

TRANSPORT FINDINGS

Did the Implementation of Low Emission Zone in Glasgow Change the Traffic Flow and Air Quality?

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Findings

This paper investigates how Glasgow's low-emission zone (LEZ), introduced in 2023, affected traffic patterns and nitrogen dioxide (NO₂) concentrations at two sites. Using Open APIs data from the pre-LEZ (Aug-Sep 2022) and post-LEZ (Aug-Sep 2023) periods, a Wilcoxon test revealed that on High Street, significant decreases in traffic flow were observed on core weekdays ($W = 359$, $p < 0.001$) and other weekdays ($W = 122$, $p = 0.03$), as were significant decreases in normalized NO₂ levels across all day groups ($p < 0.001$). Hope Street also showed significant NO₂ reductions across all day groups ($p < 0.01$), despite no significant change in traffic.

1. QUESTIONS

Glasgow is a major city in the UK that has a high traffic volume from private vehicles to Heavy Goods Vehicles (HGVs) (FleetLogging 2021). According to the Department of Transport Statistics 2022, Glasgow had the most licensed vehicles among Scottish cities in 2021, with nearly 240,000 (Williams 2020). As the city struggles to keep up with the increasing number of cars and lorries on its streets, the accompanying congestion has resulted in extraordinary quantities of nitrogen oxides from tailpipes and particulates from brake wear, tire wear, and road abrasion (Air Quality Expert Group 2019; Williams 2020). In response, Glasgow implemented a Low Emission Zone (LEZ) on June 1, 2023 in the city center area, allowing only vehicles that meet specific emission standards¹ to enter the zone. In light of this new traffic regulation, further action is necessary to evaluate the resultant environmental changes.

Our paper explores the following questions:

- How do traffic flows change within Glasgow's LEZ compare to the pre-LEZ period?
- Have NO₂ levels, as one of the major vehicular emissions, changed within Glasgow's LEZ since its enforcement?

¹ For passenger vehicles, Euro 4 for petrol vehicles (NO_x: 0.080g/kWh), Euro 6 for diesel vehicles (NO_x: 0.080g/kWh). Euro VI for heavy-duty diesel vehicles such as buses/coaches and HGVs ((NO_x: 3.5g/kWh). More information, please visit: <https://dieselnet.com/standards/eu/hd.php>

2. METHODS

2.1. Study Area

Our study area encompassed the Glasgow LEZ boundary (see [Figure 1](#)). The LEZ's implementation on June 1, 2023, marked the commencement of our main study period, which was divided into pre-LEZ (Aug-Sep 2022) and post-LEZ (Aug-Sep 2023). This time frame allowed for a comparative analysis of traffic patterns before and after LEZ enforcement and to avoid seasonal effects.

The air quality measurements and traffic counts were divided into three categories based on the days of the week due to the new working patterns after the pandemic: Non-core weekdays (Mondays and Fridays), Core weekdays (Tuesdays, Wednesdays, and Thursdays), and Weekends (Saturdays and Sundays) (Harrington and Hadjiconstantinou 2022).

2.2. Data

We gathered hourly NO₂ data from the UK's [Automatic Urban and Rural Network](#) (AURN) using the *openair* R package (Carslaw and Ropkins 2012). Our study area included two roadside monitors, Glasgow Hope Street (GLA4) and Glasgow High Street (GHSR), both located within the zone and near the LEZ boundary ([Figure 1A](#)). Our analysis focused on the daily averaged NO₂. Additionally, the meteorological data² was provided by the UK Met Office to account for the wind effect on NO₂ dispersion (MetOffice 2024). To our knowledge, there were no monitoring stations with historical data closer to center of the LEZ.

Using data obtained from the [Glasgow Open Data API](#) (Li, Zhao, and Wang 2024), we collected a daily sum of the traffic counts from two monitoring stations also located within the zone ([Figure 1C and 1D](#)). The High St air quality monitor (GHSR) is 11 meters from the road, while the Hope St air quality monitor (GLA4) is 6 meters away. Both traffic monitors from each air quality monitor are less than 2 meters away from the road. These stations were selected based upon their proximity to the pollution monitors and on the fact that they are not restricted to bus-only or taxi-only traffic. Despite being the closest available, the traffic monitors are over 100 meters away from the air quality monitors, which presents a challenge in explicitly capturing the direct impact of traffic emissions. [Table 1](#) shows the distributions for NO₂ and traffic flow over the course of the study period. Considering that NO₂ concentrations are strongly influenced by weather (Beckwith et al. 2019;

² We note that the nearest weather station with available historical data, Glasgow Clincarthill, is located around 4.6km southeast from the LEZ boundary. This distance presents a data limitation that we are unable to overcome in this study.

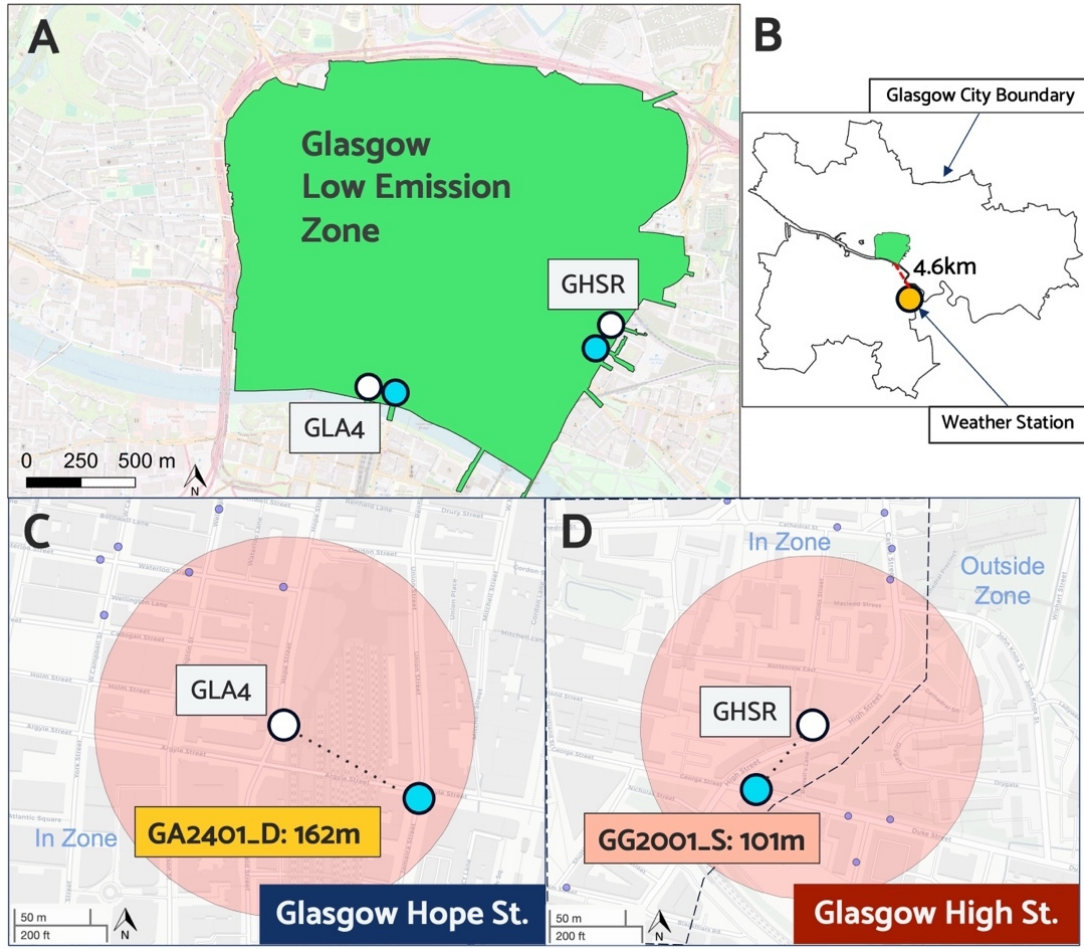


Figure 1. Location of roadside monitoring stations in the Glasgow LEZ (A), location of the nearest weather station from the LEZ (B), distances to the nearest traffic monitors from the Hope Street (C) and High Street (D) air quality stations.

DeWinter et al. 2018; Matthaïos et al. 2024), we added temperature, relative humidity, wind speed, and wind direction, all on a daily scale, to the statistical model in order to normalize the NO_2 readings.

2.3. Statistical Analysis

To assess the effect of the LEZ on traffic flow and NO_2 measurements, we perform a two-step process: 1) normalizing daily NO_2 levels to account for meteorological effects, and 2) using a Wilcoxon signed-rank test. In the first step, we converted the meteorological wind direction (0-360 degrees) to mathematical conventions (numerical values) because it ensures consistent calculations and avoids potential confusion with meteorological angles measured clockwise from true north (Earth Observation Laboratory 2024; Grange 2014). Then, we used a generalized additive model (GAM) for both Hope Street and High Street to normalize NO_2 . The specific GAM equation is as follows:

$$E(Y) = \beta_0 + s(\text{temp}_{\text{daily}}) + s(\text{humid}_{\text{daily}}) + s(\text{ws}_{\text{daily}}) + s(u_{\text{daily}}) + s(v_{\text{daily}}) + \varepsilon$$

Table 1. Descriptive statistics of average traffic volume and NO₂ across different weekday categories (Aug-Sep 2022/2023).

Station	Week group	Year	Mean Daily Traffic	Traffic Diff	Mean NO ₂ (before normalization)	NO ₂ Diff
High Street	Core Weekdays (Tue-Thu)	2022	720 (sd± 86)	-120 (-16%)	20.2 (sd± 6.60)	-5.8 (-28%)
		2023	600 (sd± 76)		14.4 (sd± 4.66)	
	Other Weekdays (Mon, Fri)	2022	716 (sd± 157)	-111 (-15%)	18.9 (sd± 6.77)	-4.4 (-23%)
		2023	605 (sd± 98)		14.5 (sd± 7.06)	
	Weekends (Sat-Sun)	2022	682 (sd± 112)	-50 (-7.3%)	17.4 (sd± 6.57)	-4.9 (-28%)
		2023	632 (sd± 110)		12.5 (sd± 5.91)	
Hope Street	Core Weekdays (Tue-Thu)	2022	1,344 (sd± 98)	+24 (+1.7%)	38.5 (sd± 10.5)	-5.1 (-13%)
		2023	1,368 (sd± 107)		33.4 (sd± 11.7)	
	Other Weekdays (Mon, Fri)	2022	1,444 (sd± 219)	+45 (+3.1%)	38.6 (sd± 12.2)	-6.1 (-16%)
		2023	1,489 (sd± 206)		32.5 (sd± 11.6)	
	Weekends (Sat-Sun)	2022	1,701 (sd± 200)	+24 (+1.4%)	35.6 (sd± 13.6)	-5.4 (-15%)
		2023	1,725 (sd± 292)		30.2 (sd± 11.7)	

where:

- β_0 is the intercept.
- $s(\cdot)$ denotes a smooth function
- $\text{temp}_{\text{daily}}$ is the daily temperature
- $\text{humid}_{\text{daily}}$ is the daily relative humidity
- ws_{daily} is the daily averaged windspeed
- u_{daily} is the vectorized daily wind direction indicating east-west³ i.e. $\text{ws} \cdot \sin(\theta)$
- v_{daily} is the vectorized daily wind direction indicating north-south i.e. $\text{ws} \cdot \cos(\theta)$
- Note θ must be in radians (if θ is in degrees, it needs to be converted by multiplying $\pi / 180$).

The residuals of this model represent the normalized concentrations of NO₂ (see details of normalization in the supplementary document).

$$\text{NO2}_{\text{Normalized}} = \text{NO2}_{\text{Mean}} + \text{E}(\text{Y})_{\text{Residuals}}$$

³ Positive u indicates wind blowing from the west (toward the east), whereas negative u indicates wind blowing from the east (toward the west). Likewise, Positive v indicates wind blowing from the south (toward the north), whereas negative v indicates wind blowing from the north (toward the south).

Table 2. Wilcoxon signed rank test results for daily traffic by week groups and years

Area	Week Group	Observations		Median Counts		W-statistics	p-value
		2022	2023	2022	2023		
High Street	Core Weekdays	27	27	709	617	359	<0.001***
	Other Weekdays	17	17	745	609	122	0.03*
	Weekends	16	16	670	664	106	0.051
Hope Street	Core Weekdays	27	27	1338	1383	136	0.21
	Other Weekdays	17	17	1432	1443	50	0.36
	Weekends	16	16	1729	1650	51	0.74

Table 3. Wilcoxon test results for normalized NO₂ by week groups and years

Area	Week Group	Observations		Median NO ₂ (µg/m ³)		W-statistics	p-value
		2022	2023	2022	2023		
High Street	Core Weekdays	27	27	19.5	14.2	373	<0.001***
	Other Weekdays	17	17	19.1	14.3	153	<0.001***
	Weekends	16	16	18.4	11.9	130	<0.001***
Hope Street	Core Weekdays	27	27	37.4	32.6	338	<0.001***
	Other Weekdays	17	17	36.9	33.5	141	0.0017**
	Weekends	16	16	34.9	30.9	128	<0.001***

Next, we employed the Wilcoxon signed-rank test (W), a non-parametric statistical method suitable for comparing various measures collected from different locations (Woolson 2007). W was chosen because the dataset did not satisfy the normality assumptions. We applied this test to compare daily traffic counts and NO₂ levels across categorized days of the week. As this analysis compares the exact grouped dates between the pre-LEZ and post-LEZ periods, we removed one day in the Other Weekdays category and one day in the Weekends category to match the days. This ensures that the pairs are comparable.

3. FINDINGS

The modelled results for traffic and normalized NO₂ are presented in [Table 2](#) and [Table 3](#) respectively. In the High Street area, the Wilcoxon test illustrates statistical differences in daily traffic flow and normalized NO₂ between pre-LEZ and post-LEZ. For traffic, changes in traffic were observed on Core Weekdays ($W = 359$, $p < 0.001$) and Other Weekdays ($W = 122$, $p = 0.03$) but not on Weekends ($W = 106$, $p = 0.051$). Regarding normalized NO₂ levels, significant differences were noted across the week groups ($p < 0.001$).

In contrast, Hope Street did not show significant changes in total traffic flow between 2022 and 2023 across any of the day groups. The Wilcoxon test for Core Weekdays ($W = 136$, $p = 0.21$), Other Weekdays ($W = 50$, $p = 0.36$),

and Weekends ($W = 51$, $p = 0.74$) indicate no significant changes in daily traffic. Regarding normalized NO_2 levels, the Wilcoxon test results showed significant differences across the week groups ($p < 0.01$).

In summary, although the monitors were not as centrally located in the LEZ, our findings indicate that significant decreases in traffic on High Street may have reduced normalized NO_2 levels on Core Weekdays and Other Weekdays, which corresponded with significant decreases in normalized NO_2 levels. Despite stable traffic patterns on Hope Street during post-LEZ, significant changes in normalized NO_2 levels were observed, indicating factors other than traffic flow might have influenced air pollution in this area.

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DATA & CODE AVAILABILITY

All data and reproducible codes are freely available from the GitHub repository (https://github.com/dataandcrowd/GlasgowLEZ_Traffic) and on Zenodo ([10.5281/zenodo.13337528](https://zenodo.org/record/105281)).

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SUPPLEMENTARY MATERIALS

Supplement 1: Explaining Wind Direction Conversions

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Supplement 2: Results

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