Impacts of a low-emission zone on air pollutant and greenhouse gas emissions in Warsaw

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FIA Foundation and the International Council on Clean Transportation (ICCT) have established The Real Urban Emissions (TRUE) Initiative. The TRUE Initiative seeks to supply cities with data regarding the real-world emissions of their vehicle fleets and equip them with technical information that can be used for strategic decision making.

EXECUTIVE SUMMARY

Air quality in Warsaw is among the worst in Europe, resulting in significant health consequences for its residents. The on-road transport sector contributes significantly to the city's air pollution. To address concerns related to transport-related air quality and strive towards climate neutrality by 2030, Warsaw has proposed the implementation of a low-emission zone (LEZ) starting in 2024. An LEZ is a designated area where vehicles must meet certain requirements, such as certification to certain emission standards, to enter the zone. As the details of the LEZ implementation are currently under discussion, it is crucial to assess the potential reductions in air pollutant and greenhouse gas (GHG) emissions that different LEZ schedule options can achieve, as well as the speed at which these benefits can be realized.

To support Warsaw's efforts to establish the LEZ, this study presents two implementation options for a zone in the city and examines their effects on air pollutant and greenhouse gas emissions. Option 1 gradually strengthens restrictions every 2 years from 2024 to 2034; Option 2 tightens restrictions each year at a more accelerated pace from 2024 to 2028. Utilizing real-world emissions data obtained from a 2020 TRUE remote sensing campaign in Warsaw, this study analyzes nitrogen oxide (NO_X), particulate matter (PM) and GHG emissions from passenger cars and light-commercial vehicles as a result of the implementation schedule options. GHG emissions include both tank-to-wheel (TTW) GHG emissions, which occur during vehicle operation, and well-to-wheel (WTW) GHG emissions, which consider energy production, transportation, and vehicle operation. Various scenarios were analyzed to assess how different responses from owners of restricted vehicles influence the air pollutant and GHG emission benefits of the LEZ. The main findings of the impacts of an LEZ on air pollutant and GHG emissions in Warsaw and related policy recommendations are summarized below.

KEY FINDINGS

- **An LEZ targeting older diesel vehicles certified to Euro 4 or below could reduce air pollutant emissions in Warsaw significantly, regardless of the actions taken by affected drivers.** As shown in Figure ES1, LEZ Option 1 could achieve a 50% reduction in fleet-average NO_X emissions by 2027 compared to 2023 levels, around four years earlier than the baseline scenario assuming no LEZ. Moreover, it could reduce fleet-average PM emissions by 50% by 2025 compared to 2023 levels, or around 5 years earlier than the baseline scenario. LEZ Option 2 could reduce both NO_X and PM emissions by 50% compared to 2023 levels 1 year ahead of LEZ Option 1.
- **By 2035, both LEZ implementation options could reduce fleet-average NO_X emissions by 95%, which is around 13 years earlier than without an LEZ.** Likewise, all LEZ scenarios could reduce fleet-average PM emissions by 88% by 2035, around 7 years earlier than in the baseline scenario with no LEZ.
- **LEZ Option 1 would reduce fleet-average TTW GHG emissions by 50% compared to 2023 levels around 3–6 years earlier than the baseline scenario of no LEZ.** Likewise, it could reduce fleet-average WTW GHG emissions by 50% compared to 2023 levels, around 6–9 years earlier than the baseline scenario of no LEZ.
- **Unlike for air pollutant emissions, the effectiveness of an LEZ to reduce TTW and WTW GHG emissions depends on the actions of affected drivers.** If drivers impacted by the LEZ choose to replace their non-compliant cars with 100% used vehicles, fleet-average TTW GHG emissions could be reduced by 50% by 2036. However, if drivers shift to alternative to zero-emission mobility options like cycling, walking, and public transport, the same 50% reduction could be achieved by 2033.
- **If drivers impacted by the LEZ replace non-compliant cars with battery electric vehicles, fleet-average WTW GHG emissions could be reduced by 50% by 2034.** This is 2 years earlier than if drivers opt to buy used vehicles to comply with LEZ restrictions.
- **The greatest cumulative savings for WTW GHG emissions could be achieved when affected vehicle owners switch to zero-emission mobility options.** Under this scenario, LEZ Option 2 could avoid 45% of the cumulative WTW GHG emissions that would be emitted until 2038 in the absence of an LEZ. LEZ Option 1 could avoid 31% of the cumulative WTW GHG emissions until 2038 without an LEZ under the same scenario. However, only LEZ Option 2 could bring Warsaw in line with the necessary GHG emission reductions needed to meet the goals outlined in the Paris Agreement.

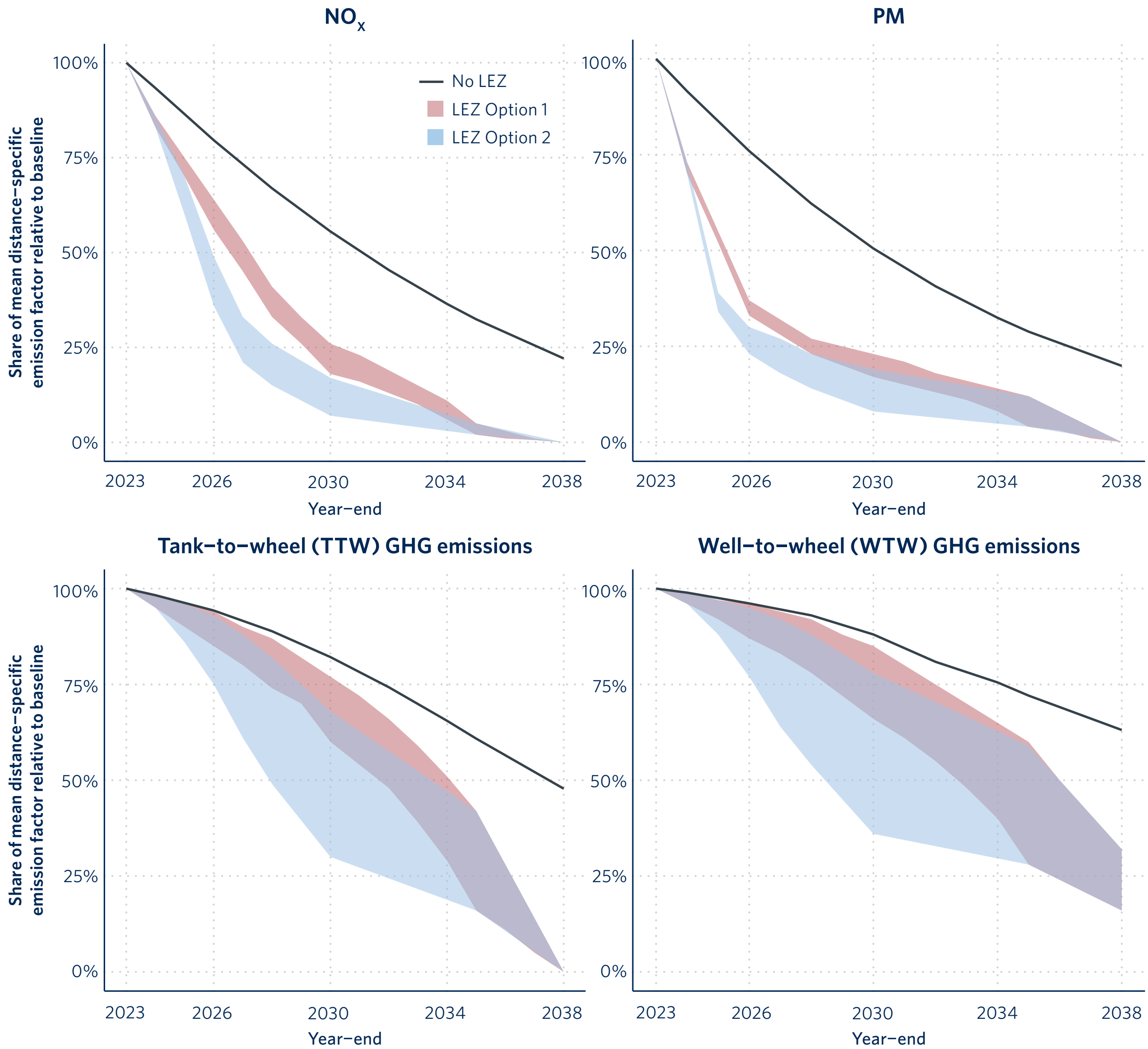

Figure ES1. Reduction in distance-specific emission factors of NO_X, PM, TTW and WTW GHG emissions relative to baseline (2023) levels as a result of LEZ Option 1: two-year interval implementation and LEZ Option 2: accelerated implementation schedules. Shaded areas show the ranges of possible emission reductions that depend on the responses of vehicle owners to LEZ restrictions. Responses range from replacing non-compliant vehicles with 100% used vehicles (upper boundary of each shaded area) to switching completely to zero-emission mobility (lower boundary of each shaded area).

POLICY RECOMMENDATIONS

1. **The restriction of older diesel vehicles with disproportionate contributions to emissions should be prioritized.** Policy measures that prioritize the restriction of older, high-emitting diesel passenger cars certified to Euro 4 and below (registered before 2011) in the early stages of LEZ implementation could reduce of both NO_X and PM emissions by 50% by 2027 and 2025, respectively.

2. **LEZ policies should promote a transition to zero-emission alternatives.** In order to achieve the highest emission benefits in terms of air pollutants and GHGs, LEZ policies should incentivize drivers to opt for zero-emission alternatives, such as battery electric vehicles, public transportation, cycling, or walking. This could be done through additional policies intended to improve cycling infrastructure and access to public transport, promote charging infrastructure

installation, and provide financial assistance for purchasing clean vehicles.

3. **Given the heavier burdens from an LEZ on households with lower incomes, supplementary policies that mitigate these impacts are essential.** Potential measures could include public subsidies to facilitate the purchase of zero-emission vehicles, discounts on public transportation fares, access to shared battery electric vehicles and, if necessary, exemptions or extended timeframes for acquiring LEZ-compliant vehicles.
4. **The success of an LEZ can be ensured with monitoring and coverage.** This can be achieved through monitoring air quality within the zone and evaluating compliance rates. Implementing a more ambitious LEZ policy that expands geographic coverage would result in greater emission benefits for more residents.
5. **Implementing a zero-emission zone could help Warsaw achieve climate goals as well as air quality improvement.** By banning all internal combustion engine vehicles from the LEZ, Warsaw could achieve near zero tailpipe emissions in the zone. This could further contribute to Warsaw's efforts to meet public health and climate objectives, including achieving climate neutrality by 2030 and compliance with the European Union's zero pollution action plan to reduce the number of premature deaths from air pollution.

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INTRODUCTION

Warsaw is one of Europe's most polluted cities.[1] Its air quality frequently surpasses World Health Organization (WHO) guidelines for particulate matter ($PM_{2.5}$) and nitrogen dioxide (NO_2) concentrations. In 2021, the city recorded an annual $PM_{2.5}$ mean concentration three times higher than the WHO guidelines.[2] Similarly, in 2019, annual NO_2 mean concentrations were roughly double WHO guidelines.[3] The European Environment Agency assessed that around 40,000 premature deaths in Poland were attributable to $PM_{2.5}$ and NO_2 exposure in 2020, a level 1.6 times higher than the EU-27 average.[4] When assessing health impacts in monetary terms, Warsaw ranks fourth among 432 cities in 30 European countries, with social costs related to air pollution estimated to be €4.2 billion in 2018.[5] These costs are expected to increase as transportation activities and the number of internal combustion engine vehicles in the city increase.

The road transport sector significantly contributes to air pollution in Warsaw due to the prevalence of older cars on the city's roads. The average age of in-use passenger cars is 14 years in Poland (2 years older than the European average).[6] Poland also has a 41% share of passenger cars over 20 years old, highest among all European Union (EU) member states.[7] This is primarily because Poland is the EU's leading importer of used cars, mostly from Germany, France, Belgium and the Netherlands.[8] A previous study from The Real Urban Emissions Initiative (TRUE) found that approximately 32% of passenger car activity in Warsaw was comprised of imported used vehicles, which had an average age of 13 years—more than double the age of domestic vehicles.[9] Furthermore, that study found that diesel passenger cars certified to Euro 4 or earlier standards accounted for around 30% of total NO_X emissions and 60% of total PM emissions,[10] despite constituting less than 11% of total passenger car activity in Warsaw.

In response to concerns about its declining air quality,[11] Warsaw recently announced a plan to introduce a low-emission zone (LEZ).[12] An LEZ is designed to enhance air quality and provide human health benefits by regulating the access of high-emitting vehicles to certain city areas. Furthermore, the introduction of an LEZ could lead to climate benefits through the reduction of vehicular greenhouse gas (GHG) emissions. The restriction criteria and geographic scope of Warsaw's prospective LEZ is currently under discussion.[13] More detailed information about the Warsaw LEZ is expected to be announced in late 2023.

This study uses real-world emission factors derived from a TRUE remote sensing study conducted in Warsaw in 2020 and identifies two LEZ implementation schedule options that prioritize the targeting of old, high-emitting passenger cars and light commercial vehicles. This study describes the methodology employed in the LEZ model, which predicts future turnover rates in the vehicle fleet, and presents various scenarios replicating the possible behavior of drivers whose vehicles become restricted. Moreover, this study analyzes the impacts of the LEZ on air pollutant and GHG emissions under these scenarios for the two implementation options. This study concludes by recommending policies Warsaw could consider.

1 "IS Global - Ranking of Cities, Urban Health study in 1,000 European cities", accessed March 29, 2023, https://isglobalranking.org/ranking/.

2 "European City Air Quality Viewer," European Environment Agency, accessed June 22, 2023, https://www.eea.europa.eu/themes/air/urban-air-quality/european-city-air-quality-viewer.

3 State of Global Air, "The European Union: A Regional Air Quality Snapshot," 2023, https://www.stateofglobalair.org/sites/default/files/documents/2023-01/soga-european-union-snapshot_1.pdf.

4 "Poland — Air Pollution Country Fact Sheet — European Environment Agency," European Environment Agency, accessed May 8, 2023, https://www.eea.europa.eu/themes/air/country-fact-sheets/2021-country-fact-sheets/poland.

5 Sandra de Bryun and Joukje de Vries, "Health Costs of Air Pollution in European Cities and the Linkage with Transport," (CE Delft, October 2020), https://epha.org/wp-content/uploads/2020/10/final-health-costs-of-air-pollution-in-european-cities-and-the-linkage-with-transport.pdf. Thirty European countries includes the EU-27 plus the United Kingdom, Norway, and Switzerland.

6 "Average Age of the EU Vehicle Fleet, by Country," ACEA - European Automobile Manufacturers' Association (blog), May 2, 2023, https://www.acea.auto/figure/average-age-of-eu-vehicle-fleet-by-country/.

7 "Passenger Cars in the EU," Eurostat, accessed May 25, 2023, https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Passenger_cars_in_the_EU.

8 Samar Automotive Market Research Institute, "Imports Are Growing Rapidly — September 2020."

9 Kaylin Lee, Yoann Bernard, Tim Dallmann, Uwe Tietge, Izabela Pniewska, and Isabel Rintanen, "Evaluation of Real-World Vehicle Emissions in Warsaw," (Washington, DC: TRUE Initiative, 2022), https://www.trueinitiative.org/data/publications/evaluation-of-real-world-vehicle-emissions-in-warsaw.

10 PM emissions includes both $PM_{2.5}$ and PM_{10}.

11 "Our successes," Polish Smog Alert, accessed June 22, 2023, https://www.polishsmogalert.org/polish-smog-alert/our/our-successes/.

12 City of Warsaw, "Mieszkańcy Warszawy chcą ograniczenia szkodliwych emisji z transportu drogowego [Warsaw residents want to reduce harmful emissions from road transport]," January 25, 2023, https://um.warszawa.pl/-/mieszkancy-warszawy-chca-ograniczenia-szkodliwych-emisji-z-transportu-drogowego.

13 City of Warsaw, "Warszawa wprowadzi strefę czystego transportu – ruszają konsultacje społeczne [Warsaw will introduce a clean transport zone – social consultations are starting], January 25, 2023," https://um.warszawa.pl/-/warszawa-wprowadzi-strefe-czystego-transportu-ruszaja-konsultacje-spoleczne.

METHODOLOGY

This study assesses the potential reductions in pollutant and GHG emissions expected from the implementation of an LEZ in Warsaw. The analysis is based on real-world emissions measurements, fleet composition, and vehicle activity data specific to the Warsaw fleet by Euro standard and fuel type.[14] The implementation of the LEZ involves gradually restricting access to various vehicle groups. Two implementation timelines are considered: Option 1 gradually tightens the minimum emission standards allowed in the zone every 2 years from 2024 to 2034; Option 2 takes a more accelerated approach with the minimum emission standards tightening every year from 2024 to 2028.

The analysis builds on the approach developed and used in a TRUE study from 2021 that examined the effects of implementing an LEZ in Sofia, Bulgaria.[15] Unlike the Sofia study, which focused only on tailpipe NO_x and PM emissions, this analysis also considers both well-to-wheel (WTW) and tank-to-wheel (TTW) GHG emissions from passenger cars and light commercial vehicles.[16] While the Sofia study assumed a constant age distribution of the fleet over time to project future fleet composition, this study considers the evolution of the age, fuel, and emissions standard distribution, as well as the vehicle activity's growth of the fleet over time, relative to the vehicle activity measured during the 2020 Warsaw remote sensing campaign. Battery electric vehicles (BEVs) and used vehicles are included in the modelling of vehicle fleet turnover. The number of BEVs in the fleet are assumed to increase in line with the EU's "Fit for 55" proposal, which aims to only allow the new registration of zero-emission passenger cars and vans by 2035.[17]

To estimate the changes in pollutant and GHG emissions resulting from the implementation of the LEZ, the average emission factor of passenger cars and light commercial vehicles is calculated.[18] The analysis primarily focuses on the impact of implementing the LEZ on air pollutant and GHG emissions from passenger cars, which are the most common vehicle type on the roads of Warsaw. The impact on emissions from light commercial vehicles is included in the appendix. The analysis did not consider heavy-duty vehicles or 2- and 3-wheelers due to the lack of sufficient measurements of these vehicles collected during the remote sensing campaign (less that 1% of total measurements).

REAL-WORLD EMISSION FACTORS

Emission factors were obtained from the TRUE campaign in Warsaw between September 24 and October 9, 2020. Out of about 220,500 valid measurements, 68% were of passenger cars and 8% were of light commercial vehicles. The methodology used in a previous ICCT study was employed to convert fuel-specific emission values collected by remote sensing instruments to distance-specific NO_x and PM tailpipe emission factors by fuel type and emission standards for different vehicle classes.[19] These emission factors represent the fleet's emissions under real driving conditions in Warsaw, which differ from those measured during laboratory type-approval tests. The real-world emission values account for a range of driving and environmental factors (e.g., temperature, speed, acceleration, and road grade) not accounted for in type-approval values.[20]

Table 1 summarizes the emission factors used in the analysis for passenger cars. As Euro 7 vehicles are expected to be available in July 2025, in line with pending final regulations, emission factors for NO_x were assumed to be 30 mg/km for both diesel and petrol passenger cars and PM emission factors were assumed to be 1.9 mg/km for diesel and 1.5 mg/km for petrol.[21] The PM emission factors were assumed

14 The analysis focuses solely on the average emissions of vehicles within the LEZ and does not consider the dimensions or geographical coverage of the LEZ.

15 Kaylin Lee, Yoann Bernard, Tim Dallmann, Caleb Braun, and Josh Miller, "Impacts of a Low-Emission Zone in Sofia" (Washington, DC: TRUE Initiative, 2021), https://www.trueinitiative.org/data/publications/the-impact-of-a-low-emission-zone-in-sofia.

16 This analysis assesses WTW GHG emissions, focusing on energy production and transport. However, it does not address the broader scope of life-cycle assessment, which considers vehicle and battery production.

17 "Fit for 55," Council of the European Union, April 27, 2023, https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/.

18 The fleet-average emission factor represents the sum of emissions factors weighted by activity share within emissions standard and pollutant type. They serve in our analysis as proxy for changes in total emissions.

19 Yoann Bernard, Uwe Tietge, John German, and Rachel Muncrief, "Determination of Real-World Emissions from Passenger Vehicles Using Remote Sensing Data" (Washington, DC: TRUE Initiative, 2018), https://www.trueinitiative.org/data/publications/determination-of-real-world-emissions-from-passenger-vehicles-using-remote-sensing-data.

20 Although the emissions from non-exhaust sources, such as brake and tire wear, are acknowledged, they have not been considered in this analysis.

21 These assumptions are based on the Medium Green Ambition scenario proposed by the European Commission's Policy option 2 (PO2a). Under proposed Euro 7 regulations, manufacturers must ensure vehicles comply with emission limits up to 10 years and 200,000 km, i.e., twice the time and mileage required under Euro 6. Additionally, Euro 7 standards are expected to fully align on-road and laboratory limits, expand testing boundaries, and require an urban trip approximatively three times shorter than the current on-road test. Consequently, the gap between real-world urban emissions and declared NO_x emissions is expected to shrink.

Table 1. Distance-specific tailpipe NO_x and PM emission factors for passenger cars derived from 2020 remote sensing measurements in Warsaw.

Standard	Fuel			
	Diesel		Gasoline	
	NO_x (mg/km)	PM (mg/km)	NO_x (mg/km)	PM (mg/km)
Euro 1	1113	95	1022	23
Euro 2	1152	61	873	15
Euro 3	1069	48	534	6.8
Euro 4	750	30	276	2.8
Euro 5	692	6.4	169	2.6
Euro 6	345	2.5	121	2.1
Euro 6d-TEMP	135	1.9	93	1.5
Euro 6d	92	1.9	93	1.5
Euro 7	30	1.9	30	1.5

to remain at Euro 6d-TEMP and Euro 6d levels, as the real-world emissions are already below the 4.5 mg/km limit proposed in Euro 7 regulations. This analysis does not consider emissions deterioration of vehicles over time. Since BEVs have zero tailpipe emissions, their real-world emission factors for NO_x and PM were set to zero.

LEZ DESIGN

The 2020 TRUE study revealed that diesel passenger cars that are currently 15 years or older (certified to Euro 4 or below) showed real-world NO_x emissions 1.6–2.5 times higher than their type-approval limits. Likewise, pre-Euro 5 diesel vehicles without diesel particulate filters emit PM at levels 4–11 times higher than their petrol equivalents. Hence, the proposed LEZ is designed to encourage the renewal of the oldest and highest-emitting passenger cars in the fleet. In the first phase of the LEZ, which starts in 2024, the impacted diesel passenger cars are 19 years and older and impacted petrol passenger cars are 28 years and older.

Table 2 shows the two LEZ implementation schedules considered in this study. By Phase 5, the minimum emission standards allowed inside the LEZ are Euro 6d for diesel cars and Euro 6 for petrol passenger cars; these standards demonstrate comparable real-world NO_x and PM emission factors. The timeline of LEZ restrictions concludes for both LEZ options at Phase 8 in 2038, when all internal combustion engine (ICE) passenger cars would be banned from entering the zone. This proposal aligns with the strategies of other European cities that plan to upgrade their LEZs to zero-emission zones to help achieve climate neutrality by 2030.[22] For example, Paris and Amsterdam have plans to allow only BEVs and fuel cell electric vehicles (FCEVs) in certain areas of the city starting in 2030.[23]

Table 2. LEZ implementation restrictions and schedule options for passenger cars for Options 1 and 2.

Passenger car	Minimum standard		Implementation schedule	
Phase	Diesel	Petrol	Option 1	Option 2
1	Euro 4	Euro 2	2024	2024
2	Euro 5	Euro 3	2026	2025
3	Euro 6	Euro 4	2028	2026
4	Euro 6d-TEMP	Euro 5	2030	2027
5	Euro 6d	Euro 6	2032	2028
6	Euro 7	Euro 6d	2034	2030
7	Euro 7	Euro 7	2035	2035
8	BEV	BEV	2038	2038

22 Clean Cities Campaign, "The development trends of low- and zero-emission zones in Europe," (2022), https://cleancitiescampaign.org/wp-content/uploads/2022/07/The-development-trends-of-low-emission-and-zero-emission-zones-in-Europe-1.pdf.

23 Sandra Wappelhorst and Hongyang Cui, "Update on Zero-Emission Zone Development Progress in Cities" (Washington, DC: ICCT, 2022), https://theicct.org/publication/update-on-zero-emission-zone-progress-aug22/.

Baseline scenario	Buy 100% used vehicles	Buy 100% new vehicles	Buy 100% BEVs	Switch to zero-emission mobility (switch to zero-emission alternatives)
Natural fleet turnover with no LEZ in place.	Vehicle owners replace their LEZ-non-compliant vehicles with used vehicles of varying emission standards that meet the LEZ requirement.	Vehicle owners replace their LEZ-non-compliant vehicles with new vehicles certified to the best available standards.	Vehicle owners replace their LEZ-non-compliant vehicles with BEVs with zero tailpipe emissions.	Owners of LEZ-non-compliant vehicles switch their means of mobility to cycling, walking, and zero- and low-emission public transport.
No LEZ in place	**Different LEZ scenarios with LEZ in place**			

Figure 1. LEZ scenarios considered based on vehicle owner response to LEZ restrictions.

GHG MODELING

This analysis simulates the impact of an LEZ on GHG emissions over time. The fleet-average GHG emission factor is estimated based on an emissions trajectory using vehicle CO_2 data collected during the remote sensing campaign in Warsaw, as well as the projection of the future fleet composition.[24] The fleet-average GHG emission factor serves as a proxy measure for changes in GHG emissions during the analysis.[25]

Fleet-average GHG emissions account for both WTW and TTW emissions. TTW GHG emissions, also referred to as downstream, focus solely on emissions that occur during vehicle operation, specifically from fuel combustion. Thus, BEVs have zero TTW GHG emissions. WTW GHG emissions additionally consider upstream emissions from energy extraction and production, refining, and transport. In the case of BEVs, WTW GHG emissions occur during electricity production and transport.[26] In 2023, the electricity grid of Poland is carbon-intensive, largely relying on coal, but is projected to decline in the future.[27]

LEZ SCENARIOS

The effects of implementing an LEZ on emissions from passenger cars are compared with the baseline scenario where no LEZ is in place. To simulate the effects of an LEZ, four scenarios were developed with different assumptions about how vehicle owners might respond to restrictions, as shown in Figure 1.[28]

The comparison between these LEZ scenarios and a baseline scenario with no LEZ is presented in terms of the reduction in the fleet-average emission factor after certain phases of LEZ implementation compared to the average emission factor in 2023. Similarly, the comparison is carried out in terms of how much earlier the benefits of achieving a certain percentage reduction in the average emission factor could be realized through LEZ implementation compared to the baseline scenario.

24 Type-approval CO_2 emissions were adjusted for real-world conditions. Historic ICE vehicle tailpipe GHG emissions values are examined by using vehicle CO_2 fleet data collected during the 2020 remote sensing campaign. With the EU's intention to phase out new ICE vehicle sales from 2035, original equipment manufacturers are expected to prioritize the transition to BEVs. Consequently, this study assumes no further improvement in tailpipe GHG emissions for ICE vehicles.

25 To determine the fleet-average GHG emission factor, both the emissions and energy intensity of the fuel are required. Emissions intensity measures the amount of GHG emissions produced per unit of energy consumed (gCO_2eq/MJ). Energy intensity refers to how many MJ of energy are released per distance travelled (MJ/km).

26 BEV efficiency is assumed to be constant throughout the years (0.2 kWh/km or 0.72 MJ/km) and includes charging losses.

27 The Joint Research Center POTEnCIA (Policy Oriented Tool for Energy and Climate Change Impact Assessment) model projects that Poland's carbon intensity will decline in the future, due to the rise in the utilization of renewable energy sources for electricity production. See Leonidas Mantzos et al., "POTEnCIA Central-2018 Scenario," October 29, 2019, http://data.europa.eu/89h/3182c195-a1fc-46cf-8e7d-44063d9483d8.

28 These scenarios were formulated to encompass a wide range of potential consumer behaviors. The expected impacts of the LEZ in reality are anticipated to fall within the broad spectrum of impact represented by these scenarios. It is important to note that the LEZ model concentrates exclusively on drivers impacted by the LEZ in each phase, and it assumes that drivers unaffected by the LEZ restrictions do not anticipate the implementation of the LEZ and, therefore, do not alter their consumer behavior accordingly.

PROJECTED IMPACT ON AIR POLLUTANTS

To evaluate the effects of the LEZ on the NO_x and PM emissions of passenger cars, the fleet-average distance-specific emission factor (in mg/km) for the reference year and subsequent phases of the LEZ are presented. This analysis encompasses results for all five scenarios, including the baseline scenario. Figures 2– 7 describe effects on tailpipe emissions; the *switch to zero-emission alternatives* scenario reflects both options of switching to cycling or walking and buying a BEV.[29] The fleet-average emission factor value varies for the different LEZ scenarios as certain vehicles become non-compliant with the LEZ restrictions due to their emission standards. Although the modeling is based on data from 2020, the reference year for this analysis is 2023, with the assumption that the LEZ will be implemented starting in 2024. The baseline scenario shows a decrease in air pollutant emissions over time as older vehicles retire and are replaced by a combination of new and used vehicles with improved emissions performance. The impact of the LEZ is assessed at the year end of each phase of implementation, assuming the policy intervention occurs at the beginning of the year and its impacts are manifested at the end of the year.

IMPACT OF AN LEZ ON NO_x EMISSIONS

Compared to the baseline scenario, all LEZ scenarios for Option 1 exhibit steeper declines in the fleet-average distance-specific NO_x emission factor, as depicted in Figure 2. Two scenarios, *buy 100% new vehicles* and *switch to zero-emission alternatives* achieve the largest reductions in NO_x emissions. Both scenarios follow similar trajectories in all succeeding phases. This is primarily because the former scenario aligns with the EU's plan to exclusively permit the new registration of zero-emission passenger cars starting in 2035, leading to a notable increase in BEVs over the years leading up to 2035. In 2023, the fleet primarily consists of petrol cars (63%), with a smaller proportion of diesel cars (around 35%). BEVs account for less than 2% of the total share.

Under the *buy 100% new vehicles* scenario, non-compliant vehicles are replaced by a higher proportion of petrol cars compared to diesel cars during the initial phases of the LEZ. By Phase 2, both *buy 100% new vehicles* and *switch to zero-emission alternatives* scenarios achieve approximately a 45% reduction in the average NO_x emission factor, while the *buy 100% used vehicles* scenario achieves around a 35% reduction and the baseline, *no LEZ* scenario achieves around a 20% reduction. In the case of the *buy 100% new vehicles* scenario, replacing high-emitting diesel Euro 4 cars with Euro 6d petrol vehicles results in a 90% reduction in NO_x emissions, leading to a substantial decrease in the NO_x emission factor. This highlights the benefits that can be achieved if affected drivers choose to replace non-compliant vehicles with cars certified to newer emission standards, emphasizing the effectiveness of this approach in significantly reducing NO_x emissions, even without transitioning to zero-emission alternatives.

The trajectory of the *buy 100% used vehicles* scenario closely resembles that of the *buy 100% new vehicles* and *switch to zero-emission alternatives* scenarios until Phase 6. By Phase 3 (2028), the *buy 100% used vehicles* scenario achieves a reduction of 58% in the average NO_x emission factor, while the baseline, *no LEZ* scenario achieves a reduction of only around 33%. Similarly, in Phase 3, the *buy 100% new vehicles* and *switch to zero-emission alternatives* scenarios achieve a reduction of around 66%.

The similar trajectories of the *buy 100% used vehicles*, the *buy 100% new vehicles*, and *switch to zero-emission alternatives* scenarios until Phase 6 are primarily because the used vehicles introduced to meet the LEZ requirements have an average age of approximately 13 years and are relatively cleaner compared to the older vehicles they replace. For example, the NO_x emission factor of Euro 5 gasoline cars is one-tenth that of Euro 3 diesel cars. In general, it is expected that consumers in Warsaw will exhibit behavior in the real world that falls within the spectrum of impacts represented by these three scenarios. The similarity of the reductions possible under all three scenarios indicates that the responses of vehicle owners do not significantly impact emissions. Although *buy 100% new vehicles* and *switch to zero-emission alternatives* offer slightly greater average NO_x emission benefits, the impact of the *buy 100% used vehicles* scenario on average NO_x emissions remains large.

All LEZ scenarios could reduce NO_x emissions by over 95% by 2035 (Phase 7). This decrease is primarily due to the widespread adoption of BEVs in all LEZ scenarios, as we assume all new car sales will be BEVs by 2035. Additionally, the performance of Euro 7 vehicles is superior in terms of the NO_x emission factor compared to older vehicles that would not be allowed to enter the LEZ.

29 For pollutant and TTW GHG emissions, replacement with BEVs generates zero tailpipe emissions. Therefore, this option is included in the *switch to zero-emission alternatives* scenario. Public transport is included, as we assume the existing network (e.g., buses, trams, metro) can absorb the expected increase in passenger activity without a significant increase in emissions.

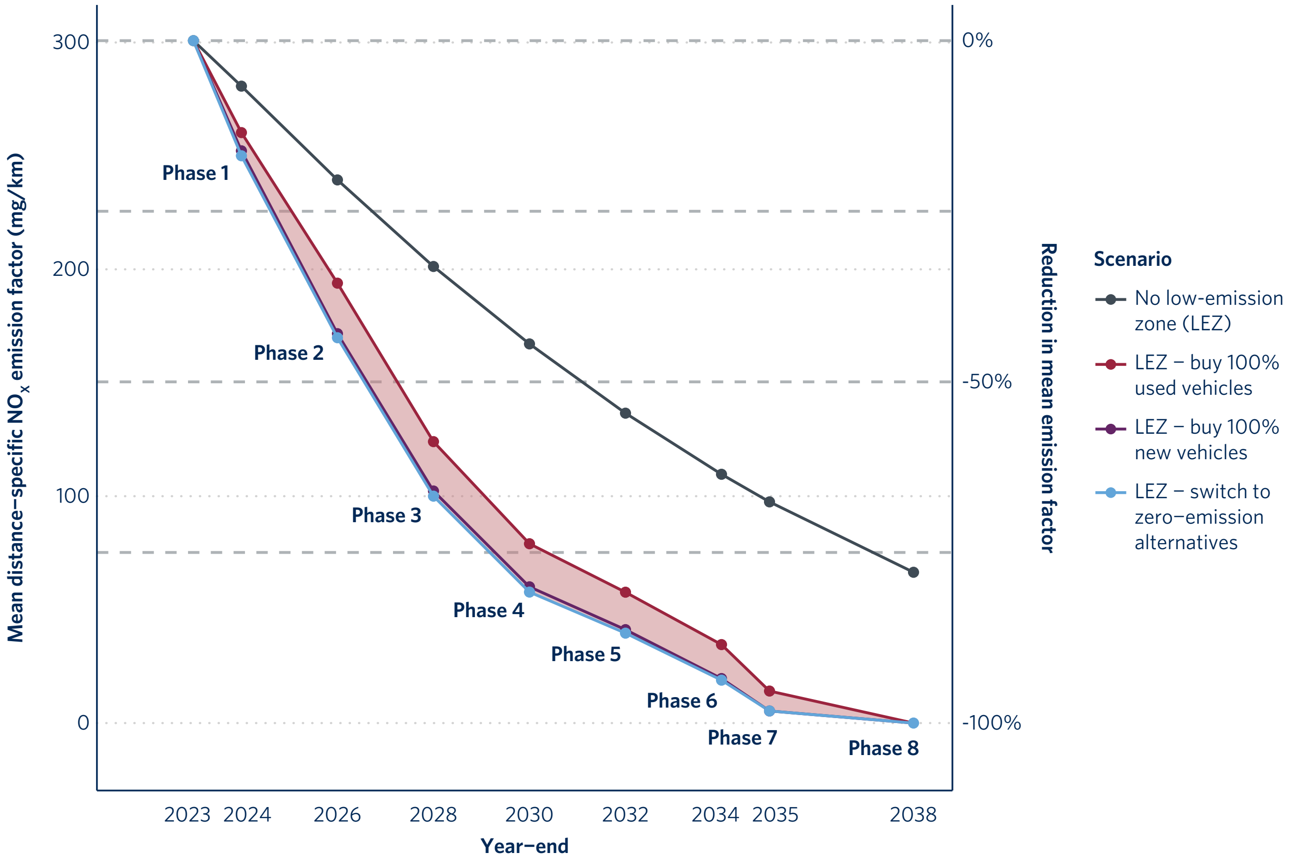

Figure 2. The effects of Option 1 (two-year interval implementation) on fleet-average passenger car NO_x emission factor for four scenarios. The shaded area shows the range of possible emission reductions that depend on responses of vehicle owners affected by LEZ restrictions, covering the best- and worst-case scenarios.

Without the implementation of an LEZ, the reduction in average NO_x emissions for the overall fleet would be limited to 68% in 2035.

The implementation of Option 2 results in accelerated emission reductions compared to Option 1. By Phase 3, fleet-average NO_x emissions are projected to decrease by over 60% for the *buy 100% new vehicles* and *switch to zero-emission alternatives* scenarios, as shown in Figure 3. In Phase 3 of the *buy 100% used vehicles* scenario, average NO_x emissions decrease by 50%. For all scenarios, this represents a 15% greater reduction compared to Option 1. Option 2 achieves this by the earlier replacement of older, higher-emitting vehicles with vehicles with better emissions performance. Additionally, all scenarios could reduce NO_x emissions by over 82% by 2030, compared to 2023 levels. The evolution of the fleet-average NO_x emission factor is summarized in the appendices.

Table 3 compares the timeframe required to achieve specific reductions in NO_x emissions under the two implementation schedule options. Option 1 achieves a 50% reduction in the average NO_x emission factor 5 years earlier than the baseline scenario. Option 2 achieves the same reduction 6 years earlier. Additionally, it is evident that implementing an LEZ is necessary to meet a 75% reduction in NO_x emissions by 2030. With Option 1, the target is achieved by 2030, whereas Option 2 achieves the target by 2027, 7–10 years earlier than without an LEZ.

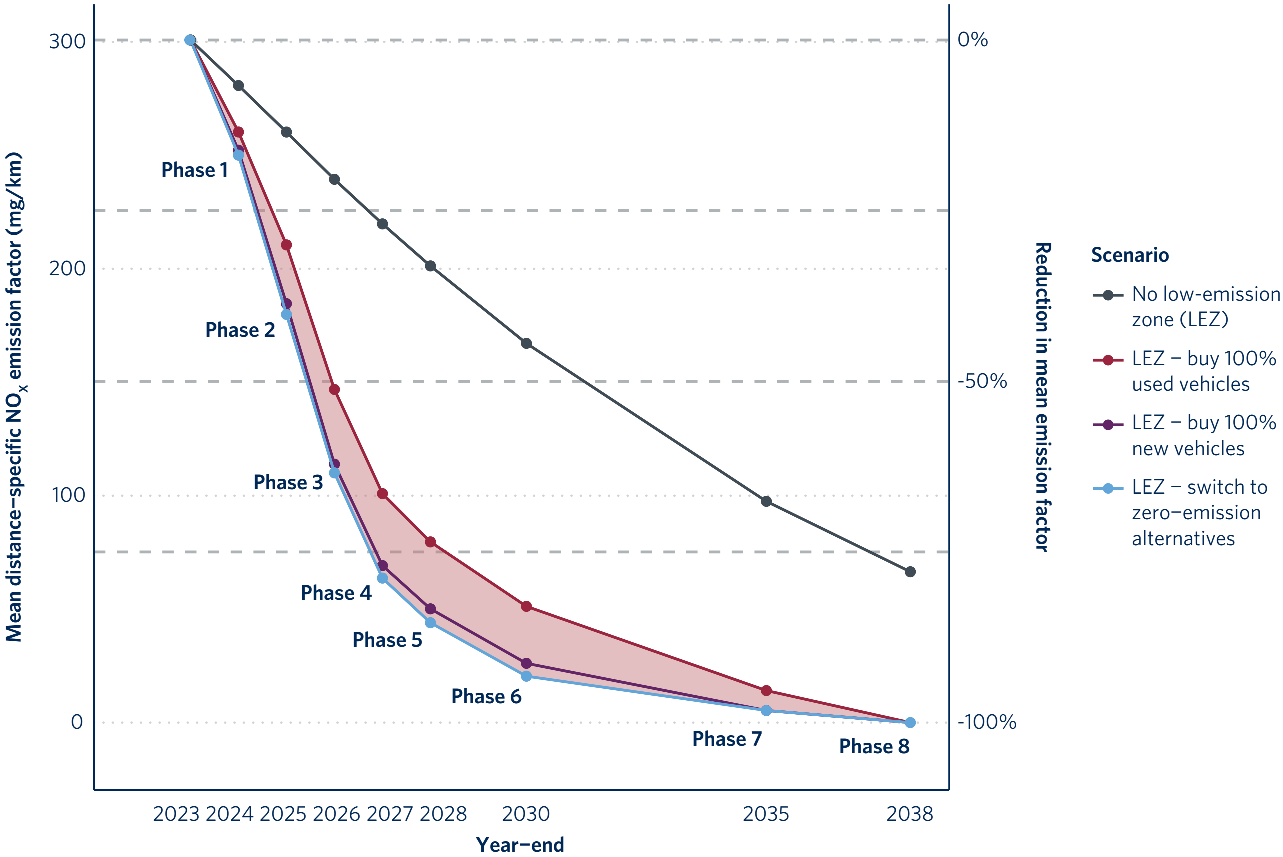

Figure 3. The effects of Option 2 (accelerated implementation) on fleet-average passenger car NO_x emission factor for four scenarios. The shaded area shows the range of possible emission reductions that depend on responses of vehicle owners affected by LEZ restrictions, covering the best- and worst-case scenarios.

Table 3. Years in which the baseline scenario and the two LEZ implementation options reach a 50% reduction in the average NO_x emission factor and the numbers of years accelerated compared to the baseline scenario.

Reduction in average NO_x emission factor	Scenario	Option 1		Option 2	
		Year	Numbers of years accelerated	Year	Numbers of years accelerated
50%	No LEZ	2031		2031	
	LEZ – buy 100% used vehicles	2027	3.8	2026	5.3
	LEZ – buy 100% new vehicles	2026	4.5	2025	5.7
	LEZ – switch to zero-emission alternatives	2026	4.5	2025	5.8
75%	No LEZ	2037		2037	
	LEZ – buy 100% used vehicles	2031	6.8	2028	8.8
	LEZ – buy 100% new vehicles	2029	7.9	2027	10.3
	LEZ – switch to zero-emission alternatives	2029	8.0	2027	10.4

IMPACT OF AN LEZ ON PM EMISSIONS

As illustrated in Figure 4, the implementation of an LEZ has a more immediate and pronounced effect on fleet-average PM emissions than average NO_x emissions. By Phase 2, all LEZ scenarios for implementation Option 1 lead to estimated average PM emission factors that are 63%–67% lower than in 2023. This substantial reduction in average PM emissions is mainly due to the ban on Euro 4 diesel vehicles in Phase 2 of the LEZ. Euro 4 diesel vehicles are the last diesel vehicles that could meet emission standards without the use of a diesel particulate filter, a technology that reduces the PM emissions of diesel vehicles. For example, diesel Euro 5 vehicles exhibit an 80% reduction in average PM emissions compared to Euro 4.

The efficacy of the LEZ is comparable until Phase 6, irrespective of how vehicle owners react to the policy. However, after Phase 6, the *buy 100% used vehicles* scenario performance lags the *buy 100% new vehicles* and *switch to zero-emission alternatives* scenarios. This is because these two scenarios include a greater share of zero tailpipe emission vehicles compared to the *buy 100% used vehicles* scenario.

Figure 5 presents the evolution of average PM emissions for the four scenarios under the implementation of Option 2. All scenarios in Option 2 show an accelerated decline in the average PM emission factor compared to Option 1. The restriction of pre-Euro 5 diesel vehicles from the LEZ starting in 2025 substantially impacts PM emissions, especially in the early phases. By 2026, all LEZ scenarios for Option 2 can achieve at least a 70% reduction compared to 2023 levels, which is larger than the reduction that can be achieved by Option 1. More details on the evolution of the average PM emission factor are summarized in the appendices.

Table 4 examines the years in which each LEZ scenario attains a 50% and 75% reduction in the fleet-average PM emission factor relative to 2023 levels under the two implementation options. The PM emission factor is expected to decrease 50% by 2030, even without the implementation of an LEZ. With Option 1, this reduction can be achieved in 2025, or 5 years earlier. Option 2 can achieve this reduction in 2024, or 6 years earlier. Option 1 can achieve a 75% reduction by 2028, 8 years earlier than the scenario without an LEZ. Option 2 can achieve the same reduction 9–11 years earlier.

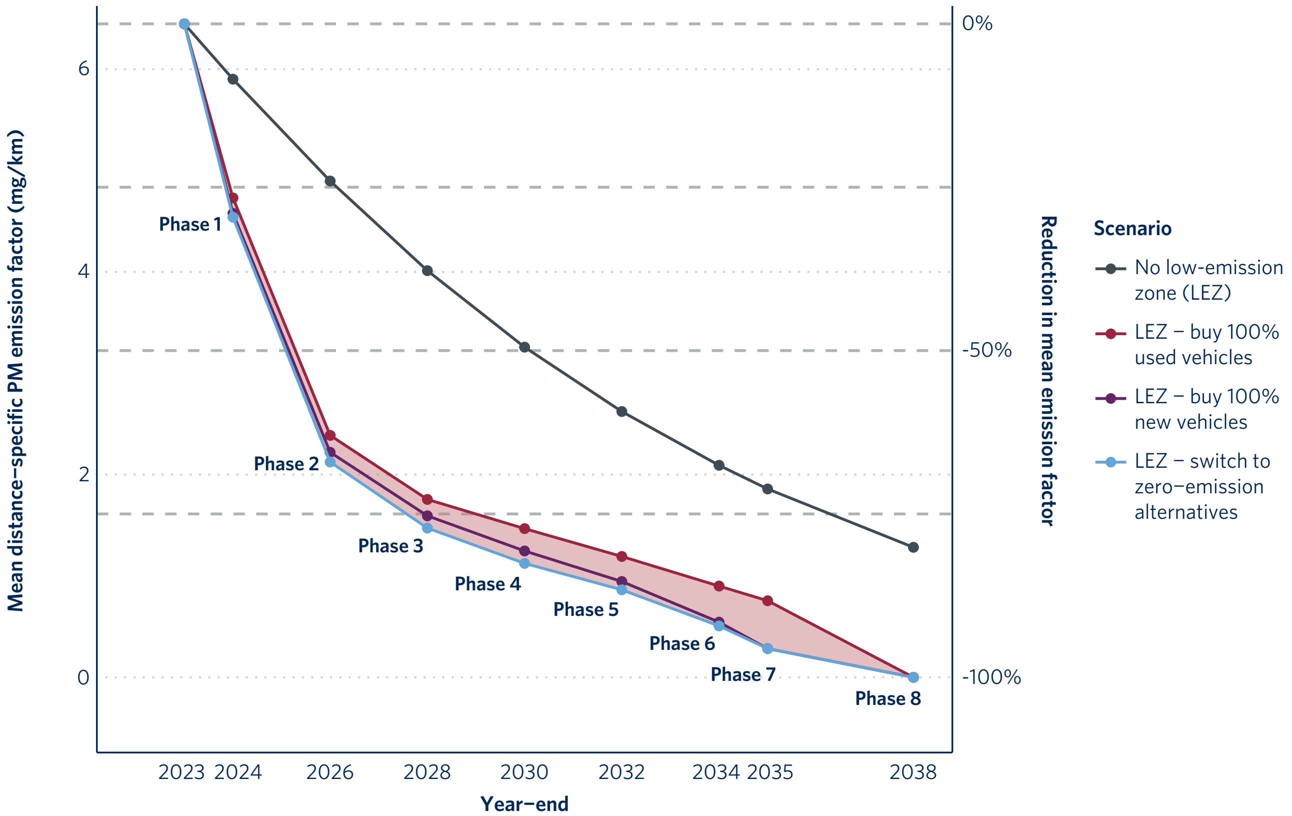

Figure 4. The effects of Option 1 (two-year interval implementation) on fleet-average passenger car PM emission factors for four scenarios. The shaded area shows the range of possible emission reductions that depend on responses of vehicle owners affected by LEZ restrictions, covering the best- and worst-case scenarios.

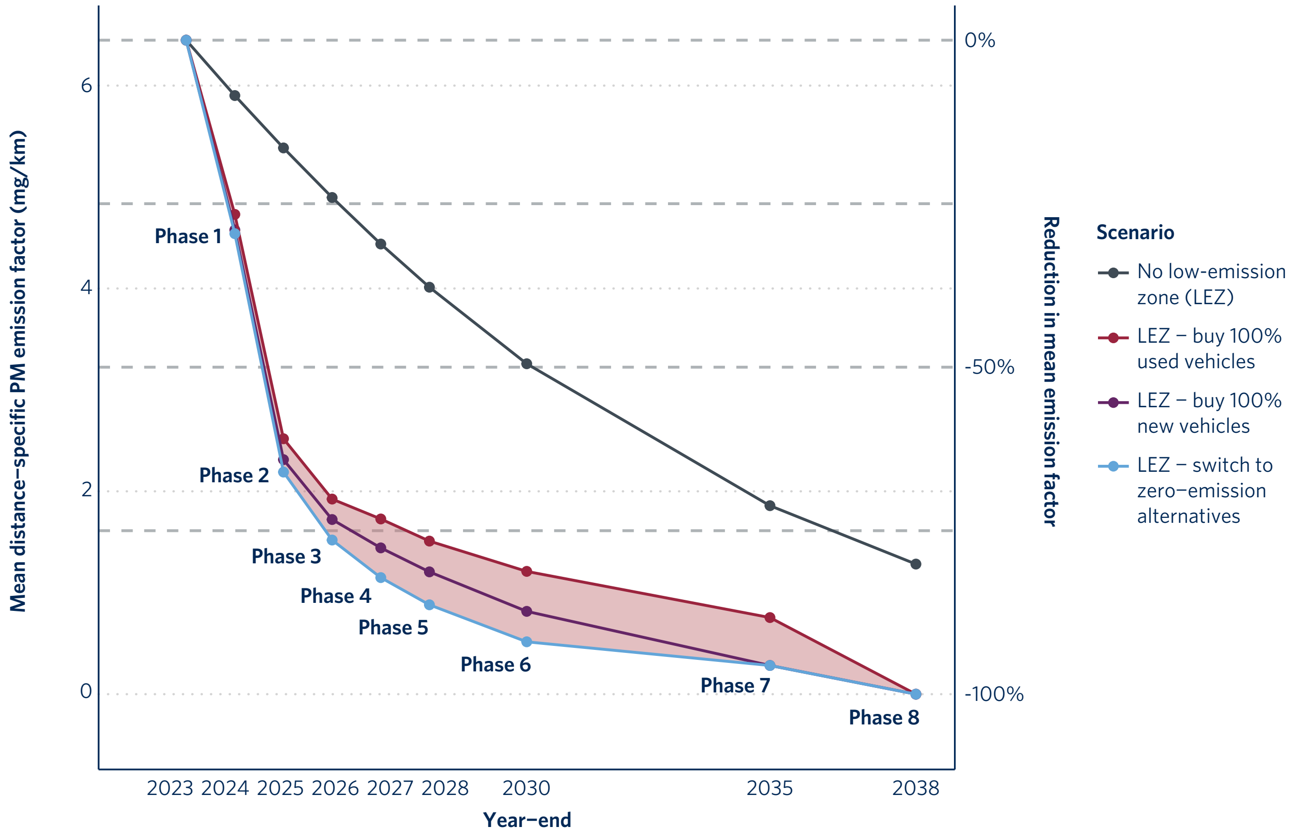

Figure 5. The effects of Option 2 (accelerated implementation) on fleet-average passenger car PM emission factors for four scenarios. The shaded area shows the range of possible emission reductions that depend on responses of vehicle owners affected by LEZ restrictions, covering the best- and worst-case scenarios.

Table 4. Years in which the baseline scenario and the two implementation options reach reductions in the average PM emission factor and the numbers of years accelerated in comparison to the baseline scenario.

Reduction in average PM emission factor	Scenario	Option 1		Option 2	
		Year	Numbers of years accelerated	Year	Numbers of years accelerated
50%	No LEZ	2030		2030	
	LEZ – buy 100% used vehicles	2025	4.8	2025	5.4
	LEZ – buy 100% new vehicles	2025	4.9	2025	5.5
	LEZ – switch to zero-emission alternatives	2025	5	2024	5.6
75%	No LEZ	2036		2036	
	LEZ – buy 100% used vehicles	2029	7.3	2028	8.7
	LEZ – buy 100% new vehicles	2028	8.3	2026	9.9
	LEZ – switch to zero-emission alternatives	2028	8.7	2026	10.4

PROJECTED IMPACT ON GHG EMISSIONS

To assess the impact of the LEZ on GHG emissions, this study examined fleet-average TTW and WTW GHG emission factors. All five LEZ scenarios, including the baseline scenario, are evaluated. However, when examining the LEZ impact on TTW GHG emissions, only four LEZ scenarios are depicted, as *switch to zero-emission alternatives* includes switching to cycling or walking along with buying a BEV. Like the analysis of the impact of the LEZ on air pollutants, this study examined the effect of the LEZ starting from late-2024 and evaluated each following phase at the end of every year of LEZ implementation.

IMPACT OF AN LEZ ON TTW GHG EMISSIONS

Figure 6 illustrates that only two scenarios under implementation Option 1, *buy 100% new vehicles* and *switch to zero-emission alternatives*, show a substantial decline in fleet-average TTW GHG emission factors compared to the baseline. In contrast, the *buy 100% used vehicles* scenario is similar to the baseline scenario, indicating that while drivers may reduce air pollutant emissions by replacing non-compliant cars with used vehicles, those used vehicles are still responsible for substantial TTW GHG emissions. This is mainly because there has not been a significant reduction of real-world CO_2 emissions in newer vehicles. Therefore, without a higher adoption rate of BEVs or a shift to zero-emission mobility, there will be no significant reduction in TTW GHG emission factors.

The *buy 100% new vehicles* and *switch to zero-emission alternatives* scenarios differ slightly only as both these scenarios involve the elimination of ICE vehicles in favor of BEVs and zero-emission mobility. As new ICE vehicle sales are banned starting in 2035 under the *LEZ – buy 100% new vehicles*, the two scenarios merge; there is a projected 80% decrease in fleet-average TTW GHG emissions by the end of 2035. Furthermore, with the ban on ICE vehicles inside the LEZ in Phase 8, the projected average TTW GHG emissions for all LEZ scenarios become zero by the end of 2038.

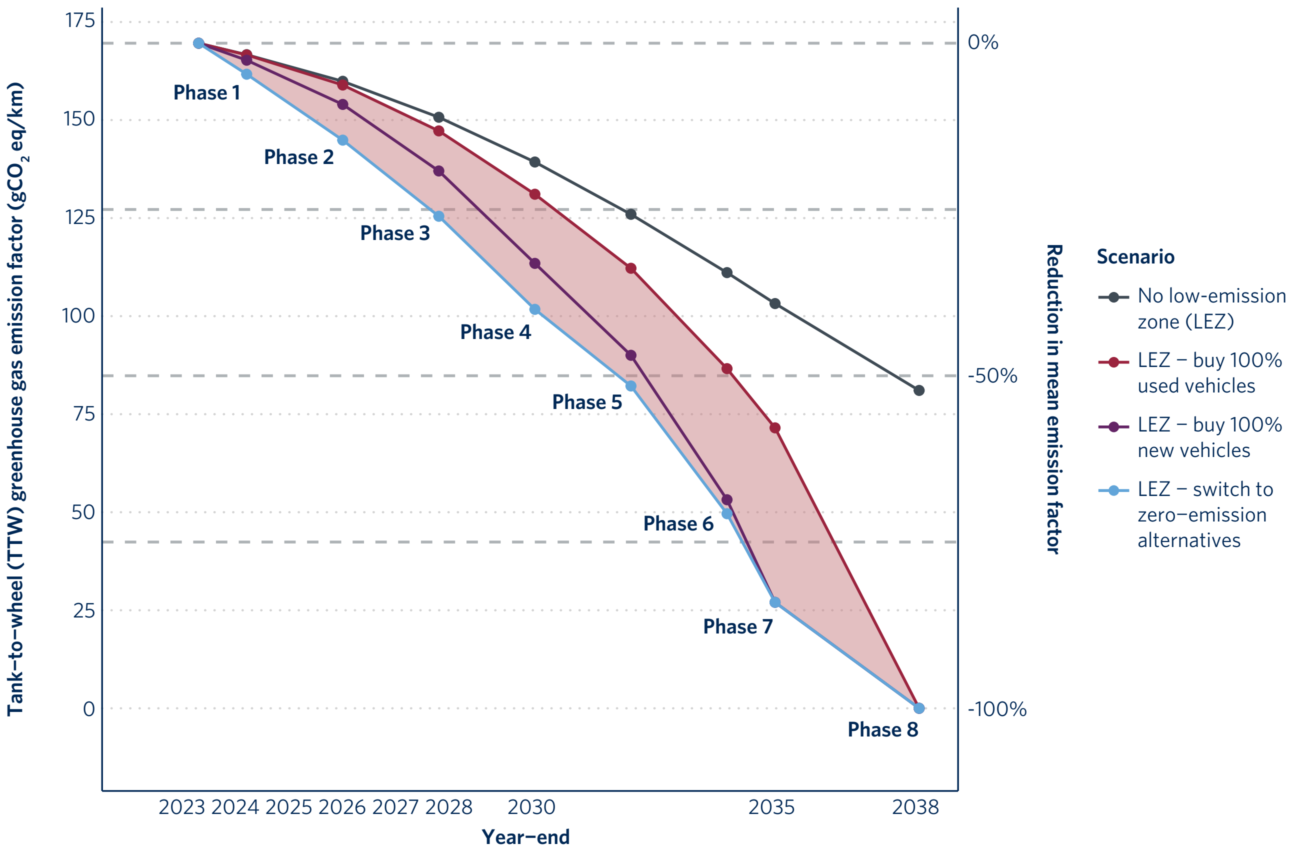

Figure 6. The effects of Option 1 (two-year interval implementation) on fleet-average passenger car TTW GHG emission factors for four scenarios. The shaded area shows the range of possible emission reductions that depend on responses of vehicle owners affected by LEZ restrictions, covering the best- and worst-case scenarios.

A faster reduction of fleet-average TTW GHG emission factors is achieved under Option 2 for the *buy 100% new vehicles* and *switch to zero-emission alternatives* scenarios, as shown in Figure 7. The *switch to zero-emission alternatives* scenario under Option 1 can only achieve a 25% reduction in average TTW GHG emission factors by 2028 compared to 2023, whereas the scenario under Option 2 can achieve a 50% reduction in the same year. The higher share of non-compliant vehicles due to the accelerated implementation of restrictions quickens the transition to BEVs or the switch to other zero-emission mobility options, resulting in an earlier reduction in average TTW GHG emission factors. There is little difference in the reduction of TTW GHG emissions between Options 1 and 2 in the *buy 100% used vehicles* scenario. By the end of 2028, the drop in TTW GHG emission factors is 16% under Option 2 for *buy 100% used vehicles* scenario, compared to 2023, whereas under the same scenario in Option 1, the reduction in GHG emissions is 13%. A shift to zero-emission alternatives results in a larger reduction in TTW GHG emission factors. If all ICE vehicles were prohibited within the LEZ in 2038, the fleet-average TTW emission factors in the area would reach net-zero from that year onward. The overall evolution of the fleet-average TTW GHG emission factors are summarized in the appendices.

Table 5 shows the years in which each LEZ scenario achieves a 50% decrease in the fleet-average TTW GHG emission factor, compared to the 2023 level, under the two LEZ options. The analysis shows a 50% reduction in the TTW GHG emission factor by 2037 without the implementation of an LEZ due to natural fleet turnover. With Option 2, replacing non-compliant vehicles with new cars or zero-emission alternatives, a 50% reduction in fleet-average TTW GHG emissions is achieved 8–10 years earlier than the baseline scenario, and 2–4 years earlier than Option 1.

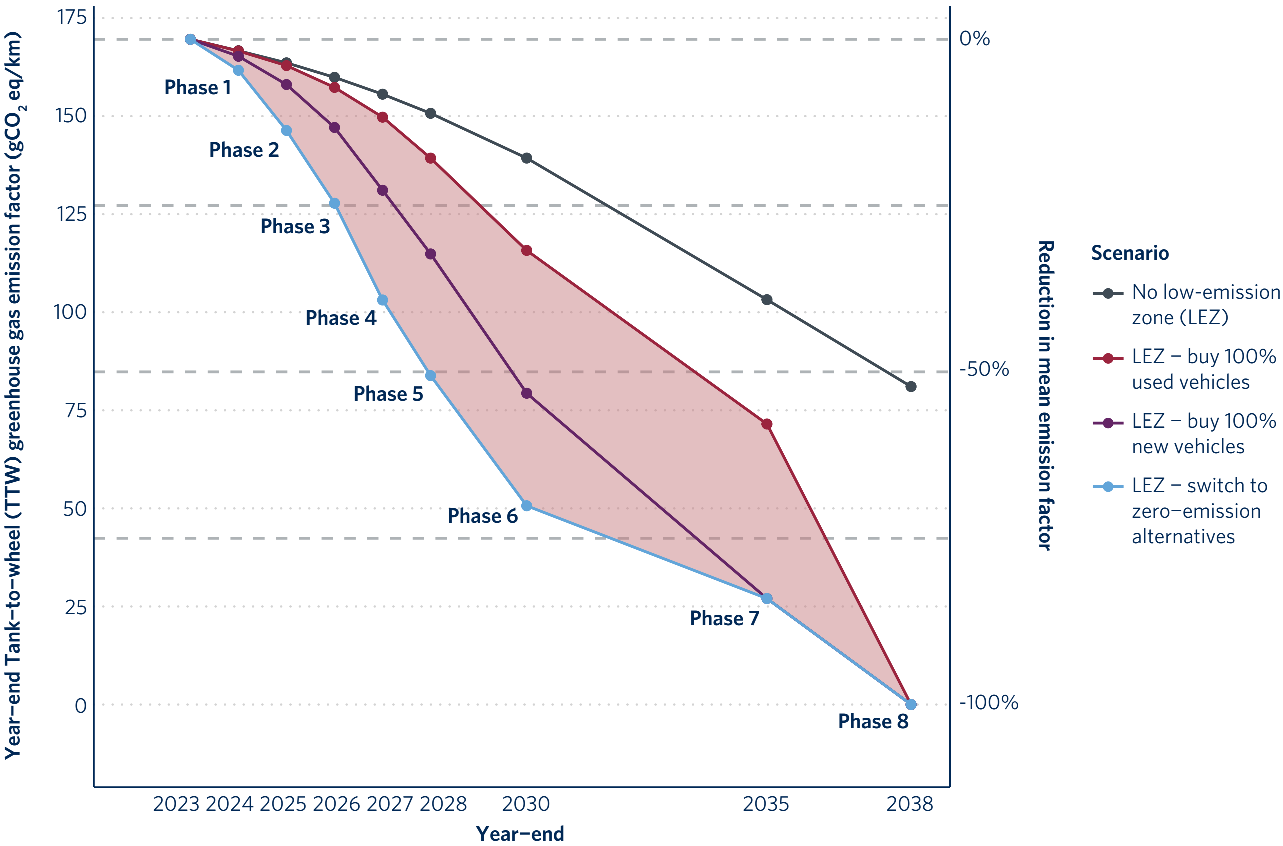

Figure 7. The effects of Option 2 (accelerated implementation) on fleet-average passenger car TTW GHG emission factors for four scenarios. The shaded area shows the range of possible emission reductions that depend on responses of vehicle owners affected by LEZ restrictions, covering the best- and worst-case scenarios.

Table 5. Years in which the baseline scenario and the two implementation options reach a 50% reduction in the average TTW GHG emission factor and the numbers of years accelerated compared to the baseline scenario.

Reduction in average TTW GHG emission factor	Scenario	Option 1		Option 2	
		Year	Numbers of years accelerated	Year	Numbers of years accelerated
50%	No LEZ	2037		2037	
	LEZ – buy 100% used vehicles	2035	2.8	2035	2.9
	LEZ – buy 100% new vehicles	2032	5.2	2030	7.8
	LEZ – switch to zero-emission alternatives	2032	5.8	2028	9.5

IMPACT OF AN LEZ ON WTW GHG EMISSIONS

The substitution of non-compliant vehicles with BEVs leads to a greater reduction in WTW GHG emission factors compared to purchasing diesel or gasoline vehicles. This indicates that even in Poland, which has one of Europe's most carbon-intensive electricity grids, there are significant GHG benefits from buying BEVs compared to ICE cars. Moreover, as the electricity grid in Poland transitions to cleaner renewable sources, the benefits of purchasing BEVs increase.[30] This is highlighted by the growing difference over time between the *buy 100% used*

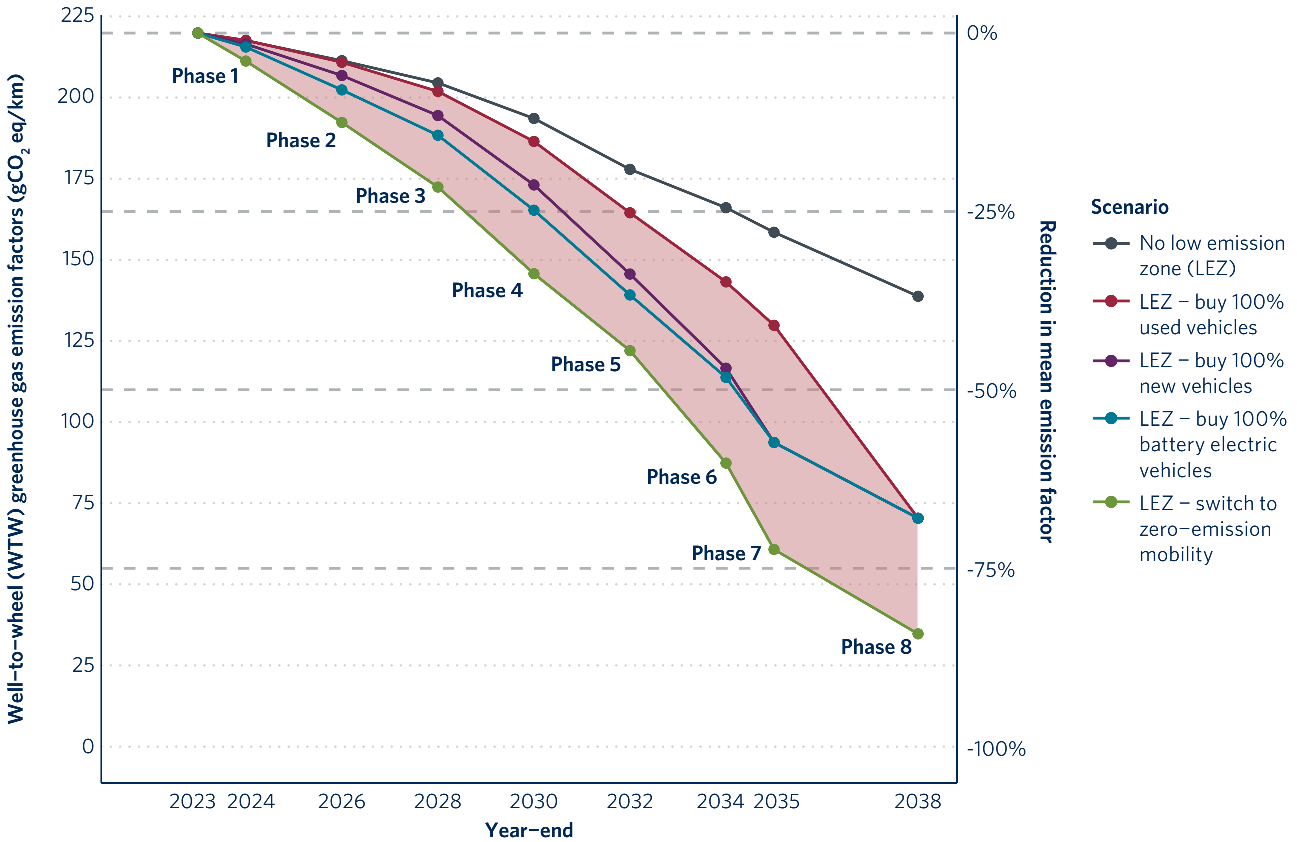

Figure 8. The effects of Option 1 (two-year interval implementation) on fleet-average passenger car WTW GHG emission factors for five scenarios. The shaded area shows the range of possible emission reductions that depend on responses of vehicle owners affected by LEZ restrictions, covering the best- and worst-case scenarios.

30 International Energy Agency, "Poland 2022: Energy Policy Review," (2022), https://www.iea.org/reports/poland-2022.

vehicles and *buy 100% BEVs* scenarios in terms of WTW GHG emission factors. Figure 8 illustrates this trend.

When the overall WTW emissions generated by vehicles is considered, there is an advantage to transitioning to zero-emission mobility—such as cycling, walking, and zero- and low-emission public transport—compared to switching from new ICE vehicles to BEVs to comply with LEZ regulations. In Phase 6 of the LEZ in 2034, the following reductions in the WTW GHG emission factor relative to the 2023 level are expected: 35% for the *buy 100% used vehicles* scenario, 47% for the *buy 100% new vehicles* scenario, 48% for the *buy 100% BEVs* scenario, and 60% for the *switch to zero-emission mobility* scenario. This variability in reductions demonstrates that the choices made by vehicle owners in response to the LEZ at earlier phases will substantially impact the emission benefits that can be realized by the end of 2034. Likewise, it is estimated that by 2038, the *switch to zero-emission activity* scenario could reduce average WTW GHG emission factors by about 84% compared to 2023 levels.

Figure 9 reveals how the choices made by drivers when their vehicles become non-compliant would lead to different average GHG emission factors by the end of 2038. For implementation Option 2, this variability in emission factor reductions is substantially higher compared to Option 1 due to the more accelerated introduction of tighter restrictions aimed at eliminating vehicles of certain standards, which can profoundly impact overall average WTW GHG emissions. In Phase 6 of the LEZ in 2030, the expected reductions in the emission factors relative to the 2023 level are as follows: 20% for the *buy 100% used vehicles* scenario, 33% for the *buy 100% new vehicles* scenario, 42% for the *buy 100% BEVs* scenario, and 63% for the *switch to zero-emission mobility* scenario. The reduction potential in terms of the WTW GHG emission factor for the *switch to zero-emission mobility* scenario is twice that of Option 1, highlighting the impact of this scenario. Details on the evolution of fleet-average WTW GHG emission factors are summarized in the appendices.

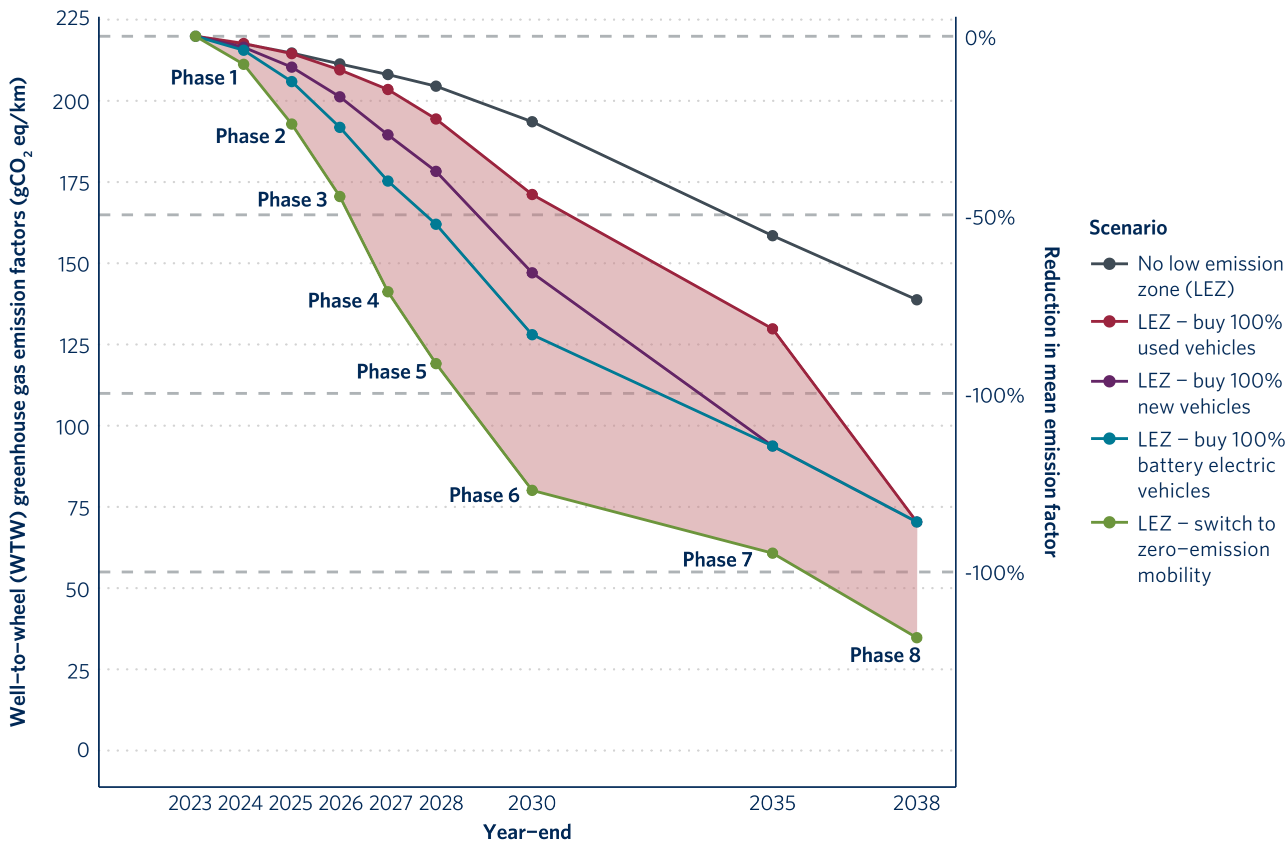

Figure 9. The effects of Option 2 (accelerated implementation) on fleet-average passenger car WTW GHG emission factors for five scenarios. The shaded area shows the range of possible emission reductions that depend on responses of vehicle owners affected by LEZ restrictions, covering the best- and worst-case scenarios.

Table 6. Years in which the baseline scenario and the two implementation options reach a 50% reduction in the average WTW GHG emission factor and the numbers of years accelerated compared to the baseline scenario.

Reduction in average WTW GHG emission factor	Scenario	Option 1		Option 2	
		Year	Numbers of years accelerated	Year	Numbers of years accelerated
50%	No LEZ	2042		2042	
	LEZ – buy 100% used vehicles	2036	5.5	2036	5.5
	LEZ – buy 100% new vehicles	2034	7.4	2033	8.2
	LEZ – buy 100% BEV	2034	7.5	2033	9
	LEZ – switch to zero-emission mobility	2033	9	2028	13

As shown in Table 6, under Option 1, replacing non-compliant vehicles with new vehicles that meet the latest emission standards or BEVs results in a 50% reduction in fleet-average WTW GHG emissions occurring 7 years earlier than the baseline scenario, which achieves the same reduction by 2042. Similarly, Option 2 achieves the same reduction 8–9 years earlier than the baseline. Furthermore, when drivers of non-compliant vehicles switch to zero-emission alternatives, a 50% reduction in fleet-average WTW GHG emissions is achieved in 2028, approximately 5 years earlier than under Option 1. This acceleration of benefits illustrates how much the *switch to zero-emission activity* scenario can reduce WTW GHG emissions.

WTW GHG CUMULATIVE BENEFITS UNTIL 2038

To showcase the cumulative WTW GHG benefits that could be achieved through the proposed LEZ, Figure 10 shows the percentage of WTW GHG emissions avoided in each scenario up to 2038 in relation to the total WTW GHG emissions with no LEZ. WTW GHG emitted by scenario are calculated by summing the product of vehicle activity and the annual average WTW GHG emission factor at various phases of the scenario. This calculation is then compared with the baseline scenario and presented in relative terms (data for actual number of passenger cars on Warsaw roads could not be obtained). Nonetheless, this methodology is helpful in quantifying the percentage of WTW GHG savings that could be achieved by following a particular pathway.

In Figure 10, implementation Option 2 shows greater potential for cumulative WTW GHG benefits than Option 1. The benefits of the *buy 100% new vehicles* and *buy 100% BEVs* scenarios are similar because of the increased use of BEVs in the fleet. In contrast, the *buy 100% used vehicles* scenario has lower benefits because of the high number of ICE vehicles in use. In line with our earlier findings, the *switch to zero-emission mobility* scenario yields substantial advantages in both implementation options. From 2023–2028, Option 2 could result in a 45% reduction in total WTW GHG emissions from passenger cars compared to the baseline scenario. Option 1 would lead to a 31% of reduction in total WTW GHG emissions under the same LEZ scenario. These findings emphasize that only the *switch to zero-emission mobility* scenario under implementation Option 2 could align with the 40%–60% reduction by 2030 necessary to meet the target set by the Paris Agreement.[31]

CONCLUSIONS AND POLICY RECOMMENDATIONS

This study indicates that the implementation of an LEZ in Warsaw could result in a 90% decrease in traffic-related NO_x and PM tailpipe emissions by 2035, regardless of how vehicle owners respond to the policy. However, the response of vehicle owners to the LEZ restrictions can significantly impact the GHG emissions reduction achieved. Overall, this study underscores the potential of an LEZ to expedite the transition toward cleaner transportation in Warsaw and help meet the city's air quality and climate goals. The conclusions that can be drawn from this study, along with policy recommendations that the city officials could implement, are described below.

31 Arijit Sen and Joshua Miller, "Emissions Reduction Benefits of a Faster, Global Transition to Zero-Emission Vehicles" (Washington, DC: ICCT, 2022), https://theicct.org/publication/zevs-global-transition-benefits-mar22/.

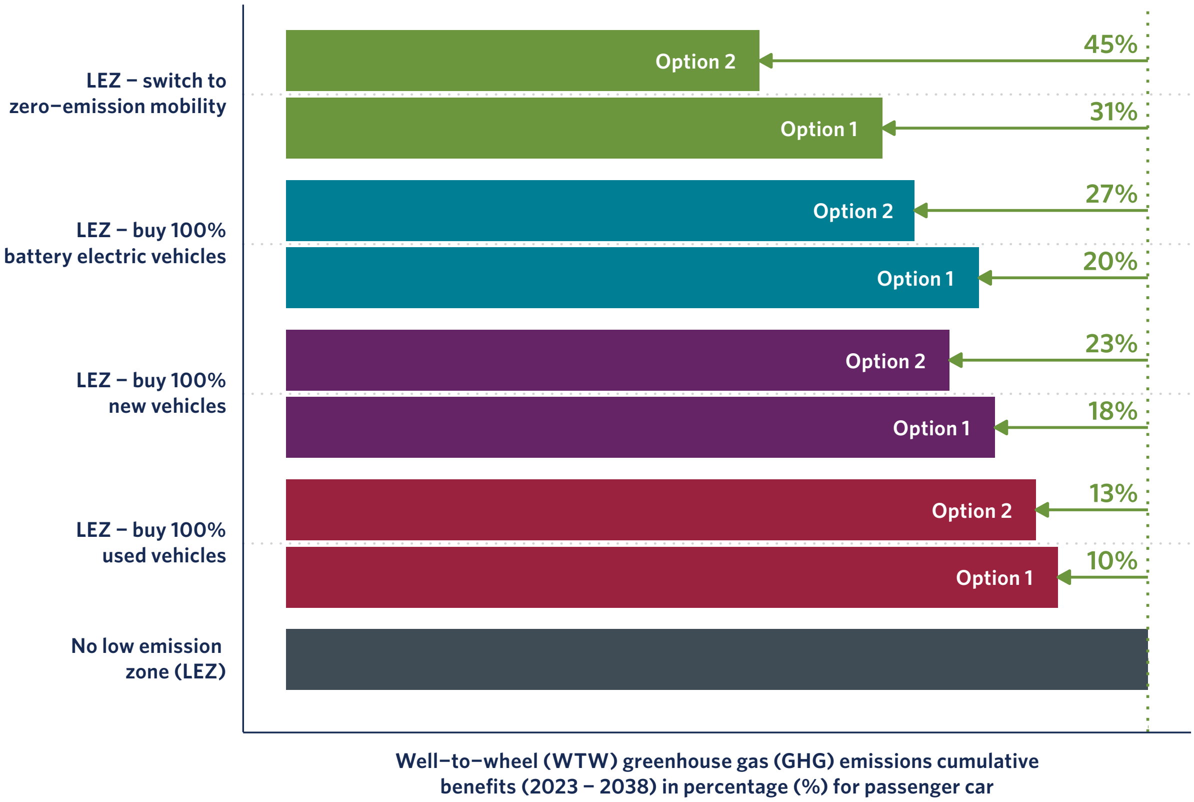

Figure 10. WTW GHG cumulative benefits (2023–2038) for two LEZ implementation options in percentage terms for different scenarios compared to the baseline scenario.

- **The introduction of an LEZ in Warsaw could help to substantially reduce air pollutant emissions from passenger cars.** An LEZ starting in 2024 could achieve a 50% reduction in both NO_x and PM emissions compared to 2023 levels by 2027 and 2025, respectively, even if affected drivers choose to purchase used vehicles meeting the minimum requirement for use of the LEZ. Targeting older diesel passenger cars certified to Euro 4 and below (registered before 2011) during the early phases of LEZ is crucial to achieve these reductions. These vehicle groups in Warsaw show a disproportionate impact, as they would represent only around 8% of passenger car activity in 2026 but would contribute about 27% of NO_x and 55% of PM emissions.
- **A more ambitious LEZ design could generate more immediate emission benefits for air pollutants and GHG emissions.** In the case of implementation Option 2, where the LEZ restrictions are tightened every year until 2028, it is possible to achieve a 75% reduction in fleet-average NO_x emissions 2–3 years earlier than in Option 1, where the LEZ restrictions are tightened at two year-intervals until 2034. Likewise, it is possible to achieve a 75% reduction in fleet-average PM emissions 1–2 years earlier than Option 1. Implementing Option 2 could lead to a 50% reduction in fleet-average TTW GHG emissions (which occur during vehicle operation) 2 years earlier than Option 1. Additionally, Option 2 could achieve a 50% reduction in fleet-average WTW GHG emissions (including energy production, transport, and vehicle operation) 1 year earlier than Option 1.
- **Transition to zero-emission mobility can achieve the greatest reduction in WTW and TTW GHG emissions.** When drivers impacted by the LEZ replace non-compliant vehicles with zero-emission mobility options like public transport, cycling, and walking, the LEZ yields a greater reduction in WTW and TTW GHG emissions. If drivers instead buy the minimally compliant vehicles, such as marginally clean used cars, the GHG emission benefits of the LEZ are delayed. In the case of implementation Option 1, the 50% reduction in TTW GHG emissions would be delayed by 4 years. This finding implies that incentives for affected drivers to opt for zero-emission mobility would maximize the impact of the

LEZ on GHG emissions. Improving the connectivity, affordability, and reliability of public transport, as well as improving cycling infrastructure could incentivize drivers to choose these zero-emission options. Warsaw could take an approach similar to Brussel's "Good Move" initiative, which reduced car traffic by 19%, improved public transport travel time by 25%, and increased the number of cyclists.[32]

- **An accelerated shift to zero-emission mobility could help Warsaw achieve its climate goals.** If affected drivers impacted by implementation Option 2 replace their non-compliant vehicles by switching to zero-emission mobility, it could help Warsaw avoid 45% of the cumulative WTW GHG emissions that would be emitted until 2038 without an LEZ. This is in line with the projected GHG emission reductions needed to meet the 1.5 °C target outlined in the Paris Agreement. Implementing an ambitious LEZ policy that expands to a zero-emission zone beginning in 2038 could yield even greater GHG emission reductions.

Supplementary policies could enhance the effectiveness of the LEZ and improve social equity. Warsaw could consider various measures, such as public subsidies aimed at facilitating the purchase of zero-emission vehicles, old vehicle scrappage programs, discounts on public transportation fares, access to shared BEVs, and exemptions or extended timeframes for acquiring LEZ-compliant vehicles. For an LEZ to succeed, it is essential that information regarding the compliance criteria, enforcement measures, and associated fees in case non-compliance is clearly communicated. Regular monitoring and robust enforcement are also key to ensuring the long-term success of an LEZ.

32 Denis Balgaranov, "Brussels' New Traffic Plan Has Reduced Cars by One-Fifth in the Last Six Months," *The* Mayor.eu, May 29, 2023, https://www.themayor.eu/en/a/view/brussels-new-traffic-plan-has-reduced-cars-by-one-fifth-in-the-last-six-months-11546.

APPENDIX A: CHANGES IN EMISSION FACTORS FOR PASSENGER CARS WITH IMPLEMENTATION OF THE LEZ

The tables below show the changes in emission factors and the percent changes compared to the reference year (2023) for air pollutants, NO_X, and PM, along with TTW and WTW GHG emissions. Table A1 corresponds to Figures 2 and 4; Table A2 corresponds to Figures 3 and 5 in the results section.

Table A1. Mean distance-specific NO_x and PM emission factors for passenger cars under all scenarios when each phase of the LEZ is implemented under Option 1.

Scenario	Phase	Year	Change in NO_x emission factor (mg/km)	Percent change compared to 2023	Change in PM emission factor (mg/km)	Percent change compared to 2023
Baseline, no LEZ	Phase 0	2023	301	0%	6.5	0%
	Phase 1	2024	281	-7%	5.9	-8%
	Phase 2	2026	239	-20%	4.9	-24%
	Phase 3	2028	201	-33%	4	-38%
	Phase 4	2030	167	-44%	3.2	-49%
	Phase 5	2032	136	-55%	2.6	-59%
	Phase 6	2034	110	-64%	2.1	-68%
	Phase 7	2035	97	-68%	1.8	-71%
	Phase 8	2038	66	-78%	1.3	-80%
LEZ – buy 100% used vehicles	Phase 0	2023	301	0%	6.4	0%
	Phase 1	2024	260	-13%	4.7	-27%
	Phase 2	2026	194	-36%	2.4	-63%
	Phase 3	2028	124	-59%	1.7	-73%
	Phase 4	2030	79	-74%	1.5	-77%
	Phase 5	2032	58	-81%	1.2	-82%
	Phase 6	2034	34	-89%	0.9	-86%
	Phase 7	2035	14	-95%	0.8	-88%
	Phase 8	2038	0	-100%	0	-100%
LEZ – buy 100% new vehicles	Phase 0	2023	301	0%	6.4	0%
	Phase 1	2024	252	-16%	4.6	-29%
	Phase 2	2026	172	-43%	2.2	-66%
	Phase 3	2028	102	-66%	1.6	-75%
	Phase 4	2030	60	-80%	1.2	-81%
	Phase 5	2032	41	-86%	0.9	-85%
	Phase 6	2034	20	-93%	0.5	-92%
	Phase 7	2035	5	-98%	0.3	-96%
	Phase 8	2038	0	-100%	0	-100%
LEZ – switch to zero-emission alternatives	Phase 0	2023	301	0%	6.4	0%
	Phase 1	2024	250	-17%	4.5	-30%
	Phase 2	2026	170	-44%	2.1	-67%
	Phase 3	2028	100	-67%	1.5	-77%
	Phase 4	2030	58	-81%	1.1	-83%
	Phase 5	2032	40	-87%	0.9	-87%
	Phase 6	2034	19	-94%	0.5	-92%
	Phase 7	2035	5	-98%	0.3	-96%
	Phase 8	2038	0	-100%	0	-100%

Table A2. Mean distance-specific NO_x and PM emission factors for passenger cars under all scenarios when each phase of the LEZ is implemented under Option 2.

Scenario	Phase	Year	Change in NO_x emission factor (mg/km)	Percent change compared to 2023	Change in PM emission factor (mg/km)	Percent change compared to 2023
Baseline, no LEZ	Phase 0	2023	301	0%	6.5	0%
	Phase 1	2024	281	-7%	5.9	-8%
	Phase 2	2025	260	-13%	5.4	-16%
	Phase 3	2026	240	-20%	4.9	-24%
	Phase 4	2027	219	-27%	4.4	-31%
	Phase 5	2028	201	-33%	4	-38%
	Phase 6	2030	167	-44%	3.2	-49%
	Phase 7	2035	97	-68%	1.8	-71%
	Phase 8	2038	66	-78%	1.3	-80%
LEZ – buy 100% used vehicles	Phase 0	2023	301	0%	6.4	0%
	Phase 1	2024	260	-13%	4.7	-27%
	Phase 2	2025	210	-30%	2.5	-61%
	Phase 3	2026	147	-51%	1.9	-70%
	Phase 4	2027	101	-66%	1.7	-73%
	Phase 5	2028	80	-74%	1.5	-77%
	Phase 6	2030	51	-83%	1.2	-81%
	Phase 7	2035	14	-95%	0.8	-88%
	Phase 8	2038	0	-100%	0	-100%
LEZ – buy 100% new vehicles	Phase 0	2023	301	0%	6.4	0%
	Phase 1	2024	252	-16%	4.6	-29%
	Phase 2	2025	185	-39%	2.3	-64%
	Phase 3	2026	114	-62%	1.7	-73%
	Phase 4	2027	69	-77%	1.4	-78%
	Phase 5	2028	50	-83%	1.2	-81%
	Phase 6	2030	26	-91%	0.8	-87%
	Phase 7	2035	5	-98%	0.3	-96%
	Phase 8	2038	0	-100%	0	-100%
LEZ – switch to zero-emission alternatives	Phase 0	2023	301	0%	6.4	0%
	Phase 1	2024	250	-17%	4.5	-30%
	Phase 2	2025	180	-40%	2.2	-66%
	Phase 3	2026	110	-63%	1.5	-76%
	Phase 4	2027	64	-79%	1.1	-82%
	Phase 5	2028	44	-85%	0.9	-86%
	Phase 6	2030	20	-93%	0.5	-92%
	Phase 7	2035	5	-98%	0.3	-96%
	Phase 8	2038	0	-100%	0	-100%

Table A3. Mean distance-specific TTW and WTW GHG emission factors for passenger cars under all scenarios when each phase of the LEZ is implemented under Option 1.

Scenario	Phase	Year	Change in TTW GHG emission factor (gCO_2 eq/km)	Percent change compared to 2023	Change in WTW GHG emission factor (gCO_2eq/km)	Percent change compared to 2023
Baseline, no LEZ	Phase 0	2023	170	0%	220	0%
	Phase 1	2024	167	-2%	217	-1%
	Phase 2	2026	160	-6%	211	-4%
	Phase 3	2028	151	-11%	204	-7%
	Phase 4	2030	140	-18%	193	-12%
	Phase 5	2032	126	-26%	178	-19%
	Phase 6	2034	111	-34%	166	-24%
	Phase 7	2035	103	-39%	158	-28%
	Phase 8	2038	81	-52%	139	-37%
LEZ – buy 100% used vehicles	Phase 0	2023	170	0%	220	0%
	Phase 1	2024	167	-2%	218	-1%
	Phase 2	2026	159	-6%	211	-4%
	Phase 3	2028	147	-13%	202	-8%
	Phase 4	2030	131	-23%	186	-15%
	Phase 5	2032	112	-34%	164	-25%
	Phase 6	2034	87	-49%	143	-35%
	Phase 7	2035	71	-58%	130	-41%
	Phase 8	2038	0	-100%	70	-68%
LEZ – buy 100% new vehicles	Phase 0	2023	170	0%	220	0%
	Phase 1	2024	165	-3%	217	-2%
	Phase 2	2026	154	-9%	207	-6%
	Phase 3	2028	137	-19%	194	-12%
	Phase 4	2030	113	-33%	173	-21%
	Phase 5	2032	90	-47%	146	-34%
	Phase 6	2034	53	-69%	117	-47%
	Phase 7	2035	27	-84%	94	-57%
	Phase 8	2038	0	-100%	70	-68%
LEZ – buy 100% BEVs	Phase 0	2023	170	0%	220	0%
	Phase 1	2024	162	-5%	216	-2%
	Phase 2	2026	145	-15%	202	-8%
	Phase 3	2028	125	-26%	188	-14%
	Phase 4	2030	102	-40%	165	-25%
	Phase 5	2032	82	-52%	139	-37%
	Phase 6	2034	50	-71%	114	-48%
	Phase 7	2035	27	-84%	94	-57%
	Phase 8	2038	0	-100%	70	-68%
LEZ – switch to zero-emission mobility	Phase 0	2023	170	0%	220	0%
	Phase 1	2024	162	-5%	211	-4%
	Phase 2	2026	145	-15%	192	-13%
	Phase 3	2028	125	-26%	172	-22%
	Phase 4	2030	102	-40%	146	-34%
	Phase 5	2032	82	-52%	122	-45%
	Phase 6	2034	50	-71%	87	-60%
	Phase 7	2035	27	-84%	61	-72%
	Phase 8	2038	0	-100%	35	-84%

Table A4. Mean distance-specific TTW and WTW GHG emissions factors for passenger cars under all scenarios when each phase of the LEZ is implemented under Option 2.

Scenario	Phase	Year	Change in TTW GHG emission factor (gCO_2 eq/km)	Percent change compared to 2023	Change in WTW GHG emission factor (gCO_2 eq/km)	Percent change compared to 2023
Baseline, no LEZ	Phase 0	2023	170	0%	220	0%
	Phase 1	2024	167	-2%	217	-1%
	Phase 2	2025	163	-4%	215	-2%
	Phase 3	2026	160	-6%	211	-4%
	Phase 4	2027	156	-8%	208	-5%
	Phase 5	2028	151	-11%	204	-7%
	Phase 6	2030	139	-18%	193	-12%
	Phase 7	2035	103	-39%	158	-28%
	Phase 8	2038	81	-52%	139	-37%
LEZ - buy 100% used vehicles	Phase 0	2023	170	0%	220	0%
	Phase 1	2024	167	-2%	218	-1%
	Phase 2	2025	163	-4%	214	-2%
	Phase 3	2026	157	-7%	209	-5%
	Phase 4	2027	150	-12%	203	-7%
	Phase 5	2028	139	-18%	194	-12%
	Phase 6	2030	116	-32%	171	-22%
	Phase 7	2035	71	-58%	130	-41%
	Phase 8	2038	0	-100%	70	-68%
LEZ - buy 100% new vehicles	Phase 0	2023	170	0%	220	0%
	Phase 1	2024	165	-3%	216	-2%
	Phase 2	2025	158	-7%	210	-4%
	Phase 3	2026	147	-13%	201	-8%
	Phase 4	2027	131	-23%	189	-14%
	Phase 5	2028	115	-32%	178	-19%
	Phase 6	2030	79	-53%	147	-33%
	Phase 7	2035	27	-84%	94	-57%
	Phase 8	2038	0	-100%	70	-68%
LEZ - buy 100% BEVs	Phase 0	2023	170	0%	220	0%
	Phase 1	2024	162	-5%	216	-2%
	Phase 2	2025	146	-14%	206	-6%
	Phase 3	2026	128	-25%	192	-13%
	Phase 4	2027	103	-39%	175	-20%
	Phase 5	2028	84	-51%	162	-26%
	Phase 6	2030	51	-70%	128	-42%
	Phase 7	2035	27	-84%	94	-57%
	Phase 8	2038	0	-100%	70	-68%
LEZ - switch to zero-emission alternatives	Phase 0	2023	170	0%	220	0%
	Phase 1	2024	162	-5%	211	-4%
	Phase 2	2025	146	-14%	193	-12%
	Phase 3	2026	128	-25%	170	-22%
	Phase 4	2027	103	-39%	141	-36%
	Phase 5	2028	84	-51%	119	-46%
	Phase 6	2030	51	-70%	80	-64%
	Phase 7	2035	27	-84%	61	-72%
	Phase 8	2038	0	-100%	35	-84%

APPENDIX B: LIGHT COMMERCIAL VEHICLES – EMISSIONS IMPACT ANALYSIS

Table B1 shows NO_x and PM real-world emission factors adopted for the impact analysis of the LEZ for light commercial vehicles in Warsaw. Table B2 shows the LEZ implementation schedule options designed for these vehicles.

Table B1. Distance-specific tailpipe NO_x and PM emission factors for light commercial vehicles derived from 2020 remote sensing measurements.

Fuel	Diesel		Gasoline	
Standard	**NO_x (mg/km)**	**PM (mg/km)**	**NO_x (mg/km)**	**PM (mg/km)**
Euro 1	1946	158	1565	23
Euro 2	2014	101	1338	15
Euro 3	1564	74	819	6.7
Euro 4	1149	43	423	4.6
Euro 5	1211	11	438	2.48
Euro 6	502	4.51	151	1.77
Euro 6d-TEMP	196	3.47	116	1.31
Euro 6d	134	3.47	116	1.31
Euro 7	30	3.47	30	1.31

Table B2. LEZ implementation restrictions and schedules for light commercial vehicles for Options 1 and 2.

Passenger car	Minimum standard		Implementation schedule	
Phase	**Diesel**	**Petrol**	**Option 1**	**Option 2**
1	Euro 4	Euro 2	2024	2024
2	Euro 5	Euro 3	2026	2025
3	Euro 6	Euro 4	2028	2026
4	Euro 6d-TEMP	Euro 5	2030	2027
5	Euro 6d	Euro 6	2032	2028
6	Euro 7	Euro 6d	2034	2030
7	BEV	BEV	2038	2038

PROJECTED IMPACT ON NO_X AND PM EMISSIONS

Figure B1 shows the impact of the LEZ on fleet-average light commercial vehicles NO_x and PM emission factors for all LEZ scenarios. Table B3 shows the years in which all LEZ scenarios, including the baseline, achieve a reduction of 50% in the average NO_x emission factor for the two proposed LEZ schedules. Similarly, this table also list the number of years meeting the reduction target is accelerated compared to the scenarios with no LEZ. Table B4 shows about the same impact in terms of years for the average PM emission factor.

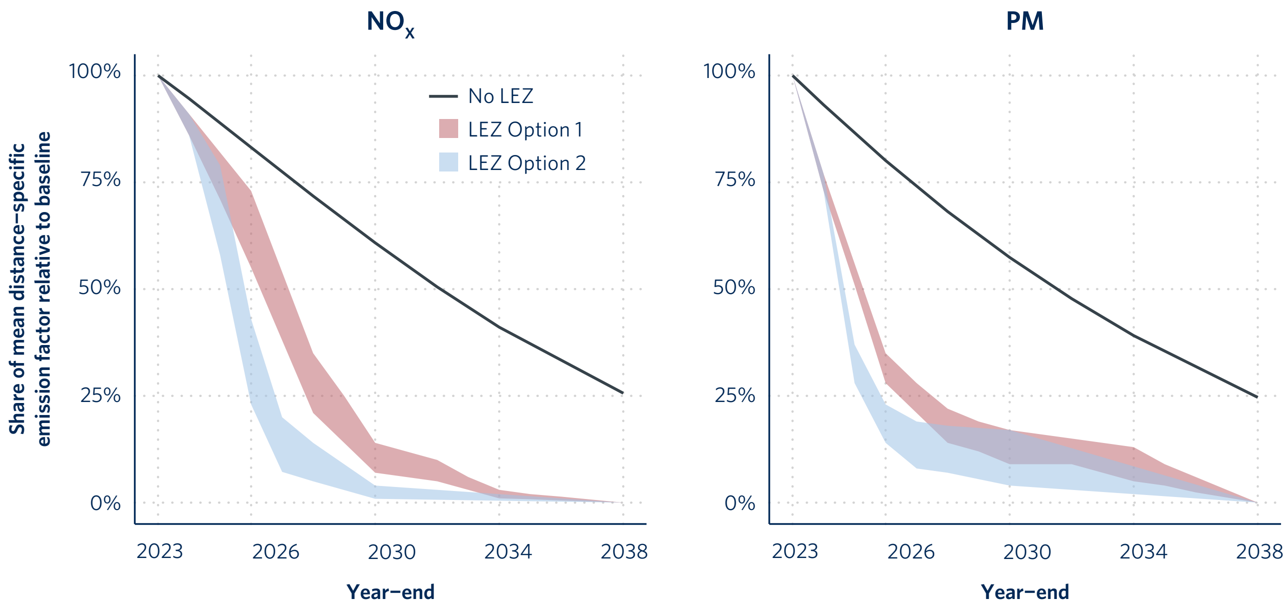

Figure B1. The effects of the LEZ on fleet-average NO_x and PM emission factors for light commercial vehicles under all LEZ scenarios. The shaded areas show the range of possible emission reductions that depend on responses of vehicle owners affected by LEZ restrictions, covering the best case and worst-case scenarios.

Table B3. Years in which the baseline scenario and the two implementation options reach a 50% reduction in the average NO_x emission factor and the numbers of years meeting the reduction target is accelerated compared to the baseline scenario.

Reduction in average NO_x emission factor	Scenario	Option 1		Option 2	
		Year	Numbers of years accelerated	Year	Numbers of years accelerated
50%	No LEZ	2032		2032	
	LEZ – buy 100% used vehicles	2027	4.9	2026	6.6
	LEZ – buy 100% new vehicles	2026	5.7	2025	7.2
	LEZ – switch to zero-emission alternatives	2026	5.8	2025	7.2
75%	No LEZ	2038		2038	
	LEZ – buy 100% used vehicles	2029	9.2	2027	11.4
	LEZ – buy 100% new vehicles	2028	10.4	2026	12.3
	LEZ – switch to zero-emission alternatives	2028	10.5	2026	12.3

Table B4. Years in which the baseline scenario and the two implementation options reach a 50% reduction in the average PM emission factor and the numbers of years meeting the reduction target is accelerated compared to the baseline scenario.

Reduction in average PM emission factor	Scenario	Option 1		Option 2	
		Year	Numbers of years accelerated	Year	Numbers of years accelerated
50%	No LEZ	2031		2031	
	LEZ – buy 100% used vehicles	2025	6.2	2025	7.1
	LEZ – Buy 100% new vehicles	2025	6.4	2024	7.2
	LEZ – switch to zero-emission alternatives	2025	6.5	2024	7.3
75%	No LEZ	2038		2038	
	LEZ – buy 100% used vehicles	2027	10.4	2026	12
	LEZ – buy 100% new vehicles	2027	10.9	2026	12.3
	LEZ – switch to zero-emission alternatives	2026	11.5	2025	12.7

PROJECTED IMPACT ON WTW AND TTW GHG EMISSIONS

Figure B2 shows the impact of the LEZ on fleet-average TTW and WTW GHG emission factors for light commercial vehicles under all scenarios. Table B5 shows the years in which all scenarios, including the baseline, achieve a reduction of 50% in the average TTW GHG emission factor for the two implementation options. Similarly, this table also shows the number of years meeting the reduction target is accelerated compared to the baseline scenario. Table B5 shows the same impact in terms of years for the average WTW GHG emission factor.

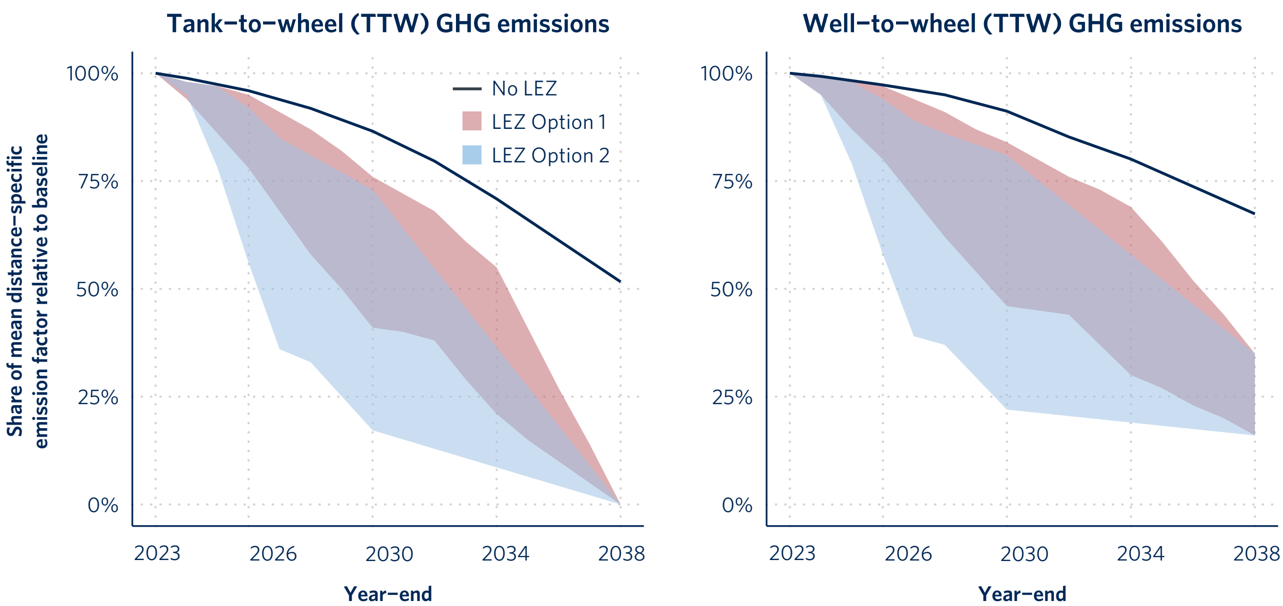

Figure B2. The effects of the LEZ on fleet-average light commercial vehicles TTW and WTW GHG emission factors for all LEZ scenarios. The shaded areas show the range of possible emission reductions that depends on responses of vehicle owners affected by LEZ restrictions covering the best case and worst-case scenarios.

Table B5. Years in which the baseline scenario and the two implementation options reach a 50% reduction in the average TTW GHG emission factor and the numbers of years meeting the reduction target is accelerated compared to the baseline scenario.

Reduction in average TTW GHG emission factor	Scenario	Option 1		Option 2	
		Year	Numbers of years accelerated	Year	Numbers of years accelerated
50%	No LEZ	2037		2037	
	LEZ – buy 100% used vehicles	2035	2.8	2035	2.9
	LEZ – buy 100% new vehicles	2032	5.2	2030	7.8
	LEZ – switch to zero-emission alternatives	2032	5.8	2028	9.5

Table B6. Years in which the baseline scenario and the two implementation options reach 50% reduction in the average WTW GHG emission factor and the numbers of years accelerated compared to the baseline scenario.

Reduction in average WTW GHG emission factor	Scenario	Option 1		Option 2	
		Year	Numbers of years accelerated	Year	Numbers of years accelerated
50%	No LEZ	2042		2042	
	LEZ – buy 100% used vehicles	2036	5.5	2036	5.5
	LEZ – buy 100% new vehicles	2034	7.4	2033	8.2
	LEZ – buy 100% BEV	2034	7.5	2033	9
	LEZ – switch to zero-emission mobility	2033	9	2028	13

Figure B3 shows the percentage of cumulative savings in WTW GHG emissions for light commercial vehicles that can be achieved in the two implementation options from 2023 to 2038 compared to absence of an LEZ.

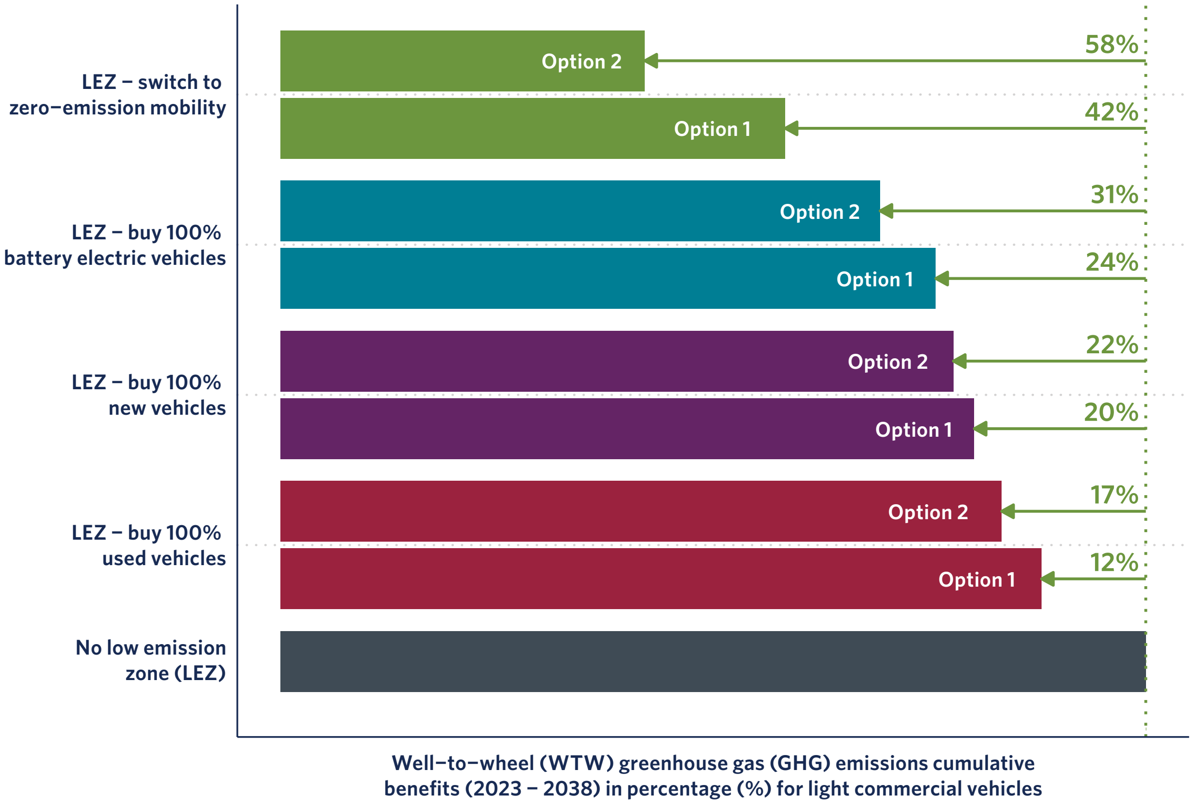

Figure B3. WTW GHG cumulative benefits from 2023–2038 for two implementation options for different LEZ scenarios compared to the baseline scenario.

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