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Positive impact of the introduction of low-emission zones in Antwerp and Brussels on air quality, socio-economic disparities and health: a quasi-experimental study

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ABSTRACT

Low emission zones (LEZ) manage traffic entering cities by granting access only to vehicles that meet certain emission standards. This study evaluated if implementation of LEZs in Antwerp (2017) and Brussels (2018) improved air pollution within the boundaries of the defined zones, if spatial spillover effects occurred, if socioeconomic inequality in air pollution exposure changed over time, and if health was affected. The study population comprised 420,007 individuals living within the LEZs, within seventeen control cities or within adjacent areas of these cities. Annual residential air pollution ($PM_{2.5}$, PM_{10}, NO_2, BC) was calculated for 2016–2022. Individual-level health outcomes (diabetes, cardiovascular disease, obstructive airway diseases, antidepressants, antithrombotic agents) were available for 2014–2023. Random effect models were constructed to assess the impact of LEZs on air pollution and socioeconomic disparities, and a comparative interrupted time series analysis was conducted to evaluate the health impact. Findings suggest that with the introduction of the LEZ, all pollutant concentrations declined significantly more rapidly in both Antwerp and Brussels and adjacent areas compared to other Belgian cities and adjacent areas. Socioeconomic disparities in BC and NO_2 concentrations decreased over time. Findings for the evolution of diabetes suggested a positive impact of the LEZ for this particular outcome. This study suggests that LEZ implementation holds strong advantages that may extend beyond the boundaries of the defined zones. As air pollution concentrations in European cities are still high, policies such as LEZs are required to attain the World Health Organisation Global Air Quality Guidelines.

1. Background

Air pollution has detrimental effects on both physical and mental health (Dominski et al., 2021; Hegelund et al., 2024; Radua et al., 2024). To improve air quality within cities and assure that individuals can enjoy cities more, there is a wide range of urban air pollution control policies and strategies. Low emission zones (LEZ) manage traffic entering cities by granting access only to vehicles that meet certain emission standards. In 2022, 320 LEZs were in force across Europe (Azdad et al., 2022).

Epidemiological studies have documented the effect of the introduction of LEZs on air pollution levels as well as on health outcomes. Most studies on the impact of LEZs on air quality report small to moderate improvements, with evidence stemming from major European cities like London (Ellison et al., 2013; Hajmohammadi and Heydecker, 2022), Rome (Cesaroni et al., 2012), Lisbon (Ferreira et al., 2015), Madrid (Salas et al., 2021), Amsterdam (Panteliadis et al., 2014) and Berlin (Cyrys et al., 2014). A systematic review of 8 studies covering the health impact of LEZs concluded that LEZs may improve health outcomes linked to air pollution. Evidence was most pronounced for

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cardiovascular disease outcomes, with less consistent results for other health outcomes (Chamberlain et al., 2022).

Of increasing scientific and political attention is the unequal exposure to air pollution across socioeconomic groups and whether policies like LEZ affect such inequalities. Evidence is mounting that socioeconomically disadvantaged regions, neighbourhoods and groups are more exposed to air pollution, resulting in disproportionate health effects. Considering 19 inequality indicators, the World Health Organization (WHO) confirmed that socially disadvantaged population subgroups are most affected by environmental hazards, carrying a disproportionate environmental burden (World Health Organization, 2019). The evidence base has particularly increased for cities in Western Europe. In a study from Paris, the most deprived census blocks appeared as one of the groups most impacted by air pollution. The analysis showed a cluster of excess premature deaths in the north-Eastern area of Paris (Kihal-Talantikite et al., 2018). In Barcelona, there was a differential exposure for almost all of the air pollutants studied. For both men and women, the risk of dying due to environmental hazards was about 30 % lower in very affluent neighbourhoods compared to more deprived ones (Saez and López-Casasnovas, 2019). A study in Ghent, Belgium, found that neighbourhoods with lower household incomes, more unemployment, more people of foreign origin, more rental houses, and higher residential mobility, are more exposed to air pollution (Verbeek, 2019). The distribution of social demographics in urban areas and the design of the LEZ play a crucial role in shaping how inequality in exposure to air pollution changes over time (Young et al., 2023). For instance, relative to the least deprived areas in London, more deprived areas had higher concentrations of air pollution and have benefited more from the introduction of the LEZ in terms of both air pollution reductions and mortality (Brook et al., 2023). However, in Rome, affluent citizens are more likely to reside in the city center, are subjected to higher levels of air pollution than less privileged groups, and benefited more from the LEZ because it targeted the city center (Cesaroni et al., 2012).

Spatial spillover effects to neighbouring areas are another interesting yet little-studied aspect of the introduction of LEZs. In Madrid, monitoring stations located in LEZ adjacent areas showed significant reductions in air pollution levels, albeit smaller compared to monitoring stations within the LEZ. According to the authors, these findings suggested that citizens' modes of transportation had changed (Salas et al., 2021). A study measuring the effects of different German LEZs, on the other hand, found that adverse spillover to adjacent areas within 500 m of LEZ borders occurred, as indicated by an increase in air pollutant concentrations. This was probably the result of traffic being rerouted to other main ring routes. This study also discovered that individuals who lived inside or near an LEZ saw a similar short-term decline in life satisfaction. The authors linked this to the cost of restricted mobility that affected both groups. Compared to individuals who lived outside of an LEZ, those who lived inside of one had a persistently lower number of doctor visits and instances of hypertension, yet similar health improvements could not be found for individuals living in adjacent areas of LEZs (Sarmiento et al., 2023).

In Belgium, LEZs in Antwerp, Brussels, and Ghent have been in place since February 2017, January 2018, and January 2020 respectively. Tighter regulations depending on the type of fuel and European emission standard have come into force ever since (Supplementary file A). These emission standards are designed to increasingly limit polluting gas emissions from vehicles in Europe. In the Belgian LEZs, different regulations may apply to different vehicle categories and some vehicles are eligible for an exemption. LEZs are a contentious policy in Belgium, as they are in many other nations. In Antwerp and Ghent, a tightening of the rules for their LEZ was foreseen for 1 January 2026 by the government of Flanders (i.e. the Dutch-speaking part in the north of Belgium) in 2022 but was abandoned by the new government in 2024 (Vlaamse Regering, 2024). In Brussels, a specific roadmap was defined, which aimed to ban diesel cars by 2030 and petrol cars by 2035. However, with the elections of 2024 the balance of power shifted, and the Brussels Parliament postponed planned milestones (Brussels Hoofdstedelijk Parlement, 2024). The Walloon Region (i.e. the French-speaking part in the south of Belgium) in 2019 decided to convert its entire region to an LEZ by 2023. Later, this was postponed to 2025, and in April 2024, the Walloon Parliament unanimously repealed the decree. The Walloon Region now aims, without further detail, to improve air quality, particularly in urban areas, using tools other than LEZ (Mouvement Réformateur & Les Engagés, 2024).

To date, although the effect of Belgian LEZs on air pollution is monitored, a comparative evaluation with control cities is lacking, and spillover effects, the evolution of socioeconomic inequalities in air pollution exposure, and the impact on health outcomes have not been studied yet.

2. Objective

This assessment of the implementation of LEZs in Belgium had three goals. First, to evaluate if the LEZs' implementation affected air pollution within the boundaries of the defined zones and if spatial spillover effects occurred. Second, to investigate if socioeconomic inequality in exposure to air pollution changed over time with the implementation of LEZs. Third, to assess how the LEZs' implementation affected population health.

3. Methods

3.1. Study design

The implementation of LEZs in three Belgian cities since 2017 creates a quasi-experimental study in which certain citizens are exposed to an LEZ and others are not, outside the control of the researchers. Our research is predicated on the supposition that the effects of the LEZs' implementation would be gradual, leading us to anticipate a slope shift in our outcome measures of health and air quality. For the Ghent LEZ, a limited number of descriptive statistics are provided since it is too soon to assess its effects.

3.2. Study population

Health outcomes and air quality were studied in the top 20 Belgian cities according to population size. This included the three LEZ and 17 control cities, 10 of which are in Flanders (Aalst, Bruges, Courtrai, Genk, Hasselt, Louvain, Mechlin, Ostend, Roeselare, Sint-Niklaas) and 7 of which are in Wallonia (Charleroi, La Louvière, Liège, Mons, Namur, Seraing, Tournai). The study population comprised 420.007 members of the Independent Health Insurance Funds (about 2.1 million members in 2014) who lived at the same address during the study period (01-01-2014 to 31–12-2023) within either the three LEZ or the seventeen control cities, or within adjacent areas (to study spatial spillover) 1, 1–2, 2–5 km of those cities.

Shapefiles that are openly available for download from official government websites were used to define the LEZs' boundaries. City centers were chosen to designate the area of the 17 control cities (Supplementary file B). Fig. 1 displays the LEZs and control cities along with the 1 km, 1–2 km, or 2–5 km adjacent areas. Individuals who lived in overlapping adjacent areas were assigned to the city they lived closest to.

3.3. Measures

3.3.1. Air quality

High resolution air quality maps, provided as open data from the Belgian Interregional Environment Agency (IRCELINE), were used for the period 2016–2022. These maps include annual averages of particulate matter with a diameter of less than 2.5 ($PM_{2.5}$) or 10 (PM_{10}) micron, black carbon (BC) and nitrogen dioxide (NO_2) estimated by the

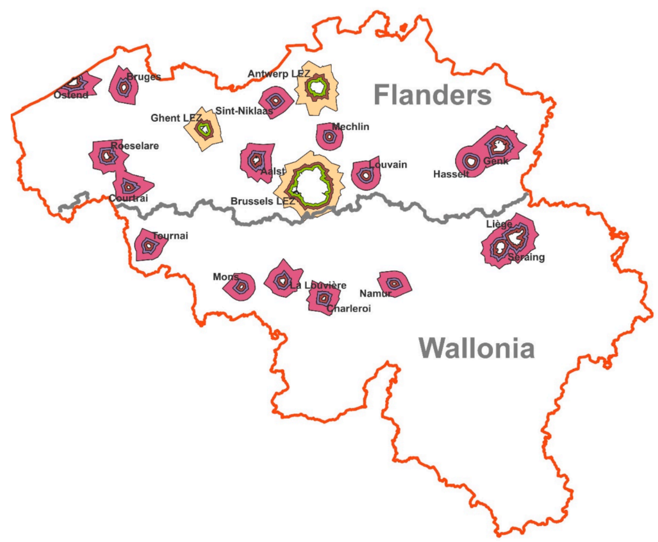

Fig. 1. Antwerp, Brussels and Ghent Low Emission Zones and 17 control cities without LEZs with adjacent areas of 1 km, 1–2 km, and 2–5 km.

ATMO-Street model. ATMO-Street is an integrated model chain that models air quality by combining three models. First, the background concentrations on a resolution of 4x4 km^2 are estimated by interpolating the fixed monitoring measurements taking into account the relationship between air pollution and land cover (Janssen et al., 2008). The number of fixed stations in Belgium varies between 2016 and 2022 from 72 to 84 for PM_{10}, from 71 to 83 for $PM_{2.5}$, from 93 to 97 for NO_2 and from 29 to 41 for BC. A large part of the stations is located in the cities of Antwerp, Brussels and Ghent. In a second step, dispersion modelling is done based on emissions from road traffic, shipping and large industrial point sources, using the actual meteorological conditions. Traffic data used as input for the model includes traffic volumes as well as vehicle fleet inside and outside the LEZ on a yearly basis and on a very detailed road network. To improve air quality estimations within street canyons, an often-occurring configuration in urban environments, the Operational Street Pollution Model (OSPM) (Jensen et al., 2017) was added to the background (RIO) and dispersion model (IFDM) calculating the extra share of accumulated air pollution within a street canyon. Double counting between the models is avoided by double-counting corrections. ATMO-Street data is a receptor model, calculated on very dense grid and eventually gridded to a high resolution of 10x10m^2. ATMO-Street model results have been available since 2016 for Flanders and Brussels, and since 2017 for the whole of Belgium. More information on the air pollution model is described elsewhere (Lefebvre et al., 2013b). The separate models, as well as the model chain as a whole have been validated in several validation campaigns. For NO_2, a root mean square error (RMSE) of 15 % was shown for the whole model chain, and 16 % without the street canyon model (Lefebvre et al., 2013b). For NO_2, PM_{10} and O_3 an RMSE (spatial) of respectively 21.7 %, 13.7 % and 8.8 % was shown (Lefebvre et al., 2013a). For BC, an RMSE of 0.32 $\mu g/m^3$ has been observed (Lefebvre et al., 2011). For $PM_{2.5}$, an RMSE (spatial) of 1.72 $\mu g/m^3$ has been reported (IRCELINE, 2016). Finally, IRCELINE also validated NO_2 by means of a massive passive sampler campaign (17,886 measurements) and reported an RMSE of 5.2 $\mu g/m^3$ (Hooyberghs et al., 2022).

Residential exposure to $PM_{2.5}$, PM_{10}, BC and NO_2 using the study population's geocoded home address was extracted from the ATMO-Street air quality model maps.

3.3.2. *Health outcomes*

To construct health outcomes, data from the Independent Health Insurance Funds were used for the period 2014–2023. These rich databases contain individual-level administrative and accounting data of reimbursed medical care and medicines provided to a person on a given date. While diagnoses are not directly available, these data allow the creation of proxy indicators of a wide variety of health outcomes that have also been evaluated in previous studies on the evaluation of LEZs or in assessment of the impact of air pollution. Long term health outcomes are the chronic use ($\geq$90 defined daily doses, a standardized measure used to determine the average daily dose of a medication used for its main indication) of medicines for one of the following conditions: diabetes (Anatomical Therapeutic Chemical (ATC) classification A10A and A10B), cardiovascular disease (ATC C01, C02, C03, C07, C08, and C09), obstructive airway diseases (ATC R03), antidepressants (ATC N06A), and antithrombotic agents (ATC B01).

3.3.3. *Socioeconomic position*

Information on socioeconomic position at the level of census tracts was available via the recently developed Belgian Indices of Multiple Deprivation (BIMD) (Otavova et al., 2023). Census tracts are a nationwide geographic subdivision of municipalities based on urban development, socioeconomic characteristics, and morphological properties. In the remainder of the text, census tracts were referred to as neighbourhoods. To avoid collinearity with health outcomes, the BIMD version without health deprivation was used, which is a composite measure of income, employment, education, and housing, and is available for the year 2011. The developers of the BIMD used BIMD scores to group neighbourhoods into deciles with the first decile comprising the 10 % most deprived neighbourhoods. Supplementary file C details the distribution of BIMD deciles across Belgium. The six upper deciles (BIMD $\geq$ 5 were combined in further analyses).

3.3.4. *Potential confounders*

The health impact analysis was controlled for individual-level characteristics as well as characteristics of neighbourhoods. At an individual level, age, sex, and nationality were included. These are directly available from administrative data sources from the Independent Health Insurance Funds. Nationality was recoded as Belgian, Western European (excluding Belgians), Eastern European, Asian, African, South American or North American. At a neighbourhood level, tree cover was included, categorized as 0–9.99 %, 10–10.99 %, 20–20.99 % and > 30 %. Information on tree cover is available for the year 2018 and is calculated from the European Union's Copernicus Land Monitoring Service information. Appendix C shows the distribution of tree cover across Belgium. Higher neighbourhood tree cover has previously been shown to be associated with less medical care utilization in Belgium (Vranken et al., 2023).

3.4. *Statistical analysis*

Baseline characteristics of individuals included in the analysis are displayed. Percentages are reported for sex and nationality and average and standard deviation are shown for age.

To evaluate the evolution of air pollution for the LEZs compared to control cities, average annual (2016–2022) residential exposure from ATMO-Street data is described, aggregated by city (Antwerp, Brussels, Ghent, control cities in Flanders, and control cities in Wallonia), both within city boundaries as well as in adjacent areas. For each pollutant separately statistical models are then constructed to compare the evolution of air pollution for individuals living within an LEZ city versus individuals living in control cities, individuals living within a 1 km adjacent area of an LEZ city versus a 1 km adjacent area of control cities, individuals living within a 1–2 km adjacent area of an LEZ city versus a 1–2 km adjacent area of control cities, and individuals living within a 2–5 km adjacent area of an LEZ city versus a 2–5 km adjacent area of control cities. Random effect models are estimated with time (i.e. year) as a continuous variable, exposure (i.e. subjects living either in the LEZ or control cities), baseline (i.e. the value of the pollutant in the year before the introduction of the LEZ), and a time by exposure interaction as fixed effects, as well as a random intercept and random slope for year. A constant association of the baseline measurement with all subsequent measurements is assumed. Antwerp is compared with control cities in Flanders only because Antwerp implemented its LEZ in 2017 and ATMO-Street data for the baseline year, 2016, are not available for Wallonia. Brussels is compared with both Flemish and Walloon cities since the LEZ was implemented in 2018 and ATMO-STREET data for the baseline year, 2017, are available in the whole of Belgium. Last, the evolution in air quality is also compared for individuals living within LEZ cities versus individuals living in adjacent areas, for both Brussels and Antwerp.

To examine if the establishment of the LEZ affected the association between socioeconomic deprivation and air quality, the distribution of the BIMD across neighbourhoods in Antwerp, Brussels, and Ghent is visualized, adding an NO_2 overlay to have a first impression of the association with air pollution. The same statistical approach as above is used, but with fixed effects for BIMD and a time by BIMD interaction instead of a time by exposure interaction.

To evaluate the health impact of the introduction of the LEZ, a propensity score method is followed by a comparative (controlled) interrupted time series (cITS) analysis. To balance the composition of the LEZ population (i.e. individuals living in any of the LEZ) and the control population (i.e. individuals living within any of the control cities), the inverse of the propensity scores (IPS) is used as weights to estimate the average treatment effect (ATE). Baseline individual covariates include age, gender, and nationality. At the level of neighbourhoods, covariates are BIMD and tree cover. Antwerp is compared with control cities in Flanders and Brussels with both Flemish and Walloon cities to account for known difference in healthcare use across regions. The cITS analysis allowed to evaluate the annual change in the health outcomes trajectory (i.e. slope), whether this trajectory changed after the introduction of the LEZ (i.e. slope change), and whether any change in trajectory differed across LEZ and control cities (i.e. difference in slope change). Repeated measurements of the health outcomes were created at an annual level for each individual. As the outcomes are binary (chronic use of medicines or not) the binary link function was used in the regression. To account for the correlation that is expected among the multiple measurements on a given subject, a Generalized Estimating Equations (GEE) model was used. Estimation was done at the event probability scale. Predictions from the logistic regression model were transformed to the probability scale for interpretation and visualization. The model, which was IPS weighted, is written as:

$$\mu_{it} = \beta_0 + \beta_1 Time + \beta_2 Post + \beta_3 Post^*Time + \beta_4 Exposure + \beta_5 Exposure^*Time + \beta_6 Exposure^*Post + \beta_7 Exposure^*Post^*Time + \varepsilon_{it}$$

where μ_{it} is the expected mean value for subject i at time t, *Time* is a variable representing the year of the outcome measurement, *Post* is a binary indicator that the outcome measurement was made before or after the implementation of the LEZ, *Exposure* is a binary indicator that the subject is living in a city in which the LEZ is eventually implemented or in a control city in which no such intervention is implemented, and ε_{it} is the error term for the outcome measure of subject i at time t. If the coefficient estimate *Exposed*Post*Time* is statistically significant (i.e. difference in slope change), the health outcome trajectories in the LEZ and control cities are not parallel, and so the LEZ has affected the health outcome in the exposed group differently.

All tests were 2-sided and assessed at a significance level of 5 %. No adjustments were made for multiple testing.

QGIS Graphical Information System 3.34 was used for the analysis of geospatial data. All statistical analyses were conducted using SAS software.

4. Findings

4.1. Study population characteristics

The number of individuals by city as well as their baseline characteristics are described in Table 1. Within the LEZ or control cities, 175.691 members resided, 58.874 members lived within 1 km of those cities, 58.506 lived within 1–2 km from those cities, and 126.936 lived within 2–5 km from those cities. Age varied largely across cities, both for individuals living within cities and individuals living in adjacent areas. Average age of individuals living within cities ranged from 38 years in Brussels and Genk to over 50 years in Namur, Tournai, and Ostend. The percentage of males varied between 45 % and 50 %, and the percentage of Belgians ranged from 77 % in La Louvière to 97 % in Roeselare.

4.2. Impact of LEZs on air pollution

4.2.1. Evolution of air pollution for individuals living within LEZ cities versus within control cities

Fig. 2 displays average annual air pollution concentrations. Compared to control cities, individuals living within Antwerp and Brussels were confronted with higher concentrations of air pollutants in the years before LEZ implementation. They then saw a greater improvement in air quality with the LEZ compared to air quality improvements in control cities. In Brussels, NO_2 concentrations reduced from 29.44 μg/m^3 in 2017, the year before the introduction of the LEZ, to 18.53 μg/m^3 in 2022. Compared to Brussels, the NO_2 concentration in Walloon control cities was thus higher in 2022 (19.21 μg/m^3) while it was lower in 2017 (26.10 μg/m^3). Similarly, the average BC concentration in Brussels in 2017 was 1.32 μg/m^3. In control cities in Flanders and Wallonia, this was 1.23 μg/m^3 and 1.19 μg/m^3, respectively. In 2022, the BC concentration was lower in Brussels (0.66 μg/m^3) compared to that in control cities in Flanders (0.79 μg/m^3) and Wallonia (0.68 μg/m^3). In 2016, the year before the introduction of the LEZ in Antwerp, the average $PM_{2.5}$ concentration was 14.03 μg/m^3. In control cities in Flanders, this was 13.46 μg/m^3. In 2022, the $PM_{2.5}$ concentration was lower in Antwerp (11.65 μg/m^3) compared to that in control cities in Flanders (11.72 μg/m^3).

Of note, two other important conclusions can be drawn from the evolution in air quality. First, lowest pollution values can be seen in 2020, i.e. during the COVID-19 crisis. Second, the evolution in air quality varied substantially across control cities (Supplementary file D).

Our statistical analysis confirmed that since the introduction of the LEZ in Antwerp and Brussels, all pollutant concentrations improved more rapidly in Antwerp and Brussels compared to control cities in Flanders and Wallonia (Table 2). With the LEZ city being the reference category, this can be observed from the positive and statistically significant estimates for control cities in Flanders and Wallonia for the time by exposed interaction. Interpretation is as follows, for example; NO_2 on average showed an annual 0.71 μg/m^3 stronger decline ($P < 0.0001$) between 2016 and 2022 in Antwerp compared to control cities in Flanders.

4.2.2. Evolution of air pollution for individuals living in adjacent areas of LEZs versus adjacent areas of control cities

Average annual air pollution concentrations for adjacent areas of LEZs and control cities are provided in Supplementary file E. Individuals living within adjacent areas of the Brussels LEZ were exposed to lower NO_2 concentrations in 2022 compared to individuals living in adjacent areas of control cities, whereas this was the other way around before the implementation of the LEZ.

Findings for the statistical modelling are displayed in Supplementary file E. Interpretation is identical to that of the previous section. For all pollutants there is a statistically significantly more rapid decrease for individuals living in adjacent areas of LEZ cities compared to individuals living in adjacent areas of control cities in Flanders and Wallonia. The

Table 1
Number and baseline characteristics of individuals included in the analysis.

City	Individuals within city				Individuals within 1 km from city				Individuals within 1–2 km from city				Individuals within 2–5 km from city			
	n	Age, avg. (SD)	Male, %	Belgian, %	n	Age, avg. (SD)	Male, %	Belgian, %	n	Age, avg. (SD)	Male, %	Belgian, %	n	Age, avg. (SD)	Male, %	Belgian, %
LEZ cities	**152.570**				**26.095**				**30.081**				**56.840**			
Antwerp	13.326	38 (22)	50	88	6804	42 (22)	47	94	11.332	41 (22)	48	95	25.074	40 (22)	48	97
Brussels	135.640	40 (23)	47	81	14.728	40 (23)	48	88	14.127	39 (23)	48	89	21.836	40 (23)	49	89
Ghent	3604	42 (22)	49	93	4563	39 (22)	47	95	4622	40 (23)	48	97	9930	40 (22)	49	98
Control cities	**23.121**				**32.779**				**28.425**				**70.096**			
Flanders																
Aalst	929	41 (22)	47	93	1334	38 (22)	48	97	1065	37 (21)	51	97	5322	37 (21)	50	96
Bruges	1049	47 (21)	48	96	2267	44 (22)	53	99	2171	42 (22)	49	99	3094	42 (22)	50	99
Courtrai	298	49 (24)	45	95	1797	40 (22)	50	98	1836	40 (21)	48	98	5793	39 (21)	51	99
Genk	1088	38 (21)	50	88	593	39 (22)	48	91	291	34 (21)	51	91	658	39 (21)	51	91
Hasselt	545	49 (23)	50	94	187	43 (24)	49	97	289	42 (22)	48	97	853	42 (22)	49	97
Louvain	639	45 (22)	45	90	1235	40 (23)	50	95	1220	43 (23)	48	95	4370	40 (23)	50	92
Mechlin	380	41 (22)	48	88	933	38 (21)	49	96	725	35 (21)	47	96	5324	37 (22)	49	93
Ostend	1504	54 (20)	46	96	2155	47 (21)	48	98	583	46 (22)	49	98	1015	43 (21)	50	98
Roeselare	811	46 (21)	49	97	1644	41 (21)	49	99	751	39 (21)	52	99	2338	39 (22)	50	99
Sint-Niklaas	337	40 (22)	48	96	773	39 (22)	49	99	504	38 (21)	49	99	1954	38 (21)	51	99
Wallonia																
Charleroi	209	49 (23)	47	89	1238	41 (23)	52	87	1632	42 (22)	46	87	6474	41 (22)	49	89
La Louvière	1173	45 (22)	47	77	2276	43 (21)	47	79	3031	40 (22)	49	79	5823	42 (21)	48	80
Liège	9121	45 (22)	47	90	8444	43 (22)	46	90	5077	43 (22)	48	90	8850	43 (22)	48	94
Mons	608	49 (21)	50	88	1763	45 (22)	46	91	1616	45 (21)	47	91	6397	43 (22)	47	85
Namur	105	50 (19)	47	91	1114	43 (23)	44	98	1387	42 (22)	48	98	3192	42 (22)	48	98
Seraing	3713	46 (22)	46	87	3648	45 (22)	47	86	5462	44 (22)	46	86	7139	46 (22)	48	92
Tournai	612	51 (20)	48	88	1378	46 (22)	45	92	785	46 (22)	45	92	1500	44 (22)	49	94
Total	**175.691**				**58.874**				**58.506**				**126.936**			

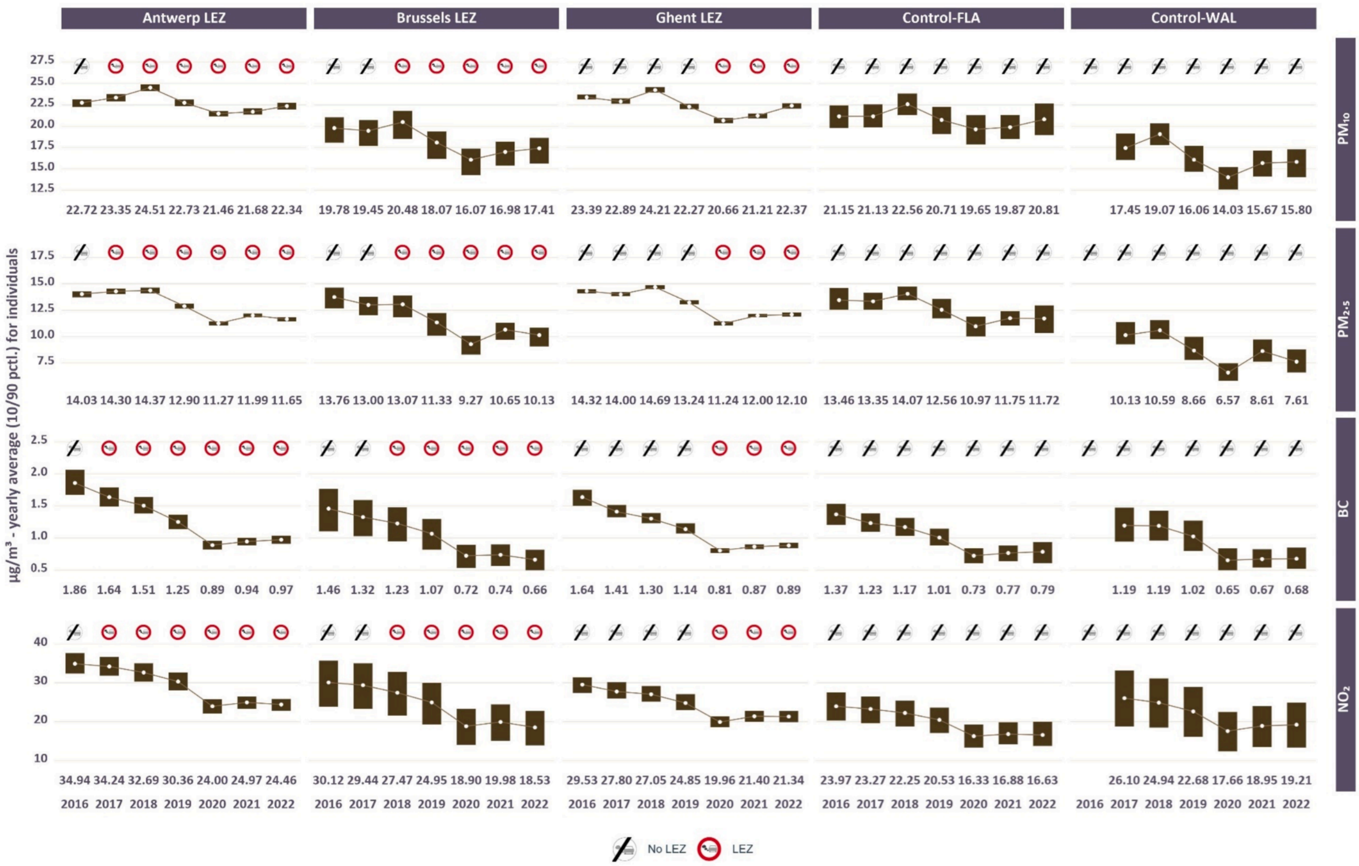

Fig. 2. Average annual residential exposure to PM_{10}, $PM_{2.5}$, BC, and NO_2 for individuals living within the Antwerp, Brussels, and Ghent Low emission Zones or within control cities: evolution 2016–2022.

Table 2
Average annual residential exposure to PM_{10}, $PM_{2.5}$, BC, and NO_2 for individuals living within the Low emission Zones or within control cities: evolution 2016–2022 for individuals living in the Antwerp Low Emission Zone versus individuals living in control cities in Flanders and for individuals living in the Brussels Low Emission Zone versus individuals living in control cities in Flanders or Wallonia.

	$PM_{2.5}$, µg/m³	PM_{10}, µg/m³	BC, µg/m³	NO_2, µg/m³
	Estimate (p-value)	Estimate (p-value)	Estimate (p-value)	Estimate (p-value)
Antwerp				
Intercept	7.087 (<0.0001)	6.723 (<0.0001)	1.022 (<0.0001)	10.434 (<0.0001)
Exposed				
Antwerp (LEZ)	Ref	Ref	Ref	Ref
Flanders (Control)	−0.556 (<0.0001)	−1.086 (<0.0001)	−0.226 (<0.0001)	−3.515 (<0.0001)
Time	−0.628 (<0.0001)	−0.422 (<0.0001)	−0.153 (<0.0001)	−2.241 (<0.0001)
Time*exposed				
Antwerp (LEZ)	Ref	Ref	Ref	Ref
Flanders (Control)	0.152 (<0.0001)	0.114 (<0.0001)	0.047 (<0.0001)	0.712 (<0.0001)
Baseline (2016)	0.560 (<0.0001)	0.767 (<0.0001)	0.384 (<0.0001)	0.740 (<0.0001)
Brussels				
Intercept	0.558 (<0.0001)	1.580 (<0.0001)	0.491 (<0.0001)	5.291 (<0.0001)
Exposed				
Brussels (LEZ)	Ref	Ref	Ref	Ref
Flanders (Control)	0.671 (<0.0001)	0.464 (<0.0001)	−0.070 (<0.0001)	−0.896 (<0.0001)
Wallonia (Control)	0.070 (<0.0001)	0.124 (<0.0001)	−0.016 (<0.0001)	−0.960 (<0.0001)
Time	−0.655 (<0.0001)	−0.722 (<0.0001)	−0.146 (<0.0001)	−2.285 (<0.0001)
Time*exposed				
Brussels (LEZ)	Ref	Ref	Ref	Ref
Flanders (Control)	0.106 (<0.0001)	0.287 (<0.0001)	0.045 (<0.0001)	0.799 (<0.0001)
Wallonia (Control)	0.054 (<0.0001)	0.029 (<0.0001)	0.008 (<0.0001)	0.765 (<0.0001)
Baseline (2017)	0.946 (<0.0001)	(<0.0001)	0.627 (<0.0001)	0.799 (<0.0001)

Note: Random effect models are estimated with time (i.e. year), exposure (i.e. subjects living either in the LEZ or control cities), baseline, and a time by exposure interaction as fixed effects, as well as a random intercept and random slope for year, assuming a constant association of the baseline measurement with all subsequent measurements.

only exception is the evolution of BC for individuals living within 2–5 km adjacent areas of control cities in Wallonia versus individuals living within 2–5 km adjacent areas of Brussels (P = 0.4205).

4.2.3. Evolution of air pollution for individuals living in LEZs versus adjacent areas of LEZs

Air quality in many instances improved statistically significantly more rapidly within the LEZs compared to adjacent areas of the LEZs (Supplementary file E). However, in Antwerp, all pollutants declined more rapidly in the 1 km adjacent area compared to within the city. For example, both BC and NO_2 concentrations were higher in the 1 km adjacent area in 2017 compared to the concentrations within the city, but in 2022 concentrations within the 1 km adjacent area were lower compared to the concentrations within the city. In Brussels, $PM_{2.5}$ also improved more rapidly in the 1 and 1–2 km adjacent areas compared to within the city.

4.3. Air pollution, socioeconomic deprivation and LEZ

A total of 821 neighbourhoods with an available BIMD score were identified for the Antwerp (n = 99), Brussels (n = 690), and Ghent (n = 32) LEZ. Fig. 3 illustrates variation in BIMD across these neighbourhoods. There was limited variation in BIMD categories within Antwerp and Ghent. In Antwerp, most neighbourhoods fell into the most deprived category (BIMD 1 (n = 55)), with much less individuals in the other categories (BIMD 2 (n = 30), BIMD 3 (n = 10), BIMD 4 (n = 3), BIMD ≥ 5 (n = 1)). In Ghent as well, most neighbourhoods fell into the most deprived category BIMD 1 (n = 14), leaving very few neighbourhoods in the other categories (BIMD 2 (n = 11), BIMD 3 (n = 2), BIMD 4 (n = 5), BIMD ≥ 5 (n = 0)). The statistical analysis focused on Brussels, which had enough neighbourhoods across BIMD categories (BIMD 1 (n = 263), BIMD 2 (n = 146), BIMD 3 (n = 112), BIMD 4 (n = 75), BIMD ≥ 5 (n = 94). In Brussels, more deprived areas are in the city center. Overlaying this with NO_2 concentrations, the inner ring road with its pentagonal shape and adjacent streets crosses the more deprived areas.

Fig. 4 presents a visual depiction of the evolution (2016–2022) in air quality across socioeconomic position in Brussels. Several observations can be made. First, air quality is consistently worse with each increase in deprivation. Both before and after the introduction of the LEZ, more deprived neighbourhoods systematically bear the heaviest burden of air pollution. For example, in 2022, most deprived neighbourhoods had an average concentration of NO_2 of 21.69 $\mu g/m^3$, while the least deprived neighbourhoods had an average concentration of 14.05 $\mu g/m^3$. Second, everyone has enjoyed reductions in air pollution, irrespective of socioeconomic position. Findings for the statistical analysis are presented in Table 3. For BC and NO_2, the LEZ resulted in a statistically significantly faster decline in concentrations for the most deprived groups. For BC, there is a consistently stronger decline with each increase in socioeconomic deprivation. For NO_2, the least deprived neighbourhoods (BIMD ≥ 5) declined less rapidly compared to other neighbourhoods.

4.4. Health impact of LEZ

A complete set of baseline characteristics was available for 133.297 of 135.640 individuals living in Brussels, 13.127 of 13.326 individuals living in Antwerp, and 22.818 of 23.121 individuals living in the control cities. IPS weighting did a good job removing differences in baseline covariates between the LEZ and control cities. There was very little difference in the cumulative distribution of propensity scores after weighting (Supplementary file F).

Fig. 5 shows the percentage of individuals who chronically used medicines for diabetes, cardiovascular disease, obstructive airway diseases, antidepressants, and antithrombotic agents, across LEZ and control cities, and before and after the introduction of the LEZs. Several

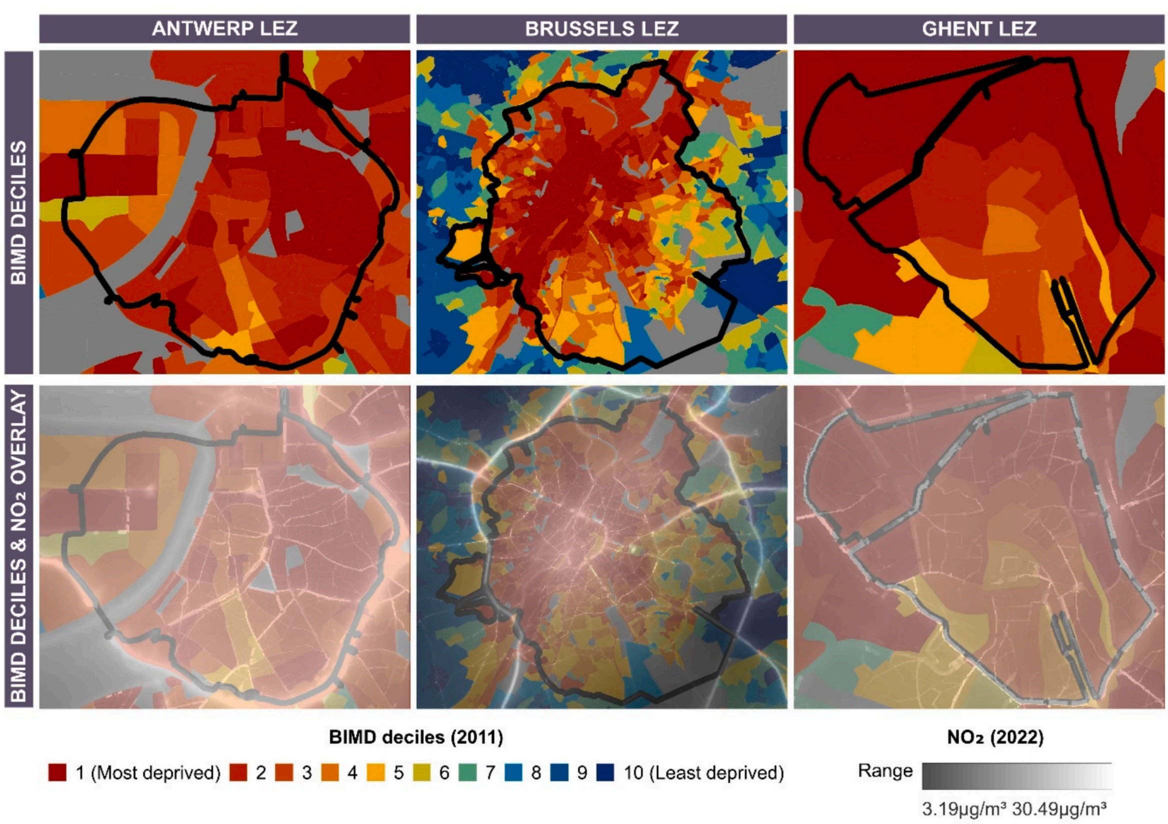

Fig. 3. Socioeconomic deprivation in the Antwerp, Brussels, and Ghent Low Emission Zones, with NO_2 overlay for 2022. Note: BIMD = Belgian Indices of Multiple Deprivation – in the remainder of the analysis all deciles above 5 have been consolidated in category BIMD 5.

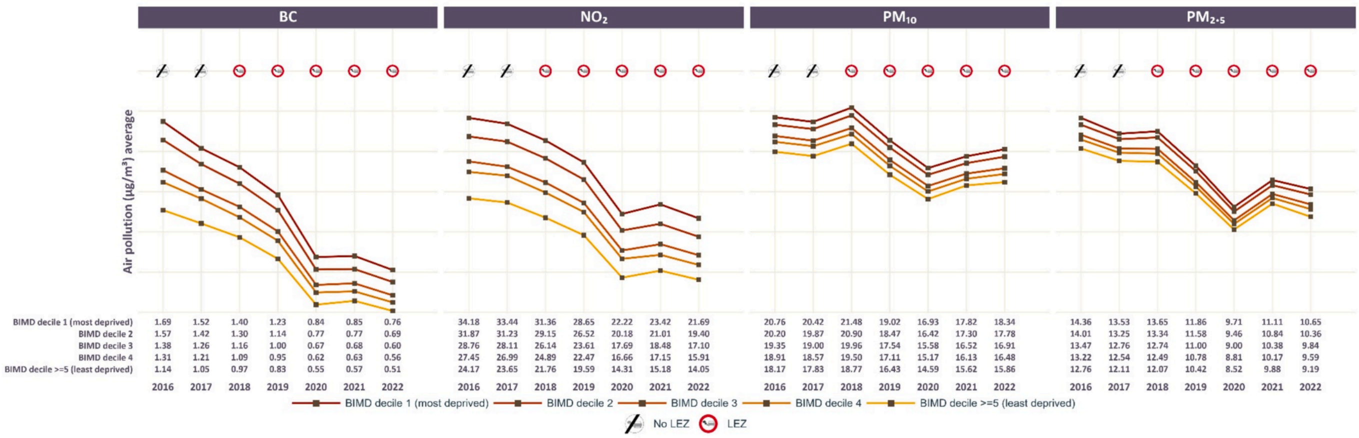

Fig. 4. Average annual residential exposure to BC, NO_2, $PM_{2.5}$, and PM_{10} for individuals living within the Brussels Low Emission Zone: evolution 2016–2022 across socioeconomic position measured using the Belgian Indices of Multiple Deprivation. Note: BIMD = Belgian Indices of Multiple Deprivation.

Table 3
Average annual residential exposure to PM_{10}, $PM_{2.5}$, BC, and NO_2 for individuals living within the Brussels Low Emission Zone: evolution 2016–2022 across socio-economic position measured using the Belgian Indices of Multiple Deprivation.

	$PM_{2.5}$	PM_{10}	BC	NO_2
	Estimate (p-value)	Estimate (p-value)	Estimate (p-value)	Estimate (p-value)
Intercept	0.719 (<0.0001)	0.862 (<0.0001)	0.411 (<0.0001)	2.679 (<0.0001)
BIMD				
Decile 1	0.205 (0.1519)	0.202 (0.1937)	0.199 (<0.0001)	1.524 (<0.0001)
Decile 2	0.175 (0.2646)	0.165 (0.3317)	0.152 (<0.0001)	1.335 (<0.0001)
Decile 3	0.013 (0.9357)	0.061 (0.7335)	0.087 (<0.0001)	0.812 (0.0023)
Decile 4	−0.01 (0.9549)	0.016 (0.9361)	0.052 (0.0015)	0.608 (0.0384)
Decile ≥ 5	Ref	Ref	Ref	Ref
Year	−0.630 (<0.0001)	−0.663 (<0.001)	−0.118 (<0.0001)	−1.983 (<0.0001)
Year*BIMD (pairwise differences)				
Decile 1 vs Decile 2 (ref)	−0.005 (0.8837)	−0.008 (0.8369)	−0.006 (0.0489)	0.042 (0.6359)
Decile 1 vs Decile 3 (ref)	−0.033 (0.3454)	−0.036 (0.4044)	−0.023 (<0.0001)	−0.137 (0.1597)
Decile 1 vs Decile 4 (ref)	−0.034 (0.4063)	−0.048 (0.3430)	−0.028 (<0.0001)	−0.130 (0.2515)
Decile 1 vs Decile ≥ 5 (ref)	−0.046 (0.2296)	−0.086 (0.0658)	−0.048 (<0.0001)	−0.475 (<0.0001)
Decile 2 vs Decile 3 (ref)	−0.029 (0.4670)	−0.028 (0.5620)	−0.017 (<0.0001)	−0.180 (0.0987)
Decile 2 vs Decile 4 (ref)	−0.030 (0.5099)	−0.040 (0.4690)	−0.022 (<0.0001)	−0.172 (0.1616)
Decile 2 vs Decile ≥ 5 (ref)	−0.041 (0.3283)	−0.077 (0.1307)	−0.042 (<0.0001)	−0.517 (<0.0001)
Decile 3 vs Decile 4 (ref)	−0.001 (0.9879)	−0.012 (0.8404)	−0.005 (0.2611)	0.007 (0.9539)
Decile 3 vs Decile ≥ 5 (ref)	−0.012 (0.7863)	−0.049 (0.3638)	−0.024 (<0.0001)	−0.337 (0.0056)
Decile 4 vs Decile ≥ 5 (ref)	−0.011 (0.8178)	−0.038 (0.5310)	−0.019 (<0.0001)	−0.344 (0.0104)
Baseline (2017)	0.924 (<0.0001)	0.975 (<0.001)	0.596 (<0.0001)	0.856 (<0.0001)

Note: BIMD = Belgian Indices of Multiple Deprivation, anchored between Decile 1 = most deprived and Decile ≥ 5 = least deprived. Random effect models are estimated with time (i.e. year), BIMD, baseline and a time by BIMD interaction as fixed effects, as well as a random intercept and random slope for year, assuming a constant correlation of the baseline measurement with all subsequent measurements.

observations can be made. First, the chronic use of these medicines surged over time for this study cohort, with almost twofold increases for medicines for obstructive airway disease, thrombolytics, and antidiabetics. Second, this increase was ongoing before the introduction of the LEZ and continued afterwards. LEZ cities and control cities evolved in parallel. Third, the slopes for LEZ cities versus control cities appear rather parallel, but despite IPS weighting, chronic use of medicines was lower among individuals in Antwerp and Brussels compared to control cities.

Table 4 presents findings from the cITS analysis. The positive, statistically significant estimates for the pre-LEZ and post-LEZ slopes, confirm the increase in the use of these medicines. The slope estimates can be interpreted as follows: for example, for the chronic use of antidepressants in Antwerp, there is a 0.21 % increase in the pre-LEZ period, and a 0.28 % increase in the post-LEZ period.

For the cITS analysis of Antwerp, the pre-LEZ versus post-LEZ slope changes are only statistically significant for antidiabetics, both in Antwerp ($\beta = 0.0009$, $P < 0.0001$) as well as in the control cities ($\beta = 0.0034$, $P < 0.0001$). The positive estimate suggests that the slope is steeper after the introduction of the LEZ, versus before. The negative difference in slope change is not statistically significant ($\beta = -0.0025$, $P = 0.066$). For Brussels, the chronic use of anti-diabetics medication shows a significant difference in pre-post slope change ($\beta = -0.0011$, $P = 0.0283$) suggesting a less steep increase in Brussels versus the control cities, by 0.11 % annually. For Brussels, pre-LEZ versus post-LEZ slope changes are also positive and significant for medicines for obstructive airway disease, cardiovascular disease, and antidepressants. However, these pre-post slope changes are not statistically significantly different between Brussels and the control cities.

Similar conclusions can be drawn from unadjusted (non-IPS weighted) analyses (Supplementary file G), but here the negative difference in pre-post slope change for the use of antidiabetics is statistically significant in both Antwerp ($\beta = -0.0019$, $P = 0.0231$) and Brussels ($\beta = -0.0017$, $P = 0.0009$).

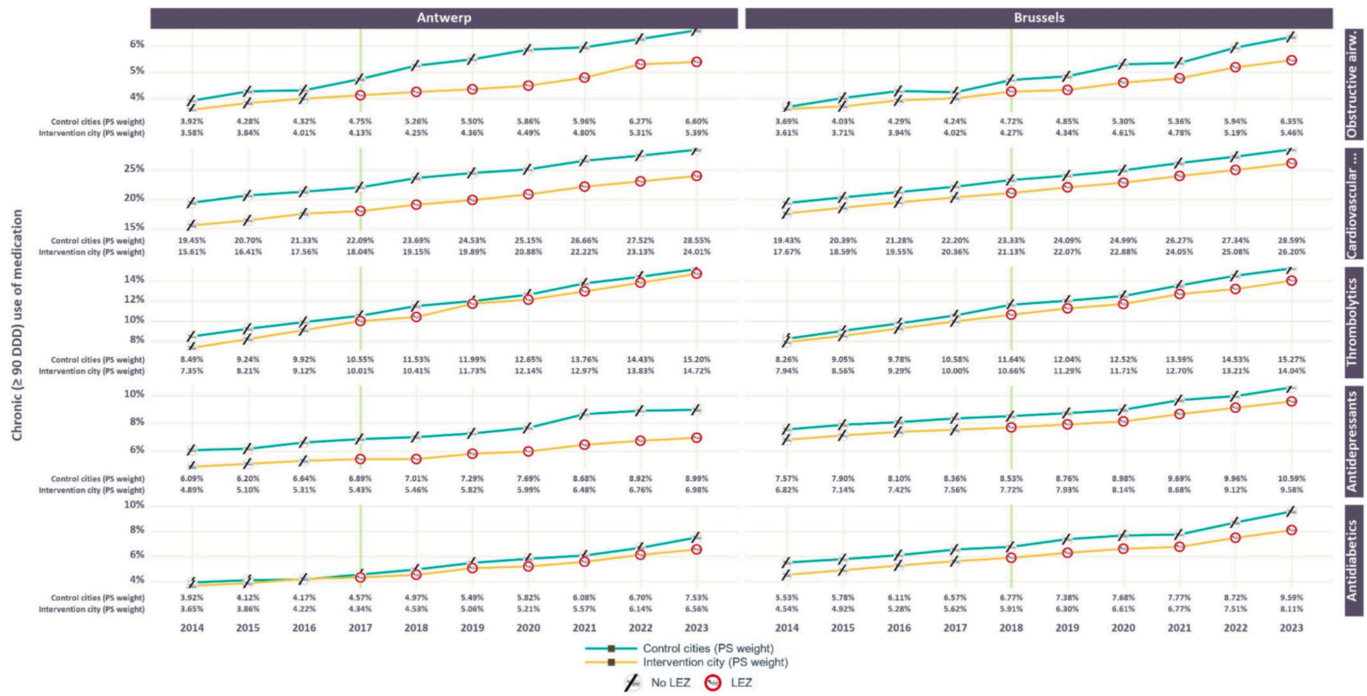

Fig. 5. Percentage chronic use (≥90 daily defined doses) of medicines for diabetes, cardiovascular disease, obstructive airway diseases, antidepressants, and antithrombotic agents across the Antwerp and Brussels Low Emission Zones and control cities: evolution 2014–2023 for IPS weighted data.

Table 4
Comparative interrupted time series analysis for health outcomes using IPS weights: comparison of slopes across the Antwerp and Brussels Low Emission Zones and control cities and before and after the implementation of the Low Emission Zone.

	Obstructive airway	Cardiovascular	Thrombolytics	Antidepressants	Antidiabetics
	Estimate (p-value)	Estimate (p-value)	Estimate (p-value)	Estimate (p-value)	Estimate (p-value)
Antwerp					
Control cities					
Pre-LEZ (2014–2016) slope	0.0020 (0.0218)	0.0094 (<0.0001)	0.0071 (<0.0001)	0.0028 (0.0039)	0.0013 (0.0304)
Post-LEZ (2017–2023) slope	0.0029 (<0.0001)	0.0085 (<0.0001)	0.0063 (<0.0001)	0.0041 (<0.0001)	0.0046 (<0.0001)
Slope change	0.0009 (0.4103)	−0.0008 (0.3391)	−0.0009 (0.2429)	0.0013 (0.4654)	0.0034 (<0.0001)
Antwerp					
Pre-LEZ (2014–2016) slope	0.0021 (<0.0001)	0.0098 (<0.0001)	0.0089 (<0.0001)	0.0021 (<0.0001)	0.0028 (<0.0001)
Post-LEZ (2014–2016) slope	0.0023 (<0.0001)	0.0083 (<0.0001)	0.0080 (<0.0001)	0.0028 (<0.0001)	0.0037 (<0.0001)
Slope change	0.0001 (0.5103)	−0.0015 (0.5921)	−0.0009 (0.7478)	0.0007 (0.4281)	0.0009 (0.1341)
Difference in slope change	−0.0008 (0.7568)	0.0007 (0.6053)	−0.0000 (0.9942)	−0.0006 (0.8599)	−0.0025 (0.066)
Brussels					
Control cities					
Pre-LEZ (2014–2017) slope	0.0019 (<0.0001)	0.0091 (<0.0001)	0.0076 (<0.0001)	0.0025 (<0.0001)	0.0034 (<0.0001)
Post-LEZ (2018–2023) slope	0.0033 (<0.0001)	0.0107 (<0.0001)	0.0076 (<0.0001)	0.0042 (<0.0001)	0.0052 (<0.0001)
Slope change	0.0014 (0.0116)	0.0016 (0.0043)	0.0000 (0.9926)	0.0016 (0.0019)	0.0018 (0.0003)
Brussels					
Pre-LEZ (2014–2017) slope	0.0015 (<0.0001)	0.0090 (<0.0001)	0.0068 (<0.0001)	0.0025 (<0.0001)	0.0036 (<0.0001)
Post-LEZ (2018–2016) slope	0.0025 (<0.0001)	0.0011 (<0.0001)	0.0068 (<0.0001)	0.0038 (<0.0001)	0.0042 (<0.0001)
Slope change	0.0010 (<0.0001)	0.0012 (<0.0001)	−0.0001 (0.7954)	0.0014 (<0.0001)	0.0007 (<0.0001)
Difference in slope change	−0.0004 (0.5339)	−0.0004 (0.6459)	−0.0001 (0.9209)	−0.0003 (0.7277)	−0.0011 (0.0283)

5. Discussion

5.1. Main findings and comparison with previous studies

This population-wide research calculated residential exposure to BC, NO_2, PM_{10} and $PM_{2.5}$ and showed that the LEZs in Antwerp and Brussels have improved air quality statistically significantly more rapidly compared to other Belgian cities on average. Antwerp and Brussels had higher air pollution concentrations than the other cities at baseline and stood to gain a lot from the implementation of their LEZ in 2017 and 2018 respectively. In most recent years they outperform other Belgian cities in terms of various air pollutant concentrations. Several reports on the effect of Belgian LEZs on air quality have previously been published, suggesting a greater decrease in measured concentrations of BC at locations in the Antwerp or Ghent LEZ compared to locations outside the LEZ (the whole of Flanders excluding the Ghent and Antwerp LEZs). For NO_2, no such evidence was found (Vlaamse Milieumaatschappij, 2024a, 2024b). However, the analyses presented in this study are more refined given the inclusion of control cities. According to a report from Leefmilieu Brussel (2023), between 2018 and 2022 the change in the composition of the vehicle fleet, stimulated by the LEZ, has had a significant impact on the reduction of NOX (−31 %), black carbon (−62 %), PM_{10} (−19 %) and $PM_{2.5}$ (−30 %) from transport, for a constant number of km travelled.

It is interesting to observe that the improvement of air quality is not limited to the LEZ. Our findings suggest strong positive spatial spillover effects of up to 5 km from the implementation of both the Antwerp and Brussels LEZ. Our research into spatial spillover did not expand beyond 5 km given the relatively small geographical area that is Belgium. The findings observed in this study confirm observations in surrounding stations of the Madrid LEZ (Salas et al., 2021). Similarly, Conte Keivabu and Rüttenauer (2022) reported spill-over effects for $PM_{2.5}$, PM_{10}, NO_2, and Benzene from a car congestion zone in London up to 3 km. The reduction was slightly larger for the area up to 1 km outside the zone.

Socioeconomic disparities in air pollution (BC and NO_2) decreased, bolstering the environmental justice case for the low emission zone's establishment. The study shows that the most deprived neighbourhoods in the Brussels-Capital Region bear the heaviest burden of air pollution – but also that for some pollutants (BC and NO_2), the LEZ resulted in a faster decrease of air pollution in those neighbourhoods. Similarly to a previous study using median income as main measure of socioeconomic disparity (Verbeek and Hincks, 2022), the recently introduced measure of socioeconomic disparity we used here, showed a concentric pattern in Brussels, with more deprived clusters in the city center and less deprived clusters to the inner border of the LEZ and especially outside the LEZ. This begs the question whether the observed positive spatial spillover effects are at least partly due to a change in car fleet to electric or hybrid vehicles as more affluent persons are living just outside the LEZ.

This study did not detect statistically significant differences in the evolution of health outcomes among persons living in the LEZs compared to control cities, although air quality had improved significantly faster in the LEZ over the same period. The only exception is the use of antidiabetics, for which there was a less steep pre-post LEZ increase among the cohort living in the Brussels LEZ versus the cohort living in control cities. This observation was also made in Antwerp for the crude, non-IPS weighted analysis. This stands in contrast to a recent systematic review showing that the health impact of LEZs is most noticeable for cardiovascular disease outcomes (Chamberlain et al., 2022). The review included two studies that looked at the impact of the LEZs in multiple German cities. Pestel and Wozny (2021) did not detect any effect for diabetes. However, they studied hospitalisations only, and it was not detailed how hospitalisations for diabetes specifically were delineated. Margaryan (2021) used both outpatient and inpatient data, but did not include data from before the introduction of the LEZ. Also, contrary to this study, both studies in Germany used yearly aggregated data on health outcomes, and no cohort was evaluated over time. It is worth mentioning that several cohort studies have demonstrated that air pollution increases the risk of diabetes (e.g. Andersen et al. (2012)) and the physiology pathway between air pollution and diabetes is well-established (Bonanni et al., 2024). Moreover, the European Environment Agency (2023) estimates that for NO_2, the highest impact on health is due to diabetes mellitus, with 314,574 disability-adjusted life years (DALYs), which is much higher compared to stroke (204,723 DALYs) and asthma (115,425 DALYs). NO_2 showed great reductions in the Antwerp (from 34.94 $\mu g/m^3$ in 2016 to 24.46 $\mu g/m^3$ in 2022) and Brussels (from 30.12 $\mu g/m^3$ to 18.53 $\mu g/m^3$) LEZs, strongly outperforming other cities. Further research may confirm whether the effects we observe here for diabetes are a precursor to possible expected effects on other disease conditions.

5.2. Strengths and limitations

This is a population-wide study with an individual-level analysis of residential exposure to air pollutants and objective, individual health outcomes from large administrative databases. We conducted a comparative interrupted time series analysis, which allowed us to identify changes in these outcomes due to the LEZ while simultaneously removing the influence of the underlying change in outcomes and adjusting for confounding variables through propensity score analysis.

Our findings should also be viewed in light of some limitations.

First, it is difficult to isolate the specific impact of the LEZ from other policy measures implemented in parallel. For example, Brussels recently introduced a city-wide 30 km/h speed limit, but as this policy only came into effect in 2022, it is likely to have influenced only the most recent two years of available data. In Ghent, by contrast, the entire city centre was designated a 30 km/h zone as early as 2015. Antwerp followed in 2018—one year after the introduction of its LEZ. It is also important to note that similar local pollution and traffic management measures have been adopted in several control cities, which complicates direct comparison. For instance, cities such as Leuven, Mechlin, and Namur (among others) have introduced significant interventions. Namur and Leuven implemented 30 km/h zones already in 2011. Since mid-2016, Leuven has further combined car-free areas in the city centre with a system of traffic loops, channeling vehicles from the ring road into the centre and back out again, with residential streets linked to these loops. Mechlin has maintained a car-free city centre since 2005, gradually expanding the area over time. These examples are non-exhaustive, but illustrate the broader context of urban traffic and pollution policies beyond the LEZ.

Second, in analysing the effect of LEZ implementation on air quality, we calculated residential air pollution exposure using all high spatial resolution data that are currently available. However the lack of more historic data did not allow evaluating if the difference between the LEZ and control cities was constant in the pre-LEZ years, and means that we cannot test the parallel groups assumption directly.

Third, the LEZs are, as previously mentioned, relatively recent, leaving us with a short-term view on potentially beneficial health effects. In the future, longer follow-up data will facilitate the estimation of potential slope changes for health outcomes.

A fourth limitation concerns the calculation of health outcomes. Belgian Health Insurance Funds' data are limited to reimbursements of medical care. No data on actual diagnoses were available, such as those used in previous studies evaluating the health impact of LEZs (Margaryan, 2021; Pestel and Wozny, 2021). Also not available is information on factors that may affect health (e.g. smoking, diet, …).

Last, the BIMD data date back to 2011. Our study is thus unable to take into account any information on potential gentrification or urban decline that may have happened since.

5.3. Avenues for further research

A promising avenue for further research is to study the impact of LEZ on specific vulnerable subpopulations. The intersection of pollution exposure and socioeconomic status is of particular concern for those subgroups of the population which are more vulnerable to health effects of pollution, including pregnant women, children, the elderly and people with pre-existing health conditions. A nation-wide study from Sweden found that children with lower socioeconomic status are particularly affected from children's respiratory problems during peak pollution times (Jans et al., 2018). The specific vulnerability of children was also highlighted in a study covering multiple cities in Spain, which demonstrated that children suffer disproportionate exposure to air pollution exceeding the maximum permitted levels; as do the elderly (Moreno-Jiménez et al., 2016). Another study covering cities in the UK, France, Spain, Norway found that in some cities pregnant women from deprived neighbourhoods were exposed to higher levels of environmental hazards (Robinson et al., 2018).

This study observed a limited impact on health outcomes from the introduction of the LEZs, although air quality improved significantly over the same period. We consider that a possible reason for not observing such differences consistently for the other health outcomes is because of the limited time distance between exposure and health manifestation. While there is a large evidence base for both short and long-term effects from air pollution exposure, the larger share of the health burden is from chronic exposure. For the majority of LEZs to have the intended effects on the environment and human health, they must be implemented for several years or have consistently effective vehicle standards (Mudway et al., 2019; Wood et al., 2015). It is thus recommended to reevaluate the health impact in the near future.

5.4. Policy implications

In Belgian cities and the whole of the EU, revised air quality limits will apply as of 2030, following the entry into force of Directive 2024/2881 on Ambient Air Quality and Cleaner air for Europe in December 2024. Member States will have 2 years to transpose the directive. By 2030, the Member States must achieve air quality standards for 2030 that are more closely aligned with the WHO recommendations. As of 2030, the Member States will have to respect an annual average concentration of 10 μg/m^3 for $PM_{2.5,}$ and an annual average concentration of 20 μg/m^3 for NO_2. With the decision to postpone (in the Brussels-Capital region) or to not tighten the LEZ (in Flanders), the regions increase the risk of failing to comply with the new 2030 requirements.

To achieve better air quality, multiple measures are needed. Cities will need to invest in various domains to reach the new EU standards for air quality, and ultimately the guidelines recommended by the WHO.

Over half (52.7 %) of individuals commuting into the Brussels-Capital Region and nearly three-quarters (73.3 %) of those living in the area who commute use their car. Between October 2021 and October 2022, residents of the Brussels-Capital Region completed nearly 30 % of their journeys by car, which is a lower percentage than walking (36 %) but still higher than public transportation (22 %) and other means (approximately 14 %) (OECD, 2024). A noticeable geographical difference in household car ownership exists in the Brussels-Capital Region; central areas have households with minimal access to vehicles, whereas peripheral areas frequently have households possessing multiple cars. This highlights the necessity for better integration of public transport systems between the Brussels Region and its outskirts, which could influence vehicle usage and improve air quality (Brussels Instituut voor Statistiek en analyse, 2022). Also, active mobility modes such as walking and cycling should be promoted, not only by investing in cycling infrastructure, but also in green zones. The presence of green zones in an urban environment plays an important role for the health of its inhabitants. Authorities increasingly attempt to apply the 3–30-300 rule, promoting that all citizens should see at least three trees from their house, have 30 % tree cover in their neighbourhood, and live within 300 m of a green space (Nieuwenhuijsen et al., 2022). A recent study showed that those who live in a neighbourhood with more than 30 % tree cover visit the doctor less, providing empirical evidence to support this rule (Vranken et al., 2023).

Urban policies to improve air quality need a social component. In this study, the most deprived neighbourhood bear the heaviest burden of air pollution and benefitted most from the implementation of the LEZ. The objective of Just Transition is to ensure that no one is left behind or pushed behind in the transition to low-carbon and environmentally sustainable economies and societies. Our study underscores the importance of one of the recommendations of the report on Just Transition in Belgium, which is that social-ecological policies can address both social and ecological goals through thoughtful policy design, overcoming existing barriers to integrative approaches and realising synergies in societal objectives, in government budgets, and in public support (Fransolet et al., 2023).

An additional dimension for policy makers is the impact of climate change. Studies have demonstrated a link between high temperatures and air pollution. High levels of air pollution (especially PM, NO_2 and ozone) increase the heat-related risk of heart and lung diseases – especially in large cities as 'heat hot spots'. Therefore, improving air quality not only has a direct positive effect on human health, but also reduces the health effects of heat (Romanello et al., 2024).

CRediT authorship contribution statement

Luk Bruyneel: Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Bianca Cox:** Writing – review & editing, Methodology, Conceptualization. **Anne Stauffer:** Writing – review & editing, Conceptualization. **Ludo Vandenthoren:** Writing – review & editing, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Frans Fierens:** Writing – review & editing, Data curation. **Tim S. Nawrot:** Writing – review & editing. **Christian Horemans:** Writing – review & editing, Supervision, Methodology, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2025.109515.

Data availability

The data that has been used is confidential.

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Glossary

ATE: average treatment effect
BC: black carbon
cITS: Comparative interrupted time series
IPS: Inverse of the propensity scores
LEZ: Low Emission Zones
NO_2: nitrogen dioxide
$PM_{2.5}$: particulate matter with a diameter of less than 2.5 μm
PM_{10}: particulate matter with a diameter of less than 10 μm
WHO: World Health Organization