



Impact of the temporary closure of a major bridge on local air quality in two large German cities: an accountability study

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Abstract

Despite recent achievements in reducing the contribution of road traffic to air pollution, agreed pollutant standards are exceeded frequently in large parts of Europe. Previous studies assessed the effectiveness of traffic interventions in improving local air quality. However, little research exists on the effect of closures of short road sections over longer periods. The multi-week maintenances on the Theodor Heuss Bridge, the main connection over the river Rhine between the German cities Mainz and Wiesbaden, offered the opportunity to investigate its effect on local air pollution. We measured ambient concentrations of major air pollutants and meteorological parameters at the Theodor Heuss Bridge before, during, and after its closure on 800 m in early 2020. We carried out time-series and closure-dependent evaluations of pollutant concentrations at the bridge accounting for wind direction. Furthermore, we performed regression analyses accounting for wind speed additionally. We compared the results with data from surrounding monitoring stations. We recorded higher concentrations at the Theodor Heuss Bridge compared to outside the closure, especially for particulate matter, nitric oxide, and black carbon. Only with wind from specific directions, we could detect reductions of concentrations during the closure for many pollutants as nitrogen dioxide (−9.8%; 95% confidence interval: −10.8–−8.7%), but not for particulate matter. Since we found similar meteorology-dependent pollution reductions during the closure at both the bridge and the surrounding monitoring stations, we assume that regional meteorological factors overlaid a potential closure-related effect on local air quality. These factors must be accounted for in accountability studies on interventions focusing on short roads.

Keywords Intervention · Air pollutants · Car traffic · Accountability study

Introduction

As stated by the international project Global Burden of Diseases, air pollution is the fourth leading cause of illness and disability in the world. Furthermore, according to the

European Environment Agency, it is the largest environmental health risk in Europe today, causing around 400,000 premature deaths annually in the EU (European Environment Agency 2020). Exposure to air pollution has been associated with several negative health effects (World Health Organization 2021), such as cardiovascular and respiratory diseases (Hayes et al. 2020; International Agency for Research on Cancer 2013; Ohlwein et al. 2019; Zhang et al. 2018), with groups such as elderly people and children being particularly affected (Bell et al. 2013; Vrijheid et al. 2016). In addition, the International Agency for Research on Cancer has established that “there is sufficient evidence in humans for the carcinogenicity of outdoor air pollution. Outdoor air pollution causes cancer of the lung. A positive association has been observed between exposure to outdoor air pollution and cancer of the urinary bladder” (International Agency for Research on Cancer 2013). Furthermore, according to the World Health Organization, reducing air pollution could also

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reduce the burden of other diseases (World Health Organization 2006).

Man-made sources of primary pollutants like particulate matter (PM_{2.5}, PM₁₀, i.e., mass concentrations of particles smaller than 2.5 µm and 10 µm, respectively, but also ultrafine particles smaller than 100 nm) or nitrogen oxides include nonmobile (e.g., factories, residential heating) as well as mobile sources (European Environment Agency 2020). On-road motorized traffic, as a mobile source, is a main contributor to air pollution and was responsible for around 39% of the nitrogen oxides and 28% of the black carbon emissions in Europe in 2017 (European Environment Agency 2019; Stanek and Brown 2019). In recent decades, air quality improvements have been achieved in many industrialized countries due to technological developments and policy measures (e.g., Burns et al. 2019; Henschel 2012), the latter of which mainly address emissions from on-road motorized traffic (European Environment Agency 2019). At the same time, however, the global increase in traffic volume partially offset the reductions in transport emissions (Health Effects Institute 2010). Indeed, agreed pollutant standards continue to be exceeded in large parts of Europe, and studies in recent decades have shown that even exposure to pollutant concentrations below the legal limit values can have adverse health effects (e.g., Burns et al. 2019; Henschel 2012), both in the short (Alessandrini et al. 2013; Orellano et al. 2020; Yee et al. 2021) and long term (Alessandrini et al. 2013; Beelen et al. 2014; Stafoggia et al. 2022; WHO Expert Consultation 2015). In response, substantial policy measures continue to be taken to reduce air pollution. Besides Europe-wide policies that include emission standards for motor vehicles and definition of national emission ceilings, local policy interventions aim to reduce urban air pollution concentrations, for example, by establishing congestion charging and low emission zones (Boogaard et al. 2012; Panteliadis et al. 2014).

In recent decades, several accountability studies, defined as studies that evaluate the extent to which air quality regulations improve public health (HEI Accountability Working Group 2003), have shown that policy interventions aiming to reduce air pollution can improve local air quality and lead to positive health effects (Burns et al. 2019; Henschel 2012; Pope 2010; Rich 2017; van Erp et al. 2012). The impact of local road traffic interventions is of particular interest in this regard. Several accountability studies in recent decades have focused on traffic interventions in form of temporary road closures and their air quality impacts, each of which found a decrease in pollutant concentrations associated with the intervention (e.g., Hong 2015; Levy et al. 2006; Quiros et al. 2013; Scholz and Holst 2007; Shu et al. 2016; Whitlow et al. 2011). However, most of these studies focused on closures of long road sections of at least several kilometers over a shorter period of up to a few days. Solely Titos et al. (2015)

investigated a short (400 m) length of a road in Ljubljana in a longer, multi-week measurement period placed around the onset of a permanent air quality-related closure. Thus, to our knowledge, there is a research gap regarding road closures that affect very localized sections of less than a few kilometers and last for more than a few days.

The closure of the approximately 800-m-long Theodor Heuss Bridge, the main road connection between the two German cities Mainz and Wiesbaden, from 12 January to 5 February 2020 offered a unique opportunity to fill this gap. We used this opportunity to analyze the extent to which a very localized reduction of on-road motorized traffic over several weeks, which simulates a potential intervention, can change local air quality.

Materials and methods

Case study

The Theodor Heuss Bridge is the center bridge of five bridges spanning the river Rhine in this area (Fig. 1) and connects two German state capitals, Mainz (210,000 inhabitants) and Wiesbaden (280,000 inhabitants). It serves as a major transportation link between these cities and is a four-lane federal highway with a speed limit of 50 km/h and some 40 000 vehicles passing the bridge daily.

From 12 January to 5 February 2020, the bridge was closed for motorized private traffic on approximately 800 m in length due to maintenance work at which truss bearings were replaced to stabilize the construction. Only buses, taxis, ambulances, and emergency vehicles as well as a few other exceptionally granted vehicles were allowed to use the bridge. Around 2,000 vehicles per day passed the bridge during the closure, which is 5% of the vehicles per day in times without any restrictions. Surrounding streets likely had reduced traffic volumes during the closure, too, as the on-road motorized traffic passing the bridge at regular times was in part redirected to other routes. However, no traffic data were available to us for streets other than the bridge. The pollution caused by the maintenance work itself, as by the construction vehicles which were regular delivery vehicles, was assumed as negligible.

Mainz and Wiesbaden are located in the Rhine-Main area, one of the largest metropolitan regions in Germany, with Frankfurt as its center located approximately 30 km to the east-northeast of the bridge. Besides traffic and residential emissions, the Frankfurt Airport (located 20 km to the east-northeast) and several smaller commercial and industrial facilities (manufactural and chemical plants, paper factory, cement plants, and power plants, among others) are the main emission sources in this region.

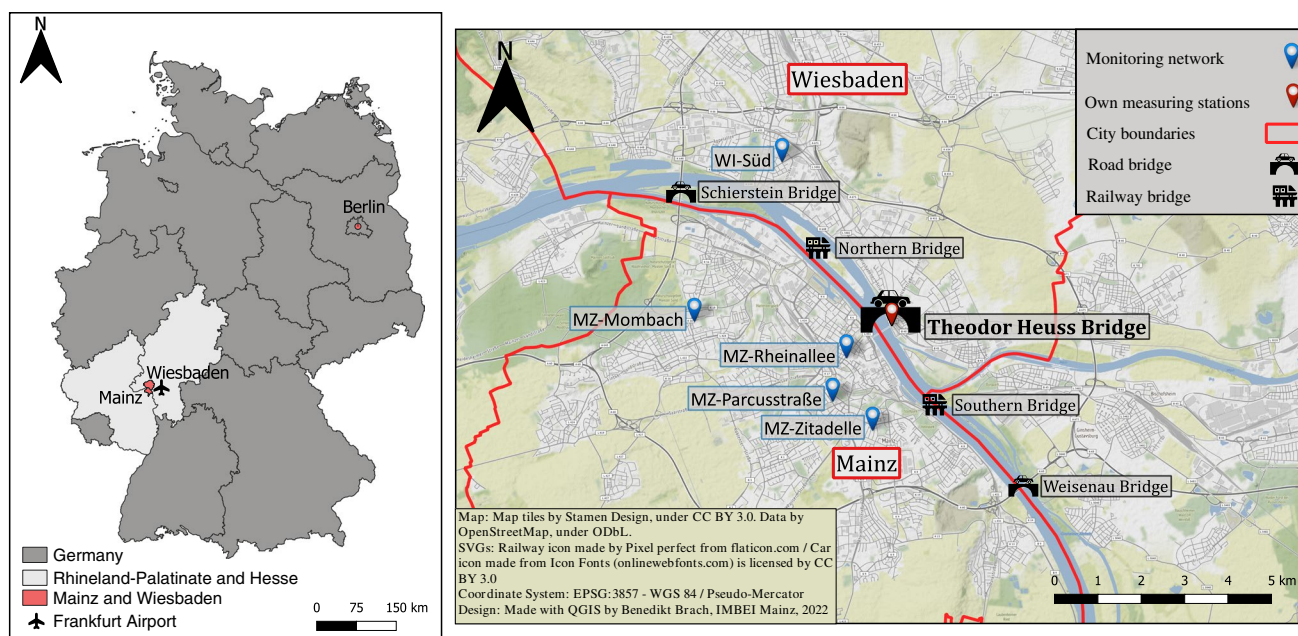


Fig. 1 a (Left) Location of the measuring sites within Germany. b (Right) Location of the Theodor Heuss Bridge with our measurement site (red marker), the air quality monitoring stations (blue markers), and other Rhine bridges between Mainz and Wiesbaden

Air pollutants and meteorological data

From 7 January until 20 February 2020, we measured concentrations of various air pollutants at the bridge, focusing on typical pollutants known to be emitted by traffic sources (e.g., nitrogen oxides, black carbon). In a room inside the northeastern bridgehead, about 5 m below the roadway and with an approximately 1-m long inlet line through an opening in the wall, we installed a rack with various online instruments measuring aerosol and trace gas variables (Fig. s1 in Supplementary material). We decided to perform measurements at the easterly end of the bridge because this end has a larger chance of being downwind of the bridge. The bridgehead was the only location available within the short time of preparation of the measurements which assured that the measurements were not dominated by emission plumes from close-by passing vehicles but rather reflect the general pollutant situation in the bridge area. The measurement rack included instruments to measure the trace gas concentrations of nitrogen monoxide (NO), nitrogen dioxide (NO₂), ozone (O₃), black carbon, and particle number concentrations as well as the particle size distribution. The latter was later used to calculate the particulate mass concentrations for the size fractions PM₁, PM_{2.5}, and PM₁₀ (i.e., with particle aerodynamic diameters below 1 μm, 2.5 μm, and 10 μm, respectively). Furthermore, NO_x was derived by addition of NO and NO₂. To measure meteorological data, we installed a Davis Vantage Pro II

weather station on a lamppost at the edge of the roadway at a height of about 5 m above the road (Fig. s1 in Supplementary material). It measured temperature, precipitation intensity, relative humidity, air pressure, total radiation and UV radiation, wind direction, and wind speed (Table s5 in Supplementary material).

After inspection for invalid data, e.g., due to instrument malfunctions or calibration cycles, all measurement data were averaged to 5-min time intervals to reduce noise as well as the influence of individual emission plumes.

In addition to our measured data, we used pollutant data from five air quality monitoring stations as a control. The stations (Fig. 1) are located within a radius of about 5 km from the bridge and are managed by the regional environmental authorities. They included three urban background stations and two urban traffic stations. We obtained hourly mean values of black carbon, NO, NO₂, O₃, PM_{2.5}, and PM₁₀ for the period from 7 January to 20 February 2020, provided that measurements of these pollutants were available at the respective stations (Table s6 in Supplementary material).

Furthermore, convective inhibition (CIN) information, a numerical measure that indicates how much energy is needed for an air parcel to be lifted from ground level up to the level of free convection, i.e., how stable the atmospheric layering is, was provided from the local air quality network (Voigt 2020). CIN values were calculated from altitude-resolved air temperature data, which were derived from microwave radiometer measurements at various angles.

Statistical analysis

For the descriptive statistical analysis of the air pollution data, mean and median pollutant concentration values for the periods before, during, and after the closure were compared. Additionally, we plotted 5-min time series of pollutant concentration levels, allowing us to evaluate the short- and long-term variability of concentrations. We also calculated diurnals (i.e., average diel cycles) with hourly pollutant concentrations for the periods during and outside the closure to assess whether the bridge closure modified daily pollutant concentration peaks due to on-road motorized traffic. To assess the regional distribution, we compared our data with those of the surrounding air quality monitoring stations. Additionally, differences in mean concentrations between the Theodor Heuss Bridge and the monitoring stations were calculated for the periods during and outside the closure. To assess the impact of meteorology on pollution levels during the bridge closure, polar graphs depicting pollutant concentration levels classified in 16 wind direction bins according to respective prevalent wind direction were produced from the data acquired at the Theodor Heuss Bridge and the monitoring stations, respectively, for both during and outside the closure. Additionally, the polar graphs for the Theodor Heuss Bridge were extended by wind speed tertiles to investigate the influence of wind speed on measured pollutant concentrations.

To analyze the combined influence of the bridge closure and the weather conditions on pollutant concentrations, we used multivariable linear regression analysis, adjusting for wind speed and wind direction (Kleinbaum et al. 2013). One model each for eight different pollutants (black carbon, NO, NO₂, NO_x, particle number concentration, PM₁, PM_{2.5}, PM₁₀) was set up. In each model, the pollutant concentration as the dependent variable was log-transformed and a restricted cubic spline transformation was used for the wind speed variable to account for the non-linear relationship with the dependent variable (Croxford 2016). The models yielded the percentage variation of the geometric mean concentrations compared to out of the bridge closure. 95% confidence intervals (95% CI) are reported with a descriptive purpose without claiming coverage, which is compromised due to the underlying dependency structure of the time series. Furthermore, as the model for ozone violated central assumptions of linear regression analysis still after these transformations, the results were not reported for this pollutant. For further details regarding the regression analysis, see also the methods section in Appendix 1 in Supplementary material.

For data analysis, we used the scientific data analysis software IGOR Pro (WaveMetrics Inc. n. d.) and the statistical analysis software R (R Core Team 2020).

Results

Time trends of pollutant concentrations

The 1-h time series of the pollutant concentrations at the Theodor Heuss Bridge from the beginning to the end of the measurements show a high variability, on both short- and longer-time scales (red traces in Fig. 2; Fig. s6 in Supplementary material for all pollutants). The short-term variability in the time series, i.e., single spikes in pollutant concentrations, is assumed to be mainly due to a number of local, single strong emission plumes reaching the measurement site. The long-term variability in turn is mainly related to changes in meteorological conditions, e.g., wind direction, air mass history, or atmospheric stability. The described trends with episodes of higher and lower concentrations were found to strongly correlate with the concentrations measured at the monitoring stations (blue traces in Fig. 2). The correlations with the time series of the Theodor Heuss Bridge are highest for ozone with Pearson correlation coefficients of 0.90 (95% CI 0.90–0.90) to 0.94 (95% CI 0.94–0.94), depending on the monitoring station compared and lowest for PM₁₀ (0.72 [95% CI 0.72–0.73] to 0.76 [95% CI 0.75–0.77]), for which a clear linear correlation is still evident. Exceptions such as the spike at the Theodor Heuss Bridge for PM₁₀ around 21 January can be caused by individual local pollution emissions from nearby on-road motorized traffic, e.g., resuspension of road dust from a dirt road passing below the bridge. A general reduction of pollution levels during the bridge closure could not be observed in the time series. The comparison of diurnal patterns of pollutant concentrations during and outside the bridge closure revealed a slight temporal shift in on-road motorized traffic-related pollutant maxima for NO, PM₁, black carbon, and the particle number concentration (Fig. s7 in Supplementary material). The morning on-road motorized traffic maximum occurred slightly later and the evening maximum slightly earlier during the closure of the bridge. These shifts are potentially associated with slightly changed mobility behaviors like a temporal shift in on-road motorized traffic. Nevertheless, also in these analyses, the pollutant levels are not lower during the traffic-related maxima within the closure period, compared to the non-closure period.

Pollution levels during and outside the closure

Most pollutants did not reveal lower concentration levels at the Theodor Heuss Bridge during the closure compared to the period outside (Table 1). The strongest excess in

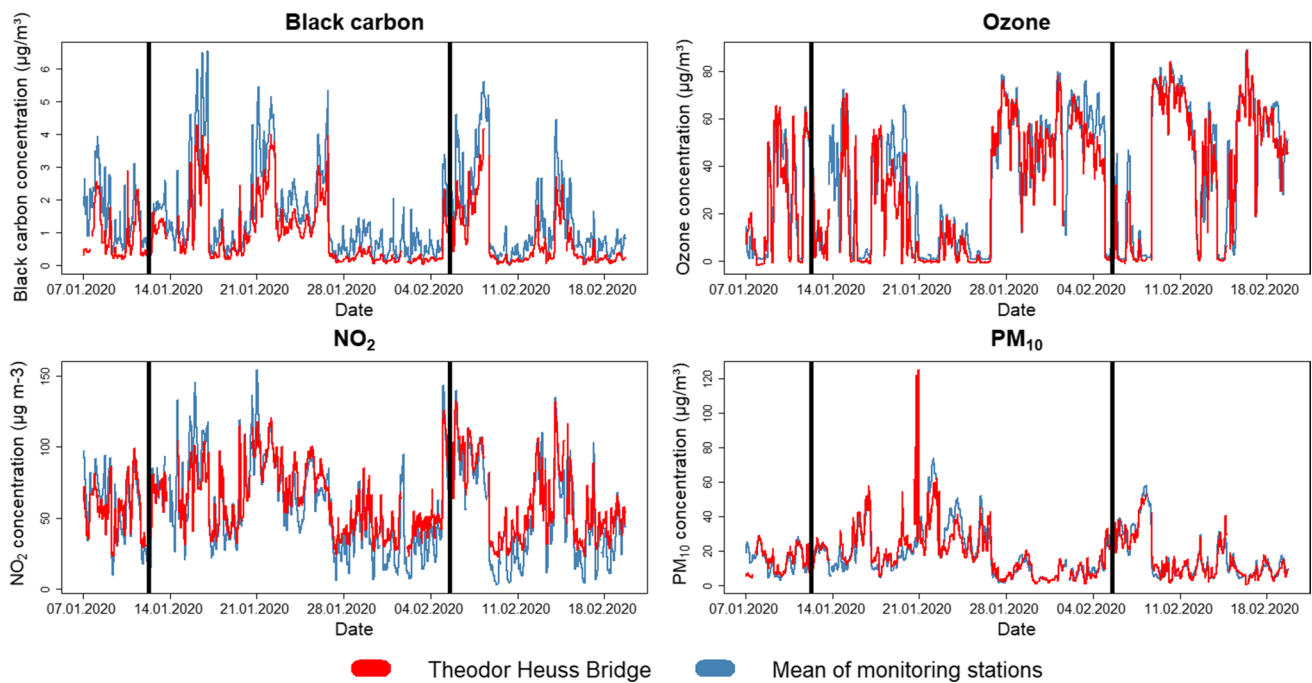


Fig. 2 1-h concentration time series (7 January–20 February 2020) of black carbon, ozone, NO_2 , and PM_{10} measured at the Theodor Heuss Bridge (red trace) and the air quality monitoring stations (blue traces)

in Mainz and Wiesbaden, Germany. The vertical black bars indicate the beginning and the end of the closure period

Table 1 Mean and 95% confidence interval (CI) of different pollutant concentrations at the Theodor Heuss Bridge before (7–12 January 2020 6 a.m.), during (12 January 6 a.m.–5 February 2020 12:30 p.m.) and after (5 February 12:30 p.m.–20 February 2020) its closure

Pollutant	Before closure Mean (95% CI)	During closure	After closure
Black carbon ($\mu\text{g m}^{-3}$)	0.90 (0.85; 0.94)	0.92 (0.90; 0.95)	0.71 (0.69; 0.74)
NO ($\mu\text{g m}^{-3}$)	10.6 (9.7; 11.4)	14.6 (13.9; 15.3)	11.5 (10.8; 12.2)
NO_2 ($\mu\text{g m}^{-3}$)	31.4 (30.9; 32.0)	32.7 (32.4; 33.0)	33.4 (32.9; 33.9)
NO_x ($\text{NO} + \text{NO}_2$) ($\mu\text{g m}^{-3}$)	42.0 (40.8; 43.2)	47.3 (46.4; 48.2)	44.9 (43.8; 46.0)
Ozone ($\mu\text{g m}^{-3}$)	21.8 (20.6; 23)	29.0 (28.4; 29.6)	40.4 (39.5; 41.3)
Particle number (particles cm^{-3})	7132 (6899; 7366)	6467 (6357; 6577)	8061 (7895; 8228)
PM_1 ($\mu\text{g m}^{-3}$)	9.5 (9.2; 9.8)	10.5 (10.3; 10.8)	7.6 (7.3; 7.9)
$\text{PM}_{2.5}$ ($\mu\text{g m}^{-3}$)	10.2 (9.8; 10.5)	11.8 (11.6; 12.1)	8.7 (8.4; 9)
PM_{10} ($\mu\text{g m}^{-3}$)	14.7 (14.3; 15.1)	19.1 (18.7; 19.5)	14.9 (14.6; 15.3)

mean concentrations compared to outside the closure was found for PM_1 (+31.0%; percentages not reported in tables), $\text{PM}_{2.5}$ (+30.9%), and NO (+29.3%). Exceptions from this general observation are mean concentrations of ozone (−19.6%, which is anticorrelated to NO levels in

urban environments since it is titrated by this pollutant), particle number (−17.9%), and NO_2 (−0.6%), which were lower during the closure, with ozone and NO_2 showing a general temporal increase from before to after the closure. In contrast to the mean concentrations, medians

(Table s7 in Supplementary material; percentages not reported in tables) of many pollutants were lower during the closure than for the short period before, e.g., for NO (−35.0%), black carbon (−18.2%), and PM₁ (−4.5%), but not for the coarser particle fractions PM_{2.5} (+3.9%), and PM₁₀ (+8.3%). However, during the longer period after the closure, the median concentrations were lower than during the closure, as for the mean values. Therefore, the median values of NO, NO_x, black carbon, PM₁, and ozone revealed a trend over time.

The closure-dependent pollution levels at the monitoring stations show similar developments as at the Theodor Heuss Bridge (Table s7 in Supplementary material). As at the bridge, for most pollutants, median concentrations were higher at the monitoring stations during the bridge closure when compared to the period afterwards (e.g., for black carbon from +7 to +50% depending on the station) but lower when compared to the period before (e.g., for black carbon −30% to −40%). In contrast to the Theodor Heuss Bridge, this time trend holds true for some mean concentrations too, i.e., of black carbon, NO₂, and at some stations for NO. For NO₂, the Theodor Heuss Bridge is the only measuring location with an increasing instead of a decreasing time trend. Neither for mean nor for median concentrations, systematic differences in pollution trends were detected between urban background and urban traffic stations.

It could not be determined that the Theodor Heuss Bridge was less polluted during the closure in relation to the monitoring network stations than outside. For none of the pollutants, a reduction of the difference between the bridge-related concentration, compared to that of the monitoring stations, was observed for the closure period, with respect to the periods before and after the closure (Table s1 in Supplementary material).

Meteorological influence on pollution levels

The polar graphs for pollutants measured at the Theodor Heuss Bridge (Fig. 3, left column; Fig. s8 in Supplementary material for all pollutants at all measuring stations) revealed that for some wind directions, the mean concentration at the bridge was lower during than outside the closure. This applies to black carbon, NO, NO_x, and the particulate matter fractions for wind directions from about west to east-northeast. The pattern is also confirmed for the inversely correlated ozone, as its mean values are higher during the closure with wind from these directions. Exceptions from this pattern are NO₂ and the particle number concentration, for which the pollution is lower for (almost) every wind direction during the closure. The polar graphs calculated correspondingly for the pollutants measured at the monitoring stations show remarkably similar patterns (Fig. 3). Extensions of the polar graphs to include the effect of wind

speed were in general consistent with the patterns described above, indicating no associations between the periods under study and wind speed (Fig. s5).

In the multiple regression models, the closure is associated with a decrease of pollution levels, which is statistically significant for black carbon (−4.7% [95%-CI −7.1–−2.1%]), the particle number (−30.4% [95%-CI −31.8–−29.0%]), NO (−22.2% [95%-CI −27.1–−17.0%]), NO₂ (−9.8% [95%-CI −10.8–−8.7%]), and NO_x (−10.2% [95%-CI −11.8–−8.5%]), but not for the particulate matter concentration fractions (Table 2).

Discussion

Comparisons of mean and median values of pollutant concentrations at the Theodor Heuss Bridge showed higher pollution levels at the bridge during its closure than outside for most pollutants. This counterintuitive result is assumed to be caused by meteorological as well as source-related influences, which overlay and overcompensate the effect of the closure. The high variability of concentrations revealed in the time series reflects the complex behavior of several pollutant-related factors such as the spatial and temporal inhomogeneity of emissions as well as factors affecting transport and dispersion of pollutants and background concentrations. The variation of these factors is a key challenge in assessing the true impact of an intervention, especially in a local and short-term study like the present one (Boogaard et al. 2017; van Erp et al. 2012) and in a relatively open setting, where emissions are not trapped in a street canyon and consequently their dispersion is strongly affected by meteorological conditions. Noticeably, concentrations of two pollutants deviated from the described patterns. Besides the expected divergence of the inversely correlated ozone, the particle number also tended to be lower during the closure. The particle number concentration is, on the one hand, very sensitive to on-road motorized traffic emissions and, on the other hand, depends very much on the distance to the emission sources, as it can decrease quite rapidly due to coagulation of particles (Weijers et al. 2004; Zhu et al. 2002). Thus, it might rather reflect the emissions in the immediate vicinity of the measurement location, which might be more strongly affected by the bridge closure than those in the further environment. However, no particle number concentration data were available from the monitoring stations, so it is not sure whether this decrease in particle number concentration was truly related to the bridge closure or whether it might rather be caused, e.g., by different meteorology or air mass history.

Studying control areas not affected by an intervention is recommended in accountability studies to detect background trends (Boogaard et al. 2017; van Erp et al. 2012). In the present study, the close agreement of the patterns of pollutant

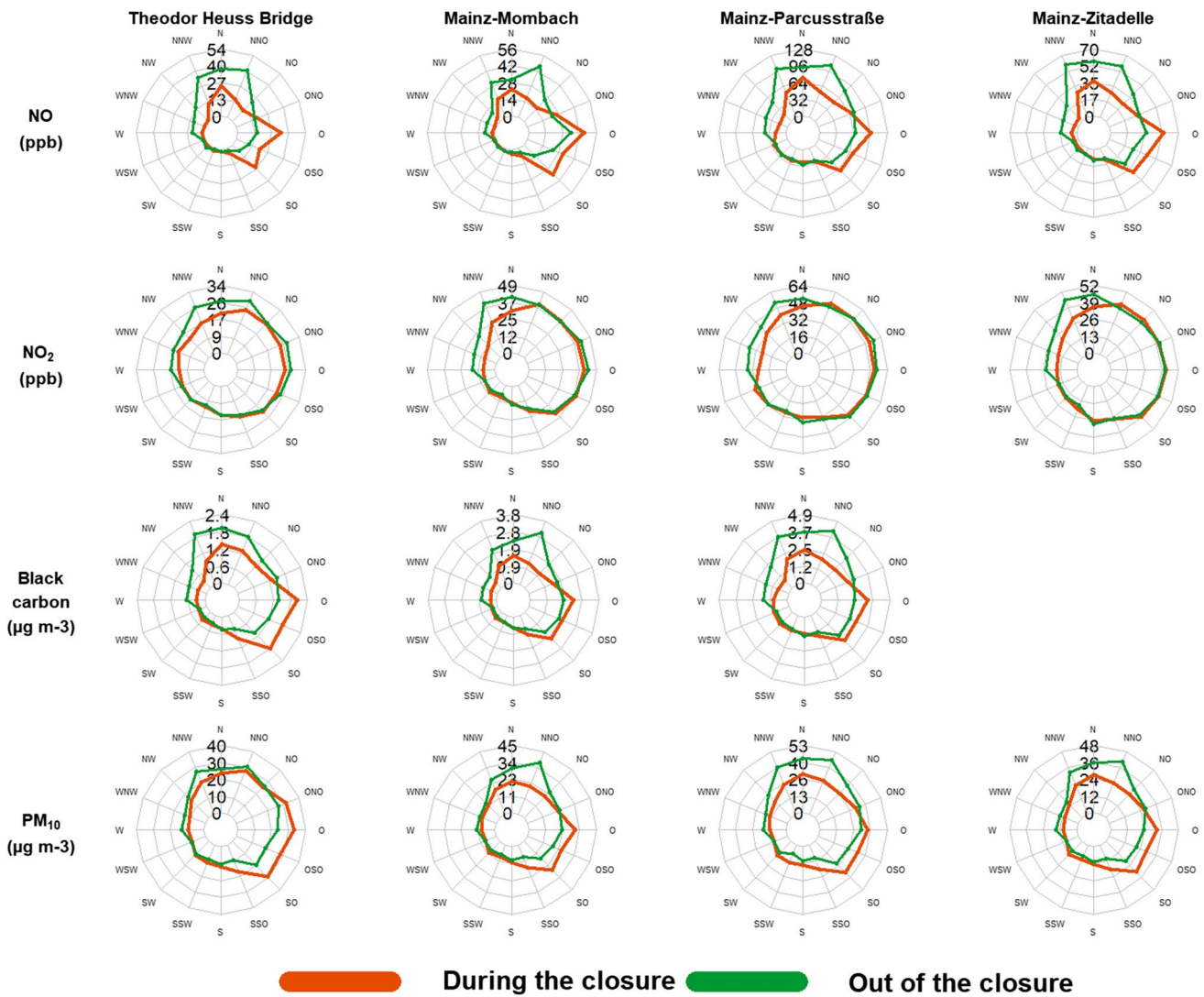


Fig. 3 Mean concentration of different pollutants separated by wind direction at the Theodor Heuss Bridge and the three monitoring stations Mainz-Mombach, Mainz-Parcusstraße, and Mainz-Zitadelle during (red traces) and out of (green traces) the closure period

concentrations at the Theodor Heuss Bridge with those of the surrounding monitoring stations suggests that the factors overlaying the effect of bridge closure are largely regional in nature. Yet, in addition to the similar temporal trends in pollutant concentrations, the separation of the closure-dependent pollution by wind direction showed a high degree of agreement with the monitoring stations, too. Therefore, the observation that pollution levels are lower in certain wind directions during the closure cannot be attributed to a local cause such as the bridge closure, even though these directions agree well with the direction where the bridge is located from the position of our measurements. A further indicator for regional influences on pollution concentrations are the CIN values, which were found to have a high degree of agreement with the observed variability in pollutant

concentrations for the Theodor Heuss Bridge measurement location and therefore (since time series were very similar, Fig. 2) also for the monitoring stations. This observation suggests a reasonable influence of the atmospheric stability on pollutant levels although this alone is not able to explain the temporal variability of pollutant levels. Furthermore, the pollutant load at the bridge in relation to the monitoring stations was not lower during than outside the closure, which is a further indicator against a dominating influence of the closure on local air quality at the Theodor Heuss Bridge.

The regression models confirm that lower average concentrations during the closure occur under certain meteorological conditions. However, as the comparison of the time series and mean and median values with the monitoring stations have shown, these lower concentrations are presumably

Table 2 Results of the regression models for the effect of the closure (12 January–5 February 2020) of the Theodor Heuss Bridge between Mainz and Wiesbaden on local pollutant concentrations: percentage variation and 95% confidence interval (CI) of the geometric mean concentrations during compared to out of the bridge closure. Results are related to all wind directions

Pollutant	Percentage variation (95% CI)
Black carbon	−4.7 (−7.1; −2.1)
NO	−22.2 (−27.1; −17.0)
NO ₂	−9.8 (−10.8; −8.7)
NO _x (NO + NO ₂)	−10.2 (−11.8; −8.5)
Particle number	−30.4 (−31.8; −29.0)
PM ₁	−1.2 (−3.7; +1.5)
PM _{2,5}	−1.6 (−4.0; +0.8)
PM ₁₀	−0.8 (−3.2; +1.6)

not related to the closure but to regional factors or local atmospheric stability, which could not be considered properly in the regression model.

Concluding, the results of the air pollution measurements for most pollutants contrast those of the previously mentioned studies (Hong 2015; Levy et al. 2006; Quiros et al. 2013; Scholz and Holst 2007; Shu et al. 2016; Whitlow et al. 2011), which detected a decrease in pollution concentrations associated with the intervention. One possible explanation for this observation might be that our study investigated a comparably short road section in contrast to the other studies and that the closed road section was within a completely open environment with a very different influence on local air quality compared to, for example, a street canyon situation, where close-by emissions might dominate the measured pollutant levels.

To evaluate the results of the study further, certain limitations must be considered. First, the relative shortness of the measurement period must be mentioned. The limited number of data points restricted some analyses, such as the additional consideration of wind speed or other potentially influencing variables like time of the day or day of the week, in addition to wind direction. Peel et al. (2010) pointed out the problem that in short interventions, changes in meteorological conditions can easily overwhelm any effect of an intervention. Furthermore, intervention and control periods are only comparable to a certain extent due to the different timings during the year and to relatively long meteorological episodes (1–2 weeks), which are of a similar order of magnitude to the length of the measurement periods. Previous

studies indicated a considerable impact of the choice of the control period on the results of the comparison (van Erp et al. 2012).

A further limitation is that some important factors influencing pollutant concentrations, such as atmospheric stratification or air mass origin, were not considered nor were the extent of pollutant concentrations from other sources, such as industry or household air pollution. Furthermore, the very few precipitation events during the measurement period prevented us to include ground level concentrations as a function of precipitation in the analyses. Emissions from ship traffic over the Rhine river and from construction work vehicles at the bridge might have also influenced measured pollutant concentrations. However, from the highly time-resolved data and from comparing pollution during maintenance work hours and hours outside the work time, we found that the contribution of none of both was significant. Overall, the impact of traffic on air pollution is highly variable and depends on a complex interplay of a large number of factors (Khreis 2020), which makes modeling difficult. For example, long-range transport of pollution is known to potentially affect local air quality up to a few thousand kilometers away (Bergin et al. 2005). In a recent systematic review, Burns et al. (2019) even pointed out the general difficulty of establishing a causal link between a single intervention and improvements in air quality (Gianicolo et al. 2020). One of the reasons given by the authors is that the interaction between an intervention and a potential improvement in air quality is highly complex. In addition, pollutants have a wide range of emission sources, of which individual interventions usually address only specific aspects at one time (e.g., only traffic-related emissions) (Burns et al. 2019) and only within a limited spatial area (Bell et al. 2011).

Furthermore, the surrounding monitoring stations did not measure all pollutants obtained at the Theodor Heuss Bridge. Therefore, a comparison with the particle number concentration, the only pollution variable indicating a decrease in pollution during the closure, was not possible. We also do not have information on how the closure changed traffic patterns in the immediate vicinity of the measurement station and the bridge.

The regression model for the pollutant concentrations is limited as it did not account for regional factors and thus presumably does not explain the effect of the closure but rather some regional developments that remain unidentified. Furthermore, the validity of the model is limited by the fact that the residuals show deviations from a normal distribution even after transforming the model and the transformations were also unable to remove autocorrelation of the values (Table s3 in Supplementary material). The latter might point to unaccounted variables with a temporal trend or seasonal variations and leads to loss of information (Fahrmeir et al. 2007). The use of quasi-experimental approaches as the

interrupted time series was not implemented in this study but will be considered in future investigations on this topic (Bernal et al. 2017; Gianicolo et al. 2021) In addition, the results for NO and ozone must be interpreted with caution, as for both pollutants, there are many missing values in the regression analysis (26% for NO and 14% for ozone), which are also unevenly distributed over the periods during and outside the closure.

Finally, we did not obtain any health outcomes but limited the analysis to the immission impacts of the intervention. However, as no immission improvements occurred, health benefits are even less to be expected. The general issue, whether pollution data collected by monitor stations are suitable for estimate exposures, is behind the aim of our work (Dominici 2004).

A strength in contrast to similar studies is the extensive data material. High temporal resolution data on many different on-road motorized traffic-related pollutants and meteorological parameters were collected, which enabled us to detect opposing trends associated with the closure for different pollutants. In addition, while no measurements from a neighboring bridge with similar conditions were available, we used data from five air quality monitoring stations in the vicinity which served as a spatial control unaffected by the intervention. Moreover, the measurement period of several weeks, although listed above as a limitation, was longer than in several comparable studies on the influence of temporary road closures on local air quality (e.g., Hong 2015; Levy et al. 2006; Quiros et al. 2013; Scholz and Holst 2007; Shu et al. 2016; Whitlow et al. 2011).

Conclusion

Concentrations of most pollutants counterintuitively showed higher local pollutant levels during the three-and-a-half-week closure of the Theodor Heuss Bridge than that outside this period. The high variability of concentrations indicates a complex interaction of different pollutant-related parameters like meteorological influences that probably overlay an effect of the closure. As the pollutant concentration patterns at the Theodor Heuss Bridge showed strong similarities to the data from the surrounding monitoring stations, these overlying factors are assumed to be mainly of regional nature, e.g., the stability of the atmosphere. Only the very locally influenced particle number concentration was reduced at the bridge during the closure, for which no comparison could be made with the monitoring stations due to missing data.

The observations indicate that large-scale influences dominate the local pollution at the Theodor Heuss Bridge and that the impact of the closure is negligible in comparison even at a very local level. The results contradict those of previous accountability studies, which might be explained in

part by the comparably short road section in our study and the open environment of the bridge. Also, the fact that another main road was in the immediate vicinity of the measurement location might have contributed, i.e., the fact that on-road motorized traffic on the Theodor Heuss Bridge might only contribute a rather low fraction of overall traffic emissions in the vicinity, and its reduction therefore has a smaller effect on overall air quality than anticipated. Future interventions will presumably need to be applied more broadly and over larger areas than a closure of a single road section to bring about an improvement in air quality in the urban environment and with this potentially public health benefits.

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Author contribution EG and FD conceived work. JP performed the field measurements and together with FF supported the data analysis and commented on the manuscript. BBr performed general data analysis and descriptive and regression analysis and drafted the paper. EG, FD, PK, and BBü supported the first author by revising different releases of the manuscript and by writing single parts of it. All authors read and approved the final manuscript.

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Data availability The datasets used during the current study are available from the corresponding author on request.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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