Are Low Emission Zones Impactful for Air Quality and Human Health?

Hyesop Shin[1], Eric Silverman[1], Alison Heppenstall[1], Nick Malleson[2], Mario Ilic[3], Sonali Abeysinghe[3], and Tabea Sonnenschein[4]

[1] MRC/CSO Social and Public Health Sciences Unit,
University of Glasgow, 90 Byres Road, Glasgow, G12 8TB, UK
hyesop.shin@glasgow.ac.uk
[2] School of Geography, University of Leeds, Leeds, LS2 9JT, UK
[3] Technical University of Munich, Arcisstraße 21, München, Germany
[4] Utrecht University, Amsterdam, The Netherlands

Abstract. Our study aims to assess the impact of Glasgow's Low Emission Zone (LEZ) on traffic flow, traffic-related emissions, and pedestrian exposure to air pollution. To lay the groundwork for a comprehensive Multi-agent System (MAS) simulation, we initially compared the changes in traffic flows and NO_2 levels within the LEZ post-implementation compared to the baseline period. In the initial phase, we performed a comparative analysis of traffic observations and NO_2 concentrations between the periods before (Jun-Aug 2022) and after (Jun-Aug 2023) LEZ implementation. Our analysis, which used the Wilcoxon Signed-Rank Test (a non-parametric alternative to one-way ANOVA), revealed significant reductions in traffic volume and NO_2 levels on High Street (at the LEZ boundary, characterised by heavy traffic), while minimal changes were observed on Hope Street (at the LEZ core, primarily restricted to buses and taxis), indicating the LEZ's positive environmental effects. We also showcase a proof-of-concept Multi-agent System (MAS) using the Simulation of Urban Mobility (SUMO) platform, and show how the results from the data can feed into the simulation. Furthermore, we present a proof-of-concept MAS employing the Simulation of Urban Mobility (SUMO) framework, demonstrating how empirical data can be integrated into the simulation to model potential outcomes. The workshop aims to foster discussions on leveraging MAS or individual-based simulations for evaluating policy interventions and developing robust metrics to accurately quantify exposure to pollutants.

Keywords: Low Emission Zone (LEZ), Glasgow, Wilcoxon Signed-Rank Test, Traffic Simulation, NO_2, Simulation of Urban Mobility (SUMO)

1 Introduction

Air pollution in Glasgow has escalated into a critical public health issue. Despite increasing concerns, a significant gap exists in epidemiological research evaluating the impact of pollution on public health. This gap is particularly concerning given the rapid increase in vehicle numbers in Glasgow, leading to higher nitrogen oxides and particulate emissions [19,1]. In response, Glasgow has initiated Scotland's first Low Emission Zone (LEZ) on June 1, 2023. The LEZ aims to reduce air pollution and protect both pedestrians and drivers by targeting vehicles that do not meet certain EURO standards.

However, the enforcement of the LEZ presents various challenges and uncertainties. Air pollution levels within the LEZ vary markedly across different roads, necessitating a thorough examination of these differences. In addition, the difficulty of providing real-time updates in air pollution modelling and the limited number of reliable monitoring stations complicate the issue further. Many previous studies on air pollution and health have depended on spatial interpolation and dispersion models, which tend to provide aggregated data on a monthly or yearly basis [5,11,4,12,3]. While this approach can illustrate the overall distribution of pollution effectively, it may not be particularly useful for policy intervention; such aggregated figures offer limited insights into the nuances of pollution levels, which are crucial for developing effective control measures. Furthermore, current exposure assessments often neglect the dynamic nature of population movement, typically relying on static data from census information. Efforts to improve these estimates through GPS studies, which track real movements and transportation modes, face challenges such as limited participant numbers and data privacy issues [17,9,10,14]. For more targeted and effective policy decisions, we need more detailed and real-time data that can capture the dynamic nature of air pollution and pedestrian mobility patterns. This approach enables more precise and timely strategies to mitigate air pollution impacts.

To address these multifaceted challenges, we propose an innovative solution: a Multi-agent System (MAS). This system is designed to assess the impact of traffic emissions on local air quality and human health more accurately, taking into account pedestrian mobility patterns. Our approach not only enhances the accuracy of exposure estimation but also establishes a versatile platform for testing hypotheses and evaluating future scenarios. By enabling researchers to probe "what if" questions, this MAS illuminates the intricate behaviours of complex systems, offering a novel tool for exploring the potential impacts of LEZ implementation and beyond.

However, while several MAS studies have provided a meticulous analysis of traffic patterns and emissions, they have primarily focused on changes in air quality levels and have not explored the positive health outcomes associated with such changes, i.e., increased life expectancy and reduced rates of low-weight full-term births [8], or providing lack of the environmental impact of LEZ and traffic-related policies. Even among the few existing studies, like that of Ge and Polhill [6] and Shin and Bithell [15], more comprehensive approaches are still needed.

This paper develops an agent-based traffic simulation to assess the impact of Glasgow's LEZ Scheme on traffic flows, emissions, and pedestrian exposure. Outlined below are the key research questions guiding this endeavour:

- How have traffic patterns and air quality been affected following the enforcement of the LEZ?
- How can an agent-based model simulate the patterns of pedestrian mobility in relation to pollutant dispersion and its adverse health effects?

2 Methods

In this agent-based modelling (ABM) project, we constructed the model on a foundation derived from the existing dataset from the real-world scenario under study, ensuring that we mirror the complexities of the real scenario as accurately as possible. To answer our first research question, we use a pre-post statistical analysis, which allows us to evaluate changes over time while focusing on identifying significant differences before and after a specific intervention or event. These findings can serve as a precursor to the ABM. For the second research question, we develop a proof-of-concept agent-based model. This approach enables us to simulate individual agents' behaviours and interactions within a defined environment, thereby illustrating potential dynamics and outcomes that could not be readily observed in the natural setting.

2.1 Study Area

The study area for the agent-based simulation encompasses the central Glasgow area, which is composed of a 4km^2 area, which is slightly larger than Glasgow's actual 1.6km^2 LEZ boundary.

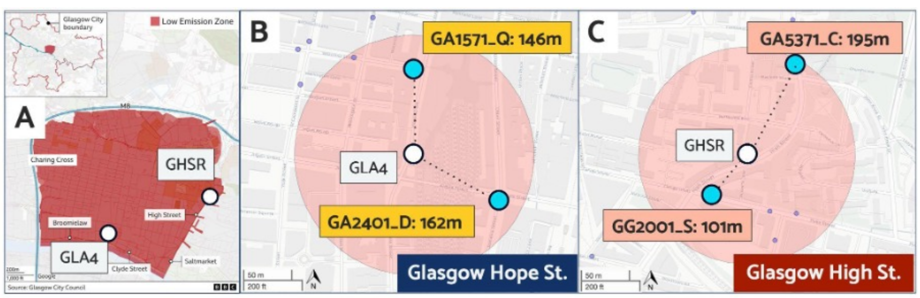

Fig. 1. The location of the roadside air quality monitoring stations in central Glasgow (A, source: https://www.bbc.co.uk/news/uk-scotland-65298944), and the distances to traffic monitors from air quality stations of Hope Street (B) and High Street (C)

2.2 Pre-Post Statistical Analysis

In this study, we hypothesise that NO_2 levels, which are primarily caused by vehicular emissions, will decrease in the study area in 2023 compared to 2022.

Using the Openair package in R as an API gateway (URL), we have acquired hourly NO_2 concentrations from two key roadside monitors from the Automatic Urban and Rural Network (AURN): Glasgow Hope Street (GLA4) and Glasgow High Street (GHSR). GLA4 is located in a busy canyon in the city centre, frequented primarily by taxis and buses that run north to south. In contrast, GHSR is located on a busy urban road on the eastern edge of the Low Emission Zone (LEZ).

For this analysis, we chose the two closest traffic monitoring stations within a 200-metre radius of each air quality monitor: Hope Street (GA1571_Q, GA2401_D) and High Street (GA5371_C, GG2001_S). This data was obtained from the Glasgow Open Data API and covers the pre-LEZ phase from June to August 2022 and the post-LEZ phase from June to August 2023.

To reflect post-pandemic work patterns, in which hybrid working arrangements have become more common, data on air quality and traffic volumes were classified by day of the week: non-core weekdays (Mondays and Fridays), core weekdays (Tuesdays, Wednesdays, and Thursdays), and weekends (Saturdays and Sundays).

We used the Wilcoxon signed-rank test (W), a non-parametric statistical method suitable for comparing various measures collected from different locations, to assess the impact of LEZs on traffic flow and NO_2 measurements. W was chosen because the dataset violated the normality assumptions from the Shapiro-Wilk test [7]. We used this test to compare daily traffic counts and NO_2 levels on various days of the week.

2.3 Application: Agent-Based Traffic Simulation using SUMO

To simulate an entire season and include vehicular traffic and pedestrian dynamics, we selected SUMO (Simulation of Urban Mobility) as our primary platform. SUMO is an open-source platform adept at managing extensive road networks within a continuous geographic realm. SUMO's primary use case is city traffic flow simulation and plotting individual vehicle routes.

We opted for SUMO due to technical and economic factors. SUMO's user-friendly graphical interface simplifies importing roadways in shapefile format, facilitating swift identification and rectification of disconnections. Road data is typically sourced from OpenStreetMap, which encompasses nodes, links, and turn signals. These features saved significant time and technical effort during model construction.

Additionally, SUMO has the ability to collaborate with various other models, including emission models. iTETRIS, a model developed by the German government to reduce emissions from vehicles, is one such example. Furthermore, since SUMO is written in C++ and Python, vehicle emissions can be calculated on High-Performance Computing such as the cluster located in our Unit at the University of Glasgow. Lastly, it's important to note that both SUMO and iTETRIS are freely available software packages that can be downloaded and used on Windows, Linux, or Macintosh operating systems. Another potential option is GRAL (Graz Lagrangian Model) [13], which accounts for urban meteorological conditions and morphology.

Our study concentrated on two pollution emission models: HBEFA and PHEM. HBEFA, or The Handbook Emission Factors for Road Transport (3rd edition), offers pollution factors like CO2, CO, HC, NOx, and PMx across vehicle categories and fuel types. PHEM (Passenger Car and Heavy Duty Emission Model) assesses emissions based on European standards. Our current focus is comprehending PHEM (proprietary, PHEM-lite is a free version to model emissions from private vehicles) and adapting it to the UK's DEFRA (Department for Environment, Food & Rural Affairs) standards.

Pedestrians Pedestrian agent behaviours can be broadly classified into three situations: 1) walking or running outdoors, where they may be exposed to ambient air pollutants; 2) in buildings, including indoor subway platforms, where pollutant concentrations may be brought in from outside; and 3) in vehicles, where road dust can enter through the vehicle filter [16]. In terms of mobility, the software's shortest path algorithm determines the agent's route to their destination, but they will pause and wait if crowd density is too high in certain areas. To estimate indoor air pollution rates, this study uses indoor/outdoor (I/O) ratios [2]. For in-vehicle exposure, an equation that takes into account the air exchange rate from windows and the ventilation system, filtration rate, and vehicle volume is strongly considered [16]. The agents' health is assumed to deteriorate if their NOx exposure exceeds the WHO threshold and improves if they walk or wheel instead.

Vehicles To model non-resident vehicles, we use buses, private vehicles, LGVs, and HGVs to assess traffic in and out of the city centre. Accurately calibrating the volume of vehicles based on factors such as time of day, day of the week, and holidays is critical to the success of the model. We will compare traffic and pollution levels before and after enforcement to determine how pollution changes hourly on each road and rank areas of potential pedestrian risk.

For MABS2024 Workshop We are looking forward to delving into the complexities of agent-based modelling using SUMO at the upcoming workshop. Our goal is to present a Proof-of-Concept model that demonstrates the capabilities and potential applications of SUMO in urban analytics. We are specifically looking for scenarios that show a 100% reduction in key metrics, demonstrating the profound impact and transformative potential that effective urban mobility simulation can have. This session will not only discuss the theoretical foundations of such simulations, but also provide practical insights into their implementation and implications for urban planning and management.

3 Findings

3.1 LEZ Effect on Traffic and NO_2

Our findings indicate that average daily traffic volumes remained relatively unchanged on Hope Street (city centre), except for a reduction at station GA1571 during weekends. However, traffic volumes on High Street experienced a significant reduction in 2023.

Regarding NO_2 levels, data from Glasgow High Street (GHSR, at the LEZ boundary) demonstrated a statistically significant decrease during weekdays, while weekend concentrations remained unchanged. In contrast, Glasgow Hope Street (GLA4, within the LEZ) exhibited reductions on Mondays and Fridays, with similar levels during core weekdays and weekends.

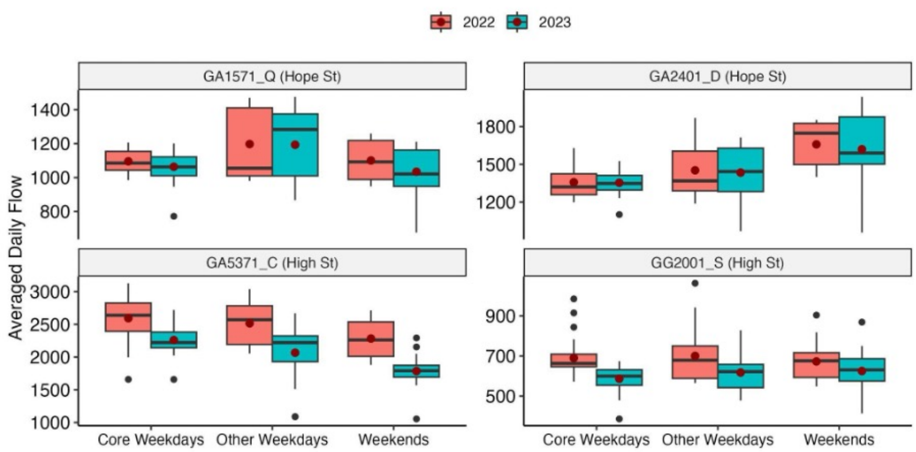

Fig. 2. Traffic counts from four monitoring stations on Hope and High Streets in 2022 and 2023 (mean value represented by a red dot). Compared to stations on Hope St, those on High St show a significant decrease on Core Weekdays (Tue-Thu), Other Weekdays (Mon, Fri), and Weekends (Sat, Sun).

3.2 LEZ Scenarios using SUMO

During the MABS workshop, we plan to showcase several demonstrations. One notable example involves managing traffic flow to achieve reductions of 30%, 50%, and even 100%. This strategy is designed to observe the subsequent effects on emissions and roadside air quality levels. To connect vehicular emissions to individual exposure rates, we will track each participant's movements and calculate their specific exposure levels.

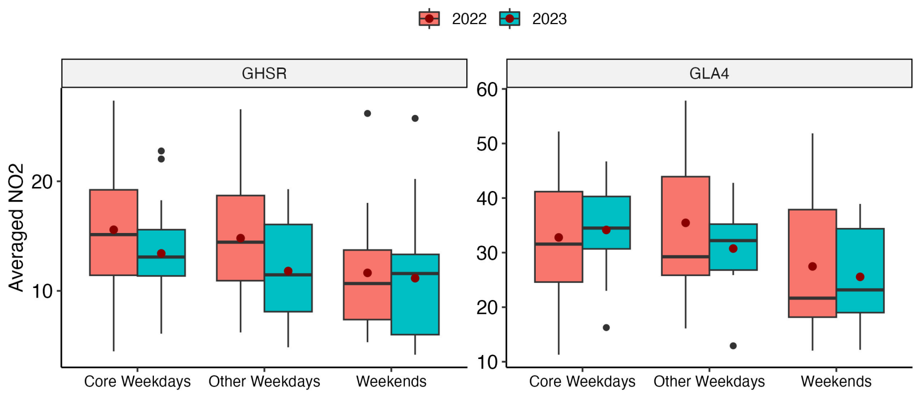

Fig. 3. NO_2 comparison between 2022 and 2023 across various days of the week. The left plot represents GHSR (Glasgow High Street, at the edge of LEZ), and the right plot GLA4 (Glasgow Hope Street, at the centre of LEZ).

4 Conclusion

4.1 Summary

Our study investigates the impact of Glasgow's Low Emission Zone (LEZ) on traffic flow, traffic-related emissions, and pedestrian exposure to air pollution. We initially contrasted the data from two critical periods: before the Low Emission Zone (LEZ) implementation (August-September 2022) and after its establishment (August-September 2023). As a result, we observed a significant decrease in vehicular movement along High Street, which lies on the periphery of the LEZ, following its introduction. Conversely, Hope Street, situated in the city centre, experienced a marginal increase in traffic volume post-LEZ implementation. In terms of NO_2 change, a notable improvement in air quality was recorded on both streets during peak weekday hours, as evidenced by the reduction in NO_2 levels. While this paper does not establish a direct causative link between traffic flow alterations and NO_2 concentration changes, our findings suggest a correlation that merits further investigation.

4.2 Future Work: Establishing the Context for Health Benefits through Policy Changes

This work examines a case study that explores the relationship between traffic patterns and human health. Specifically, we seek to address the question: "Can reducing car use and using more active travel and public transport benefit health?". This inquiry builds upon the foundational research presented in "Can air pollution negate the health benefits of cycling and walking?" by Tainio et al. [18], underscoring the importance of evaluating the potential health benefits within the context of policy changes.

We find that navigating the complexities of translating policy scenarios into effective and meaningful policies is critical during the development and implementation stages.

During the Social Simulation Conference 2023 in Glasgow, we presented our initial model and received somewhat contradictory feedback. On the one hand, some experts emphasised the importance of focusing on health impact assessments rather than the complexities of road infrastructure and traffic dynamics. On the other hand, a different set of suggestions aimed to improve the simulation's development. Given our collaboration with traffic engineering specialists, we decided to refine our traffic model first, ensuring that it accurately reflects real-world traffic conditions. We hope that this workshop will facilitate an open discussion on potential policy scenarios while also presenting case studies as evidence for reducing vehicle emissions in urban areas.

References

1. Air Quality Expert Group: Non-exhaust emissions from road traffic
2. Beevers, S.D., Kitwiroon, N., Williams, M.L., Kelly, F.J., Ross Anderson, H., Carslaw, D.C.: Air pollution dispersion models for human exposure predictions in London. Journal of exposure science & environmental epidemiology **23**(6), 647–53 (2013). https://doi.org/10.1038/jes.2013.6, http://dx.doi.org/10.1038/jes.2013.6{%}5Cnhttp://www.ncbi.nlm.nih.gov/pubmed/23443237
3. Beevers, S.D.: Traffic management strategies for emissions reduction : recent experience in London pp. 27–39 (2016)
4. Cambridgeshire City Council: Air Pollution in Cambridgeshire pp. 1–44 (2016). https://doi.org/10.1016/B978-0-08-092605-6.50007-7
5. David, N., Don, G.: An integrated agent-based framework for assessing air pollution impacts. Journal of Environmental Protection **2012** (2012)
6. Ge, J., Polhill, J.G.: Exploring the combined effect of factors influencing commuting patterns and co2 emissions in aberdeen using an agent-based model. Journal of Artificial Societies and Social Simulation **19**(3), 11 (2016). https://doi.org/10.18564/jasss.3078, http://jasss.soc.surrey.ac.uk/19/3/11.html
7. González-Estrada, E., Cosmes, W.: Shapiro–Wilk test for skew normal distributions based on data transformations. Journal of Statistical Computation and Simulation **89**(17), 3258–3272 (2019), publisher: Taylor & Francis
8. Host, S., Honoré, C., Joly, F., Saunal, A., Le Tertre, A., Medina, S.: Implementation of various hypothetical low emission zone scenarios in greater paris: Assessment of fine-scale reduction in exposure and expected health benefits **185**, 109405. https://doi.org/10.1016/j.envres.2020.109405, https://linkinghub.elsevier.com/retrieve/pii/S001393512030298X
9. Hwang, Y., Lee, K.: Contribution of microenvironments to personal exposures to PM10 and PM2.5 in summer and winter. Atmospheric Environment **175**, 192–198 (2018). https://doi.org/https://doi.org/10.1016/j.atmosenv.2017.12.009, http://www.sciencedirect.com/science/article/pii/S1352231017308269

10. Liang, L., Gong, P., Cong, N., Li, Z., Zhao, Y., Chen, Y.: Assessment of personal exposure to particulate air pollution: the first result of City Health Outlook (CHO) project. BMC Public Health **19**(1), 711 (2019). https://doi.org/10.1186/s12889-019-7022-8, https://doi.org/10.1186/s12889-019-7022-8
11. Min, K.D., Yi, S.J., Kim, H.C., Leem, J.H., Kwon, H.J., Hong, S., Kim, K.S., Kim, S.Y.: Association between exposure to traffic-related air pollution and pediatric allergic diseases based on modeled air pollution concentrations and traffic measures in Seoul, Korea: a comparative analysis. Environmental Health **19**(1), 6 (2020). https://doi.org/10.1186/s12940-020-0563-6, https://doi.org/10.1186/s12940-020-0563-6
12. Nyhan, M., Grauwin, S., Britter, R., Misstear, B., McNabola, A., Laden, F., Barrett, S.R.H., Ratti, C.: "exposure track" - The impact of mobile-device-based mobility patterns on quantifying population exposure to air pollution. Environmental Science and Technology **50**(17), 9671–9681 (2016). https://doi.org/10.1021/acs.est.6b02385
13. Romanov, A.A., Gusev, B.A., Leonenko, E.V., Tamarovskaya, A.N., Vasiliev, A.S., Zaytcev, N.E., Philippov, I.K.: Graz lagrangian model (GRAL) for pollutants tracking and estimating sources partial contributions to atmospheric pollution in highly urbanized areas **11**(12), 1375, publisher: MDPI
14. Sanchez, M., Milà, C., Sreekanth, V., Balakrishnan, K., Sambandam, S., Nieuwenhuijsen, M., Kinra, S., Marshall, J.D., Tonne, C.: Personal exposure to particulate matter in peri-urban India: predictors and association with ambient concentration at residence. Journal of Exposure Science and Environmental Epidemiology **30**(4), 596–605 (2020). https://doi.org/10.1038/s41370-019-0150-5, http://dx.doi.org/10.1038/s41370-019-0150-5
15. Shin, H., Bithell, M.: TRAPSim: An agent-based model to estimate personal exposure to non-exhaust road emissions in central seoul **99**, 101894. https://doi.org/10.1016/j.compenvurbsys.2022.101894, https://linkinghub.elsevier.com/retrieve/pii/S0198971522001387
16. Smith, J.D., Mitsakou, C., Kitwiroon, N., Barratt, B.M., Walton, H.A., Taylor, J.G., Anderson, H.R., Kelly, F.J., Beevers, S.D.: London Hybrid Exposure Model: Improving Human Exposure Estimates to NO2 and PM2.5 in an Urban Setting. Environmental Science and Technology **50**(21), 11760–11768 (2016). https://doi.org/10.1021/acs.est.6b01817
17. Steinle, S., Reis, S., Sabel, C.E., Semple, S., Twigg, M.M., Braban, C.F., Leeson, S.R., Heal, M.R., Harrison, D., Lin, C., Wu, H.: Personal exposure monitoring of PM2.5 in indoor and outdoor microenvironments. Science of the Total Environment **508**, 383–394 (2015). https://doi.org/10.1016/j.scitotenv.2014.12.003, http://dx.doi.org/10.1016/j.scitotenv.2014.12.003
18. Tainio, M., de Nazelle, A.J., Götschi, T., Kahlmeier, S., Rojas-Rueda, D., Nieuwenhuijsen, M.J., de Sá, T.H., Kelly, P., Woodcock, J.: Can air pollution negate the health benefits of cycling and walking? **87**, 233–236, publisher: Elsevier
19. Williams, C.: Air pollution from busy traffic and its 'grim reaper' effect on glasgow communities https://www.glasgowlive.co.uk/news/glasgow-news/glasgow-air-pollution-grim-reaper-18798721