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# Impact of an urban city-wide Bradford clean air plan on health service use and nitrogen dioxide 24 months after implementation: An interrupted time series analysis

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ABSTRACT

There is limited evidence of the health impact of Low Emission Zones (also known as Clean Air Zones, CAZ). This study examines the impact of the Bradford Clean Air Plan (CAP), including a CAZ, on health and nitrogen dioxide ($NO_2$) in the first two years of implementation using an interrupted time series design. Primary care and emergency department visits for respiratory and cardiovascular illness in Bradford were recorded between January 2018 to September 2023 with diabetic footcare and head injury visits as controls. A total of 157,623 primary care, and 37,865 emergency department visits for respiratory and cardiovascular conditions were recorded. At the start of implementation respiratory primary care visits decreased by 25% (RR = 0.75; 95%CI: 0.68 to 0.82) and cardiovascular visits by 24% (RR = 0.76; 95%CI: 0.64 to 0.92) compared to a pre-COVID-19 baseline (January 2018–February 2020). Post-implementation monthly respiratory and cardiovascular visits declined by 598 (95%CI: −614 to −583) and 134 (95%CI: −137 to −131), respectively, with continued downward trends (both: RR = 0.99; 95% CI: 0.99 to 0.99). Diabetic foot-care decreased (RR = 0.69; 95%CI: 0.60–0.80) but showed upward trends post-implementation (RR = 1.01; 95%CI: 1.00–1.01). Emergency department visits showed minimal changes across all outcomes. $NO_2$ concentration decreased by 11.5 $\mu g/m^3$ (95%CI: −23.2 to 0.2) and continued to decrease by 0.2 $\mu g/m^3$ (95%CI: −0.4 to −0.1) post-implementation. Policies which restrict the movement of polluting vehicles have the potential to reduce air pollution and improve health, although evaluating their impact is challenging. Studying the longer-term impact of these initiatives is warranted.

## 1. Introduction

Air pollution contributes to around 7 million premature deaths every year, predominantly in the most deprived areas of the world (World Health Organisation). In Europe, the economic cost of air pollution is an estimated $1.4 trillion every year (United Nations). In the UK, a total of 64,000 deaths due to air pollution occur every year (Lelieveld et al., 2019) amounting to a yearly loss of $83 billion (World Health Organisation).

Traffic related emissions are a key contributor to air pollution, particularly in urban areas (European Environment Agency). As such, policy makers have been advocating for urban vehicle access regulations such as Low Emission Zones (LEZ, also known as Clean Air Zones (CAZ) in the UK) across many countries in Europe (CLARS). A total of 320 LEZs were known to have been introduced across Europe by June 2022 and this figure is expected to rise to over 500 by 2025 (Tiseo). Although the details of how LEZ operate vary by location, the basic idea is that they enforce targeted restrictions on older polluting vehicles entering a

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predefined geographical zone either by imposing a fee, or by banning them entirely (CLARS). The benefits of policies such as LEZ may be seen in advance of their implementation because of the so-called ‘anticipation effect’, where changes in behaviour (for example, upgrading vehicles) are seen before policies are implemented (Ciccone, 2018)

The implementation of LEZ has been consistently related with reduction of air pollutants (Morfeld et al., 2014), (Sarmiento et al., 2021), (Simeonova et al., 2021), (Wolff, 2014). However, there is limited evidence of the impact of LEZ on health. A recent review found some evidence of positive impact on cardio-vascular outcomes, but less consistent evidence for respiratory and other outcomes(Chamberlain et al., 2023).

In 2018 the UK Government was identified by the European commission as having illegal levels of nitrogen dioxide ($NO_2$), a pollutant generated from combustion processes, across many UK cities. Ministerial directives were issued to 28 local authorities with illegal levels of pollution in England and Wales to develop Clean Air Plans, which include Clean Air Zones to reduce pollution as quickly as possible (McEachan et al., 2022).Since 2021, in addition to the London LEZ/Ultra LEZ, further LEZ or CAZ have been launched in seven English cities and four Scottish cities. However, there has been no evaluation of the health impact or air quality impact of these outside of London.

The City of Bradford, UK was one area directed by the Government to develop a Clean Air Plan to tackle illegal levels of pollution. The plan was implemented from October 2021, and a CAZ was launched on the September 26, 2022. The current study aims to investigate the impact of the Bradford Clean Air Plan (CAP) on respiratory and cardiovascular health service use, and air quality two years after the plan was implemented. It is part of a larger evaluation which will track health and economic impacts up to three years after implementation of the CAZ (McEachan et al., 2022).

## 2. Material and methods

### 2.1. Study design

This is a population based quasi-experimental Interrupted Time Series (ITS) study. The study period was between January 2018 and September 2023. A timeline of key events can be found in Table 1. Due to the outbreak of COVID-19 in March 2020, and the complexity of the intervention package, the study period was split into four phases: 1) baseline period (January 2018–February 2020); 2) COVID-19 period (March 2020–March 2021); 3) a CAP preparatory period (April 2021–September 2021); 4) CAP implementation (October 2021–September 2023). The CAP implementation period included the launch of the CAZ on the September 26, 2022. To account for the disruption caused by COVID-19 our main analysis compares the CAP implementation period with the baseline period. See Table 1.

### 2.2. Setting

Bradford is the seventh largest metropolitan district in England and Wales with around half a million population (Office of National Statistics), mainly of White British (57%) and Pakistani origin (26%) (Bradford Metropolitan District Council (BMDC)).The city is among the most deprived cities in the UK (Bradford Metropolitan District Council (Bradford Metropolitan District Council (BMDC)) and has higher morbidity from respiratory illness than the national average (Mebrahtu, 2015), (Mebrahtu et al., 2016), (Mebrahtu et al., 2015). The economic cost to the local National Health Service (NHS) of respiratory primary care and emergency department visits due to air pollution is also estimated to be £0.5million every year (Mebrahtu et al., 2023). The CAZ covers an area of 22.4 $km^2$ in the city; 20% of Bradford residents live inside the zone (McEachan et al., 2022).

**Table 1**
Timeline and intervention phases.

| Date | Event | Comment |
|---|---|---|
| **January 2018** | Start of study | |
| **March 2020** | Start of COVID-19 period | Areas of UK experienced multiple lockdowns. Health service use was profoundly impacted. For non-COVID illness there was a sharp drop in availability of primary care appointments and the numbers of people attending emergency departments(Thorlby et al., 2020). Restrictions on movement meant that traffic levels and associated traffic-related air pollution were drastically reduced at the start of the lock down periods(Barua and Nath, 2021). |
| **April 2021** | CAP preparatory phase | After the CAP is approved (March 2021) an implementation team start work on operational and logistical aspects of the plan, including installing technology needed to track vehicles in the CAZ (automatic number place recognition cameras), developing IT systems, and developing grants and mitigation offers. Signage appears around CAZ boundary. From spring 2021 a district wide and regional communications campaign ‘the CAZ is coming, cleaner air ahead’ was implemented. Most pandemic restrictions lifted by July 2021. |
| **October 2021** | CAP implementation period | Grants start to be defrayed to local businesses and bus operators. Vehicles start to be upgraded. Applications for exemptions open for Bradford residents and local businesses. Regular communications are established including newsletters, advertisements, and webinars. The CAZ was launched on the September 26, 2022. |
| **September 2023** | End of study for interim analysis | |

### 2.3. Study population

The study included the population of the Bradford metropolitan district (i.e., 537,200 in 2018 which then increased to 561,257 in 2023). Participants were those who visited primary care or the Bradford Royal Infirmary (BRI) hospital emergency department between January 2018 and September 2023.

### 2.4. Intervention: The Bradford clean air plan

The Bradford CAP is a broad policy that aims reduce air pollution in the district by restricting the movement of older polluting vehicles and providing incentives to encourage local businesses and transport operators to upgrade vehicles. The policy includes a ‘class c’ CAZ (Department of Environment Food and Rural Affairs(DEFRA), 2022) which charges non-compliant buses, coaches, heavy goods vehicles, vans, minibuses, taxis, and private hire vehicles a daily fee to enter the CAZ designated area (McEachan et al., 2022). Non-compliant vehicles are diesel vehicles lower than Euro 6 standard (typically built before 2015) or petrol vehicles below Euro 4 standard (built before 2005). Charges are £7 for taxis, £9 for light goods vehicles, and £50 for buses, coaches and heavy goods vehicles. Private vehicles are not charged. Fig. 1 shows the CAZ designated area in the city of Bradford. The CAZ covers an area of 22.4 $km^2$ in the city which includes the inner city area and a major transport corridor out to the North West, including all areas of the City which were identified as having illegal exceedances in 2018; 20% of Bradford residents live inside the zone (McEachan et al., 2022)

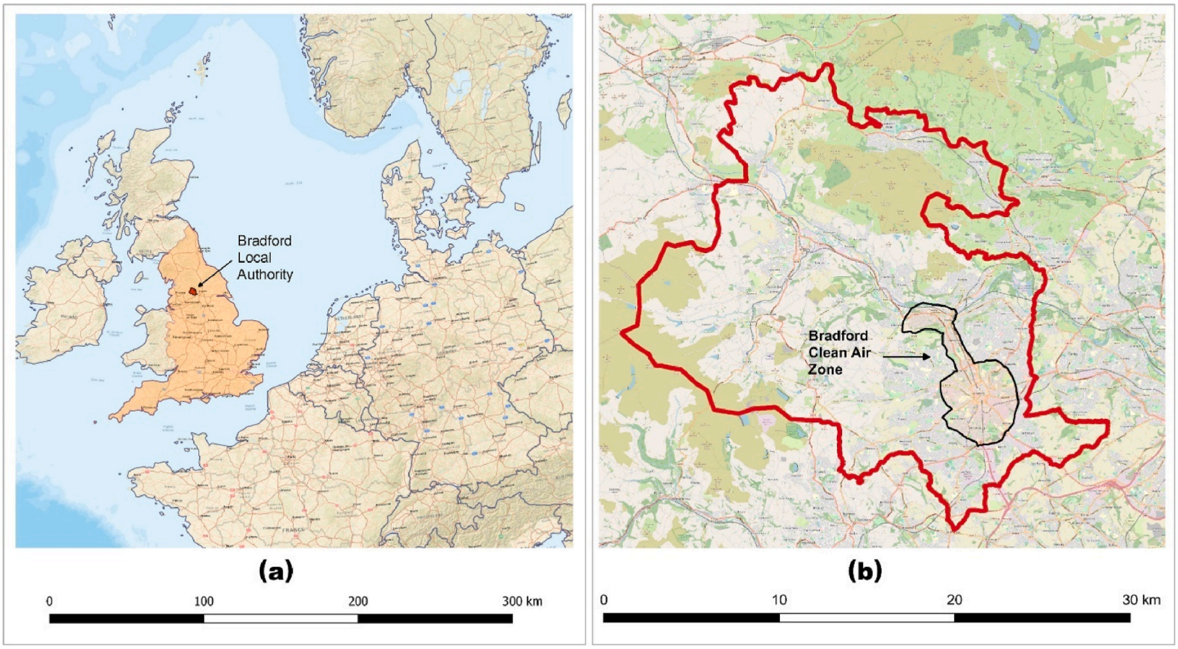


**Fig. 1.** Context map showing the City of Bradford Metropolitan Local Authority district in England, and CAZ designated area.

As part of the CAP, local businesses, including bus operators and taxis, were able to access grants to contribute to the cost of upgrading or replacing their vehicles (Bradford Metropolitan District Council (Bradford Metropolitan District Council (BMDC)). In parallel, minimum 'hybrid' standards were implemented for all registered private hire taxis. Exemptions from charges were provided on application for local small/medium enterprises, schools and charities.

The compliance of vehicles driving in the zone was first baselined in 2019, in Autumn (2022) just before the CAZ launch, and in September 2023, one year after the CAZ launch. The number of licenced private hire vehicles meeting minimum hybrid standards was 20% in 2019, rising to 86% pre-CAZ launch to 99% one-year post-CAZ launch. The figures for light goods vehicles were 28% (baseline, 2019), 50% (pre-launch) and 70% (one year post launch), and for heavy goods vehicles 41%, 80%, 97% respectively. The percent of non-compliant vehicles driving in the zone fell from 3.6% pre-launch to 1.5% one year after the CAZ launch (personal communication from Sally Jones (Bradford City Council), December 2024).

### 2.5. Outcomes and ascertainment of cases

The primary outcome was respiratory health assessed by the number of primary care and emergency department attendances due to respiratory infection, bronchitis, asthma, and chronic obstructive pulmonary disease. The secondary outcome was cardiovascular illness (assessed using emergency department and primary care attendances for angina/myocardial infarction, dysrhythmia/conduction disturbance, heart failure, stroke (haemorrhage or infarction)).

We included two non-equivalent control outcomes which we would not expect to be affected by the intervention but would respond in a similar way to our outcomes to a relevant validity threat: 1) routine diabetic foot care consultations in primary care and, 2) superficial head injuries for emergency department outcome events. These were chosen because there were an adequate number of attendances per month to include in analyses.

Primary care and emergency department outcome events were identified from Clinical Terms Version 3 (CTV3) Read codes and ICD10 codes, respectively (see Supplementary Table 1).

### 2.6. Variables for analysis

Dummy variables were created for each of the intervention components (preparatory phase, CAP implementation including CAZ launch) and the COVID-19 period. The intervention components and COVID-19 period were given a value of "1" starting from their start date until the start of next component, then a value of "0" for the rest of the period.

A continuous incremental time variable (i.e., monthly) was used for the baseline, COVID-19 period, and each of the intervention components to account for trends of each phase. The time variable was coded as, for example (for COVID-19 period) "0" in the baseline period, "1,2,3,4 …." from the onset of the of the COVID-19 period. In addition, seasonality was modelled by including dummy variables for the months in the year.

### 2.7. Data source

De-identified primary care and BRI emergency department patient visits data were obtained from the Connected Bradford database at the Bradford Institute for Health Research (Sohal et al., 2022) accessed through Google cloud computing service. Four individual spreadsheet files (i.e., events file (date and event), demographic file (age, ethnicity – White British, Pakistani, Other—and sex), and index of multiple deprivation (IMD) file) were required to create data for our analyses. The individual files were linked using anonymised patient identifiers in each file to make up a master spreadsheet file for analyses. Quality of the data capture was assessed for missing data and abnormal patterns using time-series plots prior to adopting the master spreadsheet file as a final file for the subsequent analyses.

Hourly records of ratified nitrogen dioxide ($NO_2$) between the period January 2018–September 2023 were taken from the Mayo Avenue routine Automatic Urban and Rural Network (AURN) monitoring station (located on Bradford's ring road station inside the CAZ[2]). The hourly records were then de-weathered and de-seasoned before analysis using standardised open access techniques (AQEval R package (Ropkins and Tate, 2021). Data was assessed for quality using time series plots.

[2] Site Information for Bradford Mayo Avenue(UKA00611) - Defra, UK.

### 2.8. Statistical analysis

First, outcome variables are summarised descriptively. The descriptive summary included outcomes events stratified by demographic factors, and graphical representation of the overall trend of every outcome over the study period.

Second, to assess the impact of the intervention, Poisson regression ITS was used. Tests for serial autocorrelation of residuals were conducted and all tests were non-statistically significant. Thus, models with autoregressive integrated moving average (ARIMA) errors were not used.

A four-phase interrupted time series model (phase 1: baseline; phase 2: COVID-19; phase 3: preparatory period; Phase 4: CAP implementation and CAZ) was used for the main analysis. A five-phase model (including CAP implementation and CAZ switch on as separate segments) was used as a sensitivity analysis.

The marginal number of visits were calculated as the difference between the predicted number of visits under the counterfactual scenario and the model estimated number of visits. Health service use costs were calculated by multiplying the 'excess/less' number of visits by the estimated cost of a visit (that is, £42 per primary care visit and £86 per emergency department visit) in NHS England (The King's Fund).

Akaike information criterion (AIC) and Bayesian information criterion (BIC) were used to select the best fitting models. Analyses were implemented in R (V.4.2.0)(R Core Team). A 5% significance level and 95% CIs were adopted throughout.

### 2.9. Ethics approval

Ethical approval for the Connected Bradford was granted from the NHS East Midlands –Derby Research Ethics Committee (Ref: 17/EM/0254 and 22/EM/0127).

## 3. Results

### 3.1. Primary care visits

Over the period between January 2018 and September 2023, there were a total of 129,378, 28,245 and 47,487 visits to primary care services due to respiratory illness, cardiovascular illness, and diabetic foot care, respectively (see Supplementary Table 2).

The weekly primary care respiratory visits peaked (750–950 visits per week) during the winter months of the study period until the first COVID-19 national lockdown (March 2020) then decreased sharply and remained below the pre-COVID-19 level until November 2022. They then rapidly increased to the pre-COVID-19 winter levels between December 2022 to February 2023 (Supplementary Fig. 1).

Primary care visits due to cardiovascular illnesses did not show seasonal variations although there was a sharp drop like that of respiratory illnesses visits at the start of the first COVID-19 national lockdown. It remained below the pre-COVID level until the start of the third national lockdown (January 2021) and was then above the pre-COVID level for most weeks until the end of the study period (see Supplementary Fig. 1). The diabetic foot care primary care visits showed similar patterns to that of cardiovascular primary care visits (see Supplementary Fig. 1).

The Pakistani ethnic origin population had higher incidence of respiratory and diabetic foot care primary care visits over the study period, including after the implementation of the CAZ, than the white British population. However, the white British population had higher incidence of cardiovascular visits than the Pakistani group. In addition, the elderly had higher incidences of respiratory, cardiovascular, and diabetic foot care primary care visits than the younger age groups over the study period (see Supplementary Table 3).

### 3.2. Emergency department visits

There were total of 20,768, 17,097 and 18,048 BRI emergency department visits due to respiratory illnesses, cardiovascular illnesses, and head-injury accidents, respectively (see Supplementary Table 4).

The weekly emergency department visits due to respiratory illnesses peaked during the winter months (100–120 visits per week) until the first national lockdown which then dipped to around 20 visits per week for the next four months (April–July 2020). The weekly visits remained below the pre-COVID period until 2022-23 winter months where it sharply increased to 120–150 visits per week in December 2022 and January 2023, to then drop to below 80 visits per week during the following months (see Supplementary Fig. 2).

The weekly cardiovascular emergency department visits were highest (70–100 visits per week) during the first three months of the study (January–March 2018) then showed a gradual decrease until the start of the first lockdown (March 2020) where it sharply dropped to below 40 visits per week until May 2020. It gradually increased to pre-COVID level in March 2021 which then remained relatively stable until the end of the follow-up period (see Supplementary Fig. 2).

The weekly emergency department visits due to head injury accidents peaked during March–June 2018 (100–125 visits per week) then continuously decreased until the first national lockdown. It sharply decreased to below 25 visits per week in March 2020, then increased gradually but remained below the pre-COVID level for the rest of the study period (see Supplementary Fig. 2).

The average incidence rates over the entire study period indicate that there was no difference in the incidence of respiratory, cardiovascular, and head injury emergency department visits amongst the different age groups, ethnicities, and sexes.

### 3.3. Air quality

The weekly average concentration of $NO_2$ was 35–50 μg/m$^3$ for most of the baseline period, with a peak in April 2019, but sharply dropped to 20 μg/m$^3$ in the first week of April 2020. After a sharp increase to 45 μg/m3 during the next five months (May–September 2020), the weekly average of $NO_2$ concentration stayed below the baseline concentration level for the rest of the study period (see Supplementary Fig. 3).

### 3.4. Effects of intervention (main analysis)

#### 3.4.1. Primary care visits

The incidence rate of respiratory primary care visits increased by 1% every month during the baseline period (rate ratio (RR) = 1.01; 95% CI: 1.01 to 1.01) and was substantially lower at the start of the CAP implementation period compared to the end point of baseline period. There was a decrease of 25% (RR = 0.75; 95% CI: 0.68 to 0.82) at the start of CAP implementation and a downward trend apparent (RR = 0.99; 95% CI: 0.99 to 0.99) during the remainder of the implementation period (see Table 2 & Fig. 2).

The incidence rate of cardiovascular primary care visits had a flat trend during the baseline period (RR = 1.00; 95% CI: 1.00 to 1.00) and was lower at the start of CAP implementation (RR = 0.76; 95% CI: 0.64 to 0.92) with a downward trend (RR = 0.99; 95% CI: 0.99 to 0.99) until the end of the study (see Table 2 & Fig. 2).

The incidence rate of diabetic foot care primary care visits showed an upward trend during the baseline period (RR = 1.01; 95% CI: 1.01 to 1.01). At the start of the CAP implementation period the incidence rate ratio of diabetic foot care was less than the baseline period (RR = 0.69; 95% CI: 0.60 to 0.80) however it continued to show an upward trend (RR = 1.01; 95% CI: 1.00 to 1.01) until the end of the study (see Table 2 & Fig. 2).

#### 3.4.2. BRI emergency department visits

The incidence rates of respiratory emergency department visits had a

**Table 2**
Summary of level change and trends of health visits (four-phase models).

| | | Period | Rate ratio (95% CI) | Monthly trend (95% CI) |
|---|---|---|---|---|
| Primary care visits | Respiratory | Baseline period | Reference | 1.01 (1.01–1.01) |
| | | COVID-19 period | 0.51 (0.49–0.52) | 0.97 (0.97–0.98) |
| | | Preparatory phase | 0.57 (0.53–0.62) | 1.05 (1.04–1.06) |
| | | CAP implementation + CAZ | 0.75 (0.68–0.82) | 0.99 (0.99–0.99) |
| | Cardiovascular | Baseline period | Reference | 1.00 (1.00–1.00) |
| | | COVID-19 period | 0.66 (0.61–0.72) | 1.03 (1.03–1.04) |
| | | Preparatory phase | 0.64 (0.56–0.74) | 1.00 (0.97–1.02) |
| | | CAP implementation + CAZ | 0.76 (0.64–0.92) | 0.99 (0.99–0.99) |
| | Diabetic foot care | Baseline period | Reference | 1.01 (1.01–1.01) |
| | | COVID-19 period | 0.48 (0.45–0.51) | 1.04 (1.03–1.04) |
| | | Preparatory phase | 0.62 (0.55–0.69) | 0.97 (0.95–0.98) |
| | | CAP implementation + CAZ | 0.69 (0.60–0.80) | 1.01 (1.00–1.01) |
| Emergency department visits | Respiratory | Baseline period | Reference | 1.00 (1.00–1.00) |
| | | COVID-19 period | 0.42 (0.38–0.47) | 1.01 (1.00–1.02) |
| | | Preparatory phase | 0.74 (0.62–0.89) | 1.00 (0.98–1.03) |
| | | CAP implementation + CAZ | 0.88 (0.70–1.09) | 0.98 (0.98–0.98) |
| | Cardiovascular | Baseline period | Reference | 0.99 (0.98–0.99) |
| | | COVID-19 period | 0.86 (0.78–0.95) | 1.02 (1.01–1.03) |
| | | Preparatory phase | 1.04 (0.87–1.23) | 0.97 (0.94–0.99) |
| | | CAP implementation + CAZ | 1.08 (0.86–1.36) | 1.00 (0.99–1.00) |
| | Head injury | Baseline period | Reference | 0.98 (0.98–0.98) |
| | | COVID-19 period | 0.69 (0.63–0.76) | 1.01 (1.00–1.02) |
| | | Preparatory phase | 0.97 (0.81–1.15) | 0.97 (0.94–1.00) |
| | | CAP implementation + CAZ | 0.91 (0.72–1.13) | 0.98 (0.97–0.98) |

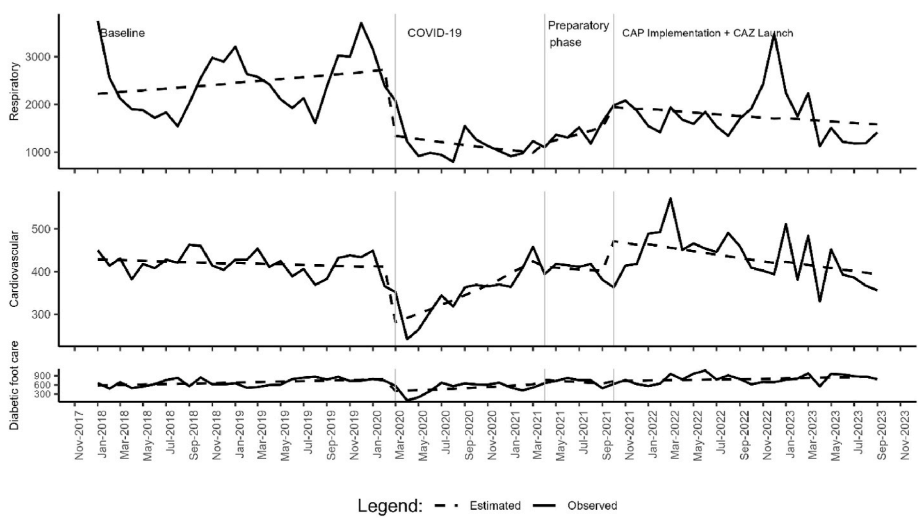


**Fig. 2.** Monthly observed and estimated primary care visits.

flat trend during the baseline period (RR = 1.00; 95% CI: 1.00 to 1.00). The incidence at the start of CAP implementation (RR = 0.88; 95% CI: 0.70 to 1.09) was lower than the incidence rate at the end of the baseline period with a downward trend until the end of the study (RR = 0.98; 95% CI: 0.98 to 0.98). See Table 2 & Fig. 3.

The incidence rates of cardiovascular (RR = 0.99; 95% CI: 0.98 to 0.99) and head injury (RR = 0.98 (0.98–0.98) emergency department visits had downward trends during the baseline period. The cardiovascular emergency department visit incidence rates at the CAP implementation (RR = 1.08; 95% CI: 0.86 to 1.36) was higher than the baseline period but had a flat trend (RR = 1.00; 95% CI: 0.99 to 1.00) until the end of the study. Incidence rates for head injury were also lower at CAP implementation (RR = 0.91; 95%CI: 0.72 to 1.13), but there was no change in the trend from baseline (RR = 0.98, 95%CI 0.97 to 0.98) (see Table 2 & Fig. 3).

### 3.4.3. *Nitrogen dioxide*

The $NO_2$ concentration showed a decrease of 0.1 μg/m$^3$ (95% CI: −0.3 to 0.1) every month during the baseline period. Compared to the baseline period, $NO_2$decreased by 11.5 μg/m$^3$ (95% CI: −23.2 to 0.2) when the CAP was implemented and showed a decrease of 0.2 μg/m$^3$ (95% CI: −0.4 to −0.1) every month until the end of the study (see Table 3 and Fig. 4).

### 3.4.4. *Number of visits and associated costs*

The average monthly respiratory, cardiovascular, and diabetic foot care primary care visits decreased by 598 (95% CI: −614 to −583), 134 (95% CI: −137 to −131), and 96 (95% CI: −99 to −92), respectively, after the implementation of CAP compared to the baseline period. There was also a respective decrease of 43 (95% CI: −46 to −41) and 20 (95% CI: −21 to −18) in the average monthly respiratory and head injury emergency department visits after the implementation of CAP although the average monthly cardiovascular emergency department visits increased by 19 (95% CI: 19 to 19) during the same period.

The monthly costs avoided in primary care during the post-implementation period were £25,133 (95% CI: £24,496 to £25,770) for respiratory visits, £5610 (95% CI: £5486 to £5733) for cardiovascular visits, and £4013 (95% CI: £3879 to £4147) for diabetic foot care visits.

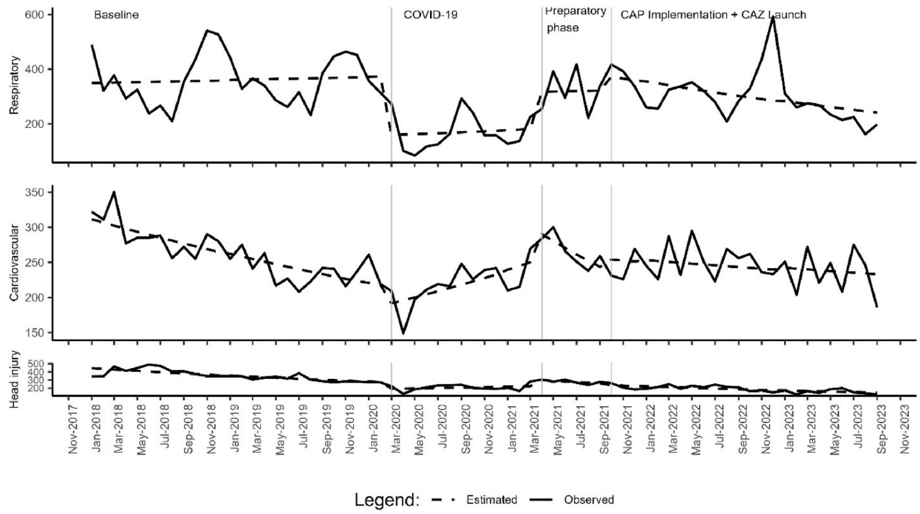


**Fig. 3.** Monthly observed and estimated emergency department visits.

**Table 3**
Summary of level change and trends $NO_2$ concentration.

| Period | $NO_2$ μg/m$^3$ change (95% CI) | Monthly trend (95% CI) |
|---|---|---|
| Baseline period | Reference | −0.1 (−0.3 to 0.1) |
| COVID-19 period | −9.3 (−13.8 to −4.7) | 0.5 (0.0–0.9) |
| Preparatory phase | −10.1 (−19.1 to −1.2) | 0.3 (−1.2 to 1.8) |
| CAP implementation + CAZ | −11.5 (−23.2 to 0.2) | −0.2 (−0.4 to −0.1) |

In the emergency department £3722 (95% CI: £3524 to £3921) and £1678 (95% CI: £1577 to £1778) monthly costs were avoided due to lower respiratory and head injury emergency department visits, respectively. However, £1631 (95% CI: £1614 to £1648) monthly costs were incurred due to increased cardiovascular emergency department visits.

Combined, the monthly primary care visits avoided during the intervention period was 828 (95% CI: 812 to 843) which equivalent to £34,756 (95% CI: 34,093 to 35,419). The respective average monthly emergency visits and costs avoided were 44 (95% CI: 41 to 46) and £3769 (95% CI: 3, 546 to 3992), respectively. The overall average monthly visits and costs avoided were a total of £38,525 (95% CI: 37, 826 to 39,224), respectively, every month after the implementation of the CAP.

### 3.5. Sensitivity analyses

#### 3.5.1. Primary care visits

When the CAP implementation and CAZ launch were considered as two separate segments, the incidence rate at the start of the CAP implementation period was lower than the baseline period (RR = 0.74; 95% CI: 0.67 to 0.81), the incidence rate at the start of CAZ launch was higher (RR = 1.40; 95% CI: 1.26 to 1.57). This higher incidence seems likely due to a peak in respiratory visits during winter 2022, in the period just after the CAZ switch on. The incidence ratios of cardiovascular and diabetic foot care primary care visits for the five-phase model were like that of the main analysis model. The estimated trends of visits due to the three conditions were consistent with main analysis model estimates (see Supplementary Table 6 and Supplementary Fig. 4).

#### 3.5.2. Emergency department visits

The incidence rate ratios of respiratory emergency department visits for the five-phase model were like that of the main analysis (four-phase) model except that the incidence rate at the start of the CAZ launch period was higher than the baseline (RR = 1.67; 95% CI: 1.29 to 2.15).

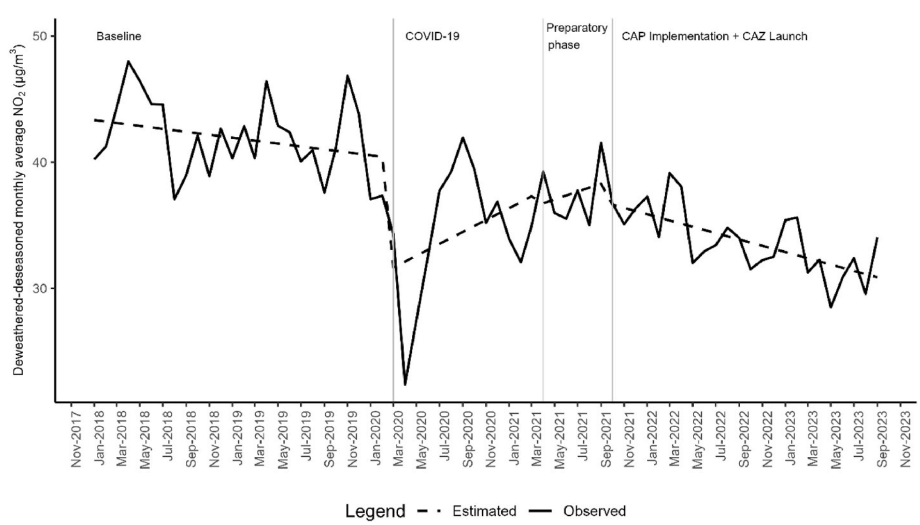


**Fig. 4.** Observed and estimated NO2 concentrations.

However, although the incidence rate ratios of cardiovascular and head injury primary care visits showed similar pattern like that of respiratory primary care visits, the incidence rates at the start of the CAZ launch were lower than the baseline, unlike that of the respiratory primary care visits (see Supplementary Table 6 and Supplementary Fig. 5).

### 3.5.3. *Air quality*

The $NO_2$ concentration decreased by 11.2 μg/m$^3$ (95% CI: −23.5 to 1.0) when the CAP was implemented, with 0.3 μg/m$^3$ (95% CI: −0.8 to 0.3) every month until the CAZ launch. There was a decrease of $NO_2$ by 11.9 μg/m$^3$ (95% CI: −25.8 to 2.0) at the start of CAZ launch and −0.1 μg/m$^3$ (95% CI: −0.7 to 0.4) every month until the end of the study (see Supplementary Table 7 & Supplementary Fig. 6).

## 4. Discussion

We explored the health and air quality impacts of the Bradford Clean Air Plan twenty-four months after the start of implementation, including a period of 12 months after a CAZ was introduced, using a quasi-experimental interrupted time series analysis. Our study is the first to explore the effectiveness of the UK Government's Clean Air Plan framework. Given the increasing number of CAZ being implemented in UK cities, and the often divisive nature of this policy (Knamiller et al., 2024), our study is highly policy relevant, and makes an important contribution to the currently limited evidence base exploring the impact of these policies on population health. We found that $NO_2$ levels showed reductions after implementation, with continued downward trends until the end of the study period. Primary care health service use for both respiratory and cardiovascular illness decreased after the plan was implemented, with on average 732 fewer visits recorded per month. Within the emergency department setting we found some evidence for reductions in respiratory, but not cardiovascular illness. Overall, our findings suggest that there may be improvements in respiratory and cardiovascular health and air quality, both in terms of reductions and continued downward trends, that may be associated with implementation of the Clean Air Plan in Bradford.

However, we recommend caution is exercised when interpreting these results. We aimed to include non-equivalent controls to strengthen our quasi-experimental design. Although the direction of trends for these controls did not show any difference between baseline period to post-intervention period (e.g. a continued downward trend for head injuries in emergency department settings, and a continued upward trend for diabetic footcare visits) they did show similar patterns of reduction at CAP implementation to our health outcomes. The COVID-19 pandemic also impacted on both health service use and pollution levels in the period before the CAP was implemented which meant that we could not reliably interpret trends and reductions from this period. We therefore set our baseline to before the impacts of the pandemic were felt. Continued follow-up will be important to ascertain whether the downward trends and improvements in health continue in the longer-term.

Our study adds to the emerging evidence of the impact of LEZ policy on respiratory and cardiovascular outcomes (Chamberlain et al., 2023). Previous studies exploring respiratory and cardiovascular illness have used diagnosis data from hospitals (Pestel and Wozny, 2021), outpatient attendances (Margaryan, 2021) or mortality (Yorifuji et al., 2016) but have not assessed burden within primary care settings, which may deal with less acute illness that that presenting in hospitals settings. In this study we found stronger impacts of the CAP for both respiratory and cardiovascular visits in our primary care data set compared with hospital emergency visits. We assessed outcomes at a relatively early stage in the plan (e.g. one year after implementation of the CAZ component), it may be that potential benefits on acute service, which may be related to conditions related to longer cumulative exposure take longer to emerge.

There is consistent evidence that implementing restrictive policies such as LEZ reduce air pollution level (Morfeld et al., 2014), (Sarmiento et al., 2021), (Simeonova et al., 2021), (Wolff, 2014). In our study, after controlling for weather related and seasonal differences, we found that levels of $NO_2$ were dropping on average 2.4 μg/m$^3$ per year after introduction of the CAP. This compares favourably with other UK LEZ; $NO_2$ concentrations reduced by a median of 1.35μg/m3 per year at roadside locations after the London LEZ had been in place for 5 years (Mudway et al., 2019). Using modelling approaches, Liu et al. estimated a reduction in $NO_2$ of 1.23 μg/m$^3$ one year after implementation of the Birmingham CAZ (Liu et al., 2023). Together with these other UK studies, our findings suggest that the UK Clean Air Zone framework is effective at reducing $NO_2$ concentrations, at least at roadside locations.

In the current study, the CAZ boundary included some of the most deprived and multi-ethnic parts of the city, which were also the most polluted. Previous research in the UK has identified whilst deprived populations are most exposed to air pollution, they are least likely to cause it(Barnes et al., 2019). This spatial inequality can heighten existing social and health inequalities, causing a 'triple jeopardy' for families living in deprived areas(Pearce et al., 2010). By targeting policies to improve air quality in areas with high levels of health need there is an opportunity to reduce this jeopardy, and in turn, reduce health inequalities. Whilst it was not within the scope of the current study to explore these impacts on health inequalities, it is planned to explore this in future research (McEachan et al., 2022).

Our study has a number of strengths. First, the study evaluated the impact of a well described city-wide clean air plan and clean air zone using rich and granular health which was available for a whole city population. The learning from this study is relevant to other urban areas who may be considering these types of policy interventions, which are inherently complex in nature. Second, we used a large sample to investigate the impact of CAP on respiratory and cardiovascular outcomes. Third the use of electronic health records minimised the biases and errors inherently seen in other types of observational data and enabled us to capture a larger pool of patients than previous studies. Finally, we employed an ITS which is a robust quasi-experimental design for controlling the effects of confounding factors by using internal control comparisons.

Our study also had a number of limitations. First, the COVID-19 pandemic led to dramatic reductions in health service use, and levels of pollution, which impacted on our ITS design. As such we designated the period between March 2020 and March 2021 as a separate segment in our models, and excluded this segment from our baseline control period, and further interpretation. However, longer term residual effects of COVID-19 on health service beyond March 2021 cannot be ruled out. Second, inclusion of comparable data from cities where CAZ have not been implemented would help to strengthen attribution of the effect but was not possible in the current study. Caution is therefore warranted in interpreting the current findings.

Third, Bradford has a multi-ethnic and deprived urban population; our results may therefore not be generalisable to more affluent areas. Fourth, our analysis also assumed that the residents of the Bradford metropolitan district would visit primary care or emergency department services whenever there are symptoms of illnesses. However, if residents did not visit health services for any reason, the number of visits we used in our analyses may not reflect the actual numbers and that the potential impact of CAP may have been under/overestimated by our models.

Fifth, although we have used cut-off dates as the start of the intervention (CAP) components, not all components (e.g. grants, retrofitting of vehicles) would start at the exact same date. Hence, the synergic impact of the intervention components may have been weaker than if the components were implemented at once.

Sixth, it has been presumed that each part of the intervention would have instantaneous effect and any delayed effect is sufficiently captured by the slope parameters of our models. Due to complexities of the intervention, lagged effects models were not sought to assert our assumption.

Seventh, we defined routine diabetic foot care (primary care) and head injury (emergency department) as non-equivalent control outcomes unlikely to be related to shorter-term changes in pollution levels (McEachan et al., 2022). However, we note that based on recent literature, road traffic injuries (Chamberlain et al., 2023) and diabetes (Yang et al., 2020) are associated with air pollution. Hence, these may not have been ideal choice for a control outcome in our study. The impact of air pollution on human health appears to be so systematic that identifying genuinely independent non-equivalent controls remains a challenge.

Finally, our study tracked a two-year implementation period, which may be too short a time to observe reliable changes in many health impacts. Longer term follow-up is warranted to determine whether the observed effects are sustained over time.

## 5. Conclusion

Our findings suggests that the Bradford CAP may be linked with improved pollution levels, and cardiovascular and respiratory health within the first two years of implementation. However, caution must be exercised when interpreting our results due to the impact of the COVID-19 pandemic in the baseline period which may have had lasting impacts on health service use. Longer-term follow-up and the use of control data from similar cities without the policy is thus warranted. The Bradford CAP included restrictions to the movement of polluting vehicles, combined with initiatives to support the uptake of cleaner vehicles. Evaluating these types of policies in real-world settings is challenging and it can be difficult to disentangle unique impacts of the policy in the context of the 'complex systems' in which they operate. Combining evaluation of longer-term health and economic impacts using appropriate quasi-experimental approaches, with research to understand how the context in which these policies operate affect implementation will be crucial to understanding the critical factors which affect these policies' success or failure.

## CRediT authorship contribution statement

**Teumzghi F. Mebrahtu:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Gillian Santorelli:** Writing – review & editing, Funding acquisition, Conceptualization. **Tiffany C. Yang:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **James E. Tate:** Writing – review & editing, Funding acquisition, Data curation, Conceptualization. **Sally Jones:** Writing – review & editing, Funding acquisition, Conceptualization. **John Wright:** Writing – review & editing, Funding acquisition, Conceptualization. **Rosemary R.C. McEachan:** Writing – review & editing, Supervision, Project administration, Funding acquisition, 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.envres.2025.120988.

## Data availability

The authors do not have permission to share data.

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