, in terms of NO_2 concentrations, similar to an UB site. The statistical tests show that there are no differences in mean (t-test) and that a statistically significant similarity of the distributions cannot be rejected (U-test and K-S-test).

Before the intervention, the weekdays concentrations at the side streets Glinkastrasse and Charlottenstrasse representing the control-like group in our DID approach (figure S3, blue lines) were also higher than at the UB sites, which is confirmed by the very low p-values indicating dissimilitude. On weekends, concentrations were similar before the intervention (high p-values indicating similitude) Unlike for Friedrichstrasse, the intervention (until the stringent lockdown policies were put in place) may have had some impact on the concentrations, in that the distribution shape is closer to the shape of the distribution at UB. However, the low p-values indicate statistically significant dissimilitude on weekdays.

Table 2. Results of the statistical tests (p-value) comparing the measurements in the city centre area and the UB measurements from the Berlin monitoring network. For a simplified reading, p-values which indicate a difference are written in bold, whereas those indicating a similitude are written in normal text.

	t-test	U-test	K-S-test
Friedrichstrasse			
Before			
weekdays (Mon–Fri)	9.1×10^{-23}	2.5×10^{-29}	0
weekends (Sat–Sun)	$\mathbf{7.0 \times 10^{-1}}$	$\mathbf{7.2 \times 10^{-1}}$	2.3×10^{-8}
After, no lockdown			
weekdays (Mon–Fri)	$\mathbf{3.4 \times 10^{-1}}$	$\mathbf{7.1 \times 10^{-1}}$	$\mathbf{5.6 \times 10^{-2}}$
weekends (Sat–Sun)	$\mathbf{6.4 \times 10^{-1}}$	$\mathbf{4.7 \times 10^{-1}}$	$\mathbf{7.2 \times 10^{-2}}$
After, lockdown			
weekdays (Mon–Fri)	2.1×10^{-11}	2.5×10^{-11}	5.1×10^{-11}
weekends (Sat–Sun)	4.4×10^{-7}	6.2×10^{-6}	2.4×10^{-4}
Glinkastrasse			
Before			
weekdays (Mon–Fri)	3.2×10^{-9}	9.5×10^{-22}	0
weekends (Sat–Sun)	$\mathbf{7.9 \times 10^{-1}}$	$\mathbf{7.6 \times 10^{-1}}$	5.7×10^{-9}
After, no lockdown			
weekdays (Mon–Fri)	8.6×10^{-6}	9.9×10^{-14}	6.0×10^{-14}
weekends (Sat–Sun)	$\mathbf{1.1 \times 10^{-1}}$	1.2×10^{-3}	2.4×10^{-4}
After, lockdown			
weekdays (Mon–Fri)	1.7×10^{-13}	4.5×10^{-15}	9.0×10^{-14}
weekends (Sat–Sun)	8.4×10^{-5}	5.5×10^{-7}	2.0×10^{-6}
Charlottenstrasse			
Before			
weekdays (Mon–Fri)	1.7×10^{-4}	7.3×10^{-10}	0
weekends (Sat–Sun)	$\mathbf{4.3 \times 10^{-1}}$	$\mathbf{7.4 \times 10^{-1}}$	5.6×10^{-11}
After, no lockdown			
weekdays (Mon–Fri)	1.4×10^{-9}	1.6×10^{-16}	4.1×10^{-14}
weekends (Sat–Sun)	$\mathbf{2.6 \times 10^{-1}}$	7.5×10^{-3}	6.9×10^{-4}
After, lockdown			
weekdays (Mon–Fri)	$\mathbf{6.5 \times 10^{-1}}$	$\mathbf{5.0 \times 10^{-1}}$	6.9×10^{-3}
weekends (Sat–Sun)	$\mathbf{1.3 \times 10^{-2}}$	$\mathbf{6.2 \times 10^{-2}}$	$\mathbf{1.4 \times 10^{-1}}$

After the stringent lockdown policies were put in place (16 December 2020), the very low p-values of the statistical tests show that concentrations were again significantly different between Friedrichstrasse and the UB, both in terms of averages and in terms of distribution. However, unlike before the intervention, the density plots show that concentrations at Friedrichstrasse were lower than at the UB (figure S3, red lines). The side street Charlottenstrasse became, in terms of NO_2 concentrations, similar to an UB site (figure S3, red lines), whereas Glinkastrasse still exhibited higher NO_2 concentrations. A possible explanation for that difference could be that Charlottenstrasse is more commercial whereas Glinkastrasse has started to become more residential. The three streets under investigation are dominated by services and residents are very few. During the stringent lockdown, with the closure of commerce, traffic probably dropped there more than in other parts of the city, leading to localized lower NO_2 concentrations.

3.4.1. Sensitivity analysis

The seven-step methodology proposed by Schmitz *et al* (2021b) and used in the present work also outputs upper and lower bounds for the individual, 5 min, measurements of the Zephyrs. That range represents the combination of the uncertainty from the model and the uncertainty from the reference instrument used to calibrate the LCS units. In order to check our results, the same statistical tests were run with the upper and with the lower bounds of the Zephyr measurements. The results are presented in table S3 (for weekdays only).

At Friedrichstrasse, Glinkastrasse and Charlottenstrasse the concentrations before the intervention are above the UB level. After the intervention the concentrations at the three locations evolve, with the different lockdown situations, towards being clearly lower than at the UB.

When considering the upper bounds, concentrations in the city centre are always higher than at the UB.

This sensitivity analysis shows that the interval given by the seven-step methodology for the city centre concentrations measured by the Zephyrs encompasses the UB levels. This highlights the fact that LCS technologies, together with the associated evaluation algorithm, are not a replacement for reference hardware and although the change produced by the intervention can be evaluated, its exact magnitude is uncertain.

A second sensitivity analysis was conducted using different co-location data. The analysis was repeated using data from co-locations 1–6, whereas the main analysis was conducted using a calibration derived from data collected during co-locations 2–4 (which occurred within the experiment dates). The repeated analysis (table S4) shows a similar trend as the main analysis (NO_2 concentrations at Friedrichstrasse were higher before the intervention, lower after the lockdown measures were put in place and intermediate in-between). The statistical significance of the relation to the UB NO_2 concentrations is different: the concentrations at Friedrichstrasse were similar in terms of means after the intervention, but dissimilitude between the distributions was statistically significant. The situation after the lockdown measures were put in place shows that the NO_2 concentrations derived from the 6 co-locations were lower than at the UB. We trace back such behaviour to the introduction of higher concentrations in the calibration process (the additional co-location periods took place within the city and outside the COVID-19-related lockdown) and show the importance of using appropriate co-location data, as argued by Schmitz *et al* (2021b).

A third sensitivity analysis was done comparing the output from two models: MLR (used for the main analysis) and RF (also output in the calibration process). Results from the RF model (p-values in table S5) show the same trend as the MLR-based analysis: NO_2 concentrations at Friedrichstrasse were clearly larger than at the UB before the intervention, similar after the intervention without lockdown and clearly lower after the lockdown measures were put in place. This shows that our findings are robust with respect to the model used to derive calibrated NO_2 concentrations.

3.4.2. Quantification of the effect of the policy

As shown above, the policy was the cause of an effect on the NO_2 concentrations at Friedrichstrasse on weekdays. In this section, we quantify that effect, together with its uncertainty in terms of roadside increment. On weekdays, the average hourly roadside increment was 4.9 $\mu g \cdot m^{-3}$ before the policy was put in place (standard deviation: 9.4 $\mu g \cdot m^{-3}$), and -0.47 $\mu g \cdot m^{-3}$ after the policy was put in place, but before the lockdown (standard deviation: 8.6 $\mu g \cdot m^{-3}$). Using the lower and upper bounds given by the calibration model (see section 3.4.1) the hourly average roadside increment was -1.8 and 12 $\mu g \cdot m^{-3}$ before the policy was put in place, respectively. After the policy was put in place, the hourly average roadside increment was -7.5 and 6.7 $\mu g \cdot m^{-3}$ when using the lower and the upper bounds, respectively.

The change introduced by the policy was thus a reduction of 5.4 $\mu g \cdot m^{-3}$ in the roadside increment. By propagating the standard deviation together with the uncertainty from the model, the uncertainty of the reduction was computed as 11 $\mu g \cdot m^{-3}$.

3.5. Kerbside measurements

Figures 6 and 7 show the data from the cargo bike together with the data from the closest Zephyr on the following days: Thursday 17 September, Wednesday 30 September, Tuesday 13 October, Monday 26 October and Saturday 21 November.

The time series plots (figure 6) show that while the peaks tend to be concurrent in time, the concentration closer to the source is much higher than at 3 m height. The distribution of the points in figure 7 further confirms higher concentrations at the kerbside, but with strong contrast between different days. A larger departure from the unity line towards higher kerbside concentrations happens on 30 September and 21 November than on the other 3 d. Meteorological conditions which favour rapid vertical mixing can be one reason for such an observation. A lesser source strength (less concentrated traffic) may also influence such an outcome.

No direct relationship could be found between the extent of the difference in the peaks at the kerbside and on the lampposts and pressure and wind speed (figure S4 and tables S2 and 3): poor vertical mixing conditions were observed on 30 September and 13 October: low boundary layer height (table S2) and a stable atmospheric vertical profile (figure S4). Charlottenstrasse has a roughly N–S orientation and the sensor was located on the western side of the street. Wind direction influences the horizontal distribution of NO_2 across the street. The most common wind directions, reported in table S2, do not show any matching pattern with the difference in the peaks at the kerbside and on the lampposts. A more complex relationship could possibly be derived, taking into consideration the local traffic, besides meteorological variables. However, detailed local traffic data is not available.

Even taking into consideration local meteorology, no clear pattern arises and such results highlight the necessity to take into consideration, when assessing the exposure to air pollutants in cities, the high temporal and spatial variability induced by the meteorology and traffic patterns. This also shows that it is critical to

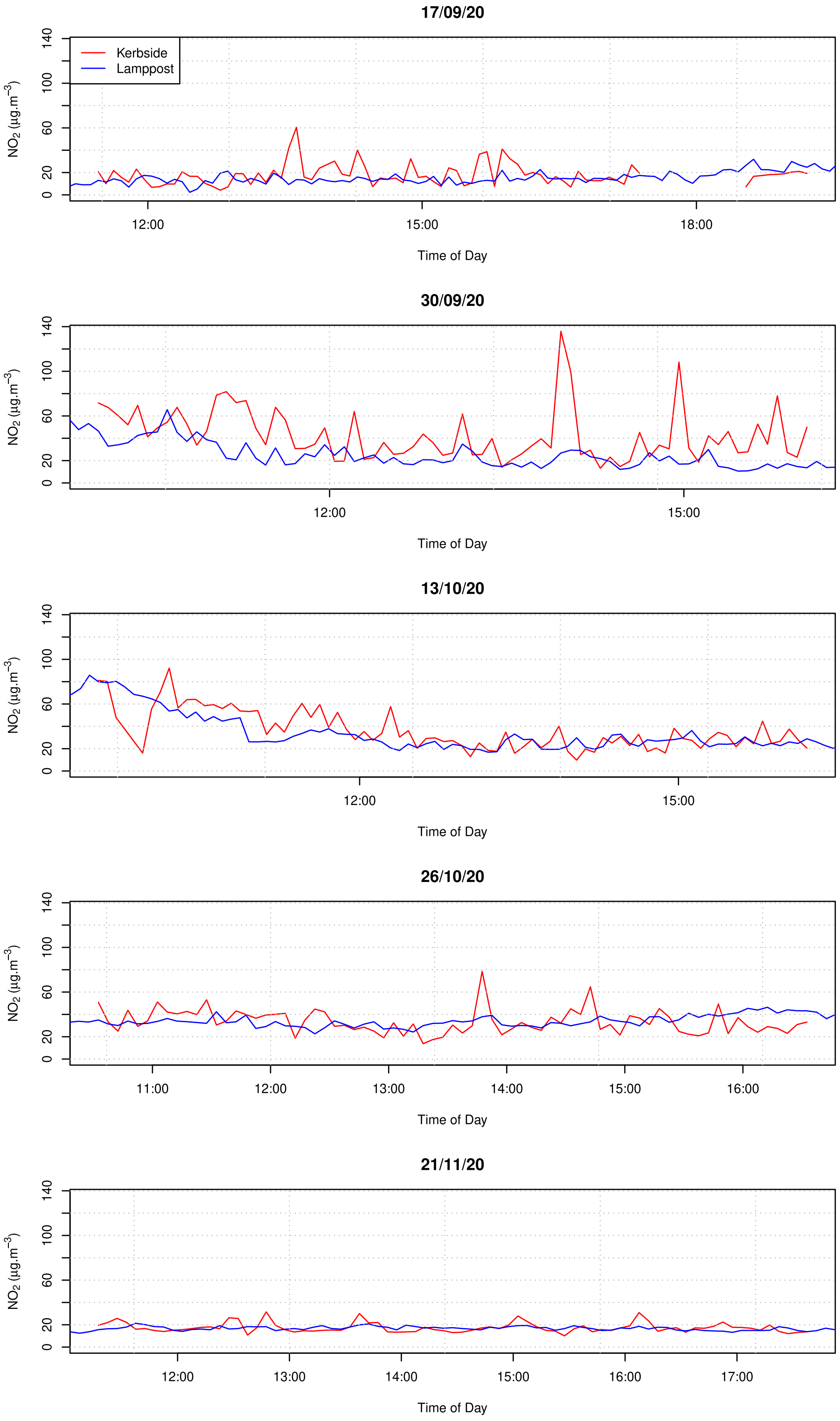

Figure 6. Time series of the NO_2 concentrations (5 min averages) measured at the lamppost height and at the kerbside at Charlottenstrasse on five different days. Time of day is UTC.

determine measurement location, including height, based on the intended application. In this case, the measurement data shows that to adequately capture population exposure, a difference of a few meters or less in measurement height can have a substantial impact on concentrations, limiting the conclusions one can draw with the data gathered. This is reinforced by the complexity of the relationship between concentrations relevant for exposure and concentrations measured a few metres away vertically.

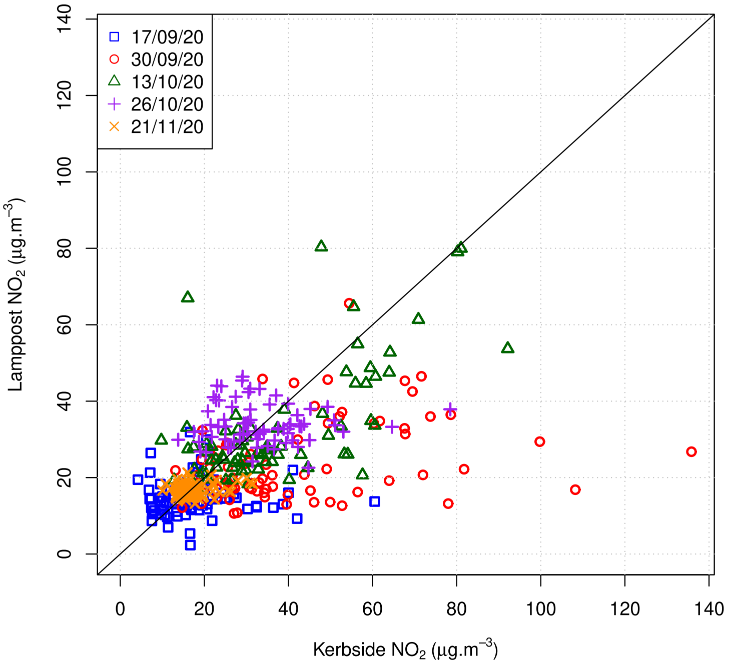

Figure 7. Scatter plot of the NO_2 concentrations (5 min averages) measured at the lamppost height and at the kerbside at Charlottenstrasse on five different days.

Table 3. Distribution statistics of the NO_2 concentrations (5 min averages) measured at Charlottenstrasse: lamppost (by Zephyr) and kerbside (by T200).

Date	Time	Location	min	P_{10}	P_{25}	P_{50}	P_{75}	P_{90}	max
17 September 2020	11:25	lamppost	1.6	9.2	12.3	15.8	21	24.3	34.8
Thursday	19:15	kerbside	4.2	7.6	11.1	16.6	20.8	30.5	60.5
30 September 2020	10:00	lamppost	10.6	17	23.4	32.9	45.9	57.4	73.6
Wednesday	16:05	kerbside	13.1	20.8	26	34.7	52.8	71.9	135.8
13 October 2020	09:30	lamppost	15.7	20.7	26	36.4	45.6	65.8	90.4
Tuesday	16:15	kerbside	9.8	17.6	23.6	30.4	48.8	59.8	92.1
26 October 2020	10:30	lamppost	11.7	19.1	22.9	31.3	35.6	39.6	47
Monday	16:35	kerbside	13.8	21.5	25.7	31.4	39.9	44.9	78.5
21 November 2020	11:15	lamppost	8.6	11.3	13.6	16.1	19.6	23	30.8
Saturday	17:40	kerbside	10.1	13.4	14.7	16.5	19	23.2	31.5

4. Discussion

This study has identified several key takeaways regarding the connections between mobility, health, and air pollution. First and foremost, the results of these measurements indicate that mobility policies, such as the street redesign on Friedrichstrasse, which removes cars from the street, reduces local emissions of pollutants, such as nitrogen dioxide and improves local air quality. That the removal or relocation of large volumes of traffic leads to reductions in NO_2 emissions has been known for some time. Such changes were measured during the Beijing Olympics in 2008 (Wang and Xie 2009, Kelly and Zhu 2016), have been modelled in various scenario-testing studies (Buchholz *et al* 2013, Holman *et al* 2015, Degraeuwe *et al* 2017, Steinberga *et al* 2019, Sousa Santos *et al* 2020) and most recently were seen in 2020 as a result of the strict lockdowns in response to the COVID-19 pandemic (Berman and Ebisu 2020, Gautam 2020, Brancher 2021, Skirienė and Stasiškienė 2021, von Schneidemesser *et al* 2021). The results presented here are further proof that a reduction in vehicle traffic leads to concomitant improvements in local air quality, but show that this improvement is restricted to levels of UB pollution in heavily trafficked areas. Other studies have shown that reductions in NO_2 concentrations in connection with traffic-reducing measures may be offset by an associated increase in O_3 pollution, resulting from lower rates of NOx titration under NOx-saturated regimes (Wang and Xie 2009, Brancher 2021, von Schneidemesser *et al* 2021). To achieve further reductions in air pollution in cities such as Berlin would require holistic measures on a city-wide scale that address emissions of NO_2 from traffic and other key sources, as well as regional scale policies that address O_3 precursor emissions.

These results further highlight the necessity to consider the high temporal and spatial variability induced by changing meteorology and traffic patterns when assessing exposure to air pollutants in cities. Other research has identified poor agreement between kerbside and ambient air pollution measurements (de Nazelle *et al* 2012, Xu *et al* 2017). However, we find evidence that even on the same block of the same street, there are differences between 3 m height and kerbside measurements, with clear implications for the calculation of personal exposure to air pollutants. This indicates it is important to carefully consider the impact of measurement location on achieving research goals, and that measurements located a few meters away vertically may already truncate the knowledge one can obtain about a population's air pollution exposure. In this case, even after taking into consideration local meteorology, only a weak relationship between these measurements on Charlottenstrasse arises, reflecting the difficulty to assess exposure from concentrations which were not measured at an ideal height, but were rather focused on understanding broader changes to the area.

Last, the results captured in this study were enabled by the flexibility of LCS. Since such small sensors can be readily deployed in higher numbers at lower cost than reference-grade instruments, measurement campaigns can now be conducted at higher spatial and temporal resolution. While other studies have taken advantage of these characteristics to measure in mobile or stationary microenvironments (Lin *et al* 2017, Lim *et al* 2019, von Schneidemesser *et al* 2019) or to establish higher resolution measurement networks (Mead *et al* 2013, Morawska *et al* 2018, Barcelo-Ordinas *et al* 2019), few studies such as this one use LCS to directly measure changes in air quality in association with mobility policies (Schmitz *et al* 2021a). These types of measurements highlight the capacity of LCS to quickly generate valuable insights for decision makers regarding changes in air pollution.

4.1. Policy implications

Over the course of the past decade, there has been an increasing policy focus on mitigating air pollution in German cities. With diesel vehicles accounting for a large proportion of air pollutant emissions (NO_2 and PM) in cities, policymakers across Germany have responded by implementing LEZs and other large-scale policies, with only marginal success in improving air quality and human health (Cyrys *et al* 2014, 2018, Margaryan 2021, Pestel and Wozny 2021). In light of the recent update to the WHO recommended air pollutant limit values (WHO, World Health Organization 2021), cities will require new policies that are more effective than LEZ to achieve their air quality goals. This study shows that, in the short-term, more stringent policies such as traffic restrictions and street closures can also be successful in reducing local emissions and improving air quality. To achieve larger scale reductions in air pollutant emissions, such as those seen during the lockdowns of the COVID-19 pandemic, cities are likely to require the widespread removal of (diesel) vehicles from their streets. To be effective in the long-term, these policies should be combined with others that promote the use of public transport and alternative mobility options, so as to prevent displacement of emissions and support citizens in switching to alternative transport modes. The Friedrichstrasse case-study exemplifies how such policies can have measurable impacts on local air pollutant concentrations when implemented on a small-scale. With respect to the Berlin Mobility Act and the city's planned mobility transition, improvements in air quality on Friedrichstrasse have already contributed to the narrative of this project as a success story that increased the quality of life for visitors and residents of the street, also serving as evidence for the need of further such policies city-wide (Senatsverwaltung für Umwelt, Verkehr und Klimaschutz 2021a, 2021b, 2021c). To ensure that the impacts of these policies can be properly quantified going forward, policymakers should further seek to measure changes in air pollution at a higher spatial resolution and in more appropriate locations to better understand the real-world total exposure of their citizens.

4.2. Limitations

There are several limitations to this study. First, while it was planned to also measure O_3 during this campaign, there was a technical failure with the reference instrument used during the co-locations that prevented calibration of the raw Zephyr O_3 data. Given that other studies have found increases in O_3 concentrations in connection with traffic-reducing measures, as described previously, the lack of O_3 data in this study prevented us from capturing a more complete picture of changes in air pollution in the study site. In addition, in the present work we did not study the impact of the Friedrichstrasse car-free measure on local concentrations of particulate matter (PM) due to limitations in instrumentation, but a comprehensive assessment of the impact of the measure on the local air quality would have to include it as well. Last, the practicality and lower cost of sensor systems allowed us to conduct this study with a higher spatial resolution of measurements than would have been possible with reference instruments. However, LCS housed in sensor systems are currently less accurate than reference devices. Although we have maximized the accuracy of the data obtained through the LCS and provided representative measures of uncertainty, these are still not, in terms of accuracy, a technological equivalent to reference methods. Therefore, while the general changes in air quality measured in this study are clear, the precise magnitude of the reduction in NO_2 concentrations cannot be determined with precision, as it is shown by the sensitivity analysis. Finally, while real-time traffic count measurements were planned, these ended up being much more limited, also affecting the analysis.

5. Conclusion

In the present study, we analyze the effect of an urban intervention—the closure to motorized traffic of a street in central Berlin—on the air quality in the vicinity (the street proper, Friedrichstrasse, and two parallel, adjacent, side streets not closed to traffic, Glinkastrasse and Charlottenstrasse). Nitrogen dioxide concentrations were measured with low-cost systems (EarthSense Zephyrs, one on each street) following a thorough calibration methodology confirmed by a comparison with passive samplers deployed on the same streets.

From our analysis, we can conclude that the intervention had an impact at Friedrichstrasse: the concentrations were brought down to the level of the UB by the intervention, both on weekdays and weekends. At the side streets Glinkastrasse and Charlottenstrasse, the concentrations of NO_2 after the intervention remained higher than the UB but did not increase relative to the concentrations prior to the intervention. After the stringent lockdown policies were put in place (16 December 2020), measurements at Friedrichstrasse consistently show lower concentrations than at the UB. At Friedrichstrasse, the stringent lockdown signal comes on top of the reduction from the intervention. On the side streets, the lockdown brings the concentrations down to the level of the UB for Charlottenstrasse only.

Our results show that even a relatively small street closure can have a relevant effect on air quality. While the hypothesis was that the emissions on side streets would increase, due to car drivers using those streets as alternative routes, this was shown to not be the case. We also highlight the difference between measuring at street level versus on lampposts at about 3 m height. While suitable for quantifying the change induced by altered traffic patterns, for exposure purposes we demonstrate that it is important to consider the measurement location carefully, and that it is not straightforward to derive exposure-relevant concentrations from measurements taken even a few meters higher.

The present study was conducted using LCS as the main instruments. The study not only demonstrates the utility of such instruments for urban deployments, but also for evaluation of policy impacts. Despite the calibration methodology used, which focuses on traceability and the maximization of the output concentration accuracy, the concentration output comes associated with an uncertainty range too large to precisely quantify the change in NO_2 concentration associated with the intervention. Instead of a precise quantification, our study based on LCS technology was able to deliver a qualitative, yet policy-relevant, outcome: closing one street in the city centre to traffic brought the NO_2 concentrations in that street down to the level of the UB, without adversely affecting the concentrations on surrounding streets.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://zenodo.org/records/12168056 (Caseiro 2024).

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Author contributions

Conceptualization: AC, SS, AK, EvS; Data curation: AC, SS; Formal analysis: AC, SS, AK, EvS; Funding acquisition: EvS; Investigation: AC, SS, EvS; Methodology: AC, SS, EvS; Project administration: AK, EvS;

Resources: EvS; Software: AC, SS; Supervision: EvS; Validation: AK, EvS; Visualization: AC; Writing—original draft: AC; Writing—review & editing: SS, AK, EvS.

Conflict of interest

The authors declare no competing interests.

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