**Low Emission Zones reduced PM10 but not NO2 concentrations in Berlin and Munich, Germany**

Jianwei Gu a,b,c \*, Veronika Deffner d, Helmut Küchenhoff d, Regina Pickford b, Susanne Breitner b, Alexandra Schneider b, Michal Kowalski b,c, Annette Peters b, Martin Lutz e, Andreas Kerschbaumer e, Rémy Slama f, Xavier Morelli f, Heinz-Erich Wichmann b, Josef Cyrys b \*

a Institute of Environmental Health and Pollution Control, School of Environmental Science and Engineering, Guangdong University of Technology, 510006 Guangzhou, China

b Institute of Epidemiology, Helmholtz Zentrum München, Ingolstädter Landstr. 1, 85764 Neuherberg, Germany

c Environment Science Center, University of Augsburg, Universitätsstr. 1a, 86159 Augsburg, Germany

d Statistical Consulting Unit StaBLab, Department of Statistics, Ludwig-Maximilians-Universität Munich, Akademiestr. 1, 80799 Munich, Germany

e Senate Department for the Environment, Transport and Climate Protection, Referat Immissionsschutz, Brückenstraße 6, 10179 Berlin, Germany

f Inserm, CNRS, University Grenoble-Alpes, Institute of Advanced Biosciences (IAB) Joint Research Center, Team of Environmental Epidemiology, Grenoble (La Tronche), France

\* Corresponding authors:

Email: [gujianwei@gdut.edu.cn](mailto:gujianwei@gdut.edu.cn)

Email: [cyrys@helmholtz-muenchen.de](mailto:cyrys@helmholtz-muenchen.de)

**Abstract**

Low emission zones (LEZs) aiming at improving the air quality in urban areas have been implemented in many European cities. However, studies are limited in evaluating the effects of LEZ, and most of which used simple methods. In this study, we utilized a general additive mixed model to account for confounders in the atmosphere and validated the effects of LEZ on PM10 and NO2 concentrations in two German cities. In addition, the effects of LEZ on elemental carbon (EC) and total carbon (TC) in Berlin were also evaluated. The LEZ effects were estimated after taking into account air pollutant concentrations at a reference site located in the regional background, and corrected for hour of the week, public holidays, season, and wind direction. The LEZ in Berlin, and the LEZ in combination with the heavy-duty vehicle (HDV) transit ban in Munich significantly reduced the PM10 concentrations, at both traffic sites (TS) and urban background sites (UB). The effects were greater in LEZ stage 3 than in LEZ stages 2 and/or 1. Moreover, compared with PM10, LEZ was more efficient in reducing EC, a component that is considered more toxic than PM10 mass. In contrast, the LEZ had no consistent effects on NO2 levels: no changes were observed in Berlin; in Munich, the combination of the LEZ and the HDV transit ban showed a reduction in NO2 at UB site in LEZ stage 1, but without further reductions in subsequent stages of the LEZ. Overall, our study indicated that LEZs, which target the major primary air pollution source in the central and highly populated parts of the city could be an effective way to improve key components of urban air quality such as PM mass concentration and EC level.

**Keywords**

low emission zone; air quality; PM10; NO2; vehicular emission; general additive mixed model

**1 Introduction**

In many parts of the world, air pollution is a major public health risk (Beelen et al., 2014). Major pollutants including particulate matter (PM) and nitrogen dioxide (NO2) cause adverse health effects (Anenberg et al., 2018; Beelen et al., 2014; Brook et al., 2010; Hoek et al., 2013; Rückerl et al., 2011). In order to protect human health, the European Union (EU) established limit values for several pollutants, including PM10, PM2.5 (particulate matter with aerodynamic diameter smaller than 10 µm and 2.5 µm, respectively) and NO2 (Council of the European Union, 2008). From 2010 on, Member States were obliged to implement measures to reduce regulated pollutants when they exceeded the limit values. Despite the continuous improvement of air quality, the European limit values for PM10, PM2.5 and NO2 are still exceeded in many European countries (European Environment Agency, 2018). Moreover, for PM, no threshold level exists, below which no adverse health effects would occur (WHO, 2006, 2013a). Results from a large multicenter European Study, the European Study of Cohorts for Air Pollution Effects (ESCAPE) also showed significant positive associations between PM and adverse health effects even at levels far below the current EU limit values (Beelen et al., 2014; Raaschou-Nielsen et al., 2013). The scientific community also argued that the current European limit values for PM2.5 and PM10 are too high and provide no incentive for the implementation of those national and local strategies needed to achieve more ambitious goals. It has been advocated that the European Commission should adopt the lower WHO Air Quality Guideline values as limit values for PM in the near future (Brunekreef et al., 2015).

To improve the air quality, air quality action plans such as promotion of public transportation usage, ring road utilization, traffic flow improvements, speed limit reduction, and the implementation of low emission zones (LEZ) were established. LEZs are areas where access to road vehicles is restricted, usually on the basis of their emission class. In Europe, there are more than 200 LEZs in operation (Holman et al., 2015; Silva et al., 2014). As in urban areas, traffic is one important source of PM and the major source for NO2 (Belis et al., 2013; Degraeuwe et al., 2017; Viana et al., 2008), the implementation of LEZ could be an effective measure to reduce traffic related pollution and to improve urban air quality (Sadler, 2011).

LEZ regulations vary between different cities in size, types of vehicles regulated and the ways of control and enforcement. In Germany, LEZs are operated in three different stages, LEZ 1, LEZ 2, and LEZ 3. The individual municipality decides on the implementation of a LEZ, on its area and the stage of the LEZ. In general, LEZ 3 has the most stringent requirements allowing gasoline vehicles with Euro 1 emission standard or Diesel vehicles with Euro 4, Euro 3 with diesel particle filters (DFP) or higher emission standards to enter. Detailed description of German LEZs is provided in the supplementary material part S1.

The effects of LEZs have been evaluated in the decision-making stage by emission models or in combination with dispersion models (Emplan, 2010; LfU, 2010; Watkiss et al., 2003). Some studies have been carried out to assess the effects after LEZ implementation using monitoring data (Boogaard et al., 2012; Cesaroni et al., 2012; Cyrys et al., 2014; Ellison et al., 2013; Fensterer et al., 2014; Jiang et al., 2017; Löschau et al., 2015; Malina and Scheffler, 2015; Morfeld et al., 2014a; Panteliadis et al., 2014; Santos et al., 2019; Tartakovsky et al., 2020). Overall, there is some evidence from Germany that LEZs reduced PM10 by a few percent, but in other countries the evidence is much less clear, as Holman et al. (2015) summarized in their review. This is partly due to the fact that particulate matter emitted from traffic exhaust accounts for a small fraction of ambient PM10 levels (Belis et al., 2013; Querol et al., 2004; Thorpe and Harrison, 2008). Indeed, EC is considered as a better indicator of diesel vehicle emission and more toxic than the regional background PM10 fraction (Janssen et al., 2011), and may be more suitable for evaluating the effects of LEZ on reducing traffic related emissions. Besides, LEZs showed weaker effects on NO2 than on PM10 (Jiang et al., 2017; Löschau et al., 2016), as NO2 emission under real driving conditions has not significantly been improved from Euro 4 to Euro 6 (Anenberg et al., 2017; Franco et al., 2014).

Many of the above-mentioned studies evaluated the effect of a LEZ by comparing air pollutant concentrations before and after LEZ implementation or between cities with and without LEZs. However, a simple comparison of concentrations neglects several factors other than LEZs that affect the concentrations of air pollutants. These factors include meteorology, variations in the strength of emissions, long-range transport of aerosols and temporal factors such as season, public holidays, day of the week and rush hour times. Therefore, it is advisable to account for the confounding environmental conditions using the air pollutant concentrations at a reference site (Boogaard et al., 2012; Holman et al., 2015). Additionally, long-term measurements should also be used (Cyrys et al., 2014). In order to properly address these confounders, a general additive regression model was developed for validating the effects of LEZ on PM10 levels in Munich, Germany (Fensterer et al., 2014).

In the present study, we applied the sophisticated model in validating the effects of all stages of LEZs on PM10 and NO2 in Berlin and Munich, respectively, and at both traffic sites and urban background sites. In addition, the long-term monitoring of elemental carbon (EC) and total carbon (TC) in Berlin provides a unique opportunity to evaluate the effectiveness of the LEZ on EC and TC concentrations in urban air. Overall, the aim of this study is to evaluate the effects of LEZs in reducing PM10, NO2, and EC and TC concentrations in urban air.

**2 Methods**

**2.1 Study area and period**

We focused our analysis on the two German cities of Berlin and Munich. The LEZs in both cities are located in and around the city center, as depicted in Figure 1. Table 1 provides more information about the two LEZs. The LEZ in Munich has an area of 44 km2, equivalent of 14% of the urban area. In Berlin, the largest city of Germany, the LEZ covers an area of 88 km2, i.e. 10% of the urban area. The time of implementation of the LEZ stages were different in the two cities: in Berlin, stage 1 was introduced on 1 January 2008 and stage 3 on 1 January 2010 (note that in Berlin no stage 2 LEZ was implemented); in Munich, stage 1 was introduced on 1 October 2008, stage 2 on 1 October 2010 and stage 3 on 1 October 2012. In addition to the LEZ, a HDV transit ban came into force in Munich on 1 February 2008 (eight months before the implementation of the LEZ): HDVs are not allowed to enter the city area if their final destination is not Munich.

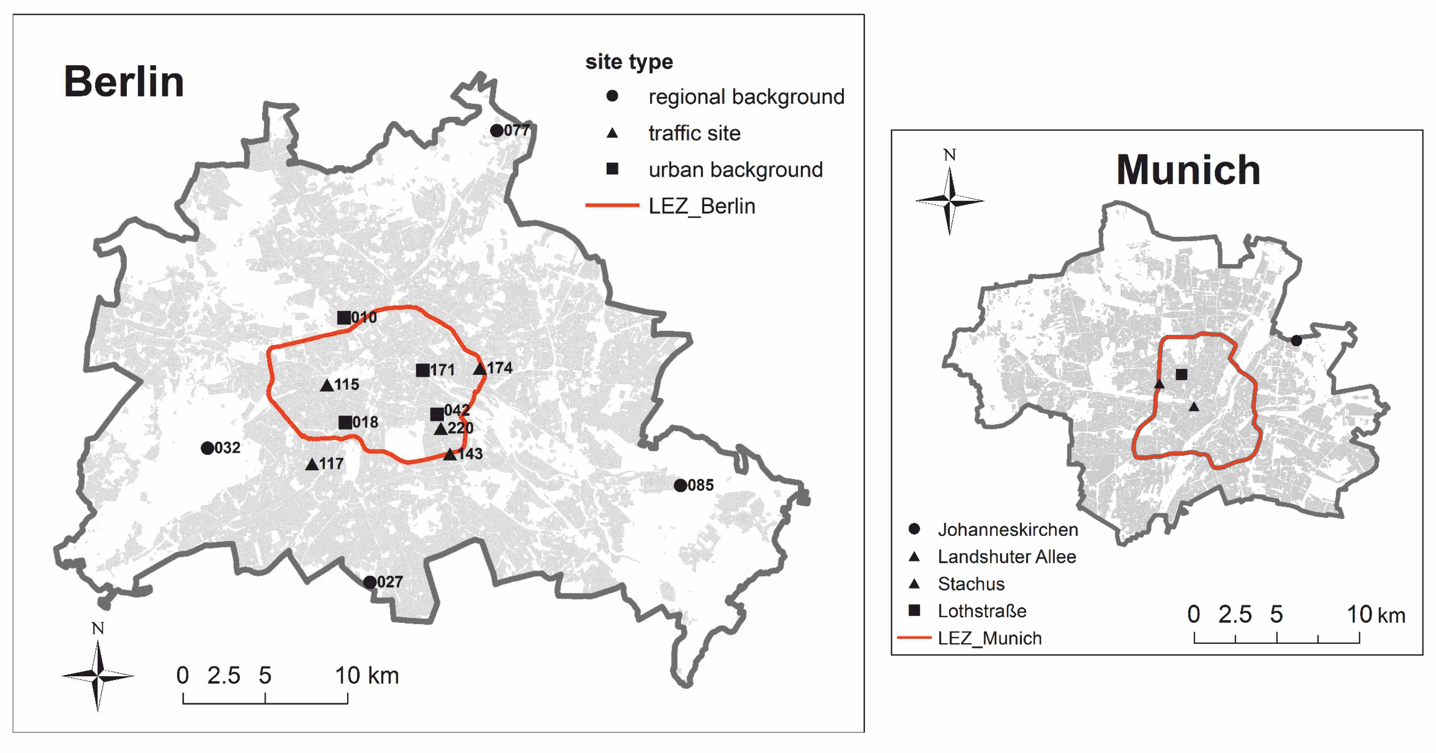


Figure 1. LEZ area and monitoring sites in Berlin and Munich. The regional background sites are represented by rounds, urban background sites by squares, and traffic sites by triangles. Detailed information on the measurement sites in Berlin are provided in Table S1.

Table 1 gives the time periods of LEZ 1, LEZ 2 and LEZ 3 for the analysis in the two cities. In addition, a period before the LEZ implementation was defined as reference period (LEZ 0): 1 January 2004 - 31 December 2006 for Berlin and 1 January 2005 - 30 September 2007 for Munich. We did not include the data within one year before the LEZ became effective into the analysis. Rather, we left a buffer of one year between the reference period and the LEZ stage 1 (LEZ 1). This is because the composition of the vehicle fleets in Munich and Berlin started to change rapidly within one year before the LEZ became officially effective. Thus, the introduction of the LEZ may affect the vehicle fleet immediately after the announcement of their implementation, and before the official LEZ launch date (Lutz, 2012).

Table 1. Information of low emission zones in Berlin and Munich.

|  |  |  |
| --- | --- | --- |
|  | Berlin | Munich |
| LEZ Area (% of urban area)  (% of urban area) | ~ 88 km2 (10%) | ~ 44 km2 (14%) |
| Population within LEZ (%) | ~ 1.000.000 (29%) | ~ 420.000 (32%) |
| HDV transit ban (start) a | No ban | 1 Feb. 2008 |
| Reference period (LEZ 0) | 1 Jan. 2004 – 31 Dec. 2006 | 1 Jan. 2005 – 30 Sep. 2007 |
| Buffer b | 1 Jan. 2007 – 31 Dec. 2007 | 1 Oct. 2007 – 30 Sep. 2008 |
| LEZ 1 | 1 Jan. 2008 – 31 Dec. 2009 | 1 Oct. 2008 – 30 Sep. 2010 |
| LEZ 2 | – | 1 Oct. 2010 – 30 Sep. 2012 |
| LEZ 3 | 1 Jan. 2010 - 31 Dec. 2012 | 1 Oct. 2012 – 30 Sep. 2014 |

a HDV transit ban in Munich forbade trucks whose final destination is not the city from entering the city area;

b Buffer is a one-year period before the implementation of LEZ.

**2.2 Air pollution measurement data**

Figure 1 shows the locations of monitoring sites used in the analysis. Hourly PM10 and NO2 data were collected from the official monitoring network. The measurement stations in Munich are operated by the Bavarian Environmental Agency (Bayerisches Landesamt für Umwelt, LfU), whereas the measurement stations in Berlin are operated by the Senate Department for the Environment, Transport and Climate Protection (Senatsverwaltung für Umwelt, Verkehr und Klimaschutz Berlin, SenUVK). We included as many monitoring sites as possible and grouped them in three categories: traffic sites (TS), urban background sites (UB), and regional background sites (RB) (Table S1 in the Supplementary Material).

**Berlin**

Hourly PM10 and NO2 data were obtained from 13 official monitoring stations in Berlin: four RB stations, four urban background stations, and five traffic stations. Berlin is one of the few European cities where TC and EC concentrations were measured biweekly at major roads since the 1990s (Clemen and Kaupp, 2018). TC and EC data are available at four traffic sites and one urban background site. TC and EC were determined according to the method VDI (Verein Deutscher Ingenieure, The Association of German Engineers) 2465 part 2 (VDI 2465, 2016). Filter subsamples were first heated up to 650 °C in helium atmosphere, when the organic compounds were considered evaporated, and later oxidized to carbon dioxide (CO2) which was determined by Nondispersive infrared (NDIR) sensor. In the second step, the filters were heated up to 700 °C with the presence of oxygen (O2), the remaining soot were converted to CO2 and analyzed by NDIR. TC was defined as the sum of organic matter (OM, OM= OC×1.2) and EC.

**Munich**

Hourly PM10 and NO2 data were used, specifically, from four LfU monitoring sites in Munich including one UB site (Lothstraße), one traffic site on the border of LEZ (Landshuter Allee), one traffic site in the city center (Stachus), and one regional background site in the outskirts of the city and outside the LEZ (Johanneskirchen (JOH)) (Regierung von Oberbayern, 2007). Meteorological parameters were obtained from a meteorological station from German Weather Service (Deutscher Wetterdienst, DWD) in Oberschleißheim located northwest of Munich.

**2.3 Statistical models**

**2.3.1 Models for hourly PM10 and NO2 data (Model 1)**

Due to the diverse characteristics of the two LEZs we decided to study each LEZ separately, rather than to combine them like e.g. Malina and Scheffler (2015) and Morfeld et al. (2014b). Separate general additive regression models were applied for the hourly PM10 and NO2:

*log*(*Pi*) = *β*0 + *β*1*log*(*Pref*) + *βLEZ1 ILEZ1* + *βLEZ2 ILEZ2*  + *βLEZ3 ILEZ3*  + *fLEZ0(hour) ILEZ0* + *fLEZ1(hour) ILEZ1* + *fLEZ2(hour) ILEZ2* + *fLEZ3(hour) ILEZ3* + *fwd* (*wind direction*) + *β2\_public holiday + β3\_season* + *βSiISi + ϵ* (1)

where *Pi* represents the concentrations of PM10 or NO2 at the station of interest*.* Since the data of several stations were analyzed in a single model, an indicator function *ISi* for the station *i* was included in the model. *Pref* denotes the concentrations of PM10 or NO2 at the reference station, i.e., the regional background station. If several reference stations were available, averaged values were used. *ILEZj* is theindicator function for the stages of the low emission zone (*j* = 0, 1, 2, 3); *hour* is the hour of the week; *wind direction* is a variable covering 0 to 360 degrees. *public holiday* is a dummy variable indicating the German public holidays; and *season* denotes a dummy variable indicating whether the season is summer (April – September) or winter (October – March). Confounders include hour of the week, wind direction, public holidays and season. *ϵ* denotes the model error.

A sensitivity analysis was conducted using a slightly modified model (Model S1). Model S1 used averaged PM10 or NO2 concentrations of the same types of monitoring stations (e.g., averaged hourly PM10 concentration from all traffic sites in Berlin). Details of the model S1 are provided in part S3 of the Supplementary Material.

The models were implemented in R, version 3.5.1 with the package “mgcv” (<https://cran.r-project.org/web/packages/mgcv/mgcv.pdf>).

**2.3.2 Model for biweekly TC and EC data (Model 2)**

TC and EC concentrations in Berlin from four traffic sites (Nr. 117, 143, 220, 174, see Figure 1) were included in the analysis, and an urban background site 042 (see Figure 1) was used as reference site. In order to compare the results of the TC and EC levels with the results of the PM10, biweekly PM10 concentrations based on the hourly data were calculated. Because of the biweekly temporal resolution, confounders such as hour of the week and national holidays were no longer relevant for in Model 2 (in comparison to Model 1). The remaining influencing factors were the reference site concentration, LEZ stage, wind direction, season, and station:

*log*(*Pi*) = *β*0 + *β*1*log*(*Pref*) + *βLEZ1 ILEZ1* + *βLEZ2 ILEZ2*  + *βLEZ3 ILEZ3*  + *fwd* (*wind direction*) + *β*3\_*season* + *βSiISi + ϵ*

(2)

where *Pi* represents the concentration measurements of TC, EC or PM10 at the stations of interest*.* Model 2 was applied to biweekly TC, EC and PM10 concentrations in Berlin, respectively.

The goodness of fit of the models to the data is assessed by the adjusted coefficient of determination. The results can be found in part S5 of the Supplemental Material.

**2.4 Distinguish the LEZ effects from the natural vehicle renewal**

The model analysis based on air quality data alone that can barely disentangle the default fleet renewal from the additional pure LEZ impact. In order to separate the own impact from LEZ, we utilized the changes in vehicle emissions of exhaust particles and NOx in Berlin without LEZ and with LEZ, respectively (Lutz 2013). Briefly, the real fleet evolution in 2007 before the LEZ, as well as from 2008 till 2012, was obtained by recording the vehicle number plates at a couple of representative spots and retrieving the Euro standard of the vehicles from the registration database. The trend scenario assuming the normal fleet turnover without LEZ was estimated using the Handbook Emission Factors for Road Transport (HBEFa, <https://www.hbefa.net/e/index.html>), which is the main tool or database for emission and traffic-related pollution modelling used in Germany and many other EU member states.

Based on the fleet data, the vehicle emissions for NOx and PM for the real-world LEZ case and without LEZ scenario were obtained. When comparing the emissions of the year 2008, 2010 and 2012 with the reference year 2007, the reductions in the exhaust particle and NOx emissions were calculated. For detailed description, refer to Lutz (2013).

Table 2 shows the percentages of the contributions of LEZ, which were used to correct the GAM model results. Because the estimation has its own limitations and uncertainties, we present the corrected net LEZ effects as an addition to the main GAM model results.

Table 2. Reductions in exhaust particle emissions and NOx (tons/year) in Berlin from traffic by natural fleet renewal and by combined effects of natural fleet renewal and LEZ.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Year (LEZ stage) | Reduction by natural vehicle renewal | Real-world reduction with LEZ | percentage of LEZ |
| Particle | 2010 (LEZ 1) | 76 | 247 | 69% |
|  | 2012 (LEZ 3) | 123 | 281 | 56% |
| NOx | 2010 (LEZ 1) | 1103 | 2620 | 58% |
|  | 2012 (LEZ 3) | 1736 | 3055 | 43% |

**3 Results**

**3.1 PM10**

**3.1.1 Average PM10 levels before and after LEZ implementation**

Figure 2 shows the time series of PM10 yearly mean concentrations in two cities from 2004 to 2014. PM10 was highest at traffic sites, followed by UB and regional background sites. The differences between traffic and background sites (RB and UB) were larger in Munich than in Berlin. There is an overall decreasing trend of PM10 concentrations in Berlin (2004-2012) and Munich (2005-2014), although inter-annual variations exist.

A close up of a map

Description automatically generated

Figure 2. Yearly mean PM10 concentrations in Berlin and Munich. RB: regional background sites; UB: urban background sites; TS: traffic sites.

Table 3 shows the PM10 concentrations before and during the operation of LEZs (LEZ0, LEZ 1, LEZ 2 and LEZ 3) at all three types of measurement sites in Berlin and Munich. The ratios and differences were calculated against RB concentrations, and used as indicators of absolute and relative deviations in PM10 between TS and RB, as well as UB and RB.

In Berlin, PM10 concentrations decreased (statistically significantly using Mann-Whitney U test) from LEZ 0 to LEZ 1 for all three types of monitoring sites. but barely from LEZ 1 to LEZ 3. The ratios and differences of PM10 were very close between LEZ 0 and LEZ 3 at UB, but decreased at TS. In Munich, PM10 significantly decreased consistently from LEZ 0 to LEZ 3. At TS, the ratios of PM10 to the RB concentrations were very similar for LEZ 0, 1, 2 and 3; by contrast, the differences between TS and RB decreased from LEZ 0 to LEZ 3. At UB sites of Munich, the ratios and differences of PM10 to RB decreased from LEZ 0 to LEZ 2, and increased from LEZ 2 to LEZ 3.

Table 3. Mean and median hourly PM10 concentrations (µg/m3) before LEZ (reference period, LEZ 0) and during different LEZ stages in Berlin and Munich.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| City | Site type a | Variable | LEZ 0 | LEZ 1 | LEZ 2 | LEZ 3 |
| Berlin | RB | mean±std b | 24.4±18.0 | 20.7±12.4 |  | 21.0±16.6 |
|  |  | median | 19.9 | 17.9 |  | 16.3 |
|  | UB | mean±std | 28.8±22.3 | 24.6±16.0 | skipped | 24.9±19.8 |
|  |  | median | 23.6 | 21.6 |  | 19.8 |
|  |  | ratio c | 1.18 | 1.19 |  | 1.19 |
|  |  | diff d | 4.4 | 4.0 |  | 4.0 |
|  | TS | mean±std | 36.5±32.0 | 29.8±31.6 |  | 29.0±22.5 |
|  |  | median | 31.2 | 26.5 |  | 23.9 |
|  |  | ratio | 1.50 | 1.44 |  | 1.38 |
|  |  | diff | 12.2 | 9.2 |  | 8.0 |
| Munich | RB | mean±std | 22.9±19.6 | 22.0±21.8 | 19.5±15.0 | 16.4±14.9 |
|  |  | median | 18.0 | 17.5 | 15.5 | 13.0 |
|  | UB | mean±std | 26±22.2 | 24.5±23.2 | 20.7±14.4 | 18.6±15.5 |
|  |  | median | 21.0 | 19.5 | 17.0 | 15.0 |
|  |  | ratio | 1.14 | 1.11 | 1.07 | 1.14 |
|  |  | diff | 3.1 | 2.4 | 1.3 | 2.2 |
|  | TS | mean±std | 36.7±26.0 | 35.2±25.1 | 31.5±20.4 | 26.7±21.0 |
|  |  | median | 32.0 | 30.5 | 27.0 | 22.8 |
|  |  | ratio | 1.61 | 1.6 | 1.62 | 1.63 |
|  |  | diff | 13.9 | 13.2 | 12.0 | 10.3 |



a RB: regional background site; UB: urban background site; TS: traffic sites.

b std: standard deviation.

c, d The ratios and differences of the mean PM10 between UB or TS sites and the RB sites, respectively.

**3.1.2 Effects of LEZ - Hourly PM10 (Model 1)**

Figure 3 shows the effects of LEZ (LEZ with HDV transit ban in Munich) on PM10 at traffic and UB sites in Berlin and Munich. Detailed results are presented in Table 4. It should be noted that RB is not shown since it is used as reference for the adjustment of UB and TS.

A close up of a map

Description automatically generated

Figure 3. Changes of PM10 concentrations in Berlin and Munich in LEZ stage 1 to 3 compared with the period before the introduction of LEZ. The results for TS and UB were obtained from Model 1, and RB is used as reference.

Table 4. Changes of PM10 concentrations in Berlin and Munich in LEZ stage 1 to 3 compared with period before the introduction of LEZ. The results for TS and UB were obtained from Model 1, and RB is used as reference.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| City | Site type a | | Effect | 95% CI | | p-value | | Net LEZ effect b |
| Berlin |  | LEZ 1 | | | | | | | |
| UB | | -2.1% | (-3.0%, -1.3%) | | < 0.001 | | -1.5% |
| TS | | -11.5% | (-12.5%, -10.5%) | | < 0.001 | | -7.9% |
|  | LEZ 3 | | | | | | | |
| UB | | -5.5% | (-6.3%, -4.7%) | | < 0.001 | | -3.1% |
| TS | | -16.8% | (-17.6%, -15.9%) | | < 0.001 | | -9.4% |
| Munich |  | LEZ 1 + HDV transit ban | | | | | | | |
| UB | | -4.4% | (-6.8%, -2.0%) | < 0.001 | | -3.0% | | |
| TS | | -6.0% | (-8.0%, -4.0%) | < 0.001 | | -4.1% | | |
|  | LEZ 2 + HDV transit ban | | | | | | | |
| UB | | -7.5% | (-9.8%, -5.2%) | < 0.001 | | NA | | |
| TS | | -11.3% | (-13.2%, -9.4%) | < 0.001 | | NA | | |
|  | LEZ 3 + HDV transit ban | | | | | | | |
| UB | | -14.7% | (-16.8%, -12.6%) | < 0.001 | | -8.2% | | |
| TS | | -23.7% | (-25.3%, -22.1%) | < 0.001 | | -13.3% | | |

a UB: urban background sites; TS: traffic sites.

b corrected using the percentages in Table 2. Effects for LEZ 2 cannot be corrected.

In Berlin, significant reductions of PM10 concentrations by 2.1% (UB) and 11.5% (TS) were observed during LEZ 1, and by 5.5% (UB) and 16.8% (TS) during LEZ 3, compared to LEZ 0. The reductions were greater at TS than at UB. In Munich, significant and gradually stronger decreases of PM10 concentrations were observed in parallel to the introduction of LEZ 1, LEZ 2 and finally LEZ 3: in comparison to LEZ 0, the PM10 concentrations were reduced by 4.4% (UB) and 6.0% (TS) during LEZ 1, by 7.5% (UB) and 11.3% (TS) during LEZ 2, and by 14.7% (UB) and 23.7% (TS) during LEZ 3. In LEZ 1, there were very small differences in the reduction effects between UB and TS. In LEZ 2 the difference became larger, while in LEZ 3, a very pronounced difference was observed between UB and TS. Table 4 also shows the net LEZ effects on PM10 corrected using the percentages from Table 2, which were 69% and 56% of the GAM model results for LEZ stage 1 and 3, respectively. The highest net LEZ effects for PM10 in Berlin (9.4%) and Munich (13.3%) were at traffic sites at LEZ stage 3.

The effects by seasons are shown in part S4 of the Supplementary Material.

**3.1.3 Effects of LEZ - biweekly PM10, TC and EC in Berlin (Model 2)**

In addition to PM10, we also evaluated the effects of the LEZ on TC and EC in Berlin. Figure 4 shows the effects of LEZ on biweekly PM10, TC and EC concentrations in Berlin using Model 2. Note that in Model 2 the reference site is Nansenstraße, an UB site within the Berlin LEZ. All effects shown in the figure are statistically significant. All three air pollutants showed reductions of around 10% (PM10: 11.1%, TC: 9.7%, EC: 9.1%) in LEZ stage 1. Reductions of TC and EC concentrations were much larger in LEZ stage 3 compared to PM10 (PM10: 9.7%, TC: 17.3%, EC: 24.9%).

When correcting the model 2 results with the percentages of net LEZ effects, the net effects of LEZ stage 1 become 7.7% (PM10), 6.7% (TC) and 6.3% (EC), and the net effects of LEZ stage 3 become 6.7% (PM10), 11.9% (TC) and 17.2% (EC).



Figure 4. Changes of biweekly PM10, TC and EC at traffic sites in Berlin in LEZ stage 1 and 3 compared with the period before the introduction of LEZ. Error bars indicate the 95% confidence interval. The results for traffic sites were obtained from Model 2, and urban background site is used as reference.

**3.2 NO2**

It should be noted that LEZs were implemented to regulate PM10 and other PM components, but not to regulate NO2. Nevertheless, it might be of interest to observe the indirect effects on NO2.

**3.2.1 Average NO2 levels before and after LEZ implementation**

Figure 5 shows the time series of NO2 yearly mean concentrations in two cities from 2004 to 2014. There was a clear gradient in NO2 levels between TS, UB and RB sites (much more pronounced than PM10). In Berlin, the NO2 concentrations were generally stable from 2004 to 2012; however, in Munich, NO2 showed a decreasing trend from 2005 to 2012, and stabilized from 2012-2014.

A close up of a map

Description automatically generated

Figure 5. Yearly mean NO2 concentrations in Berlin and Munich. RB: regional background sites; UB: urban background sites; TS: traffic sites.

Table 5 shows the NO2 concentrations before and during the operation of LEZs (LEZ 0, LEZ 1, LEZ 2 and LEZ 3) at all three types of measurement sites in Berlin and Munich. The ratios and differences were calculated against regional background concentrations, used as an indicator of absolute and relative deviation in NO2 between traffic or urban background site and regional background site. The ratios and differences of NO2 (TS vs. RB, UB vs. RB) in Berlin did not change with the different stages of LEZ (LEZ 1, LEZ 3) compared to LEZ 0. In Munich, an increasing trend in NO2 ratios between TS and RB was observed.

Table 5. Mean and median hourly NO2 concentrations (µg/m3) before LEZ (reference period, LEZ 0) and during different LEZ stages in Berlin and Munich.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| City | Site type a | Variable | LEZ 0 | LEZ 1 | LEZ 2 | LEZ 3 |
| Berlin | RB | mean±std b | 15.7±10.0 | 14.5±9.0 |  | 14.6±9.8 |
|  |  | median | 13.6 | 12.5 |  | 12.3 |
|  | UB | mean±std | 29.3±15.6 | 27.5±15.1 |  | 28.4±16.1 |
|  |  | median | 26.1 | 24.3 |  | 24.8 |
|  |  | ratio c | 1.86 | 1.89 |  | 1.90 |
|  |  | diff d | 13.6 | 13.0 |  | 13.8 |
|  | TS | mean±std | 56.1±24.0 | 52.7±22.6 |  | 53.3±24.2 |
|  |  | median | 53.3 | 50.5 |  | 50.7 |
|  |  | ratio | 3.56 | 3.63 |  | 3.6 |
|  |  | diff | 40.3 | 38.2 |  | 38.7 |
| Munich | RB | mean±std | 31.7±19.7 | 28.9±18.5 | 23.3±16.8 | 22.6±15.1 |
|  |  | median | 26.5 | 24.5 | 18.5 | 19.0 |
|  | UB | mean±std | 43.8±23.6 | 34.5±21.1 | 32.6±20.2 | 31.5±18.7 |
|  |  | median | 38.0 | 30.0 | 28.0 | 27.5 |
|  |  | ratio | 1.38 | 1.2 | 1.4 | 1.39 |
|  |  | diff | 12.1 | 5.7 | 9.2 | 8.9 |
|  | TS | mean±std | 84.7±32.8 | 86±33.6 | 77.4±30.3 | 71.7±29.3 |
|  |  | median | 82.5 | 82.8 | 74.8 | 69.3 |
|  |  | ratio | 2.67 | 2.98 | 3.31 | 3.17 |
|  |  | diff | 53.0 | 57.1 | 54.0 | 49.1 |



a RB: regional background site; UB: urban background site; TS: traffic sites.

b std: standard deviation.

c, d the ratios and differences of the mean NO2 between UB or TS sites and the RB sites, respectively.

**3.2.2 Effects of LEZ - Hourly NO2 (Model 1)**

Figure 6 shows the effects of the LEZs (LEZ with HDV transit ban in Munich) on NO2 concentrations in Berlin and Munich. Detailed results are presented in Table 6. In Berlin, the effects for NO2 were small and not statistically significant, except for LEZ 1 at UB. At traffic sites in Munich, there were very small effects for LEZ 1 (increment of 2.4%) and LEZ 2 (reduction of 2.6%). A statistically significant reduction of about 10% was found in LEZ 3. Overall, the effect of the LEZ on the NO2 concentration intensified from LEZ 1 to LEZ 3 at Munich traffic sites. In contrast, a large decrease of 20.8% in NO2 concentration was seen in LEZ 1 at the Munich UB (Lothstraße), which somewhat declined during the subsequent stages of the LEZ (15.8% in LEZ 2, 17.8% in LEZ 3). There was no clear trend of NO2 reduction with LEZ stages.

Table 6 also shows the net LEZ effects on NO2 corrected using the percentages from Table 2, which were 58% and 43% of the GAM model results for LEZ stage 1 and 3, respectively.

The effects by seasons are shown in part S4 of the Supplementary Material.

A close up of a map

Description automatically generated

Figure 6. Changes of NO2 concentrations in Berlin and Munich in LEZ stage 1 to 3 compared with the period before the introduction of LEZ. The results for TS and UB were obtained from Model 1, and RB is used as reference.

Table 6. Changes of NO2 concentrations in Berlin and Munich in LEZ stage 1 to 3 compared with period before the introduction of LEZ. The results for TS and UB were obtained from Model 1, and RB is used as reference.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| City | Site type a | Effect | 95 % CI | p-value | Net LEZ effect b |
| Berlin |  | LEZ 1 | | |  |
| UB | -3.2% | (-4.3%, -2.1%) | < 0.001 | -1.9% |
| TS | -0.4% | (-1.7%, 0.9%) | 0.517 | -0.2% |
|  | LEZ 3 | | |  |
| UB | 0.2% | (-0.8%, 1.2%) | 0.667 | 0.1% |
| TS | -0.1% | (-1.0%, 1.3%) | 0.856 | 0.0% |
| Munich |  | LEZ 1 + HDV transit ban | | |  |
| UB | - 20.8% | (-22.3%, -19.4%) | < 0.001 | -12.1% |
| TS | 2.4% | (0.9%, 3.9%) | 0.002 | 1.4% |
|  | LEZ 2 + HDV transit ban | | |  |
|  | UB | -15.8% | (-17.4%, -14.3%) | < 0.001 | NA |
| TS | -2.6% | (-4.0%, -1.1%) | 0.001 | NA |
|  | LEZ 3 + HDV transit ban | | |  |
| UB | -17.8% | (-19.3%, -16.4%) | < 0.001 | -7.7% |
| TS | -9.9% | (-11.2%, -8.6%) | < 0.001 | -4.3% |

a UB: urban background sites; TS: traffic sites.

b corrected using the percentages in Table 2. Effects for LEZ 2 cannot be corrected.

**4 Discussion**

**4.1 Trend of PM10 and NO2 concentrations**

As Figure 2 and 5 show, the time trend in Germany is quite different for PM10 and NO2. The decreasing trend of PM10 concentration reflects the use of particle traps in vehicles, the introduction of LEZs and the reduction of PM emissions from industry (Luft, 2002) and fuel combustion and residential heating (European Environment Agency, 2018). In contrast, the situation of NO2 is based on four influencing factors (Bruckmann et al., 2019) which together are responsible for the fact that NO2 concentrations do not show a deceasing trend. Firstly, the percentage of passenger cars with Diesel engines increased from about 14% in 2000 to 33% in 2018 (Kraftfahrt-Bundesamt, 2019). Secondly, there was a shift in the conversion of NO to NO2 in the exhaust gas in Diesel cars by the use of oxidation catalysts (Kurtenbach et al., 2008). Thirdly, the real driving emissions of NOx from Euro 4 and 5 diesel cars haven’t improved much compared with Euro 3 (Lutz 2018); therefore, the vehicle fleet update may have a limited effect in reducing NOx. And lastly, the manipulation of the software of some automobile companies with frequent deactivation of exhaust cleaning in real driving mode further underestimated the real NO2 emissions (Borgest, 2017).

Furthermore, one should keep in mind that the observation of health effects from PM2.5 on mortality, respiratory and cardiovascular morbidity is classified as causal or likely to be causal (US EPA, 2010) whereas for NO2 this classification is used only for the risk of asthma and other respiratory endpoints (US EPA, 2016). WHO comes to similar conclusions and with respect to mortality uses a risk coefficient for 1 µg/m³ PM10 which is clearly higher than the risk coefficient for 1 µg/m³ NO2 (WHO, 2013a, b). For Germany in 2014 this results in estimated years of life lost which are more than 5 times higher for PM2.5 compared to NO2 (Wichmann, 2018).

**4.2 Effects of LEZ on PM10 and PM components**

Significant decreases of PM10 concentrations after the enforcement of LEZs (in Munich in combination with HDV transit ban) were observed in Berlin and Munich for both UB and TS. The more rigorous restrictions from LEZ (i.e., stage 3 LEZs) led to larger reduction of PM10. Stronger effects on PM10 were found at traffic sites in comparison to UB sites, which is in line with the fact that the share of PM10 attributable to vehicular exhaust is larger at a TS site than at an UB site. Our results are in line with the results obtained by Fensterer et al. (2014), who in a first analysis of the Munich data for the time period from 2006 to 2010, used a very similar statistical model to estimate the changes in PM10 concentrations after the implementation of the LEZ. The reduction of PM10 concentrations after the implementation of LEZ stage 1 was larger at a single traffic site (13.0%) and smaller in the UB site (4.5%). IA very similar reduction of 4.4% at the background site was observed, whereas the reduction at two traffic sites was somewhat smaller (6.0%) compared to Fensterer et al. (2014). However, in Fensterer et al. (2014) data from the traffic site at Prinzregentenstraße were used, while in present study data from two other sites: Stachus and Landshuter Allee were used. The monitoring sites at Prinzregentenstraße was closed and the data for the time periods of LEZ 2 and LEZ 3 were not available. Compared to Fensterer et al. (2014), the current study is extended to LEZ stages 2 and 3 in Munich (showing further reduction of PM10), includes the effects of LEZ on NO2, and additionally includes Berlin LEZ for PM10, NO2, TC and EC.

We showed that TC and EC concentrations in Berlin were reduced more strongly than PM10 concentrations after the introduction of LEZ stage 3 (PM10: 10%, TC: 17%, EC: 25%). The results confirm the argument of Cyrys et al. (2014) that EC or BC would be much better indicators when evaluating the effectiveness of LEZs. Both parameters are more specific metrics for combustion related particles than PM10, and in this way also for traffic exhaust emissions. The combination of PM10 and BC monitoring in urban areas could potentially generate a useful approach to evaluate the impact of road traffic emissions on air quality. Unfortunately, BC or EC concentrations are not currently routinely measured in urban air quality networks. As BC is considered as a highly health-relevant particle fraction, the implementation of LEZs may lead to a higher health benefit than its literal reduction to the PM10 mass concentration.

**4.3 Effects of LEZ on NO2**

The NO2 concentrations responded differently to LEZs (in Munich in combination with HDV transit ban) than PM10, and differently between Berlin and Munich. Only very small and mainly non-significant effects without a clear tendency were found in Berlin. In contrast, NO2 at UB in Munich significantly decreased with the introduction of the LEZ but the NO2 levels did not further decrease during LEZ 2 and LEZ 3. Reductions of NO2 concentrations at TS in Munich were observed only from LEZ 2.The decrease of NO2 concentrations due to the introduction of LEZs was much weaker than for particulate matter. In 2012 to 2017, at around 60% of the traffic sites in Germany, exceedances of the limit values for NO2 are still being observed (UBA, 2017a).

In Munich, HDV transit ban was implemented before LEZ 1, while no such measure was introduced in Berlin. The HDV transit ban may have contributed to the decrease of NO2 in Munich. There are two possible explanations for the observed reductions of NO2 at the Munich UB site. First, the HDV transit ban came into force eight months before LEZ 1. This might have had an overall effect on the urban background concentration of NO2 in Munich. As the effects did not become stronger from LEZ 1 to LEZ 3, it is likely that the LEZ did not contribute to the reduction of NO2 at urban background site. However, the HDV transit ban seemed to have a weaker effect on NO2 at traffic sites. The second explanation could be the local influences on NO2 at Munich urban background site. In this study, only one urban background site was available in Munich (Lothstraße). Some potentially unknown changes in local NO2 sources near Lothstraße before LEZ 1 implementation may have caused such results. This underlines the disadvantage of relying on a single monitoring site. In contrast, the current study included two traffic sites in Munich, four urban background sites and five traffic sites in Berlin.

**4.4 Strengths and limitations**

The regression models developed in this study used the air pollutant measurements at regional background as reference. This allowed us to account for many confounders including meteorology, diurnal variation, long-range transport of air pollution, and secondary aerosol formation that may influence the absolute levels of air pollutants. We also used this model to evaluate the LEZ on the key components of PM10 (EC and TC).

Some limitations are inherent to our methodology. As we compared the relative difference of air pollutants between TS and RB, and between UB and RB adjusting for confounding variables, it cannot be ruled out that other mitigation measures (e.g., speed limit control, HDV transit ban, traffic rerouting, and natural vehicle renewal) than the LEZ were the cause for the observed differences. Therefore, other mitigation measures or policies that influenced the car fleet or emission of vehicular exhaust could not be distinguished by the GAM models. During the economic crisis from 2008, the German government initiated a car scrappage program in beginning of 2019 to stimulate the economy, however, it was launched one year later than LEZ which already bans the old cars in 2008. In Munich, a HDV transit ban was introduced at the similar time with LEZ. In Berlin, no additional control measures on traffic were introduced. We tried to differentiate the effects of natural vehicle renewal from net LEZ effects in reducing the PM10 and NO2 concentrations by estimation of the emission reductions by real-world scenario with LEZ and normal fleet turnover without LEZ, respectively.

The second limitation is due to the availability of monitoring sites and data. In Berlin, there is a sufficient number of monitoring sites (4 RB, 4 UB and 5 TS), while in Munich, the number of monitoring stations is more limited (1 RB, 1 UB and 2 TS). In the case that only a single monitoring station is available, the result is more susceptible to, e.g., the change of any local sources in the long-term measurement. In contrast, when multiple sites of the same category are available, the mean urban air pollution level represents the estimations more robustly.

**4.5 Final remarks on LEZ**

There have been doubts before the implementation of LEZs about whether they could constitute a suitable and effective measure in improving urban air quality. Many studies have been carried out to evaluate the effects of LEZs. In the case of Germany, most studies have found an effect in reducing PM10 concentrations (Cyrys et al., 2014; Fensterer et al., 2014; Lutz and Rauterberg-Wulff, 2009; Malina and Scheffler, 2015). Our study showed a clear effect for PM10 in the range of 2% to 24%, depending on the site category (background vs. traffic) and the LEZ stage. The effect for EC in Berlin is much stronger than for PM10. The effect on NO2 was not clear and not consistent, which might be caused by the fact that NO2 emissions in real-life driving conditions have not been significantly reduced.

After many years of implementation of LEZs, the vehicle fleet today meets the most stringent requirement of LEZ stage 3; therefore, the additive effect of LEZ now may be smaller than right after its implementation. Nevertheless, a mitigation measure, such as LEZs, which targets the major primary air pollution source in a highly populated city center could be a feasible way to improve urban air quality.

**5 Conclusions**

Overall, our study showed that LEZs (in Munich in combination with the HDV transit ban) proved to be effective in reducing PM10. The strongest effects were observed in LEZ stage 3, the strictest stage so far. LEZs are were effective in reducing PM10 concentrations near traffic than in urban background areas. In contrast, it is not clear whether the LEZ was responsible for the reduced NO2 concentrations; more likely the HDV transit ban contributed to the observed NO2 reduction in Munich.

The results clearly demonstrated that the LEZ had a much larger effect in reducing the EC concentration near traffic than for PM10 (25% vs. 10% in LEZ 3 in Berlin). This has a twofold implication: firstly, LEZ is more efficient in mitigating the more toxic fraction of PM10 (soot particles); secondly, the health benefit of the LEZ may be larger than the estimation based on the reduction of PM10.

**Acknowledgement**

This work was carried out within the ACCEPTED project, supported by the ERA-ENVHEALTH network (grant Number 219337), with funding from ANSES, ADEME, BelSPO, UBA and the Swedish EPA. The authors thank V. Maier, T. Ungar, S. Shewamal, M. Hutter, M. Dörsch and J. Ficekfor their assist in the data analysis, and Dr. E. Giemsa for preparing the maps of LEZ. The authors also thank Bavarian Environmental Agency (Bayerisches Landesamt für Umwelt) for providing the monitoring data for Munich.

**References**

Anenberg, S.C., Henze, D.K., Tinney, V., Kinney, P.L., Raich, W., Fann, N., Malley, C.S., Roman, H., Lamsal, L., Duncan, B., Martin, R.V., van Donkelaar, A., Brauer, M., Doherty, R., Jonson, J.E., Davila, Y., Sudo, K., Kuylenstierna, J.C.I., 2018. Estimates of the Global Burden of Ambient PM2.5, Ozone, and NO2 on Asthma Incidence and Emergency Room Visits. Environ. Health Persp. 126, 14.

Anenberg, S.C., Miller, J., Minjares, R., Du, L., Henze, D.K., Lacey, F., Malley, C.S., Emberson, L., Franco, V., Klimont, Z., Heyes, C., 2017. Impacts and mitigation of excess diesel-related NOx emissions in 11 major vehicle markets. Nature 545, 467.

Araujo, J.A., Nel, A.E., 2009. Particulate matter and atherosclerosis: role of particle size, composition and oxidative stress. Part. Fibre Toxicol. 6, 19.

Beelen, R., Raaschou-Nielsen, O., Stafoggia, M., Andersen, Z.J., Weinmayr, G., Hoffmann, B., Wolf, K., Samoli, E., Fischer, P., Nieuwenhuijsen, M., Vineis, P., Xun, W.W., Katsouyanni, K., Dimakopoulou, K., Oudin, A., Forsberg, B., Modig, L., Havulinna, A.S., Lanki, T., Turunen, A., Oftedal, B., Nystad, W., Nafstad, P., De Faire, U., Pedersen, N.L., Östenson, C.-G., Fratiglioni, L., Penell, J., Korek, M., Pershagen, G., Eriksen, K.T., Overvad, K., Ellermann, T., Eeftens, M., Peeters, P.H., Meliefste, K., Wang, M., Bueno-de-Mesquita, B., Sugiri, D., Krämer, U., Heinrich, J., de Hoogh, K., Key, T., Peters, A., Hampel, R., Concin, H., Nagel, G., Ineichen, A., Schaffner, E., Probst-Hensch, N., Künzli, N., Schindler, C., Schikowski, T., Adam, M., Phuleria, H., Vilier, A., Clavel-Chapelon, F., Declercq, C., Grioni, S., Krogh, V., Tsai, M.-Y., Ricceri, F., Sacerdote, C., Galassi, C., Migliore, E., Ranzi, A., Cesaroni, G., Badaloni, C., Forastiere, F., Tamayo, I., Amiano, P., Dorronsoro, M., Katsoulis, M., Trichopoulou, A., Brunekreef, B., Hoek, G., 2014. Effects of long-term exposure to air pollution on natural-cause mortality: an analysis of 22 European cohorts within the multicentre ESCAPE project. Lancet 383, 785-795.

Belis, C.A., Karagulian, F., Larsen, B.R., Hopke, P.K., 2013. Critical review and meta-analysis of ambient particulate matter source apportionment using receptor models in Europe. Atmos. Environ. 69, 94-108.

Boogaard, H., Janssen, N.A.H., Fischer, P.H., Kos, G.P.A., Weijers, E.P., Cassee, F.R., van der Zee, S.C., de Hartog, J.J., Meliefste, K., Wang, M., Brunekreef, B., Hoek, G., 2012. Impact of low emission zones and local traffic policies on ambient air pollution concentrations. Sci. Total Environ. 435, 132-140.

Borgest, K., 2017. Manipulation von Abgaswerten. Springer, Wiesbaden, Germany.

Brook, R.D., Rajagopalan, S., Pope, C.A., 3rd, Brook, J.R., Bhatnagar, A., Diez-Roux, A.V., Holguin, F., Hong, Y., Luepker, R.V., Mittleman, M.A., Peters, A., Siscovick, D., Smith, S.C., Jr., Whitsel, L., Kaufman, J.D., 2010. Particulate matter air pollution and cardiovascular disease: An update to the scientific statement from the American Heart Association. Circulation 121, 2331-2378.

Bruckmann, P., Krämer, U., Wichmann, H.E., 2019. Wissenschaft trifft Politik – die Basis der europäischen Grenzwerte für Stickstoffdioxid und Feinstaub. Umweltmed – Hygiene – Arbeitsmed 24, 83-100.

Brunekreef, B., Künzli, N., Pekkanen, J., Annesi-Maesano, I., Forsberg, B., Sigsgaard, T., Keuken, M., Forastiere, F., Barry, M., Querol, X., Harrison, R.M., 2015. Clean air in Europe: beyond the horizon? Eur. Respir. J. 45, 7-10.

Cesaroni, G., Boogaard, H., Jonkers, S., Porta, D., Badaloni, C., Cattani, G., Forastiere, F., Hoek, G., 2012. Health benefits of traffic-related air pollution reduction in different socioeconomic groups: the effect of low-emission zoning in Rome. Occup. Environ. Med. 69, 133-139.

Clemen, S., Kaupp, H., 2018. Two decades of soot measurements in the Berlin Air Monitoring Network (in German). Gefahrstoffe - Reinhaltung Der Luft 78, 109 - 116.

Council of the European Union, 2008. Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe, Official Journal of the European Union, pp. 1 - 44.

Cyrys, J., Peters, A., Soentgen, J., Wichmann, H.E., 2014. Low emission zones reduce PM10 mass concentrations and diesel soot in German cities. J. Air Waste Ma. 64, 481-487.

Degraeuwe, B., Thunis, P., Clappier, A., Weiss, M., Lefebvre, W., Janssen, S., Vranckx, S., 2017. Impact of passenger car NOX emissions on urban NO2 pollution – Scenario analysis for 8 European cities. Atmos. Environ. 171, 330-337.

Ellison, R.B., Greaves, S.P., Hensher, D.A., 2013. Five years of London's low emission zone: Effects on vehicle fleet composition and air quality. Transport Res D-Tr. E. 23, 25-33.

Emplan, 2010. Lufthygienische Untersuchung, Augsburg, Germany.

European Environment Agency, 2018. Air quality in Europe — 2018 report (EEA Report No 12/2018).

Fensterer, V., Kuchenhoff, H., Maier, V., Wichmann, H.E., Breitner, S., Peters, A., Gu, J.W., Cyrys, J., 2014. Evaluation of the Impact of Low Emission Zone and Heavy Traffic Ban in Munich (Germany) on the Reduction of PM10 in Ambient Air. Int. J. Env. Res. Pub. He. 11, 5094-5112.

Franco, V., Sánchez, F.P., German, J., Mock, P., 2014. Real-World Exhaust Emissions from Modern Diesel Cars - A Meta-Analysis of PEMS Emissions Data from EU (EURO 6) and US (Tier 2 BIN 5/ ULEV II) Diesel Passenger Cars. Part 1: Aggregated Results. International Council on Clean Transportation Europe, Berlin.

Hoek, G., Krishnan, R.M., Beelen, R., Peters, A., Ostro, B., Brunekreef, B., Kaufman, J.D., 2013. Long-term air pollution exposure and cardio- respiratory mortality: a review. Environ. Health 12, 43.

Holman, C., Harrison, R.M., Querol, X., 2015. Review of the efficacy of low emission zones to improve urban air quality in European cities. Atmos. Environ. 111, 161-169.

Janssen, N.A.H., Hoek, G., Simic-Lawson, M., Fischer, P., van Bree, L., Brink, H.t., Keuken, M., Atkinson, R.W., Anderson, H.R., Brunekreef, B., Cassee, F.R., 2011. Black carbon as an additional indicator of the adverse health effects of airborne particles compared with PM10 and PM2.5. Environ. Health Persp. 119, 1691–1699.

Jiang, W., Boltze, M., Groer, S., Scheuvens, D., 2017. Impacts of low emission zones in Germany on air pollution levels. Transp. Res. Proc. 25, 3370–3382.

Kraftfahrt-Bundesamt, 2019. Fahrzeugzulassungen (FZ) Bestand an Kraftfahrzeugen nach Umwelt-Merkmalen. Kraftfahrt-Bundesamt, Flensburg, Germany.

Kurtenbach, R., Becker, K.H., Bruckmann, P., Kleffmann, J., Niedojadlo, A., Wiesen, P., 2008. Das innerstädtische Stickstoffdioxid (NO2)-Problem: Welchen Einfluss haben direkte Verkehrsemissionen? Mitt Umweltchem Ökotox 14, 69–73.

LfU, 2010. Minderungswirkung von Umweltzonen auf die Luftschadstoffbelastung- Umweltzone München. Bayerisches Landesamt für Umwelt.

Löschau, G., Wiedensohler, A., Birmili, W., Rasch, F., Spindler, G., Müller, K., Wolf, U., Hausmann, A., Anhalt, M., Dietz, V., Herrmann, H., Uwe, B., Horst-Günter, K., 2016. Messtechnische Begleitung der Einführung der Umweltzone in der Stadt Leipzig, Teil 5: Immissionssituation von 2010 bis 2015 und Wirkung der Umweltzone. Landesamt für Umwelt, Landwirtschaft und Geologie, Dresden.

Löschau, G., Wiedensohler, A., Birmili, W., Rasch, F., Spindler, G., Müller, K., Wolf, U., Hausmann, A., Böttger, M., Bastian, S., Anhalt, M., Dietz, V., Herrmann, H., Uwe, B., 2015. Messtechnische Begleitung der Einführung der Umweltzone in der Stadt Leipzig, Teil 4: Immissionssituation von 2010 bis 2014 und Wirkung der Umweltzone. Landesamt für Umwelt, Landwirtschaft und Geologie, Dresden.

Luft, T., 2002. Erste Allgemeine Verwaltungsvorschrift zum Bundes-Immissionsschutzgesetz:

Technische Anleitung zur Reinhaltung der Luft – TA Luft vom 24.7.2002. Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit, pp. 511-605.

Lutz, M., 2012. Modellierung der verkehrsnahen NO2-Belastung 2009: Symposium: Wie gesund ist unsere Stadt? Senatsverwaltung für Stadtentwicklung und Umwelt, Referat Immissionsschutz, Graz, Austria.

Lutz, M., 2013. Mitigation Strategies, Berlin, Germany in M Cruz, Minguillón, M Viana, X Querol (Ed.), Particulate Matter, Environmental Monitoring and Mitigation, Ebook, p. 74-95, Nov. 2013, Future Science Ltd, eISBN: 978-1-909453-13-5, doi: 10.4155/ebo.13.489.

Lutz, M., 2018. Successes and challenges of twenty years air quality management in Berlin, Germany, in Querol, X. (ed), Air quality in cities. A global challenge. Fundación gasNatural fenosa. Barcelona, Spain. ISBN: 978-84-09-01905-2, http://www.fundacionnaturgy.org/en/product/libro-la-calidad-del-aire-las-ciudades-reto-mundial/

Lutz, M., Rauterberg-Wulff, A., 2009. Ein Jahr Umweltzone Berlin: Wirkungsuntersuchungen. Senatsverwaltung für Gesundheit, Umwelt und Verbraucherschutz, Berlin.

Malina, C., Scheffler, F., 2015. The impact of Low Emission Zones on particulate matter concentration and public health. Transport. Res. A: Pol. 77, 372–385.

Morfeld, P., Groneberg, D.A., Spallek, M., 2014a. Effectiveness of low emission zones of stage 1: analysis of the changes in fine dust concentrations (PM10) in 19 German cities. Pneumologie 68, 173-186.

Morfeld, P., Groneberg, D.A., Spallek, M.F., 2014b. Effectiveness of Low Emission Zones: Large Scale Analysis of Changes in Environmental NO2, NO and NOx Concentrations in 17 German Cities. Plos One 9.

Panteliadis, P., Strak, M., Hoek, G., Weijers, E., van der Zee, S., Dijkema, M., 2014. Implementation of a low emission zone and evaluation of effects on air quality by long-term monitoring. Atmos. Environ. 86, 113-119.

Querol, X., Alastuey, A., Ruiz, C.R., Artiñano, B., Hansson, H.C., Harrison, R.M., Buringh, E., Brink, H.M.t., Lutz, M., Bruckmann, P., Straehl, P., Schneider, J., 2004. Speciation and origin of PM10 and PM2.5 in selected European cities. Atmos. Environ. 38, 6547–6555.

Raaschou-Nielsen, O., Andersen, Z.J., Beelen, R., Samoli, E., Stafoggia, M., Weinmayr, G., Hoffmann, B., Fischer, P., Nieuwenhuijsen, M.J., Brunekreef, B., Xun, W.W., Katsouyanni, K., Dimakopoulou, K., Sommar, J., Forsberg, B., Modig, L., Oudin, A., Oftedal, B., Schwarze, P.E., Nafstad, P., De Faire, U., Pedersen, N.L., Östenson, C.-G., Fratiglioni, L., Penell, J., Korek, M., Pershagen, G., Eriksen, K.T., Sørensen, M., Tjønneland, A., Ellermann, T., Eeftens, M., Peeters, P.H., Meliefste, K., Wang, M., Bueno-de-Mesquita, B., Key, T.J., de Hoogh, K., Concin, H., Nagel, G., Vilier, A., Grioni, S., Krogh, V., Tsai, M.-Y., Ricceri, F., Sacerdote, C., Galassi, C., Migliore, E., Ranzi, A., Cesaroni, G., Badaloni, C., Forastiere, F., Tamayo, I., Amiano, P., Dorronsoro, M., Trichopoulou, A., Bamia, C., Vineis, P., Hoek, G., 2013. Air pollution and lung cancer incidence in 17 European cohorts: prospective analyses from the European Study of Cohorts for Air Pollution Effects (ESCAPE). Lancet Oncol. 14, 813-822.

Regierung von Oberbayern, 2007. Luftreinhalte-/Aktionsplan für die Stadt München, 1. Fortschreibung.

Rückerl, R., Schneider, A., Breitner, S., Cyrys, J., Peters, A., 2011. Health effects of particulate air pollution: A review of epidemiological evidence. Inhal. Toxicol. 23, 555–592.

Sadler, 2011. Low Emission Zones in Europe, for ADEME, final report. Sadler Consultants, Emmendingen, Germany.

Santos, F.M., Gómez-Losada, Á., Pires, J.C.M., 2019. Impact of the implementation of Lisbon low emission zone on air quality. J. Hazard. Mater. 365, 632-641.

Silva, F.N.d., Custódio, R.A.L., Martins, H., 2014. Low Emission Zone: Lisbon’s Experience. J. Traffic Logist. Eng. 2, 133–139.

Tartakovsky, D., Kordova – Biezuner, L., Berlin, E., Broday, D.M., 2020. Air quality impacts of the low emission zone policy in Haifa. Atmos. Environ. 232, 117472.

Thorpe, A., Harrison, R.M., 2008. Sources and properties of non-exhaust particulate matter from road traffic: a review. Sci. Total Environ. 400, 270–282.

UBA, 2017a. Air Quality 2017 - Preliminary Evaluation. Umweltbundesamt, Dessau-Roßlau, Germany.

US EPA, 2010. Quantitative Health Risk Assessment for Particulate Matter, https://www3.epa.gov/ttn/naaqs/standards/pm/data/PM\_RA\_FINAL\_June\_2010.pdf, pp. 1-596.

US EPA, 2016. Integrated Science Assessment for Oxides of Nitrogen – Health Criteria., https://cfpub.epa.gov/ncea/isa/recordisplay.cfm?deid=310879.

VDI 2465, 2016. Part 2, Measurement of soot (ambient air) Thermographic determination of elemental carbon after thermal desorption of organic carbon. Verein Deutscher Ingenieure e.V., Düsseldorf.

Viana, M., Kuhlbusch, T.A.J., Querol, X., Alastuey, A., Harrison, R.M., Hopke, P.K., Winiwarter, W., Vallius, M., Szidat, S., Prévôt, A.S.H., Hueglin, C., Bloemen, H., Wåhlin, P., Vecchi, R., Miranda, A.I., Kasper-Giebl, A., Maenhaut, W., Hitzenberger, R., 2008. Source apportionment of particulate matter in Europe: A review of methods and results. J. Aerosol Sci. 39, 827–849.

Watkiss, P., Allen, J., Anderson, S., Beevers, S., Browne, M., Carslaw, D., Emerson, P., Fairclough, P., Francsics, J., Freeman, D., Haydock, H., Hidri, S., Hitchcock, G., Parker, T., Pye, S., Smith, A., Ye, R., Young, T., 2003. London Low Emission Zone Feasibility Study. Phase II. Final Report to the London Low Emission Zone Steering Group.

WHO, 2006. Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide, Global update 2005: Summary of risk assessment.

WHO, 2012. Health effects of black carbon. World Health Organization Regional Office for Europe, Copenhagen, Denmark.

WHO, 2013a. Review of evidence on health aspects of air pollution – REVIHAAP project: final technical report. Regional Office for Europe, Copenhagen, Denmark.

WHO, 2013b. Review of evidence on health aspects of air pollution. Technical Report. WHO Regional Office for Europe. , http://www.euro.who.int/\_\_data/assets/pdf\_file/0004/193108/REVIHAAP-Final-technical-report-final-version.pdf?ua=1.

Wichmann, H.E., 2018. Gesundheitliche Risiken von Stickstoffdioxid im Vergleich zu Feinstaub und anderen verkehrsabhängigen Luftschadstoffen. Umweltmedizin – Hygiene – Arbeitsmedizin 23, 57-71.