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Impacts of low emission zones in Germany on air pollution levels

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Abstract

Since 2008 low emission zones (LEZ) have been introduced in many German cities to improve air quality and to protect human health. In order to assess the effectiveness of LEZ, both descriptive and statistical analyses have been conducted based on concentrations of air pollutants (PM_{10}, $PM_{2.5}$, NO, NO_2, and NO_x) from relevant monitoring stations in Germany from year 2002 to 2012. The results indicate that the introduction of LEZ has brought positive effects on reducing air pollutant concentrations. But the potential of further reduction by additional LEZ in Germany without further development of this measure seems to be small.

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Keywords: Low Emission Zone; Air Quality; Traffic Management; Particulate Matter; Nitrogen Oxides; T-Test; Emission; Monitoring Station

1. Introduction

Air pollution has significant negative impacts on human health. There are clear indications that premature mortality due to air pollution exceeds significantly the number of traffic accident fatalities (compare e.g. Lelieveld et al. [1]). In Germany, for example, this number is about three times higher. To prevent the harm from air pollution, the European Union has set up minimum standards for ambient air quality, which is specified in the European Directive 2008/50/EC (EU [2]). After the release of the directive, there was a debate in the popular press about its applicability in Germany, since the defined limit values for ambient air quality would be exceeded in many German cities without further control measures in action.

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In Germany, there are concrete laws to implement the European directive on controlling ambient air quality. If the limit values of air quality are exceeded, cities must propose corresponding clean air plans and action plans to reduce the air pollution level and to protect public health. One control measure, which has drawn a lot of attention and been proposed in the action plans, is the introduction of low emission zones (LEZ) as specified in the German regulations (39. BImSchV [3]; StVO [4]). According to the regulations of LEZ at different stages (red, yellow or green), only vehicles that fulfill certain emission standards and have the corresponding sticker are allowed to enter the zone. The vehicles are assigned a sticker (red, yellow or green) according to the tax class and Euro emission standard. The first LEZ in Germany were implemented in the year 2008 in cities such as Berlin, Hannover and others. After that, new LEZ have been introduced and existing LEZ have been upgraded step by step from the lowest stage (red) to the highest stage (green). So far, there are 50 LEZ introduced in total, most of which only allow the vehicles with green sticker (highest stage) to enter the zone.

LEZ are not only implemented in German cities, but also in many other European countries or cities such as United Kingdom (London), The Netherlands (e.g. Amsterdam) and others. Some of the LEZ target at heavy duty vehicles only (e.g. in The Netherlands) while others target at all vehicles such as in the case of Germany.

There are several previous studies on analyzing the effects of LEZ in Germany (e.g.Bruckmann et al. [5], Cyrys et al. [6], GAA-HI [7], Laberer and Niedermeier [8], LANUV NRW [9], Lutz and Rauterberg-Wulff [10], Morfeld et al. [11], Rasch et al. [12], Rauterberg-Wulff and Lutz [13], Stadt Frankfurt am Main Umweltamt [14]). The effects of LEZ in other European countries (or cities) have also been investigated. Some recent examples of studies are Panteliadis et al. [15] and Boogaard et al. [16] about LEZ in the Netherlands; Ellison et al. [17] and Jones et al. [18] about an LEZ in United Kingdom (London); Jensen et al. [19] about an LEZ in Denmark, Copenhagen.

Positive effects of LEZ on reducing air pollution concentrations (PM_{10}, $PM_{2.5}$) have been concluded in most of previous studies mentioned above, even though the concrete regulations in the countries are different. In some of the studies, there were no significant effects of LEZ identified. Especially for the case of NO_2 and NO_x, half of the studies have found no obvious effects of LEZ. However, in most of the studies the effects of LEZ overlapped with the effects of other measures which were introduced almost at the same time. One example comes from the City of London, where the LEZ was implemented at the same time as the introduction of `sulphur free´ diesel fuel (Jones et al. [18]). The combination of implemented measures resulted in an overlap of both measures and made it difficult to investigate the effects of each single measure. It must also be mentioned that studies on the effectiveness of LEZ investigating a relatively small number of LEZ or even just one LEZ are strongly influenced by its specific characteristics such as topography and meteorology. Furthermore, the use of data for a single city cannot consider well the general development of the pollution level in a country.

To draw more general conclusions on the effectiveness of LEZ, instead of analyzing the air quality at a single location, this paper presents an analysis of data from a large number of monitoring stations located inside and outside the LEZ in cities all over Germany. The wide implementation of LEZ in Germany provides a rich data basis which is necessary for the investigation. The basic assumption for this study was that the air quality at a station inside LEZ ought to develop significantly better than that at a station outside LEZ in the last few years. Both the different locations of the stations and the general trend of air quality level are going to be considered.

2. Data basis

The analysis is based on air pollution concentrations at monitoring stations in Germany, provided by the German Federal Environmental Protection Agency (UBA). For particles smaller than 10 µm (PM_{10}), the data obtained were the annual mean concentrations (µg/m³) and the number of days per year exceeding the daily limit value of 50 µg/m³ (exceedance days). For particles smaller than 2.5 µg ($PM_{2.5}$), nitrogen monoxide (NO), nitrogen dioxide (NO_2) and oxides of nitrogen (NO_x), the annual mean concentrations (µg/m³) were derived from the monthly mean concentrations (µg/m³) provided by UBA. The NO_x concentrations were calculated based on NO and NO_2 concentrations with reference to Nagel and Gregor [20].

The investigation time period is from 2002 to 2012. Data of $PM_{2.5}$ mass concentration are only available since the year 2005.

The monitoring stations, from which the data were collected, were divided into the following three groups. The classification is according to the European council decision 97/101/EC, which is generally used in Germany and other European countries (EU [21]). Traffic stations are monitoring stations which are located in urban areas with high traffic density. Urban background stations are monitoring stations which are located in an urban area but away from local emissions such as traffic. Therefore, the pollution level at traffic stations is significantly higher than that at urban background stations due to the emission of air pollutants from road traffic.

- Group 1 (IN LEZ): traffic stations, which were located within a LEZ for at least one year within the investigation period (further divided according to the year when LEZ were first introduced, see below). Multiple monitoring stations within the same LEZ are all included (e.g. in Stuttgart and Munich).
- Group 2 (reference group, OUT LEZ): traffic stations, which were not located in a LEZ during the investigation period.
- Group 3 (reference group, BG): urban background stations (inside or outside LEZ).

The measuring data of some stations don't cover the whole investigation period. For some stations, there were no data measured after the year 2008. For few temporary stations, the data were only measured for one year. Therefore, a quality test was conducted to avoid a bias by the above-mentioned types of stations. Only stations which fulfill the following criteria were included in the analysis:

- Stations of group 1 (IN LEZ): the measuring data are available for at least two years before and after the introduction of the LEZ.
- Stations of group 2 (OUT LEZ) and 3 (BG): the measuring data are available at least for 4 years between the year 2002 and 2012.

The number of monitoring stations, which are finally included in the analysis, is shown in Table 1.

Table 1. Number of monitoring stations in the investigated groups.

	LEZ beginning in year	PM_{10} annual mean concentration & exceedance days	$PM_{2.5}$ annual mean concentration	NO. NO_2. NO_x annual mean concentration
Group 1 (IN LEZ)	All	33	7	28
	2008	19	2	15
	2009	8	1	5
	2010	2	2	2
	2011	4	2	6
	2012	0	0	0
Group 2 (OUT LEZ)		114	27	126
Group 3 (BG)		103	36	112

Stations of group 1 were further divided according to the year of the implementation of the LEZ (2008, 2009, 2010, 2011, 2012). For more than half of the monitoring stations, the LEZ were first introduced in the year 2008. Only these stations with an introduction of LEZ in 2008 were included in the descriptive analysis (section 3.1). However, all the monitoring stations from group 1 were included in statistical analysis as explained in section 3.2.

3. Method

3.1. Descriptive analysis

For the descriptive analysis of the data set, the annual arithmetic mean concentrations of stations from group 1 with an introduction of LEZ in 2008 were averaged for each year, in order to demonstrate the overall trend of air quality at monitoring stations in figures.

$$\bar{X}_j = \frac{1}{a}\sum_{i=1}^{a} X_{ij} \quad (1)$$

with

a number of stations in group 1 with an introduction of LEZ in 2008
j the corresponding year
X_{ij} concentration of air pollution at station i in year j
$\bar{X}_j$ average air pollutant concentration of stations from group 1 (introduction of LEZ in 2008) in year j

Equation (1) was also applied to the stations of group 2 and 3. However, the calculation included all the stations from each group, which fulfill the above-mentioned quality criteria. The average air pollutant concentration was marked as $\overline{R}_j$ (group 2) und $\overline{H}_j$ (group 3).

In order to compare the three groups, a graphical analysis was conducted first. The objective was to observe, whether there is a relative stronger reduction in average annual concentration at stations of group 1 (only LEZ introduced in 2008) in comparison with stations outside LEZ (group 2) and urban background stations (group 3) after the introduction of LEZ.

Furthermore, the average air pollutant concentrations of all years were summarized using equations (2) and (3) to calculate the amount and percentage of reduction in concentration after LEZ were introduced in 2008.

$$\bar{V}_{2008} = \sum_{j=2002}^{2008} \bar{X}_j \quad (2)$$

$$\bar{N}_{2008} = \sum_{j=2008}^{2012} \bar{X}_j \quad (3)$$

with

$\bar{X}_j$ average air pollutant concentration of stations from group 1 (introduction of LEZ in 2008) in year j
$\bar{V}_{2008}$ average air pollutant concentration before the introduction of LEZ in 2008
$\bar{N}_{2008}$ average air pollutant concentration after the introduction of LEZ in 2008

Similar calculations were processed for the analysis of exceedance days. Instead of air pollutant concentration, the absolute number of exceedance days per year was used as the parameter. Specialties for the analysis of certain groups and parameters will be explained in the corresponding subsection.

3.2. Statistical analysis

In addition to the descriptive analysis, statistical tests were conducted to investigate the effects of LEZ. As shown in the descriptive analysis, the air pollutant concentrations are subject to yearly fluctuations due to variations in weather conditions. The different station groups usually follow similar trends for fluctuations.

Therefore it was assumed that the measured data at stations in LEZ and other reference stations (group 2 and 3) followed the same fluctuations along the investigation time period. If the LEZ lead to a reduction of air pollution concentration, the difference in annual mean concentrations between group 1 and reference groups should become smaller after the introduction of LEZ. Based on this idea, the t-tests for paired two samples were used to check whether there was a significant reduction of the above mentioned difference between group 1 and reference groups after the introduction of LEZ. The values used here were from all traffic stations in group1 which fulfill the quality criteria, not only those where LEZ was first introduced in the year 2008. The null hypothesis to reject is that there is no reduction or even an increase of the difference.

The measurement data were analyzed as follows to test the hypothesis. Firstly, the difference between annual mean concentration of group 1 in one year and the average of all reference groups in the same year was calculated for each station and for each year:

$$\Delta X_{i,j} = X_{i,j} - \bar{R}_j \quad (4)$$

with
$X_{i,j}$ concentration of air pollutant X at station i in year j
$\Delta X_{i,j}$ difference of concentration at station i to the average concentrations of reference groups in year j
$\bar{R}_j$ average air pollutant concentration of stations from group 2 in year j

In the next step, the calculated difference in concentrations was aggregated for the time period before and after the introduction of LEZ at each station:

$$V_i = \frac{1}{b}\sum_1^b \Delta X_{i,j} \quad (5)$$

$$N_i = \frac{1}{c}\sum_1^c \Delta X_{i,j} \quad (6)$$

with
V_i average difference of concentrations between station i of group 1 and the corresponding reference value before the introduction of LEZ
b number of annual mean concentrations available at station i before the introduction of LEZ
N_i average difference of concentrations between station i of group 1 and the corresponding reference value after the introduction of LEZ
c number of annual mean concentrations available at station i after the introduction of LEZ

There is a pair of values for each station i. V_i represents the difference before the introduction and N_i represents the difference after the introduction. A statistical t-test for paired samples was conducted to test, whether in general there was a significant reduction in the difference and whether the null hypothesis can be rejected. The null hypothesis is that there is no difference between V_i and N_i. If the null hypothesis is rejected and V_i is higher than N_i, it is to conclude that the introduction of LEZ has contributed to a reduction of air pollutant concentrations.
In the tests, the values for each station were then aggregated together to calculate the mean value as follows:

$$\bar{V} = \frac{1}{d}\sum_{i=1}^d V_i \quad (7)$$

$$\bar{N} = \frac{1}{d}\sum_{i=1}^d N_i \quad (8)$$

with
d number of stations in group 1
$\bar{V}$ aggregated mean value of average difference of concentrations before introduction of LEZ
$\bar{N}$ aggregated mean value of average difference of concentrations after introduction of LEZ

The difference between these two values ($\bar{V}$ and $\bar{N}$) can be considered as the average contribution of LEZ to reduce air pollutant concentration if the reduction is significant.

4. Results

4.1. PM_{10} annual mean concentration

Fig. 1 shows the trend of average annual PM_{10} concentrations at three groups of stations from the year 2002 to 2012. Table 2 shows the average PM_{10} concentration before and after the introduction of LEZ in the year 2008.

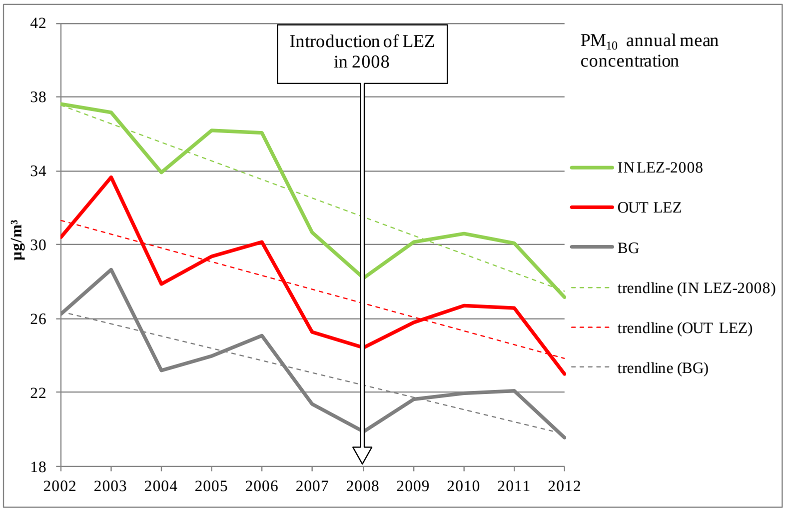

Fig. 1. Trend of average annual PM_{10} concentration from 2002 to 2012

Table 2. Average PM_{10} concentration before and after the introduction of LEZ

PM_{10}	Average before introduction [µg/m³]	Average after introduction [µg/m³]	Reduction [µg/m³]	[%]
Group 1 (introduction of LEZ 2008)	35.26	29.24	6.03	17.1%
Group 2 (outside LEZ)	29.47	25.29	4.18	14.2%
Group 3 (urban background)	24.75	21.01	3.74	15.1%

In general, all groups showed a reduction of annual mean PM_{10} concentrations in the investigation period. The concentration level was reduced not only at urban background stations (group 3), but also at traffic stations both inside and outside the LEZ (group 1 and 2). The trend was identical with that of traffic-related emissions of PM_{10} in Germany, which declined from 55.3 kt in the year 2002 to 35.4 kt in the year 2011 (Table 3). This suggests that the measures implemented in different sectors to control air pollution (including LEZ) have demonstrated their effectiveness in the recent years. However, at this stage it is not quantified to which extent the LEZ contributes to the reduction of PM_{10} concentrations.

The PM_{10} concentrations at stations in group 1 (IN LEZ-2008) are always higher than those at stations in group 2 (OUT LEZ) and group 3 (BG) in the same year since LEZ are mainly implemented in regions with high air pollution concentrations, where there is urgent need to improve air quality and thus protect residents' health. The trend of the curves for the three groups was basically parallel. This shows that the stations are subject to similar yearly fluctuations and are mainly influenced by the overall meteorological conditions.

Table 3. Emission of air pollutants (kt/a) in Germany from the year 2002 to 2011 (Source: UBA 2013)

Air pollutant	Sector	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
PM_{10}	Transport	55.3	51.7	51.2	48.5	46.7	44	40.3	37.7	36.4	35.4
	Total	244.4	237.3	232.2	224.1	223.3	217.6	211.5	202.8	211.4	208.6
$PM_{2.5}$	Transport	46.4	42.9	42.2	39.7	37.8	35	31.4	28.8	27.4	26.1
	Total	138.2	133.6	130	124.6	122.7	117.4	113.3	109	116.9	111
NO_x	Transport	1018.2	940.5	897.3	832	804	734.7	649.6	594.5	569	538.2
	Total	1767.4	1712	1644.6	1573.5	1558.9	1481.1	1403.7	1305.1	1328.7	1288.3

It is recognized that the difference between the average PM_{10} concentration in group 1 (with introduction of LEZ in 2008) and group 2 (reference group outside LEZ) was smaller after the year 2008 than before 2008. In general, the average mass concentration at the stations of group 1 declined by about 6 µg/m³ (17 %) after the introduction of LEZ. At the traffic stations outside LEZ (group 2) the reduction amounted to only about 4 µg/m³ (14 %), as well as at background stations (group 3) with a similar amount of reduction for about 4 µg/m³ (15 %) in the same investigation period. Therefore, it could be estimated that the introduction of LEZ has caused an additional reduction of PM_{10} concentration of about 2 µg/m³. It shall be mentioned that this value becomes even smaller (only about 1.4 µg/m³) if we consider that even without any impact from the LEZ the absolute differences between the groups of stations are reduced due to the overall decrease of the pollution level.

The results of the statistical data analysis are shown in Table 4. Here all stations of group 1 were included in the analysis, and not only those, where the LEZ were introduced in the year 2008.The t test confirmed a significant decrease of the difference between group 1 and reference group 2 before and after introduction of LEZ of about 1.96 $\mu g/m^3$. This indicates that the PM_{10} concentration at stations inside LEZ has been reduced to a greater extent than at stations outside LEZ. It is interpreted as a positive direct effect of LEZ on reducing PM_{10} concentration. In the descriptive analysis (Table 2), it was also found that the decreasing trend at stations of group 1 (introduction of LEZ in 2008) was stronger than that at stations outside LEZ.

Table 4. Significance test for annual mean concentrations

Difference between group 1 and reference group 2	Mean before introduction [µg/m³]	Mean after introduction [µg/m³]	Number of samples	Difference in mean value [µg/m³]	T value	P value two-tail
PM_{10}	5.22	3.26	33	1.96	5.20	0.000
PM_{10} exceedance days	17.99 days	8.84 days	33	9.15 days	3.49	0.001
NO	15.10	11.47	28	3.63	2.75	0.011
NO_2	13.92	13.24	28	0.68	0.89	0.383
NO_x	36.98	30.60	28	6.37	2.45	0.021

4.2. Number of days exceeding the daily PM_{10} limit value

Other than the PM_{10} concentration, another parameter considered is the number of days in one year that exceeds the daily limit value of 50 µg/m³. Fig. 2 shows the trend of the number of exceedance days at stations from group 1 to 3 in the investigation period.

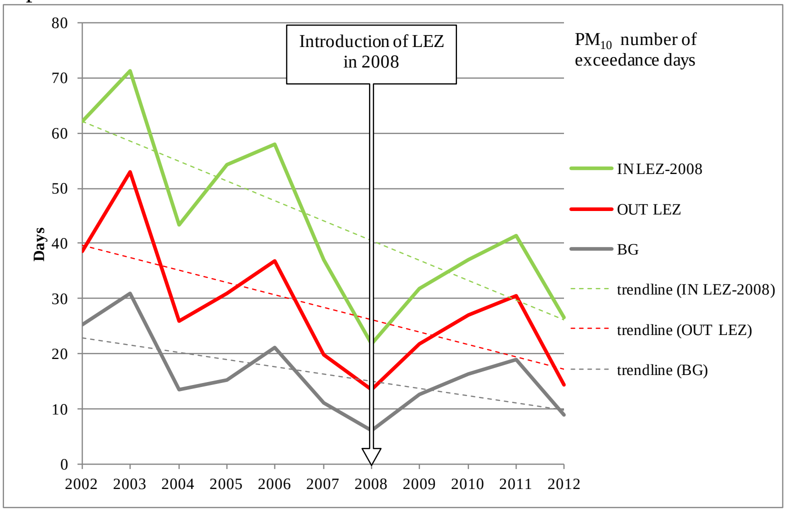

Fig. 2. Trend of average PM_{10} exceedance days from 2002 to 2012

Compared to the average annual PM_{10} concentrations, the same yearly fluctuations were observed. There was a decreasing trend of the number of exceedance days along the years.

As shown in Fig. 2 and Table 5, the average number of exceedance days in groups 1 (introduction LEZ 2008) declined from 54 days until 2008 to 32 days after 2008. The reduction was about 22 days (42%). In the reference groups 2 and 3, the reduction was around 13 days (37%) and 7 days (36%), respectively. The decreasing trend at stations with LEZ (2008) was significantly stronger than that at other reference groups. The difference between the number of exceedance days in group 1 and group 2 has also clearly decreased.

Table 5. Mean values of annual exceedance days before and after the introduction of LEZ

PM_{10} exceedance days	Average before introduction [number of days]	Average after introduction [number of days]	Reduction	
			Number of days	%
Group 1 (introduction of LEZ 2008)	54.41	31.75	22.66	41.6%
Group 2 (outside LEZ)	34.13	21.45	12.69	37.2%
Group 3 (urban background)	19.56	12.49	7.07	36.2%

The statistical test confirms this decreasing trend, similar with the results for PM_{10} concentration. The difference between the average annual exceedance days of group 1 and 2 has decreased significantly by about 9 days in the investigation period after the introduction of LEZ (as seen in Table 4), which can be considered as the effect of LEZ.

However, in comparison with the results of PM_{10} concentration, a strong decline in exceedance days has led to the compliance of the allowed exceedances of 35 days in many cases. Thus, it is believed that the effects of LEZ on controlling air pollution are more significant in reducing the number of exceedance days, although the absolute values are also not particularly high. The reduction of exceedance days has mainly legal benefits for those cities where the annual number of allowed exceedances are violated.

4.3. $PM_{2.5}$ annual mean concentration

There are significantly less data for the analysis of $PM_{2.5}$ mass concentrations available in the investigation period in comparison to other parameters. As shown in Table 1, there were only two stations available for the analysis of $PM_{2.5}$ concentration, which are located in an LEZ introduced in 2008 and also fulfill the quality criteria explained in section 2. Hence, it is not feasible to give a representative trend of the $PM_{2.5}$ concentration for the stations in group 1 (IN LEZ-2008). Due to the lack of data, a statistical analysis for the whole investigation period is not possible either. It has been examined, whether it is possible to conduct a primary analysis with less strict quality criteria. However, the data basis has barely improved even when less strict quality criteria were used.

The emission data from UBA (Table 3) showed that the total $PM_{2.5}$ emission from the transport sector in Germany has declined from 39.7 kt (2005) to 26.1 kt (2011). A similar decreasing trend was observed in the development of $PM_{2.5}$ mass concentrations at stations in group 2 and group 3. Generally the curves for group 2 and 3 were representative for the corresponding areas since there were a relative high number of qualified stations in the two groups, respectively 27 (group 2) and 36 (group 3) according to Table 1.

4.4. NO, NO_2, and NO_x annual mean concentrations

First of all, it must be pointed out that the effects of LEZ on NO_x are more indirect and complicated than those on particulate matter. This is due to the fact that the harmful NO_2 is not only emitted directly from vehicles but also produced by the chemical reaction of NO and ozone (O_3). Thus, their concentrations depend on many external factors. On the other hand, the change in motor technology (e.g. for diesel engines) which is optimized to lower energy consumption and lower particle emissions, can lead to an increase in direct NO_2 emission (e.g. Rauterberg-Wulff and Lutz [13], Dünnebeil et al. [22]). This can partly eliminate the effect of LEZ on renovation of old vehicles with low emission modern vehicles, which emit less NO_x. Nevertheless, an analysis on the trend of NO_x in the

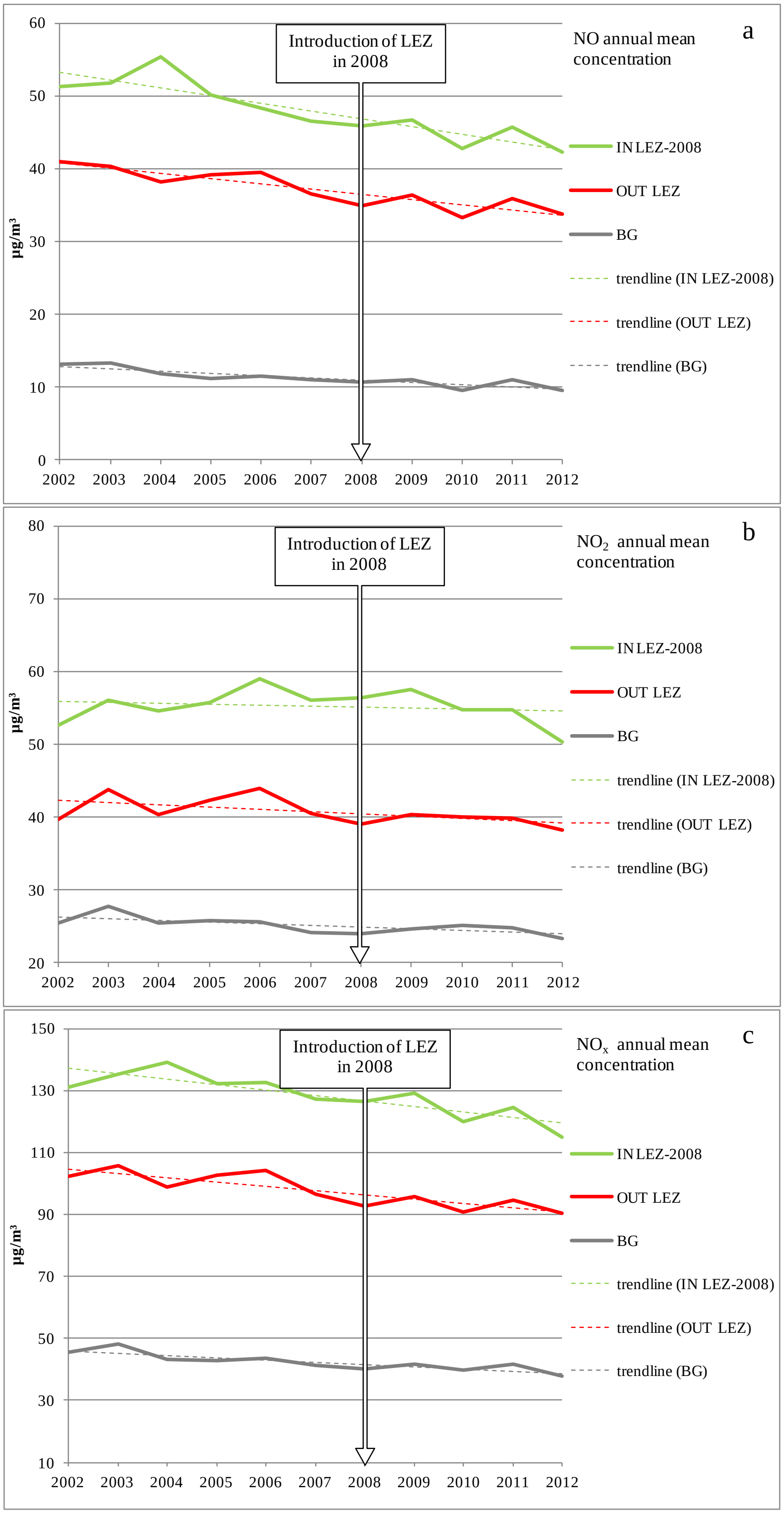

Fig. 3. (a) Trend of average annual NO concentration from 2002 to 2012; (b) trend of average annual NO_2 concentration from 2002 to 2012; (c) trend of average annual NO_x concentration from 2002 to 2012

investigation period was made. The concentration values for NO, NO_2 and NO_x were investigated according to the calculation methods mentioned above.

For NO, there was a constant slight decreasing trend of the concentration over the whole investigation period (Fig. 3a). However, it was not correlated with the introduction of LEZ, since it was clearly shown that the difference between group 1 and 2 was not significantly smaller after the introduction of LEZ. The reduction of NO concentration in absolute values at stations of group 1 was slightly larger than that at stations outside LEZ (see Table 6).

For NO_2, there were no significant changes in the measured data at stations of group 1 over the investigation period. However, the concentrations at stations of group 2 and 3 had a slight decreasing trend.

There were in general slight decreasing trends of NO_x concentrations (Fig. 3c). According to the calculation of UBA (Table 3), the total NO_x emissions from the transport section was reduced from 1018 kt in the year 2002 by approximately 50% to 538 kt in 2011.

Table 6 shows that the absolute and percentage reduction of NO_2 and NO_x concentration at stations outside LEZ and at background stations was even stronger than at stations inside LEZ. The effects of LEZ on nitrogen oxides emission are still uncertain after the primary data analysis, probably due to the complicated interrelation explained above.

Table 6. Average NO, NO_2 and NO_x concentration before and after introduction of LEZ

Air pollutant		Average before introduction [µg/m³]	Average after introduction [µg/m³]	Reduction [µg/m³]	Reduction %
NO	Group 1 (introduction of LEZ 2008)	50.57	44.67	5.9	11.7%
	Group 2 (outside LEZ)	39.13	34.79	4.33	11.1%
	Group 3 (urban background)	11.99	10.34	1.65	13.8%
NO_2	Group 1 (introduction of LEZ 2008)	54.9	54.74	0.16	0.3%
	Group 2 (outside LEZ)	41.76	39.49	2.27	5.4%
	Group 3 (urban background)	25.7	24.42	1.28	5.0%
NO_x	Group 1 (introduction of LEZ 2008)	132.26	123.08	9.18	6.9%
	Group 2 (outside LEZ)	101.66	92.89	8.77	8.6%
	Group 3 (urban background)	44.03	40.25	3.78	8.6%

The statistical analysis included all stations which fulfill the quality criteria (see section 2), not only the stations with an introduction of LEZ in 2008. The result showed a significant reduction (p value 0.021) of the difference between NO_x concentration at stations of group 1 and 2 before and after the introduction of LEZ of about 6 µg/m³. As mentioned in the descriptive analysis, the reduction of NO was significant, but not for NO_2. Previous studies showed that changes in motor technology would emit more direct traffic-related NO_2 emissions (not considering the oxidation from NO to NO_2) (Rauterberg-Wulff and Lutz [13], Dünnebeil et al. [22]). This could be a probable explanation to the calculated results shown here. Anyway, the direct and indirect effects of LEZ on NO_2 concentration should be further investigated.

5. Discussion and conclusions

First of all, the data analysis showed clearly that in Germany significant progress has been achieved in reducing the particle concentration in the last 10 years. This is partially due to the general reduction of emissions from the transport sector through new vehicle technologies, whose dissemination can be partially attributed to the introduction of LEZ. Furthermore, the introduction of LEZ has raised awareness of the population for problems with air pollutants, and hence has led indirectly to the reduction of air pollutant concentrations. However, the amount of such indirect effects of LEZ cannot be quantified here.

The following results have been achieved by comparing several parameters from stations inside and outside of LEZ:

- The local PM_{10} concentration at traffic stations in LEZ has reduced in average by 2 µg/m³ more than that at traffic stations outside LEZ. A part of these 2 µg/m³ can be explained just be the overall decrease of the pollution level, therefore only 1,4 µg/m³ remain as an effect of the LEZ. Vehicle exhaust is most responsible for small-sized particles in urban areas, which cause more harm on human health (Valavanidis et al. [23]). Since the particles emitted from the transport sector amount to about 20% of the total emission (Table 3), even the slight reduction can have positive impacts on the public health, as proved by other research (Wichmann [24], Zellner et al. [25]).
- The number of PM_{10} exceedance days declined at traffic stations in LEZ more significantly than at traffic stations outside LEZ. In average, the number decreased by extra 9 exceedance days. This effect has released the stress of respective cities with regards to the legal regulations as mentioned above.
- No statements can be given for the effects of LEZ on $PM_{2.5}$ concentration due to the lack of data base. It can only be concluded that the total emission and immission of particles showed a decreasing trend including $PM_{2.5}$. This is partially due to the effect of filter technology vehicle fleet and partially due to the indirect effect from the introduction of LEZ.
- The results for nitrogen oxides concentration are not easy to interpret. There is only very limited positive direct effects of LEZ on reducing nitrogen oxides concentration (if at all). Therefore, a more detailed investigation is necessary to consider both the complicated chemical processes and the developments in technology.

The results of this study are in compliance with results of other studies which investigated the effects of single LEZ. For example, according to Rauterberg-Wulff and Lutz [13], the LEZ in Berlin has reduced the annual mean PM_{10} concentration by about 2 µg/m³ and the number of exceedance days by 10 days. However, in contrast to the data presented in this study, the Berlin study found that the nitrogen oxides concentration exhibited a decreasing trend, too.

In total, the LEZ are evaluated to be positive considering its overall impacts on fleet composition and emissions as well as the reduction of number of exceedance days. The successive implementation in Germany and other countries in Europe also suggests that this instrument can be used by developing countries with severe air pollution problems (e.g. China and India) to improve air quality and more importantly to protect human health.

For the future, the following considerations should be kept in mind:

- The introduction of further LEZ in Germany doesn't have much more additional reduction potential with regards to the current limit value for ambient air quality, since the percentage of vehicles with green sticker in Germany has already reached 89% (ADAC Ressort Verkehr [26]). The rest of the vehicles usually fulfill the exception rules. Therefore, the introduction of new LEZ would have larger impacts only if new limit values are set up or other emitters are included. New limit values for air quality would give more incentives to a further reduction of air pollution. In the meanwhile, new regulations of LEZ for vehicles (including the consideration of other emitters) can control the emission from road transport more strictly.
- Currently, there is a large problem in many cities in Germany that the limit value for nitrogen dioxide is often exceeded. The analysis in this study doesn't provide any indication that introducing new LEZ is going to help with solving this problem.
- It should be noted that the LEZ does not influence all air pollutants under the current regulations. And LEZ do not serve to solve problems such as climate change. In the public opinion as well as expert interviews, which the co-author conducted in the framework of a research project about climate protection in the transport sector, measures to control air pollution are however often mixed up with measures for GHG reduction (Groer and Boltze [27]).
- Measures to control air pollution can also have disadvantages, and this should be considered and adequately assessed. On the one hand, there is too little knowledge about the concrete effects of other air pollution control

measures, e.g. about the impacts of truck bans on the logistics and production processes. Thus, integrated strategies with a bundle of measures are necessary in order to minimize or even eliminate goal conflicts. To reduce negative side-effects, such strategies should be dynamic and situation-responsive. These strategies should be updated according to the up-to-date challenges after application.

In conclusion, it is not the aim of this paper to question the recent decisions of introducing LEZ but only to discuss about the effectiveness of LEZ particularly. However, it is clear that there is not much potential in further reducing air pollution concentration by introducing new LEZ under the current characteristics. Instead, the instrument of LEZ should be further developed, towards stricter limit values and regulations and towards an inclusion of all relevant air pollutants and emitters. Furthermore, the potential of other measures to avoid, shift and improve traffic flows should be fully exploited (e.g. truck ban). Another option for many cities, with no doubt, is a comprehensive optimization of traffic signal control, which needs investments in the necessary technology.

Subsequent remark

After finishing this study, it was becoming public in September 2015 that at least one German car manufacturer has manipulated vehicle emission tests and therefore has created significantly more emissions in real traffic with its cars. Without detailed analysis, the effect of this manipulation is difficult to estimate but the authors assume that the effectiveness of LEZ could have been better than it was.

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