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TESI DI LAUREA

**AN ASSESSMENT FRAMEWORK TO
EVALUATE THE EXPECTED AIR QUALITY
IMPACTS OF A LOW EMISSION ZONE: THE
CASE STUDY OF PADOVA, ITALY**

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Abstract

As cities seek to reduce greenhouse gas emissions and improve air quality, Low Emission Zones (LEZs) and other targeted mobility measures are gaining in importance. Instead of relying on wide national statistics, specific assessments at the street level are strictly necessary to evaluate the accurate environmental impact of these initiatives. This study presents a highly localized model coupling microscale atmospheric dispersion and spatial vehicular emission methodologies to quantify the tailpipe emissions and roadside concentrations of Carbon Monoxide (CO), Particulate Matter (PM), and Nitrogen Oxides (NO_x) for a hypothetical LEZ in the historical center of Padova, Italy.

The methodology begins with an analysis of the current characteristics of circulating vehicles at the regional level and employs a “bottom-up”, high-resolution approach to determine the actual technological composition of the city’s fleet. The European EMEP/EEA Tier 3 approach was applied, and tailored emission factors (EF) were computed using dynamic, speed-dependent mathematical techniques. With these parameters, a highly accurate baseline was generated using a QGIS framework, utilizing traffic volumes, related fleet compositions, and continuous speed vectors to calculate the total mass of pollutants for each specific road section. These localized line-source emissions are integrated with local meteorological boundary layer conditions analyzed and run through the AERMOD dispersion engine to translate tailpipe emissions into actual human exposure estimates.

Using this coupled technique, the future LEZ Scenario where non-compliant cars (including standard Euro 0-6 compression-ignition engines) are entirely banned from the urban core was precisely compared to the current Base Scenario. The findings reveal a highly divergent environmental outcome. The LEZ successfully mitigated inner-city pollution, driving a massive 83.69% network-wide reduction in PM and a 27.43% reduction in CO. However, the spatial simulation uncovered a severe peripheral "spillover effect." Because the restricted, diesel-heavy fleet was forced onto outer ring roads for extended bypass detours at higher speeds, total network NO_x emissions inadvertently increased by 45.05%.

This work ultimately shows that while the proposed approach coupling emission and dispersion models can be effectively adopted by local authorities to perform an ex-ante evaluation of the expected benefits of sustainable mobility interventions, highly localized cordons can exacerbate pollution in surrounding communities. To prevent this spatial penalty, future urban mobility strategies must pair central LEZs with comprehensive regional fleet modernization and peripheral interception infrastructure.

Keywords: Urban Climate Mitigation, Air Dispersion Modeling, Low Emission Zone (LEZ), Traffic-Related Air Pollution (TRAP), EMEP/EEA Tier 3, AERMOD, QGIS.

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List of Abbreviations

- ACI: Automobile Club d'Italia
- AERMET: AERMOD Meteorological Preprocessor
- AERMOD: AMS/EPA Regulatory Model
- AFV: Alternative Fuel Vehicle
- ARPAV: Agenzia Regionale per la Prevenzione e Protezione Ambientale del Veneto
- BEV: Battery Electric Vehicle
- CNG: Compressed Natural Gas
- CO: Carbon Monoxide
- COPERT: Computer Program to calculate Emissions from Road Transport
- EEA: European Environment Agency
- EMEP: European Monitoring and Evaluation Program
- LEZ: Low Emission Zone
- LPG: Liquefied Petroleum Gas
- NOx: Nitrogen Oxides
- PBL: Planetary Boundary Layer
- PHEV: Plug-in Hybrid Electric Vehicle
- PM: Particulate Matter
- QGIS: Quantum Geographic Information System
- TDM: Transportation Demand Management
- TRAP: Traffic-Related Air Pollution
- ULEZ: Ultra Low Emission Zone

1. INTRODUCTION

1.1. Background

The worsening of urban air quality is one of the most important public health and environmental problems of our day. The main driver of localized air pollution in densely populated metropolitan centers is anthropogenic emissions in the road transport sector, especially internal combustion engine automobiles. Serious cardiovascular and respiratory morbidity in urban populations is strongly linked to the continuous emission of air pollutants from traffic, especially nitrogen oxides (NO_x), carbon monoxide (CO) and fine particulate matter (PM) (Boogaard et al., 2012; Ceccato et al., 2024).

In some regions, topographical and climatic constraints add to the complexity of the problem. Municipal authorities are transitioning from passive monitoring to active Transportation Demand Management (TDM) measures to proactively manage such high pollution concentrations. One of the most effective coercive policy instruments at hand is the Low Emission Zone (LEZ). A LEZ is a focused environmental sieve rather than generic congestion charging schemes just pricing urban access. It is a geographically delimited metropolitan cordon where entrance for vehicles is allowed, limited or totally forbidden depending on specific engine technology, fuel types and Euro emission criteria (Ceccato et al., 2024; Delgado-Lindeman et al., 2025).

However, the implementation of a LEZ does not simply make traffic disappear from a city but causes a complicated spatial and technological redistribution of the circulating fleet (Ceccato et al., 2024). The LEZ can contribute to change the local emission flux by promoting cleaner technology (battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs) and new spark-ignition engines) and at the same time prohibiting older compression-ignition (diesel) engines (Peters et al., 2021). The inner restricted zone has a much "cleaner" fleet because of the artificial restrictions, while the outlying road networks can be affected by high congestion levels due to diverted non-compliant vehicles. Understanding the full environmental imprint of the policy hinges on capturing this spatial difference (Poulhès & Proulhac, 2021).

To assess the real effectiveness of an LEZ, one has to disentangle these very specific traffic changes from the larger macroeconomic patterns. Many environmental assessments have traditionally relied on "top-down" emission inventories that use generic national fleet averages

and static emission factors (Rodriguez-Rey et al., 2021). Older software models also sometimes lack the technological granularity to reflect the diversity of today's automobile market. For example, legacy tools such as the 2018 version of COPERT sometimes fail to correctly emulate the current widespread use of particular hybrid technologies or the harsh emission penalty of urban traffic jams (Host et al., 2020).

A complete “bottom-up” modeling architecture is needed to fully evaluate the localized air quality effects of a LEZ (Rodriguez-Rey et al., 2021). Tailpipe emissions are extremely sensitive to the immediate vehicle speed; a car trapped in stop-and-go congestion at 10 km/h produces a drastically different amount of pollution to the identical vehicle going at 50 km/h. Thus, robust predictive modeling must be combined with real-world, very localized vehicle registration databases and mathematically rigorous speed-dependent emission formulas, such as those provided by the EMEP/EEA Air Pollutant Emission Inventory Guidebook (European Environment Agency [EEA], 2023).

The push for Low Emission Zones in Italy is not just a localized environmental goal; it is a strict legal requirement. Under the European Union Air Quality Directive (2008/50/EC), member states face severe financial penalties if they consistently fail to meet safety limits for PM10 and NO2. Italy has repeatedly faced infringement procedures from the European Commission because its northern regions frequently breach these thresholds. This regulatory pressure is heavily complicated by geography. Located in the Po Valley, Padova suffers from a severe topographical penalty. The surrounding Alps and Apennines block natural wind circulation, causing frequent winter thermal inversions that act as a lid over the city, trapping traffic exhaust near the ground. Because the atmosphere cannot naturally dilute the pollution, municipal authorities are forced to rely on aggressive traffic restrictions to meet EU laws.

1.2.Problem Statement

Careful separation of traffic distribution and environmental dispersion variables is necessary for assessing the predicted spatial effects of a LEZ. When a municipality restricts a significant portion of its passenger car fleet from entering the city center, the local area-based emission flux (g/s/m²) fundamentally transforms. However, calculating this change is analytically complex due to the tripartite nature of post-LEZ traffic flows. In particular, traffic patterns after LEZ

introduction can be categorized into three distinct behaviors: unaffected baseline traffic, allowed "clean" traffic inside the cordon, and banned "dirty" traffic diverted to the periphery.

Standard environmental assessments frequently fail to dynamically weight these segregated fleet fractions against localized, street-by-street speed vectors. Furthermore, failing to couple dynamic tailpipe emissions with high-fidelity, microscale atmospheric dispersion models' tools capable of accounting for local mechanical turbulence and historical building topography ultimately leads to highly inaccurate estimations of an LEZ's actual public health benefits.

1.3.Objectives of the Study

The main aim of this work is to design and deploy a high-resolution assessment methodology combining spatial emission and microscale dispersion models for assessing the potential air quality consequences of a hypothetical Low Emission Zone (LEZ) in Padova, Italy.

To achieve this general purpose the study will target the following specific sub-objectives:

Fleet Characterization and Scenario Definition:

Perform a detailed analysis of the local Automobile Club d'Italia (ACI) registration database for 2023 to identify the precise technological composition of the circulating fleet in the area. Establish a precise baseline and segregate the non-compliant vehicles limited by the urban core LEZ.

Bottom-Up Emission Modeling:

To deploy the European EMEP/EEA Tier 3 mathematical methods for the computation of customized, dynamic, speed-sensitive emission factors (EF) and hence to accurately calculate tailpipe emissions at the street level.

Geospatial and meteorological integration:

Spatially distribute traffic volumes and localized fleet compositions in a QGIS framework and analyze local atmospheric boundary layer conditions this phase is intended to compute the exact total quantity of Carbon Monoxide (CO), Nitrogen Oxides (NOx) and Particulate Matter (PM) for each given road section.

Microscale Dispersion and Policy Evaluation:

To apply an advanced dispersion model to translate the estimated tailpipe emissions to actual roadside human exposure estimates ($\mu\text{g}/\text{m}^3$). The aim is to measure precisely the absolute reductions of emissions, the percentage reduction overall, and the improvements in urban air quality, by a direct comparison of the current Base Scenario with the future LEZ Scenario.

1.4. Thesis outline

This thesis is structured to guide the reader from the theoretical framework of urban traffic policies to the microscale spatial analysis of the Padova Low Emission Zone, organized as follows:

Chapter 1: Introduction: Establishes the environmental, legal, and topographical context of the study, defining the core research problem and specific objectives.

Chapter 2: Literature Review: Evaluates the efficacy of existing LEZs, the behavioral impacts of traffic reallocation, and the principles of dynamic emission and atmospheric dispersion modeling.

Chapter 3: Methodology: Details the coupled assessment framework, including localized fleet segregation, application of EMEP/EEA Tier 3 emission formulas, and the AERMOD configuration.

Chapter 4: Results and Discussion: Presents high-resolution dispersion contours, mathematically quantifying the absolute and relative concentration differences for PM, CO, and NO_x between the Base and Future scenarios.

Chapter 5: Conclusions and Policy Recommendations: Synthesizes the overall environmental impact, addresses the peripheral NO_x penalty, acknowledges study limitations, and provides data-driven mobility strategies.

2. LITERATURE REVIEW

2.1. Traffic-Related Air Pollution (TRAP) and the Shift to LEZs

Urban public health still suffers heavily from standard combustion engine traffic (Delgado-Lindeman et al., 2025). Car flow alone does not explain the severity of the problem. What happens to exhaust after it leaves the tailpipe depends entirely on local geography. In this respect, the Po Valley in northern Italy suffers a large climatological penalty (Ceccato et al., 2024). Mountains box the region in completely: The Alps sit to the north and the Apennines to the south. This physical bowl blocks prevailing winds. A highly stable atmospheric boundary layer sets up directly over Padova. Cold weather ruins the air quality further. Winter thermal inversions happen constantly in the valley. The warm air over the surface air acts as a lid and traps it in the air people breathe. Convective mixing heights fall to critical lows. This mixing height measure is the actual volume of air available to dilute street-level exhaust. When that ceiling drops, vertical dispersion just ceases. Traffic does not even need to be heavy to cause an issue. Everyday tailpipe emissions quickly turn into toxic ground-level clouds of nitrogen oxides (NO_x), carbon monoxide (CO), and particulate matter (PM). The gases just sit in the streets for days. Historical data from the regional environmental protection agency (ARPAV) proves the severity of this problem. The European Union sets a strict daily limit for PM₁₀ at 50 µg/m³. By law, municipalities cannot exceed this threshold more than 35 days per calendar year. Padova routinely breaks this legal limit. During severe winter inversions, the city frequently records dozens of consecutive exceedance days. The local topography simply traps the traffic exhaust faster than the atmosphere can clear it. (Agenzia Regionale per la Prevenzione e Protezione Ambientale del Veneto [ARPAV], 2023). Because the weather behaves this way, Padova has to implement aggressive traffic rules. It is a meteorological necessity. In addition to passive air monitoring, planners across Europe try to control the vehicles directly using Transportation Demand Management (TDM) strategies. Low Emission Zones (LEZs) are the main regulatory tool right now (Ceccato et al., 2024). The strategy is extremely common. Delgado-Lindeman et al. (2025) counted 363 active zones across the continent. LEZs operate on a strange logic, though. They rarely drop the number of cars driving through a neighborhood. The zone acts as a technological filter instead, forcing people into buying newer engines. Total vehicle counts stay basically flat. This dynamic leaves academics arguing over the real-world data. Yet

researchers still disagree on whether these boundaries really solve the environmental and social problems they address (Ceccato et al., 2024).

2.2.Efficacy and Limitations of Low Emission Zones

Setting up a LEZ boundary on paper does not guarantee clean air. Policy success depends entirely on how strict the bans are and exactly which vehicles get targeted (Holman et al., 2015). History shows that weak cordons fail completely. Boogaard et al. (2012) tracked several early LEZs across Dutch municipalities, including Amsterdam, The Hague, and Utrecht. The researchers used high-resolution street measurements but found zero statistically significant drops in ambient PM or NOx. These early designs suffered from a massive blind spot. The cities banned older heavy-duty trucks but gave regular private passenger cars a free pass. Unrestricted passenger cars generate a huge portion of the urban emission flux. By ignoring them, the Dutch policies left the main pollution driver completely untouched (Boogaard et al., 2012). Zones only succeed when they hit the broader passenger fleet with aggressive limits. Haifa, Israel provides a great example. In its very first year of operation, the Haifa LEZ drove down ambient NOx by 12.9% and cut Black Carbon by 10.6% (Tartakovsky et al., 2020). Lisbon experienced similar results, but only after fixing its rules. Weak initial restrictions did almost nothing. Real improvements only showed up when Lisbon launched "Phase 2" of its policy, forcing all drivers to meet stricter Euro 2 and Euro 3 standards. That specific update knocked PM10 down by 23% and dropped NO2 by 12% (Ferreira et al., 2015). London's Ultra Low Emission Zone (ULEZ) confirms this exact trend. Stringent controls on every high-polluting vehicle cut NO2 up to 19% in the most congested parts of the city (Prieto-Rodriguez et al., 2022). The real-world data make a very clear point. Half-measures do not work. To actually clean the atmosphere and deliver public health benefits, an LEZ has to force a comprehensive technological shift across the entire circulating passenger fleet.

While international examples provide a good baseline, evaluating a city like Padova requires looking at similar Italian policies. Milan offers one of the most relevant case studies through its dual-zone system: Area C, which operates as a central congestion charge, and Area B, a broader LEZ restricting older diesel vehicles across most of the metropolitan area. Recent evaluations of Milan's Area B show that while it successfully accelerated the retirement of Euro 3 and Euro 4 diesel cars, the outer perimeter experienced temporary traffic increases as non-compliant drivers adjusted their routes to bypass the cameras. Similarly, Rome's "Fascia Verde" (Green Belt) has

historically struggled with enforcement gaps and behavioral pushback, proving that an LEZ only works if the boundaries are strictly monitored and the public is provided with viable transit alternatives. These regional cases highlight that Italian LEZs must carefully manage displaced traffic to avoid simply pushing the pollution into the surrounding suburbs.

2.3.The Behavioral Dimension: Fleet Renewal and Traffic Reallocation

Restricted vehicles do not disappear when an LEZ is introduced. The policy forces the public to adapt, often in complex ways (Ceccato et al., 2024). Predictive modelling for Padova is a good example of these probabilistic choices. Some drivers buy cleaner cars or use public transport. Many others, however, simply drive to the cordoned boundary and park their older cars in peripheral neighborhood's (Ceccato et al., 2024). Ignoring this diverted traffic skews estimates of vehicle kilometres travelled (VKT) significantly. It leads to localized pollution spikes right outside the restricted zone, a phenomenon known as the “spillover effect” (Ceccato et al., 2024). Even high policy compliance may not result in environmental gains. Vehicle registration data from Madrid's LEZ rollout confirms a sharp rise in alternative fuel vehicle (AFV) sales. Yet consumers overwhelmingly bypassed strict zero-emission models to purchase plug-in hybrid electric vehicles (PHEVs) and alternative fossil-fuel cars (Peters et al., 2021). Since real-world PHEV driving relies heavily on the internal combustion engine, the projected drop in fleet CO₂ emissions barely materialized (Peters et al., 2021). Parking incentives designed for clean vehicles can also cause behavioral "entrenchment" (Gonzalez et al., 2022). Madrid provided free on-street parking inside the LEZ for environmentally friendly cars. This particular perk created a strong disincentive for drivers to use public transit, locking urban congestion at baseline levels (Gonzalez et al., 2022).

2.4.Environmental Justice and Spatial-Temporal Exposure

The public health benefits generated by a LEZ are rarely distributed equally among the urban population. Moving toward a realistic spatio-temporal approach, recent studies have mapped dynamic NO₂ concentrations against household travel surveys to track exactly what air citizens breathe as they move through their daily activities (Poulhès & Proulhac, 2021).

Applying this methodology to the Paris Region LEZ exposed a stark socio-spatial inequity: the wealthiest residents, who generally live inside the central LEZ and possess the capital to quickly upgrade their vehicles, emerge as the primary beneficiaries of the clean air policies (Poulhès &

Proulhac, 2021). On the other hand, low-income groups and the unemployed are severely blocked financially from acquiring compliant vehicles and often live in the peripheral areas to which diverted “dirty” traffic is pushed, thus benefiting the least from the intervention (Poulhès & Proulhac, 2021). Moreover, fine-scale dispersion modeling in Greater Paris showed that the most effective way to more equitably distribute health benefits across socio-economic populations was to extend the LEZ perimeter outward to include suburban municipalities (Host et al., 2020).

2.5.The Mathematics of Emission Flux: Macroscopic vs. Microscopic Approaches

Measuring the real environmental impact of an LEZ requires "bottom-up" mathematical modeling. Researchers have to capture the exact kinematic movements happening on the street level (Rodriguez-Rey et al., 2021). Older "top-down" regional models fail at this. They average emissions across massive grid cells and rely on generic national fleet data, which completely hides local pollution peaks (Rodriguez-Rey et al., 2021). To get real numbers, modern environmental engineering links traffic flows directly to emission calculators. These coupled systems generally operate on either a microscopic or macroscopic scale. Microscopic models track everything. They use Dynamic Traffic Assignment to map the exact position, acceleration, and specific engine power of every single car on the road (Rodriguez-Rey et al., 2021). The accuracy is excellent, but the computational load is massive. Because they require so much processing power, microscopic models only really work for a single intersection or a very small neighborhood (Rodriguez-Rey et al., 2021). When evaluating an entire metropolitan area like the municipality of Padova, researchers have to scale up. This means shifting to macroscopic frameworks that run on Static Traffic Assignment (Rodriguez-Rey et al., 2021). The main problem here is how macroscopic models handle severe traffic jams. Static systems do not make it easy to map queue spillbacks. This blind spot means that they are completely unaware of the physical realities of ‘stop-and-go’ driving (Rodriguez-Rey et al., 2021). A coupled simulation in Barcelona proved exactly how bad this gap can be. Rodriguez-Rey et al. (2021) showed that actual NO_x emissions during stop-and-go congestion spiked up to 65% higher than what macroscopic models originally predicted. Internal combustion engines simply operate at terrible efficiency levels when drivers constantly alternate between the gas and the brake. We cannot use static, average emission factors if we want to fix this macroscopic blind spot. Current methodologies solve the problem by using dynamic, speed-dependent polynomial formulas.

When calculating these emissions, researchers generally have to choose between Tier 2 and Tier 3 methodologies. A Tier 2 approach relies on average national speeds and general fuel consumption data. While this is acceptable for estimating massive national greenhouse gas inventories, it fails completely at the urban scale. Tier 2 equations cannot account for the harsh emission spikes caused by stop-and-go traffic or vehicles idling at intersections. To accurately model a LEZ, where traffic is artificially slowed down or diverted into congested bypasses, a Tier 3 approach is strictly necessary. By using specific polynomial equations and empirical coefficients, the Tier 3 method recalculates the emission factor dynamically based on the exact speed of the vehicle on a specific road link. This mathematical adjustment captures the physical reality that a diesel car crawling at 15 km/h on a crowded peripheral road emits significantly more NO_x than it would cruising steadily at 50 km/h.

The EMEP/EEA Air Pollutant Emission Inventory Guidebook 2023 defines these rules strictly (European Environment Agency, 2023).

$$EF_{(v)} = \frac{\alpha v^2 + \beta v + \gamma + \frac{\alpha}{v}}{\epsilon v^2 + \zeta v + \eta}$$

where:

$EF(v)$ = the speed-dependent emission factor for a specific pollutant (g/km) v = the mean travel speed of the vehicle on the road segment (km/h) $\alpha, \beta, \gamma, \delta, \epsilon, \zeta, \eta$ = empirical, technology-specific mathematical coefficients. These constants are derived from experimental dynamometer testing and are provided in the EMEP/EEA Guidebook database. Their exact values vary strictly depending on the target pollutant (e.g., NO_x, CO, PM), the fuel type (e.g., Petrol, Diesel, CNG), and the Euro emission standard of the specific vehicle category (e.g., Euro 3, Euro 6).

The Tier 3 method adjusts the estimated emission rate according to the local speed of the road segment, with the formulas using specific empirical coefficients directly from experimental dynamometer testing (European Environment Agency, 2023). The use of mathematical speed penalties allows the Tier 3 formulas to reproduce accurately the extreme pollution spikes for slow urban traffic. This calculation allows a macroscopic network model to provide an accurate output of the continuous, area-based emission flux required for spatial atmospheric dispersion.

2.6. The Physics of Microscale Atmospheric Dispersion Modeling

Before advanced models became the standard, regulatory dispersion modeling often relied on simpler Gaussian plume models (such as ISC3) that used rigid stability classes. Those older models struggled to simulate complex urban environments accurately, especially during the low-wind, highly stable winter conditions typical of the Po Valley. Today, researchers use continuous boundary layer models to solve this problem. AERMOD improves on older systems by using micrometeorological data to track exactly how surface heat and physical obstacles create turbulence. For extremely localized traffic assessments, specialized dispersion tools like the AERMOD model are also frequently integrated into these frameworks, as they are specifically coded to handle near-surface line sources like continuous urban traffic. By combining the continuous turbulence tracking of AERMET with models designed specifically for road networks, researchers can accurately map how tailpipe exhaust disperses around historical city blocks.

Calculating the raw mass of pollutants emitted from a tailpipe (g/km) does not directly answer the question of human health; those emissions must be translated into ambient breathing concentrations ($\mu\text{g}/\text{m}^3$) through the application of advanced atmospheric dispersion physics.

Historically, regulatory dispersion models relied on discrete Pasquill-Gifford stability classes, which categorized the atmosphere into rigid, generalized states. These older models frequently failed to accurately predict near-field urban dispersion during highly stable, low-wind conditions exactly the conditions prevalent in the Po Valley. To overcome these critical limitations, modern environmental engineering utilizes steady-state Gaussian plume models based on continuous planetary boundary layer (PBL) similarity theory, such as AERMOD (Cimorelli et al., 2005)

The predictive superiority of AERMOD in urban environments is driven entirely by its meteorological preprocessor, AERMET. Rather than assigning a generic stability class, AERMET calculates continuous turbulence scaling parameters utilizing fundamental surface energy balance equations. Specifically, it determines the friction velocity (u) to account for mechanical turbulence and the sensible heat flux (H) for convective buoyancy, mathematically combining them to derive the Monin-Obukhov length (L), which dictates atmospheric stability

AERMET uses these surface parameters to calculate the exact Monin-Obukhov length (L) using the following boundary layer equation: -

$$L = \frac{-\rho C_p T_v u_*^3}{kgH}$$

Where ρ represents air density, C_p is the specific heat of air at constant pressure, and T_v represents the virtual temperature. The equation uses the friction velocity u_*^3 cubed to account for mechanical mixing. It divides this by the von Kármán constant (k), gravity (g), and the sensible heat flux (H). This mathematical relationship allows AERMOD to continuously track how thermal buoyancy and mechanical friction fight each other in the urban canopy.

Crucially, in complex micrometeorological domains like Padova, the accuracy of these dispersion physics is entirely dependent on localized surface characteristics. The system requires distinct geophysical parameters to map the urban canopy:

- Surface Roughness Length (Z0): Dictates the mechanical turbulence induced by the friction of wind moving across physical obstacles, such as dense historical buildings and street canyons (Cimorelli et al., 2005).
- Albedo (r): The fraction of total incident solar radiation reflected by the urban surface back into space, which directly affects the sensible heat available to drive convective atmospheric mixing (Cimorelli et al., 2005).
- Bowen Ratio (Bo): The mathematical ratio of sensible heat to latent heat flux, serving as an indicator of surface moisture and deeply influencing daytime boundary layer evolution (Cimorelli et al., 2005).

By precisely parameterizing these localized surface variables, the Gaussian engine ensures that the limited air volume available for pollutant dilution within the LEZ boundary is modeled using rigorous, high-fidelity atmospheric physics.

2.7. Research Gaps and the Conceptual Framework of this Study

Current literature demonstrates a distinct methodological gap between environmental modeling and transportation planning. Environmental researchers frequently model atmospheric dispersion using generic emission inventories, often overlooking the high-resolution dynamics of municipal vehicle registries (Rodriguez-Rey et al., 2021). Conversely, transportation studies accurately capture spatial traffic reallocation but rarely translate these shifts into microscale human exposure metrics (Poulhès & Proulhac, 2021).

This research bridges this interdisciplinary gap by deploying a coupled, high-resolution assessment framework tailored to the unique atmospheric constraints of the Padova municipality (Ceccato et al., 2024). The proposed methodology rigorously segregates the local fleet database into compliant and non-compliant fractions to predict the spatial diversion of the restricted fleet. By computing dynamic, speed-dependent emissions via exact EMEP/EEA Tier 3 formulas (European Environment Agency, 2023) and feeding these localized fluxes directly into the microscale dispersion engine, this study ensures that the estimated air quality impacts of the LEZ are grounded in strict atmospheric physics and precise vehicular telemetry rather than generalized regional assumptions.

3. METHODOLOGY

3.1. Architecture Overview

This chapter details the comprehensive methodological framework utilized to quantify the environmental impact of current traffic flows (Base Scenario) and the Low Emission Zone (LEZ) in the municipality of Padova. The framework synthesizes raw geospatial metrics and localized fleet registry data into a high-resolution "Bottom-Up" emission model, ultimately generating line-source matrices for atmospheric dispersion mapping. To ensure a rigorous and mathematically sound progression from raw data to final environmental outcomes, the computational workflow is strictly segmented into three core architectural phases, as outlined below:

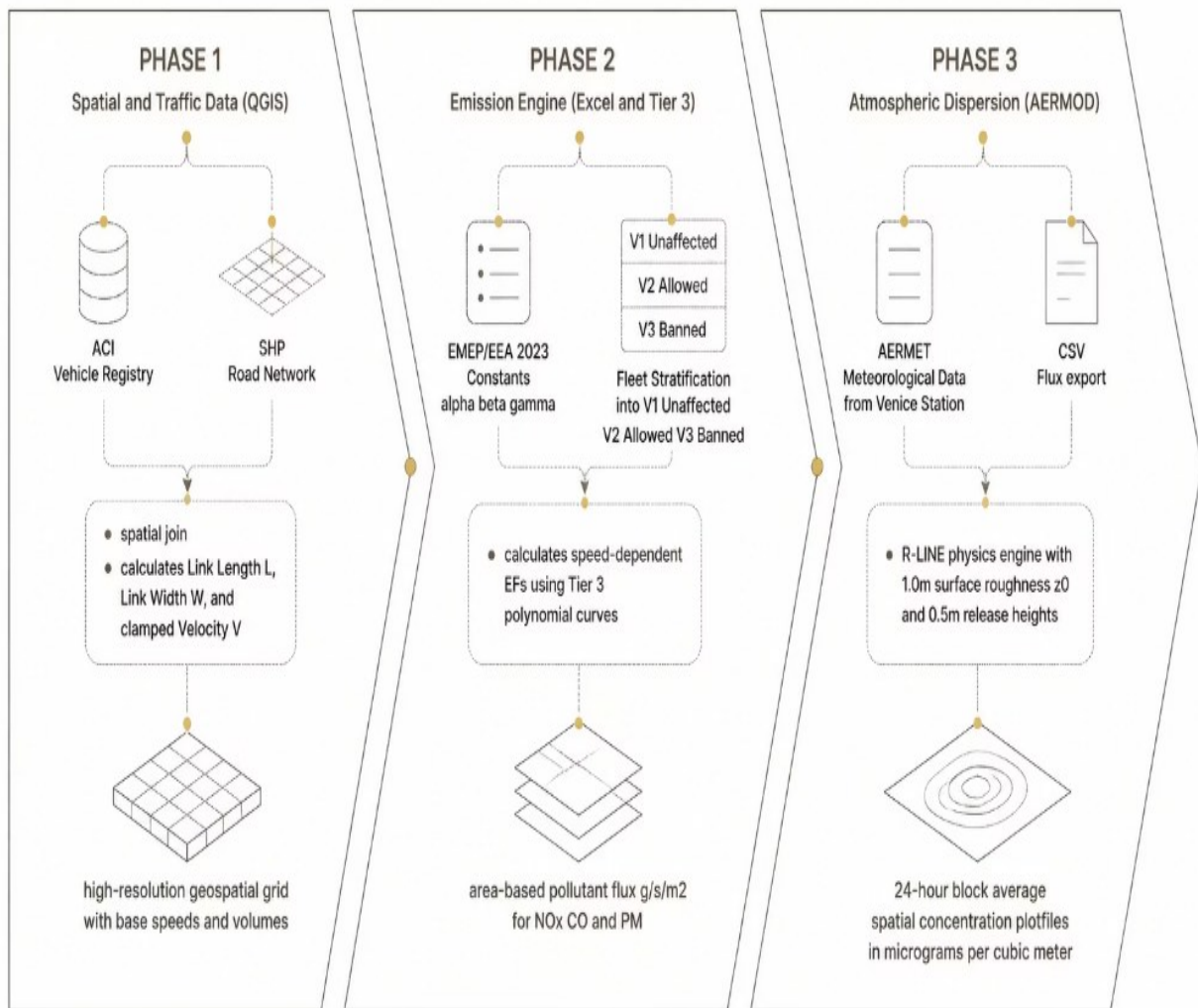


Figure 1 Methodology Workflow

- **Phase 1: Spatial & Traffic Data (QGIS)**
 - **Input:** ACI Vehicle Registry (Base Fleet) + SHP Road Network
 - **Process:** QGIS spatial extraction, calculation of Link Length (L), Link Width (W), and clamped Velocity (V)
 - **Output:** High-resolution geospatial grid with base speeds and volumes.
- **Phase 2: Emission Engine (Excel)**
 - **Input:** EMEP/EEA 2023 Constants (α, β, γ , etc.)
 - **Process:** Fleet Stratification (V1_1 vehicle Unaffected by the new regulation, V2_1 vehicle Allowed to access the new LEZ, V3_1 vehicle Banned from the new LEZ) → Calculate speed-dependent EFs using Tier 3 polynomial curves.
 - **Output:** Area-based pollutant flux (g/s/m^2) for NO_x , CO , and PM .
- **Phase 3: Atmospheric Dispersion (AERMOD)**
 - **Input:** AERMET Meteorological Data (Venice Station) + CSV Flux export.
 - **Process:** AERMOD physics engine execution, applying 1.0m surface roughness (z_0) and 0.5m release heights.
 - **Output:** 24-hour block average spatial concentration plot files ($\mu\text{g/m}^3$).

3.2. Study Area Context and Meteorological Framework

The spatial domain is the municipality of Padova, located in the Veneto region of northern Italy. The dense historical street network is susceptible to localized accumulations of Nitrogen Oxides (NO_x), Carbon Monoxide (CO), and Particulate Matter (PM) due to restricted atmospheric ventilation. Atmospheric dispersion relies on localized synoptic and surface meteorology. Data was parameterized from the closest Station (ID: 16105099999 located in Venice, 45.50N, 12.33E). Raw observations were preprocessed via AERMET to generate Surface (.sfc) and Profile (.pfl) files. To accurately reflect severe mechanical turbulence induced by dense historical building footprints, the surface roughness length (z_0) was conservatively set to 1.0 meter (U.S. Environmental Protection Agency, 2022).

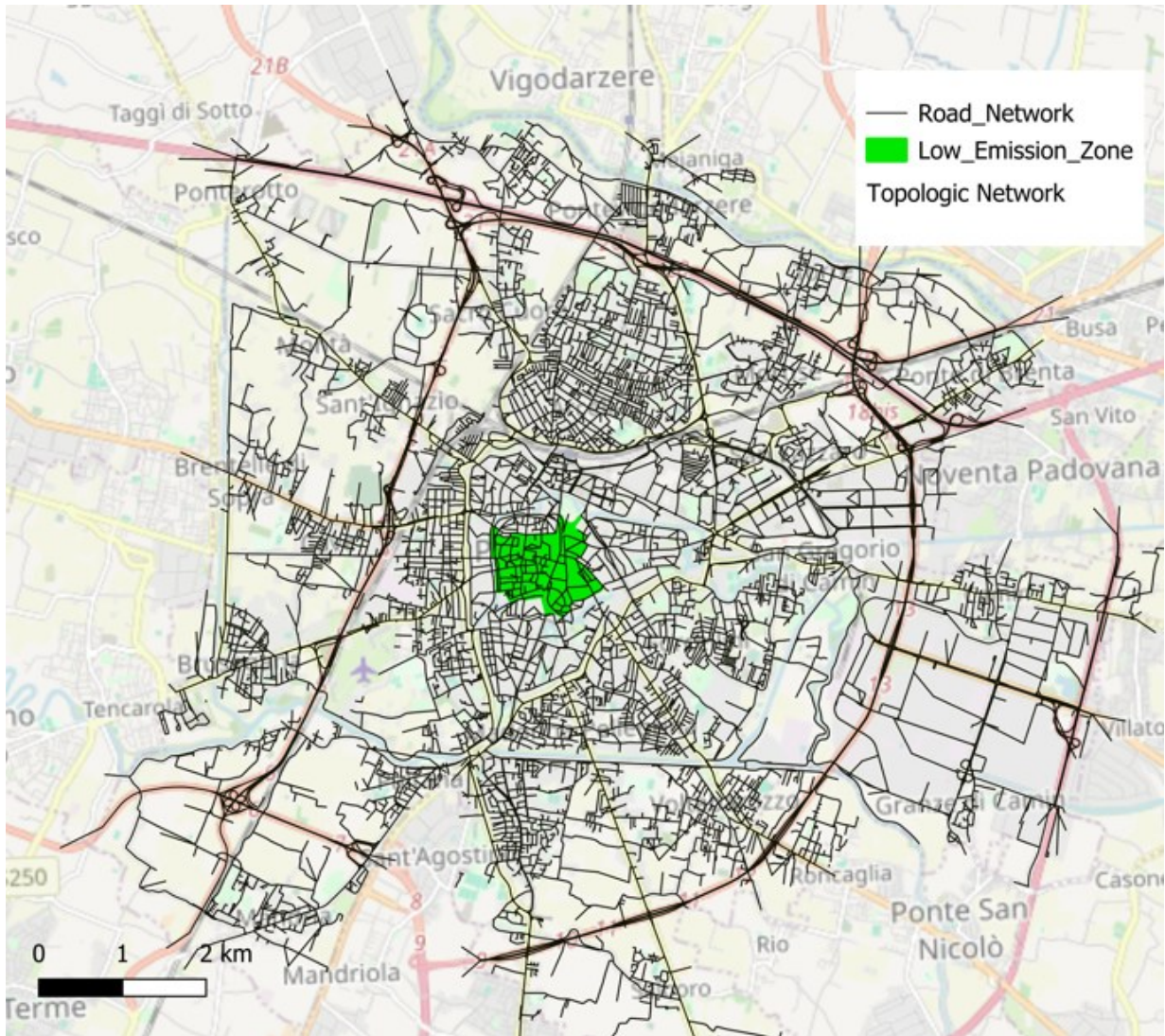


Figure 2 Study Area

3.3.Data Framework

The fundamental architecture of this study was structured around a specific spatial and regulatory dataset, establishing a baseline and a hypothetical future policy state. To accurately estimate vehicular emissions and evaluate the environmental impact of a Low Emission Zone (LEZ), the methodological framework was divided into spatial data extraction, fleet characterization, and mathematical emission modeling. The spatial analysis utilized high-resolution road network shapefiles to construct two distinct traffic models

- **Base Scenario (Sc_Base):** Representing current traffic conditions where vehicles are allowed to enter the city center ($V1$).
- **Future Scenario (Sc_Fut_7):** Introducing the hypothetical LEZ boundary, which segregates traffic into three behavioral streams: unaffected vehicles outside the zone ($V1_1$), permitted vehicles inside the zone ($V2_1$), and non-compliant diverted vehicles ($V3_1$)

For both scenarios, the spatial networks provided the critical geometric and temporal variables required for emission modeling, specifically the segment length (L) and the travel time, which were used to compute link-specific velocities.

To populate these traffic volumes with real-world characteristics, baseline vehicle fleet compositions—categorized by passenger car type, fuel, and Euro standard—were extracted from the national ACI database

This study utilized the state-of-the-art EMEP/EEA air pollutant emission inventory guidebook 2023 to estimate tailpipe emissions. In particular, total network mass emissions were calculated strictly using the advanced Tier 3 methodology, applying speed-dependent polynomial curves (utilizing specific α, β, γ parameters) to the extracted network speeds.

Finally, the regulatory core of the Future Scenario was governed by a hypothetical LEZ framework. To determine the allowed ($V2_1$) and banned ($V3_1$) fleets, strict engine criteria were applied. Compliance was granted exclusively to fully electric vehicles, Euro 2 through Euro 6 petrol and petrol-hybrids, alternative fuel bi-fuels (CNG/LPG), and Euro 2 through Euro 6 Diesel Plug-in Hybrids (PHEV). Consequently, all Euro 0 and Euro 1 vehicles, alongside all standard diesel engines, were banned from the city center, driving the emission reductions analyzed in this study.

3.4. Fleet Stratification

Generic national averages were discarded in favor of a highly localized dataset. The primary dataset was the 2023 vehicle registration database provided by the Automobile Club d'Italia (ACI) for the Province of Padova (**Automobile Club d'Italia, 2023**), yielding 633,604 registered vehicles. To bridge computational load and Tier 3 accuracy, the fleet underwent a rigorous

decomposition algorithm. Zero-tailpipe Battery Electric Vehicles (BEVs) were systematically excluded. The internal combustion fleet (474,013 vehicles) was split into two primary streams:

- **Petrol-Like Stream (54.2%):** Spark-ignition engines (Standard Petrol, Hybrid-Petrol, CNG, LPG).
- **Diesel-Like Stream (45.8%):** Compression-ignition engines (Standard Diesel, Hybrid-Diesel).

The data analysis revealed Euro 6d-Temp diesels were statistically absent (~9 vehicles). To preserve conservative impact estimates, 100% of the Euro 6 diesel fleet was manually routed to the 'Euro 6 Old (a/b/c)' algorithm.

3.5.Geospatial Network Preprocessing

The foundation of the emission model relies on the geospatial delineation of the urban road network within the QGIS environment. Spatial data was processed using two primary shapefiles: the base scenario (Sc_Base), representing current traffic conditions, and the future scenario (Sc_Fut_7), which incorporates the Low Emission Zone (LEZ) boundary. The network was broken down into approximately 23,000 individual line segments. To ensure a strict 1:1 connection between the spatial grid and the subsequent emission calculation matrix, a composite primary key (LINK_ID = A_B or Road ID) was established for each segment.

For each road segment, fundamental geometric and spatial parameters were extracted and dynamically calculated directly within QGIS. Crucially, the baseline and future traffic volumes (vehicle counts), as well as the link-specific travel times used to calculate vehicle speeds, were not statically assumed; they were extracted directly from the shapefiles generated by a macroscopic traffic simulation model, ensuring the physical redistribution of the fleet was mathematically robust.

- **Spatial Coordinates:** The exact starting and ending geographical nodes (X1, Y1, X2, Y2) for every road link were extracted to mathematically define the geometric line source.
- **Link Length:** The length of each segment (LUNGH) was retrieved in kilometers to be used in vehicle speed calculations. Additionally, the metric length (L) was verified and

dynamically calculated using the QGIS length geometry function to ensure precise spatial accuracy in meters for later dispersion mapping.

- **Road Width:** The physical width of each segment was dynamically calculated within the QGIS Attribute Table utilizing Italian legal standards (D.M. 5 November 2001). This was determined by mapping the road class variable (TIPO) and the number of lanes (NUMLANES) using the following logic: Width = "NUMLANES" × (CASE WHEN "TIPO" >= 30 AND "TIPO" <= 99 THEN 3.50 WHEN "TIPO" >= 1 AND "TIPO" <= 29 THEN 3.75 ELSE 3.50 END).

3.6.The Tier 3 Mathematical Emission Engine (COPERT)

The core emission rates across the entire spatial network were calculated utilizing the Tier 3 methodology from the EMEP/EEA air pollutant emission inventory guidebook (**European Environment Agency, 2023**). The calculation engine utilizes rational and polynomial functions parameterized by high-precision coefficients ($\alpha, \beta, \gamma, \epsilon, \zeta, \eta$) that are uniquely mapped to the clamped vehicle speed (v) for every road segment. The governing formula for dynamic tailpipe exhaust is defined as:

$$EF_{(v)} = \frac{\alpha v^2 + \beta v + \gamma + \frac{\delta}{v}}{\epsilon v^2 + \zeta v + \eta}$$

Initial mathematical testing with simplified polynomial trendlines which lacked the high-speed coefficient (α) or the critical low-speed penalty variable (δ/v) were explicitly rejected due to significant inaccuracies during simulated congestion. For example, omitting the δ constant for Nitrogen Oxides (NO_x) during severe 10 km/h traffic forced the formula to mathematically collapse, yielding an artificially low baseline of just 1.62 g/km. This failed to capture the exponential emission spikes that occur when engines run rich and inefficiently in stop-and-go traffic. Consequently, the finalized model strictly utilizes the complete high-precision coefficient matrix to mathematically guarantee that heavy pollution nodes are accurately represented in the dispersion mapping.

3.6.1. NOx and CO Dynamics

To demonstrate the structural variability of the engine across different regulatory classes and fuel streams, the following primary equations were integrated into the model to calculate *NOx* and Carbon Monoxide (*CO*) emission factors (*EF*, in g/km):

- **NOx Petrol Euro 0 (ECE 15/04):** $EF =$

$$\frac{(0.00873590 * V^2) + (1.53468501 * 2 + 175.19019607)}{118.05269277}$$

- **NOx Petrol Euro 6 (GDI d-temp):** $EF =$

$$\frac{(-0.00031454 * v^2) + (0.10305678 * v) + 0.23905658 + (-\frac{0.33927915}{v})}{0.03453583 * v^2 + (1.98601275 * v) + 1.26376326}$$

- **NOx Diesel Euro 6 Old (a/b/c):** $EF =$

$$\frac{-0.011381v + 0.945952 + \frac{1.923608}{V}}{-0.000051V^2 + 0.004264V + 1.0000}$$

- **CO Petrol Euro 0 (ECE 15/04):** $EF =$

$$\frac{(0.000007 * v^2) + (-0.0000786 * v) - 0.016810 + (\frac{4.962271}{v})}{0.000001 * v^2 + (-0.000228 * v) + 0.016879}$$

- **CO Diesel Euro 5 & 6:** $EF =$

$$\frac{(0.21 * v) - 0.74 + (\frac{0.72}{v})}{(0.03 * v^2) + (1.51 * v)}$$

3.6.2. PM Exhaust Simplification & Equivalency

While the EMEP/EEA Tier 3 methodology primarily utilizes dynamic, speed-dependent polynomial curves to calculate tailpipe emissions, the model structurally adapts to accommodate pollutants with negligible sensitivity to varying traffic conditions. This mathematical

simplification is evident when evaluating exhaust Particulate Matter (*PM*) for modern spark-ignition (petrol) engines, as their particulate output remains relatively static across the entire engine operating map.

Using the standard Tier 3 formula, the parameter matrix assigns a value of zero to all speed-dependent multipliers (α , β , δ , ϵ , and ζ) while setting the denominator's baseline constant (η) to 1. Consequently, the entire equation mathematically collapses, neutralizing the vehicle speed variable (v) entirely. The calculation is reduced to a simple baseline fraction (γ/η), resulting in a constant emission factor of 0.00322 g/km, regardless of whether the vehicle is experiencing severe congestion or traveling at highway speeds.

Furthermore, because internal combustion generates microscopically fine sub-micron particles, the EMEP/EEA methodology establishes a strict mathematical equivalence for tailpipe exhaust where the calculated mass accurately represents both sizes:

$$PM_{Total_Exhaust} = PM_{10} = PM_{2.5}$$

3.7. Speed Calculation and Clamping Logic

Accurate vehicle velocity (V) is a critical input required to trigger the speed-dependent polynomial emission formulas. Using the segment length in kilometers ($LUNGH$) and the segment travel time in seconds ($TIME_1$) provided by the shapefiles obtained from a traffic simulation software, the baseline velocity for every single road segment was established using geometric division: $V = (LUNGH/TIME1) * 3600$.

Because the EMEP/EEA Tier 3 mathematical emission engine relies on integer-bound curves, feeding continuous speed vectors directly into the formula could induce mathematical errors, particularly division-by-zero scenarios during severe traffic congestion. To safely integrate the QGIS speeds into the calculation matrix, a strict clamping and rounding array was constructed: $SPEED_LOOKUP = IF (Speed < 10, 10, IF (Speed > 130, 130, ROUND (Speed, 0)))$.

This algorithm explicitly rounds the calculated speed to the nearest whole number while restricting the operational speed domain strictly between 10 km/h and 130 km/h. This ensures every spatial link correctly maps to the exact high-resolution constants required for the emission calculation.

3.8. Fleet Re-Normalization for LEZ Scenarios

To accurately simulate the environmental impact of the Low Emission Zone (LEZ), a localized fleet stratification approach was required. The fleet re-normalization was structurally based on a

hypothetical LEZ regulation framework (Ceccato et al., 2024). Rather than applying a generic arithmetic average to the permitted EMEP/EEA Tier 3 emission factors which introduces severe empirical errors this study utilized a strict mathematical re normalization of the localized ACI registry data. The total ACI baseline fleet was segregated into two mutually exclusive regulatory profiles based on the LEZ access criteria.

In particular, to ensure high-fidelity spatial mapping, generic national averages were discarded in favor of localized 2023 vehicle registration data provided by the Automobile Club d'Italia (ACI) for the Province of Padova. The complete baseline dataset accounted for 633,604 registered vehicles.

Table 1 Padova city Vehicle Fleet Composition by Fuel

Euro Standard	Petrol Fleet	Diesel Fleet	Total Vehicles	Total Fleet (%)
Euro 0	26,958	3,776	30,734	4.85%
Euro 1	6,330	1,228	7,558	1.19%
Euro 2	28,034	6,155	34,189	5.40%
Euro 3	27,870	20,183	48,053	7.58%
Euro 4	82,143	42,168	124,311	19.62%
Euro 5	48,719	60,208	108,927	17.19%
Euro 6	116,281	104,019	220,300	34.77%
Subtotal (ICE)	336,335	237,737	574,072	90.60%
Others (Hybrids)	-	-	59,532	9.40%
Grand Total	336,335	237,737	633,604	100.00%

To balance computational efficiency with the rigorous demands of the EMEP/EEA Tier 3 methodology, the fleet was systematically filtered and categorized:

- Zero-tailpipe Battery Electric Vehicles (BEVs) were excluded from the exhaust calculation matrix, leaving an active internal combustion fleet of 474,013 vehicles
- The Petrol-Like Stream (54.2% of the combustion fleet): This category aggregated standard petrol, hybrid-petrol, CNG, and LPG vehicles, as these spark-ignition engines share similar thermal operating characteristics and urban emission profiles
- The Diesel-Like Stream (45.8% of the combustion fleet): This category aggregated standard diesel and hybrid-diesel compression-ignition engines

A critical data correction was applied to the diesel stream. Statistical analysis of the ACI records revealed that the highly efficient Euro 6d-Temp diesel vehicles were virtually absent from the local fleet (comprising only ~9 out of over 230,000 diesel units. To prevent the model from underestimating real-world pollution, 100% of the Euro 6 diesel fleet was mathematically routed to the higher-emitting 'Euro 6 Old (a/b/c)' emission calculation algorithm. For the baseline scenario (Sc_Base), the traffic volume variable (V_1) on every road segment represents this standard, unadjusted local fleet mix

3.9.LEZ Scenario Definition and Traffic Volume Redistribution

To simulate the environmental impact of the Low Emission Zone (Sc_Fut_7), the traffic volume was mathematically redistributed across the network based on the hypothetical LEZ access regulations traffic flows were divided into three mutually exclusive operational streams. (Ceccato et al., 2024).

Table 2 Baseline vehicle categories

Vehicle Category	ACI Count	Unaffected (V1_1) (Full Mix)	Allowed (V2_1) (LEZ Clean)	Banned (V3_1) (LEZ Dirty)
Petrol Euro 0	26,958	4.25%	0.00%	9.95%
Petrol Euro 1	6,330	1.00%	0.00%	2.33%
Petrol Euro 2	28,034	4.42%	7.73%	0.00%
Petrol Euro 3	27,870	4.40%	7.69%	0.00%
Petrol Euro 4	82,143	12.96%	22.66%	0.00%
Petrol Euro 5	48,719	7.69%	13.43%	0.00%
Petrol Euro 6	116,281	18.35%	32.07%	0.00%
Diesel (All)	237,737	37.52%	0.00%	87.72%
Others (LPG/Hybrid)	59,532	9.41%	16.42%	0.00%
TOTAL	633,604	100.00%	100.00%	100.00%

For Petrol Euro 0: Comprising 26,958 units, its Unaffected share is evaluated against the total city fleet will yield us 4.25 %. Due to the hypothetical Low Emission Zone (LEZ) policy restricting pre-Euro 2 conventional internal combustion vehicles, its Allowed share is 0%. Conversely, its Banned share is re-normalized strictly against the cumulative non-compliant vehicle pool (271,025units), yielding 9.95%.

The remaining vehicle categories were processed using an identical normalization protocol driven by the LEZ policy rules: compliant classes were re-normalized against the allowed vehicle total (362,579 units), non-compliant classes were re-normalized against the banned vehicle total (271,025 units), and the unaffected stream reflected the full city-wide distribution (633,604 units).

- V1 (Unaffected Volume): Traffic on roads completely unaffected by the LEZ, retaining the standard baseline fleet mix

$$EF_{w_Unaffected} = \sum (EF_i \cdot \%_ACI_i)$$

- V2 (Allowed Volume): Vehicles permitted to operate strictly within the LEZ. This represents the "clean" fleet, limited to Electric vehicles, and Euro 2 through 6 compliant units for CNG, Petrol, Petrol Hybrid, LPG Biofuel, and Diesel PHEV

$$EF_{w_Allowed} = \frac{\sum Allowed (EF_i \cdot \%_ACI_i)}{0.5724}$$

- V3 (Banned/Diverted Volume): Vehicles prohibited from entering the LEZ, which are diverted to the peripheral network. This represents the "dirty" fleet, consisting primarily of older petrol engines (Euro 0-1) and all standard diesel vehicles (Euro 0-6).

$$EF_{w_Banned} = \frac{\sum Banned (EF_i \cdot \%_ACI_i)}{0.4276}$$

Because taking a simple mathematical average of the allowed vehicles introduces severe empirical errors, a strict mathematical re-normalization of the localized fleet was required the ACI registry was stratified into two regulatory profiles: An Allowed Fleet Fraction (representing 57.24% of the baseline, or 362,579 vehicles) and a Banned Fleet Fraction (representing 42.76%, or 271,025 vehicles).

3.10. Dispersion Modeling (AERMOD)

To transition from the mass emission inventory computed in QGIS to atmospheric dispersion simulations, vehicular emissions were defined as line sources within the Fortran-based AERMOD modeling system. The final segment-level mass calculations were integrated into the AERMOD Physics engine to calculate ambient atmospheric concentrations ($\mu\text{g}/\text{m}^3$).

AERMOD requires line source emissions to be defined as an area-based flux. For each pollutant (NO_x , CO , PM) across all scenarios, the raw emission rate was converted into flux ($g/s/m^2$) using the exact geometric parameters:

$$Flux = \frac{Emission}{L * W * 3600}$$

Where L is the calculated length of the road segment in meters, W is the standardized road width in meters, and 3600 is the temporal conversion factor from hours to seconds. Because these microscale flux values frequently reach magnitudes of 10^{-5} to 10^{-8} , the QGIS attribute table was strictly exported to a Comma Separated Value (CSV) format to maintain maximum decimal precision and prevent computational truncation errors. To ensure a clean data architecture, unnecessary attributes were excluded, and only the following critical fields were exported: LinkID, X1, Y1, X2, Y2, Width, Rel_Ht, Flux_CO, Flux_PM.

To interface this raw dataset with AERMOD's Input (.inp) file structure, Microsoft Excel was utilized as a data engineering bridge. String concatenation algorithms were deployed to automatically generate the geometric and physical identity of all 22,456 road segments.

- **Spatial Location (SO LOCATION):** The geographical coordinates were assembled with a base elevation of 0 meters using the logic: ="SO LOCATION " & LinkID & " LINE " & X1 & " " & Y1 & " " & X2 & " " & Y2 & " 0".
- **Source Parameterization (SO SRCPARAM):** The physical dispersion characteristics of the emission plumes were standardized. The release height (Rel_Ht) was set to **0.5 meters** to accurately represent the average height of vehicle tailpipes, and the initial vertical mixing caused by vehicle wake turbulence (σ_{zo}) was fixed at **0.23 meters**. This generated the final string: ="SO SRCPARAM " & LinkID & " " & Flux & " " & Rel_Ht & " " & Width & " 0.23".

3.11. Dispersion Modeling Parameterization (AERMET & AERMOD)

To simulate how the calculated vehicular fluxes, disperse into atmospheric concentrations ($\mu g/m^3$), the AERMOD physics engine within AERMOD was deployed. Five distinct model input files were engineered to cover the complete spatial network: Base NO_x , Base CO , Base PM , Future CO , and Future PM .

3.11.1. Meteorological Preprocessing

Accurate atmospheric dispersion modeling relies heavily on localized synoptic and surface meteorology. Meteorological parameters were gathered from Station ID: 16105099999 (Venice, 45.50N, 12.33E). To accurately calculate continuous boundary layer turbulence and convective mixing heights, two distinct meteorological datasets were assimilated. Hourly surface observations were extracted from the NOAA Integrated Surface Database (ISHD format), while twice-daily vertical atmospheric profiles were obtained from the Integrated Global Radiosonde Archive (IGRA). These raw observations were preprocessed via the three-stage AERMET engine to merge cloud cover, temperature, and upper-air soundings, ultimately generating the final Surface (PADOVA_1.SFC) and Profile (PADOVA_1.PFL) files.

3.11.2. Receptor Grid Network

To capture the resulting pollution concentration contours, a Cartesian receptor grid was configured (GRIDCART PADGRID). The receptors were established at a standardized human breathing height of **1.8 meters**. To ensure high-fidelity mapping specifically within the study area, a nested spacing approach was utilized: receptors were configured at a highly granular **20-meter spacing within the restricted LEZ boundary**, expanding to a **100-meter spacing outside the LEZ**.

3.11.3. Parallel Cloud Execution

The simulation was executed utilizing the CONC FLAT model option to calculate **24-hour block averages** (AVERTIME 24), ultimately outputting detailed spatial plot files (.PLT) designed for final geospatial mapping in QGIS. Because calculating 22,456 discrete line sources over an extended temporal boundary requires massive computational power, the Fortran-based AERMOD execution was deployed on a distributed Cloud Virtual Machine (VM) featuring 4 logical processors. To prevent hardware bottlenecks (such as 125% CPU Load limits) and thread time-slicing crashes, a strict staggered deployment protocol was adopted. Phase One executed the three Base scenarios sequentially, and only upon completion and thread-clearing did Phase Two initialize the Future scenarios.

4. RESULTS AND DISCUSSION

4.1. Study Area and Spatial Context

The primary study area encompasses the municipality of Padova, which has been modeled through a high-resolution topological road network using QGIS. As illustrated in Figure 3, the complete Road Network (represented by the extensive black lines) captures the vast urban and peri-urban web of vehicular movement across the municipality and surrounding arteries. In stark contrast, the hypothetical Low Emission Zone is a localized, highly restricted polygon situated centrally within the historical urban core (highlighted in green).

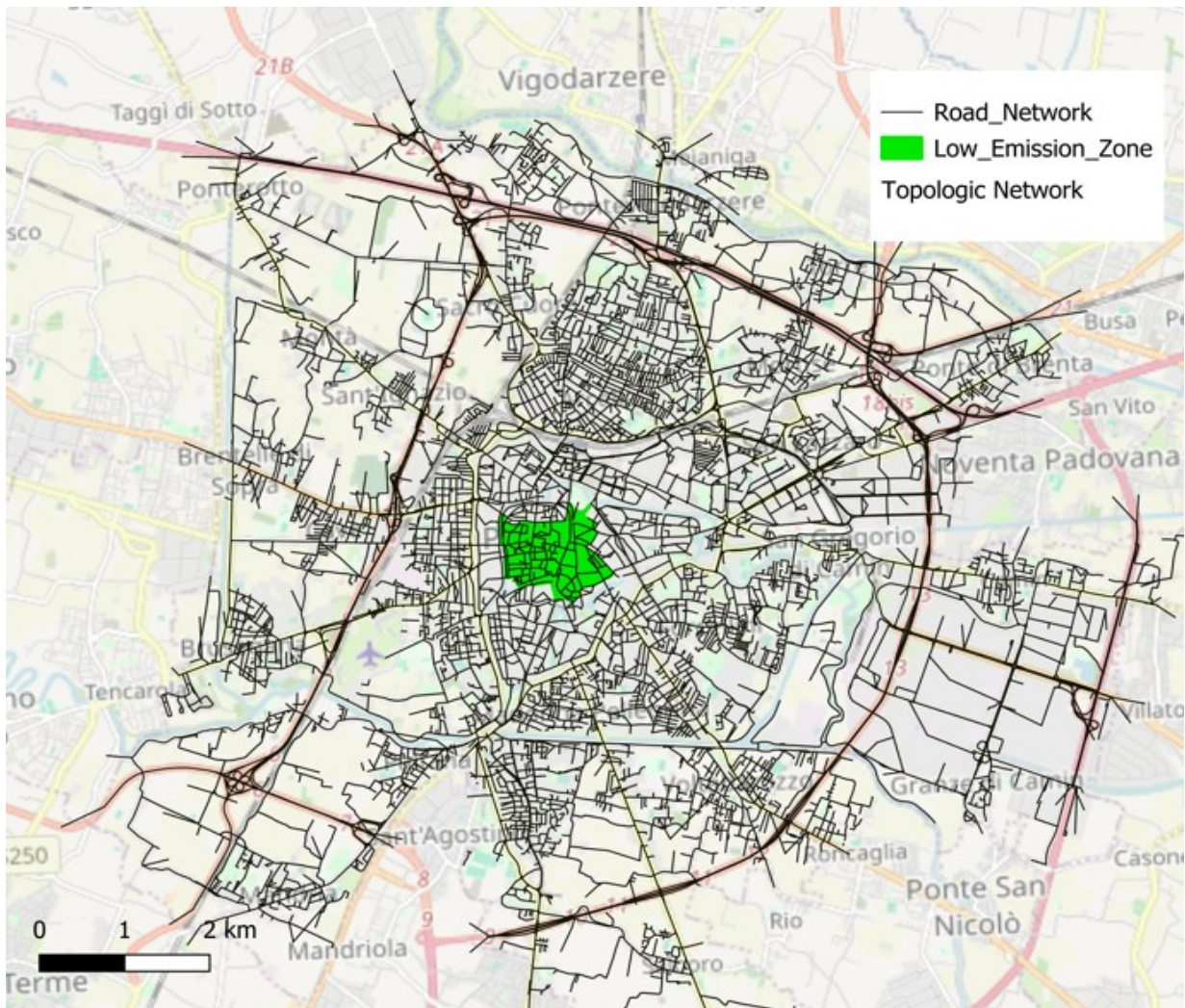


Figure 3 Geospatial visualization of Padova study area, detailing the complete topological road network and centrally located (LEZ).

Establishing this spatial layout is critical for understanding the subsequent environmental results. The physical disparity between the small restricted zone and the expansive surrounding network dictates the core dynamic of the simulation: while strict engine regulations inside the green LEZ trigger massive localized pollution reductions, the non-compliant vehicles are simultaneously forced onto the wider black road network to execute detours, triggering the displacement effects analyzed in this chapter

4.2. Introduction to Scenario Outcomes

This chapter presents the quantitative environmental outcomes of implementing the hypothetical Low Emission Zone (LEZ) in the municipality of Padova. To comprehensively evaluate the effectiveness of the spatial policy, the analysis follows a rigorous three-phase bottom-up architecture. Phase 1 quantifies the behavioral shifts and traffic redistribution across the QGIS spatial network. Phase 2 applies the EMEP/EEA Tier 3 mathematical engine to calculate the raw tailpipe mass emissions (g/hr) for each road segment. Finally, Phase 3 translates these localized mass emissions into atmospheric dispersion concentrations ($\mu\text{g}/\text{m}^3$) simulated through the AERMOD system.

4.3. Geospatial Network and Traffic Distribution

Before calculating the localized emission mass reductions, it was necessary to quantify the exact composition of the local vehicle fleet and how the Low Emission Zone (LEZ) redistributed these vehicles across the QGIS spatial network.

4.3.1. Baseline Fleet Characterization

As described in Chapter 3, to ensure high-fidelity spatial mapping, generic national averages were discarded in favor of localized 2023 vehicle registration data provided by the Automobile Club d'Italia (ACI) for the Province of Padova. To balance computational efficiency with the rigorous demands of the EMEP/EEA Tier 3 methodology, the fleet was systematically filtered and categorized. After excluding zero-tailpipe Battery Electric Vehicles (BEVs) from the exhaust calculation matrix, the baseline scenario (*Sc_Base*) active internal combustion fleet totaled 474,013 vehicles.

The baseline fleet was relatively balanced but leaned slightly toward spark-ignition engines. The "Petrol-Like Stream" (aggregating standard petrol, hybrid-petrol, CNG, and LPG vehicles, as these spark-ignition engines share similar thermal operating characteristics) constituted **54.2%** of the combustion fleet. The "Diesel-Like Stream" (standard diesel and hybrid-diesel) constituted the remaining **45.8%**.

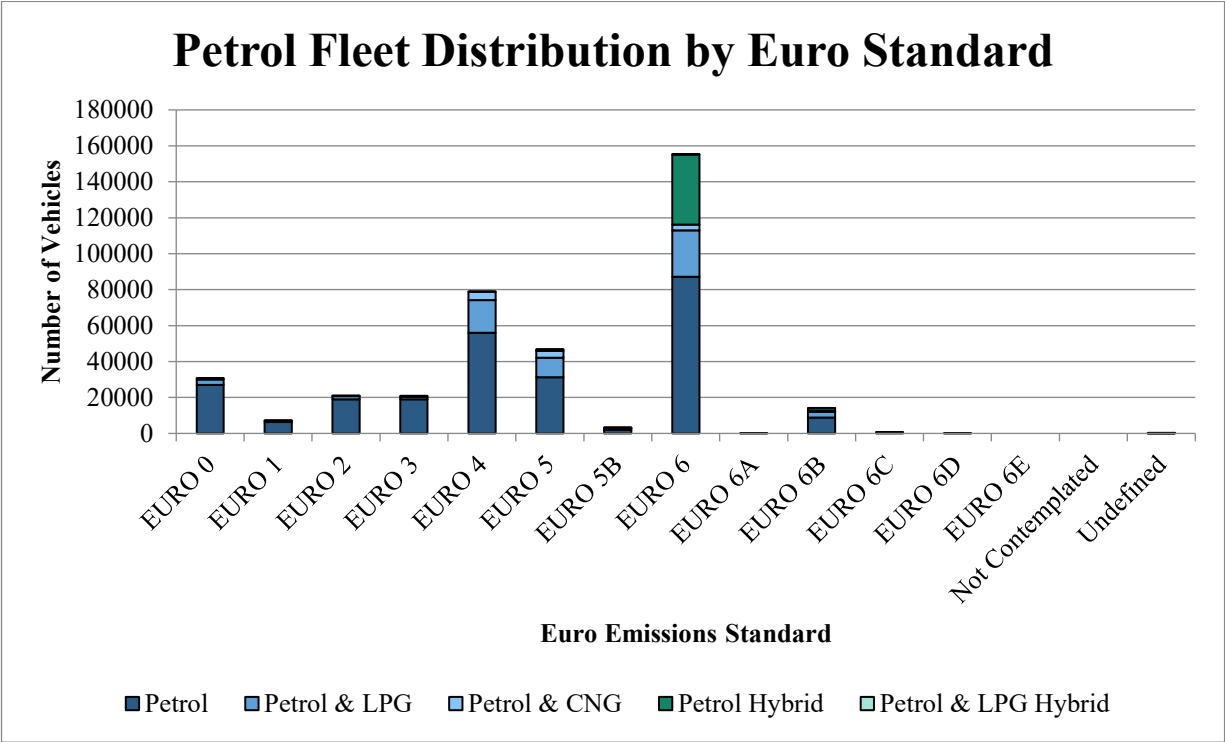


Figure 4 Baseline distribution of thePetrol- Like fleet across Euro standards.

As illustrated in the fleet distribution charts, modern Euro 6 vehicles numerically dominate both fuel categories. However, a critical statistical anomaly was observed in the local diesel stream: the highly efficient Euro 6d-Temp variants were virtually absent (comprising only ~9 out of over 230,000 diesel units). To prevent the model from underestimating real-world pollution, 100% of the modern Euro 6 diesel fleet was mathematically routed to the higher-emitting 'Euro 6 Old (a/b/c)' emission calculation algorithm, significantly impacting the baseline urban pollution levels. For the baseline scenario (Sc_Base), the traffic volume variable (V_1) on every road segment represents this standard, unadjusted local fleet mix.

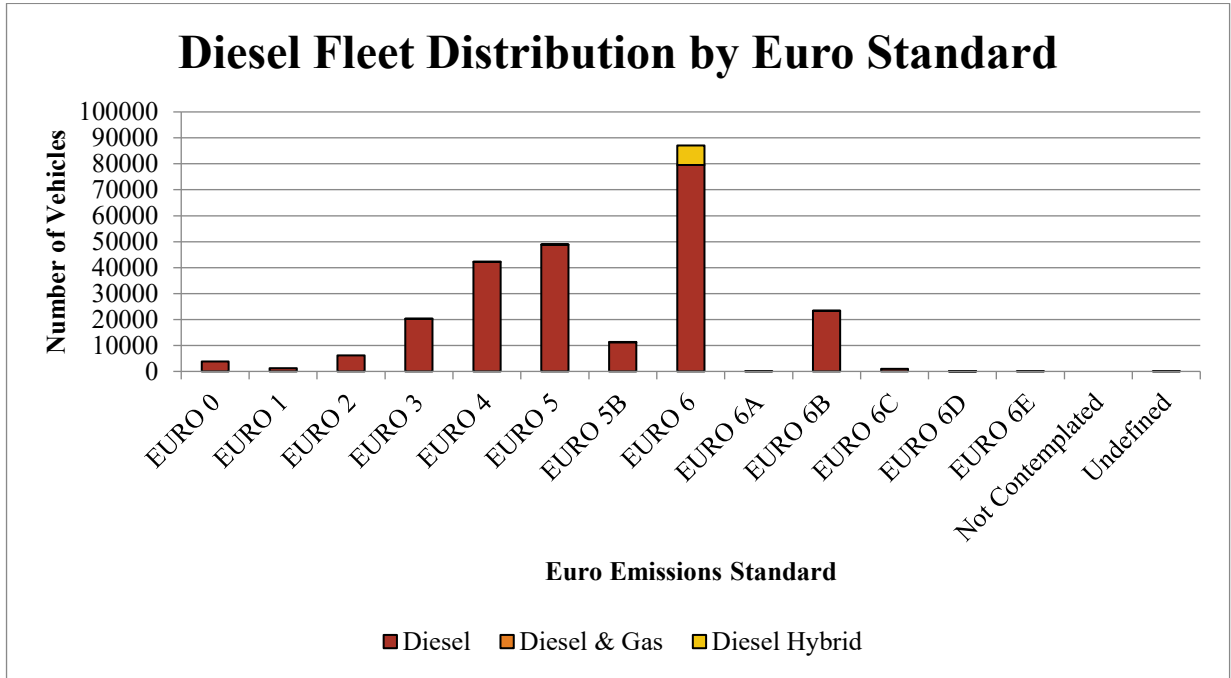


Figure 5 Baseline distribution of the Diesel-Like fleet across Euro standards.

4.3.2. LEZ Scenario Traffic Redistribution

To simulate the environmental impact of the Future LEZ Scenario (*Sc_Fut_7*), traffic flows were divided into three mutually exclusive operational streams: Unaffected (*V1*), Allowed inside the LEZ (*V2*), and Banned/Diverted from the LEZ (*V3*).

The redistribution matrix reveals the strict exclusionary nature of the simulated policy. Standard compression-ignition vehicles were entirely purged from the city center; Diesel Euro 0, Diesel Euro 5, and Diesel Euro 6 categories all show a 0.00% allowance in the *V2* stream, forcing massive percentages (up to 38.35% for Diesel Euro 6) into the banned *V3* routing. Similarly, older spark-ignition engines like Petrol Euro 0 were completely diverted. Consequently, the internal *V2_Allowed* fleet was exclusively concentrated among modern cleaner vehicles, primarily driven by Petrol Euro 6 (32.07%), Petrol Euro 4 (22.66%), and Hybrids (16.42%).

Table 3 Redistribution of baseline vehicle categories into: Unaffected, Allowed, & Banned.

Category	Total Count	V1 Unaffected	V2 Allowed	V3 Banned
Petrol Euro 0	26,958	4.25%	0.00%	9.95%
Petrol Euro 4	82,143	12.96%	22.66%	0.00%
Petrol Euro 6	116,281	18.35%	32.07%	0.00%
Diesel Euro 0	3,776	0.60%	0.00%	1.41%
Diesel Euro 5	60,208	9.50%	0.00%	22.22%
Diesel Euro 6	104,019	16.40%	0.00%	38.35%
Others (Hybrids)	59,532	9.41%	16.42%	0.00%

4.4.Tier 3 Mass Emission of road segment (COPERT)

4.4.1. Carbon Monoxide (CO) Mass Reductions

Network-wide CO emissions dropped by 27.43% under the Low Emission Zone (LEZ) scenario. In the baseline scenario, absolute values were heavily dominated by high-capacity corridors, such as the highway and the major roads surrounding the city, which locally exceeded 14,000 g/hr.

Map 1: Base CO Emissions (g/hr)



Figure 6 Base scenario Carbon Monoxide (CO) emissions (g/hr) across the Padova network

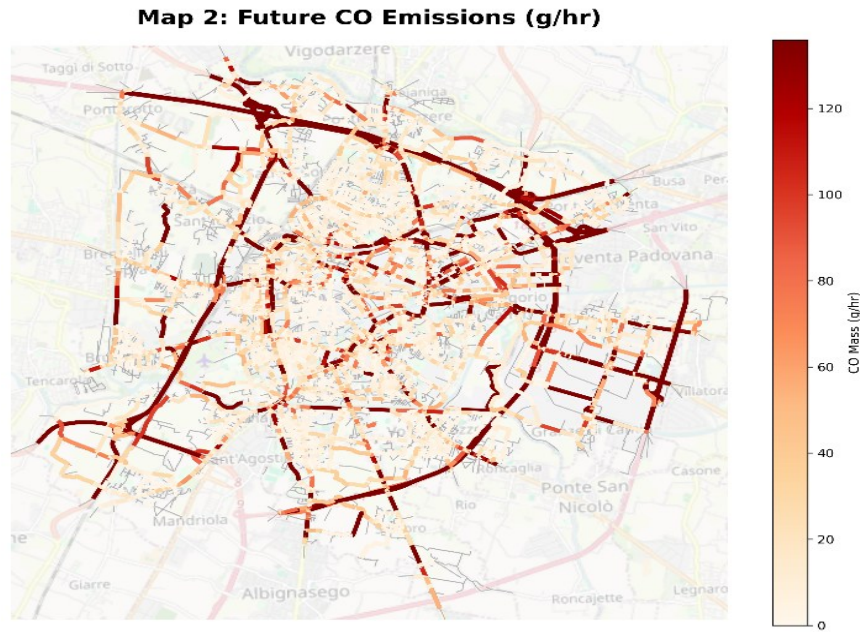


Figure 7 Future scenario Carbon Monoxide (CO) emissions (g/hr) following the LEZ implementation.

Comparing the baseline to the future scenario, the spatial mapping confirms that the LEZ successfully restricts older, higher-emitting passenger vehicles from entering the urban core. Consequently, the remaining absolute mass of CO stays highly concentrated on the periphery, as these exterior routes continue to serve heavy, unrestricted traffic flows. To precisely evaluate the localized impacts of this policy, the change in emissions across the network is calculated as a strict mathematical difference ($\Delta = \text{Future} - \text{Base}$). Under this standardized formulation, a negative value directly corresponds to an emission reduction, whereas a positive value corresponds to an emission increase. This ensures immediate clarity regarding the environmental benefit or penalty on any given road segment.

Map 3: Absolute CO Difference (g/hr)



Figure 8 Absolute difference in CO emissions (g/hr).

Negative values (purple, down to -176 g/hr) indicate emission reductions within the LEZ, while positive values (orange, up to +1 g/hr) indicate localized increases on alternative routes.

Map 4: Relative CO Difference (%)

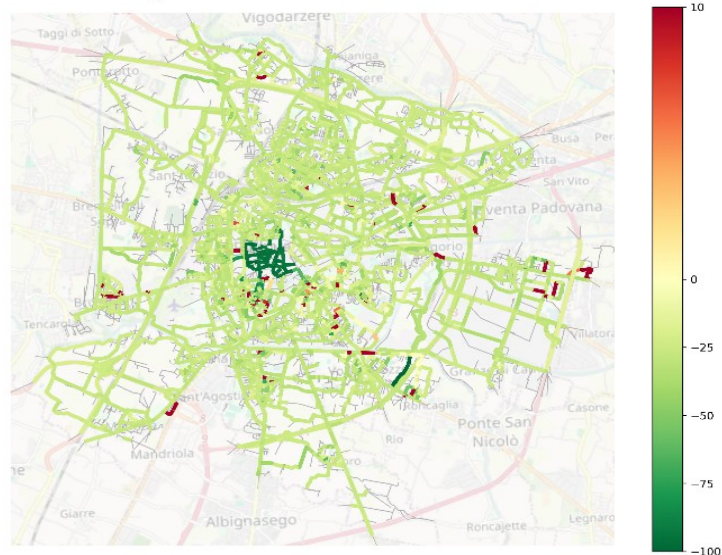


Figure 9 Relative difference in CO emissions (%).

Negative values (blue, peaking at -95%) represent efficiency gains, whereas positive values (red, up to +9%) highlight peripheral diversion penalties.

To maintain visual consistency and clarity, differing diverging colormaps were utilized: a purple-orange scale for absolute mass and a blue-red scale for relative percentages. The difference maps illustrate a clear spatial dichotomy resulting from the LEZ. The urban center exhibits pervasive environmental improvements, driven by the removal of the targeted fleet. Simultaneously, the minor positive values localized on the outer network validate the physical traffic routing model. These specific segments confirm that the restricted vehicles were actively diverted to the higher-capacity exterior corridors, successfully absorbing the displaced traffic with highly manageable, low-level emission increases.

4.4.2. Particulate Matter (PM) Mass Reductions

The LEZ policy is highly effective at mitigating particulate pollution, achieving an 83.69% network-wide reduction. In the baseline scenario, while emissions on individual inner-city links generally remain under 1.4 g/hr, the arterial roads and ring corridors exhibit the most significant PM loading due to heavy, unrestricted traffic flows.

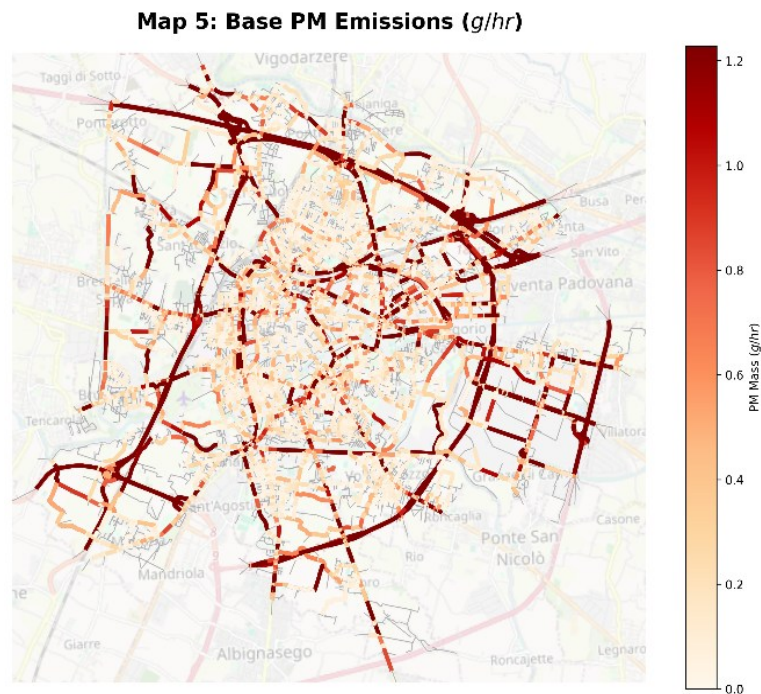


Figure 10 Base scenario Particulate Matter (PM) emissions (g/hr) across Padova network.

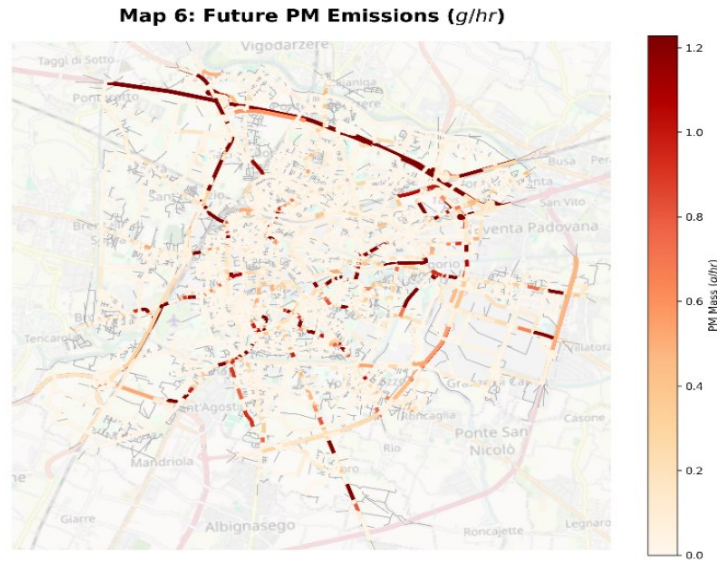


Figure 11 Future scenario Particulate Matter (PM) emissions (g/hr) following the LEZ implementation.

The Future scenario demonstrates targeted, intensive PM reductions within the LEZ boundary, successfully clearing the urban core of high-emitting vehicles. To scientifically quantify these localized impacts, the change in emissions is calculated as a direct mathematical difference ($\Delta = \text{Future} - \text{Base}$). Under this formulation, negative values indicate a drop in particulate mass, while positive values indicate localized emission penalties caused by traffic diversion.

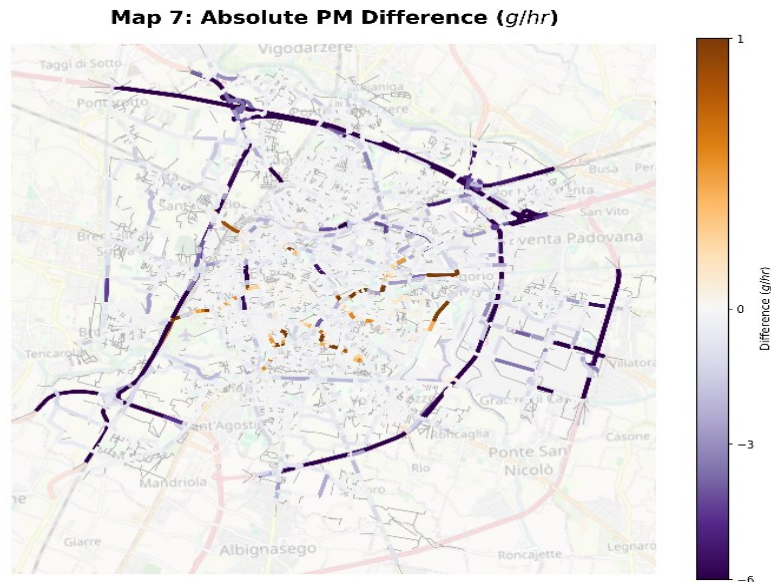


Figure 12 Absolute difference in PM emissions (g/hr).

Negative values (purple, down to -6 g/hr) indicate emission reductions within the LEZ, while positive values (orange, up to +1 g/hr) indicate isolated increases on alternative peripheral routes.

Map 8: Relative PM Difference (%)

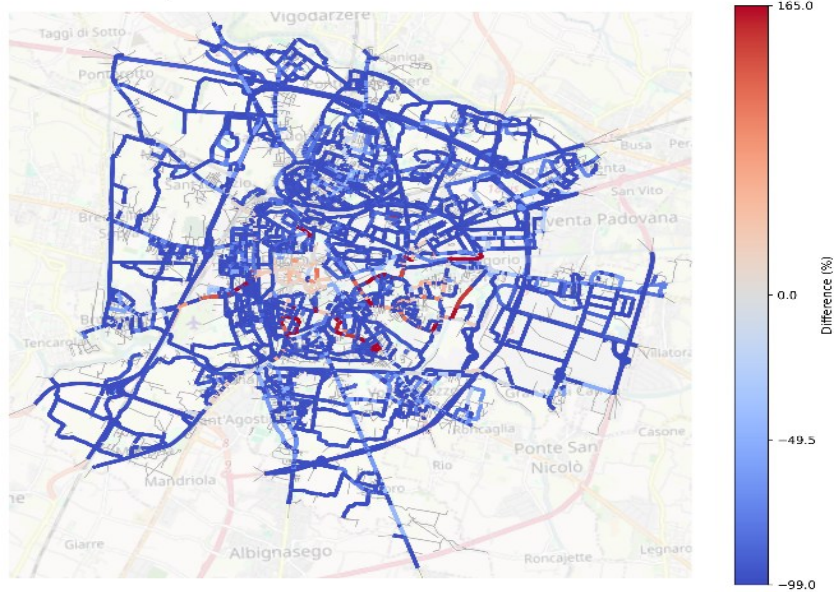


Figure 13 Relative difference in PM emissions (%).

Negative values (blue, peaking at -99%) represent maximum efficiency gains, whereas positive values (red, up to +165%) highlight relative diversion penalties on exterior roads.

The difference maps confirm that banning older vehicle tiers nearly eradicates PM emissions on restricted central links, driving local reductions as low as -6 g/hr (a -99% relative drop). To isolate these spatial patterns clearly, differing diverging colormaps were utilized: a purple-orange scale for absolute mass and a blue-red scale for relative percentages. While the relative percentage map shows distinct diversion penalties reaching +165% on specific outer ring roads, the absolute map confirms that the physical mass of this diverted pollution is highly diluted, capping at a maximum penalty of just +1 g/hr. This demonstrates that the high-capacity exterior network absorbs the displaced fleet with minimal absolute environmental degradation.

4.4.3. Nitrogen Oxides (NOx) Mass/ Reductions

Unlike Carbon Monoxide and Particulate Matter, the baseline emissions for Nitrogen Oxides (NOx) are heavily dominated by the high-capacity ring roads and arterial corridors, with localized emissions exceeding 40 g/hr.

Map 9: Base NOx Emissions (g/hr)



Figure 14 Base scenario Nitrogen Oxides (NOx) emissions (g/hr) across Padova network.

Map 10: Future NOx Emissions (g/hr)



Figure 15 Future scenario Nitrogen Oxides (NOx) emissions (g/hr) following LEZ implementation.

Visually, the Base and Future scenarios appear nearly identical on the macro scale. This occurs because the LEZ primarily targets older passenger vehicles, while NOx emissions are disproportionately driven by Heavy Goods Vehicles (HGVs), commercial transit, and high-speed combustion—classes that remain largely unrestricted on the primary network.

Map 12: Relative NOx Difference (%)

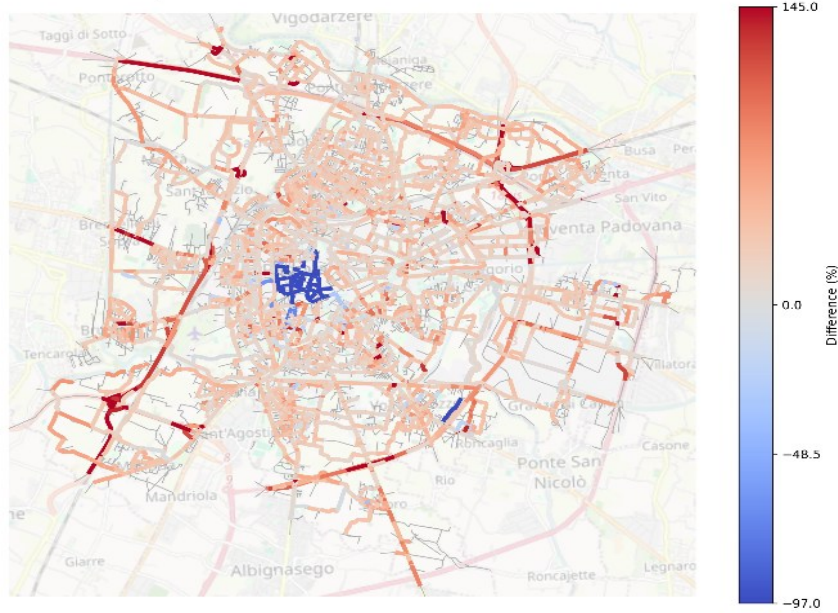


Figure 17 Relative difference in NOx emissions (%).

Negative values (blue, down to -97.0%) highlight highly localized central drops, whereas positive values (red, up to +145.0%) dominate the exterior network.

This severe spatial penalty is a direct result of traffic physics: NOx emissions scale aggressively with engine load, speed, and distance traveled. By forcing the targeted passenger fleet to detour around the urban core via higher-speed, longer-distance ring roads, the LEZ inadvertently triggered a massive localized spike in NOx generation. These results demonstrate that while the LEZ successfully mitigates CO and PM within the historic center, a passenger-targeted routing policy fundamentally exacerbates NOx pollution on the urban periphery.

Table 4 Total Network Emissions by Scenario

Pollutant	Base Scenario (g/hr)	Future Scenario (g/hr)	Absolute Diff. (g/hr)	Relative Diff (%)
PM	4,579.89	747.09	-3,832.80	-83.69%
CO	546,160.86	396,326.69	-149,834.17	-27.43%
NOx	130,008.67	188,573.75	+58,565.09	+45.05%

Table 4 summarizes the aggregate network-wide emissions for both the Base and Future scenarios. The implementation of the LEZ yields a divergent environmental impact across the urban network. While the policy successfully mitigates total network Particulate Matter (PM)

and Carbon Monoxide (CO) by relative differences of -83.69% and -27.43% respectively, total network Nitrogen Oxides (NOx) emissions increased substantially, showing a positive difference of +45.05%. This highlights the complex tradeoffs inherent in urban traffic rerouting, where localized inner-city improvements may inadvertently increase the total atmospheric loading of specific pollutants along peripheral, higher-speed corridors.

4.5.AERMOD Atmospheric Dispersion Concentrations of the road segment

While the Tier 3 calculations confirm significant mass reductions within the LEZ, atmospheric dispersion modeling via AERMOD is required to evaluate the final ambient air quality ($\mu\text{g}/\text{m}^3$) experienced at the 1.8-meter human breathing height. The summary statistics extracted directly from the dispersion engine confirm the spatial impacts visualized in the high-resolution QGIS heatmaps.

4.5.1. CO Dispersion Contours

The Carbon Monoxide (CO) dispersion contours demonstrate a highly successful and uniform environmental improvement. In the Base Scenario, CO accumulation is heavily concentrated along high-capacity corridors, with a network mean of $10.951\mu\text{g}/\text{m}^3$ and an absolute peak of $432.679\mu\text{g}/\text{m}^3$. Following the implementation of the LEZ and the strict purging of older Euro 0 and Euro 1 spark-ignition engines, the atmospheric clearing is profound. The Future Scenario visualizes a heavily diluted footprint, which is statistically backed by the dispersion engine showing the absolute maximum dropping to $300.673\mu\text{g}/\text{m}^3$ and the mean dropping to $7.951\mu\text{g}/\text{m}^3$. Utilizing a unified sequential scale for both absolute concentration maps confirms the network-wide recession of high-pollution zones from dark red to lower-concentration orange and yellow thresholds.

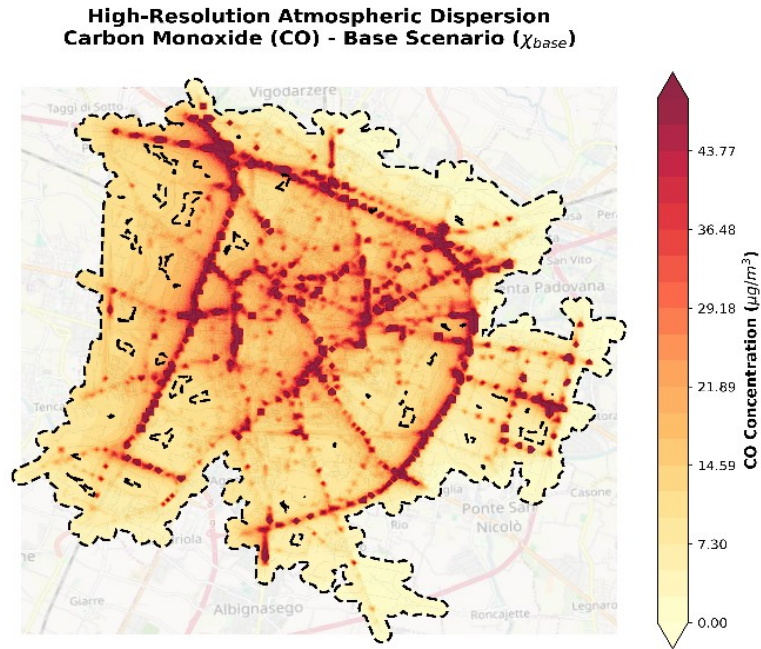


Figure 18 High-Resolution Atmospheric Dispersion of CO ($\mu\text{g}/\text{m}^3$) for the Base Scenarios.

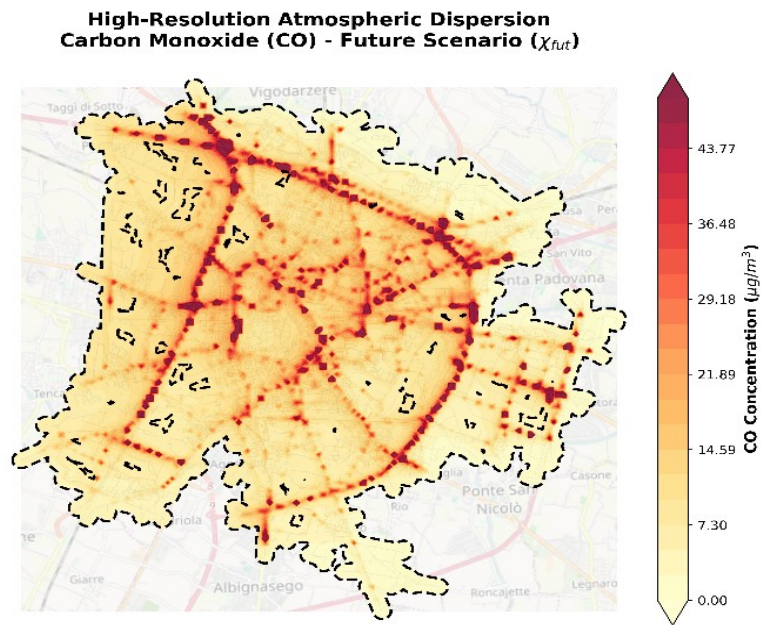


Figure 19 High-Resolution Atmospheric Dispersion of CO ($\mu\text{g}/\text{m}^3$) for the Future Scenarios.

To explicitly evaluate both the physical mass mitigated and the proportional efficiency of the policy, the dispersion changes are quantified through Absolute Difference and Relative Percentage Difference maps. The Absolute Difference map illustrates the precise raw mass of CO removed from the 1.8-meter human breathing height. The deepest negative gradients strictly

trace the primary arterial roads, reflecting where the highest sheer volume of CO was eliminated (achieving localized absolute differences approaching $-24.00 \mu\text{g}/\text{m}^3$). Conversely, the peripheral edges and suburban zones, which exhibited minimal baseline pollution, register near-zero absolute changes.

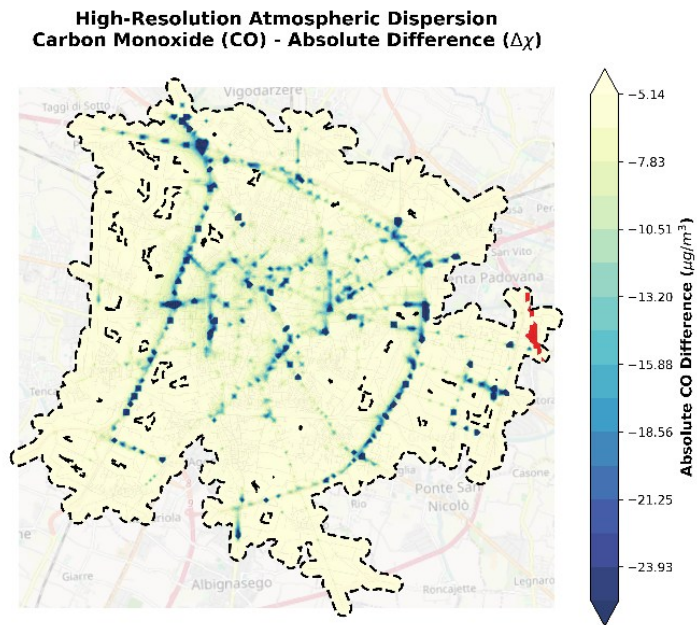


Figure 20 High-Resolution Atmospheric Dispersion of CO - Absolute Difference $\mu\text{g}/\text{m}^3$

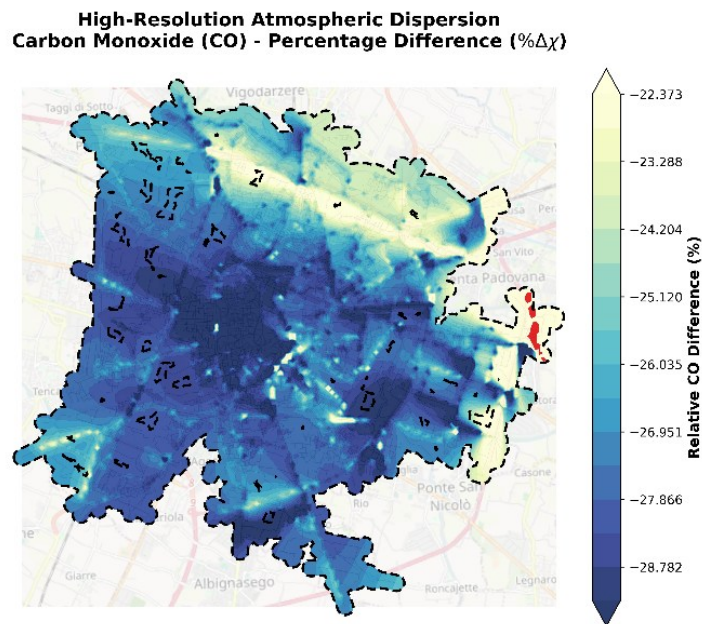


Figure 21 High-Resolution Atmospheric Dispersion of CO - Absolute Difference $\mu\text{g}/\text{m}^3$ and Relative Percentage Difference (%).

The High-Contrast Percentage Difference map illustrates widespread ambient air quality improvement, yielding a mean overall CO reduction of 26.57% across the entire simulation grid. By constraining the visual scale strictly to the core reduction cluster (between -22.3% and -28.7%), intricate street-level gradients become visible, proving the policy's structural efficacy within the historical center. However, mapping the relative and absolute differences explicitly captures the spatial penalties associated with LEZ traffic rerouting. While the urban core experienced significant uniform improvement, isolated receptors on the eastern peripheral boundary registered localized concentration spikes (highlighted in high-contrast red). These warning zones structurally confirm that while the LEZ successfully removes CO from the protected center, it displaces a minor fraction of the combustion burden onto the surrounding bypass routes utilized by the diverted fleet.

4.5.2. PM Dispersion Contours

The atmospheric dispersion modeling for Particulate Matter (PM) visually confirms the most profound environmental success of the simulated Low Emission Zone. In the Base Scenario, severe PM accumulation traces the primary arterial corridors and central street canyons, with a mean concentration of $0.091 \mu\text{g}/\text{m}^3$ and an absolute peak reaching $2.354 \mu\text{g}/\text{m}^3$. Following the implementation of the LEZ, the Future Scenario heatmap illustrates a near-total eradication of these micro-particle hotspots. Strictly banning older compression-ignition (diesel) engines drastically reduced atmospheric loading, plummeting the network mean concentration to just $0.015 \mu\text{g}/\text{m}^3$. Utilizing a unified sequential scale (Purple-Red) for both absolute concentration maps confirms the network-wide recession of high-pollution zones, effectively clearing the highly turbulent urban street canyons of accumulating sub-micron particles.

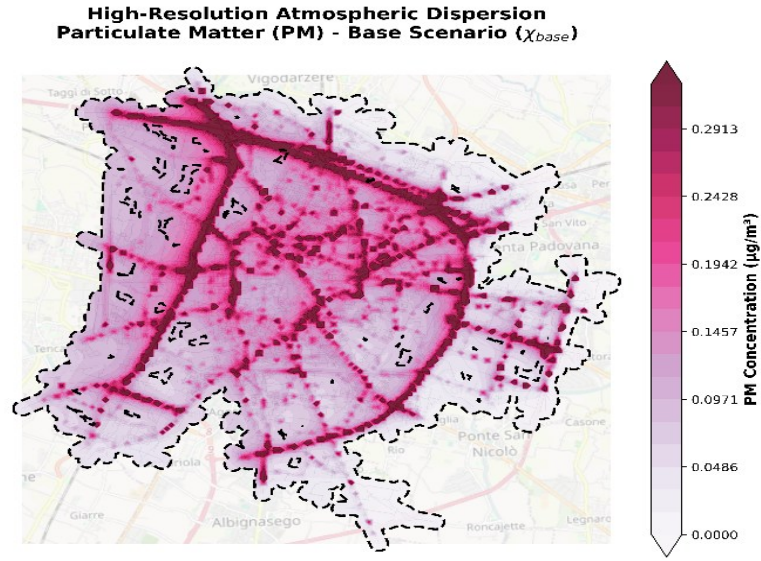


Figure 22 High-Resolution Atmospheric Dispersion of PM ($\mu\text{g}/\text{m}^3$) for the Base Scenarios,

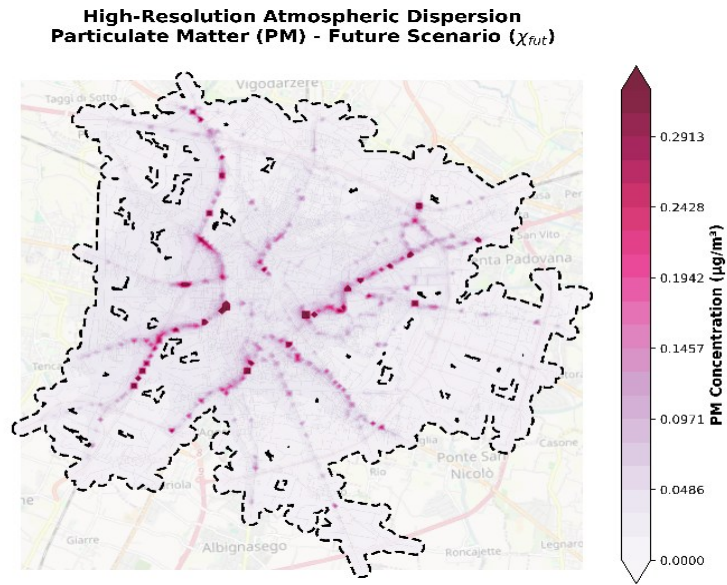


Figure 23 High-Resolution Atmospheric Dispersion of PM ($\mu\text{g}/\text{m}^3$) for the Future Scenarios, showing the near-total eradication of hotspots.

To explicitly evaluate both the physical mass mitigated and the proportional efficiency of the policy, the dispersion changes are quantified through Absolute Difference and Relative Percentage Difference maps. The Absolute Change map illustrates the precise raw mass of PM removed from the ambient environment. The deepest negative blue gradients strictly trace the primary arterial roads, reflecting where the highest sheer volume of PM was eliminated (achieving localized absolute reductions of up to $0.23 \mu\text{g}/\text{m}^3$).

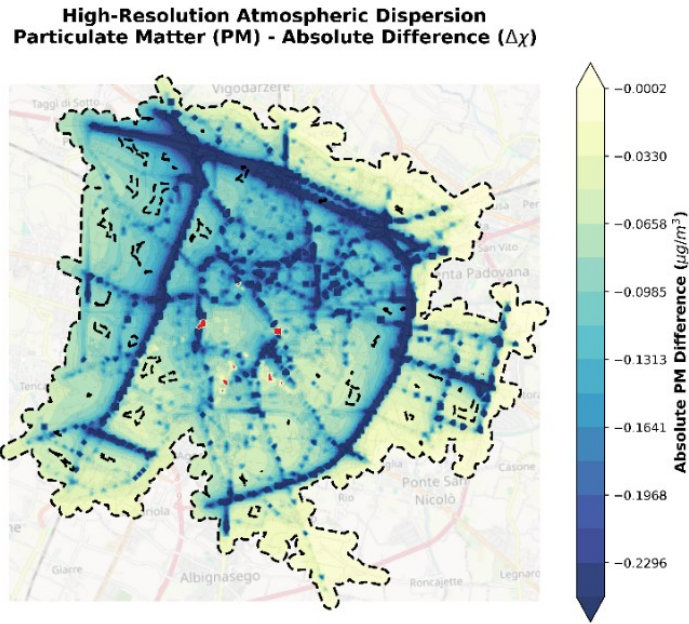


Figure 24 High-Resolution Atmospheric Dispersion of PM - Absolute Difference ($\mu\text{g}/\text{m}^3$)

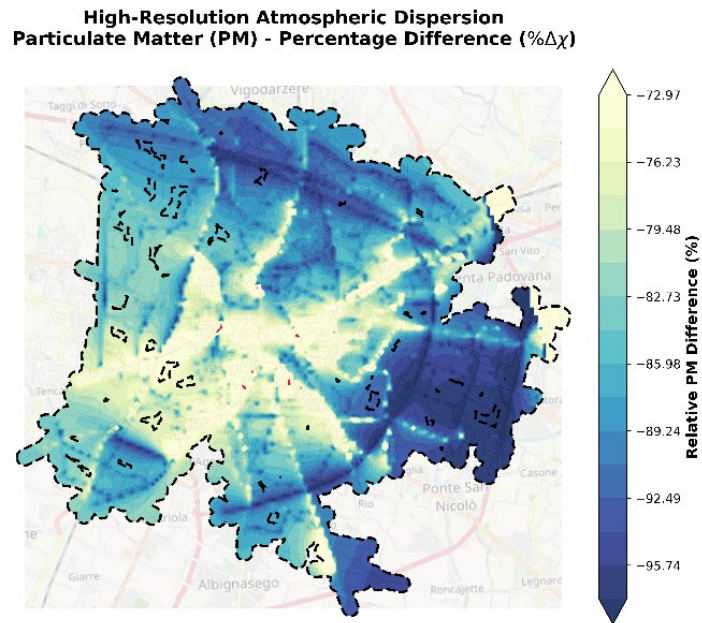


Figure 25 High-Resolution Atmospheric Dispersion of PM Relative Percentage Difference.

The High-Contrast Percentage Difference map quantifies this extraordinary clearing, showing massive geographic swathes achieving up to a 100% relative reduction, with a network-wide mean reduction of 85.48%. By constraining the visual scale strictly to the core reduction cluster (between -72.97% and -95.74%), the comprehensive nature of the policy becomes evident. Unlike the peripheral displacement penalty observed with other pollutants, the PM dispersion

contours prove that the LEZ triggered a network-wide 'halo' effect. While a few isolated boundary receptors register mathematically negligible increases due to traffic displacement (highlighted in red), the overwhelming structural reality is a massive, network-wide environmental mitigation of particulate matter.

4.5.3. NO_x Dispersion Contours

The atmospheric dispersion modeling for Nitrogen Oxides NO_x exposes the fundamental spatial and physical trade-offs inherent to Low Emission Zone implementation. Unlike the widespread network improvements observed for Carbon Monoxide and Particulate Matter, NO_x exhibits a pronounced redistribution pattern driven by traffic displacement dynamics.

In the Base Scenario, high ground-level concentrations strictly trace the primary radial corridors and arterial ring roads, reflecting the dominance of heavy commercial and diesel passenger traffic. The receptor grid records a baseline mean concentration of 2.593 $\mu\text{g}/\text{m}^3$. In the Future Scenario, the network-wide mean concentration marginally increases to 2.608 $\mu\text{g}/\text{m}^3$. Evaluating both absolute scenarios under a unified sequential scale (0.00 to 11.60 $\mu\text{g}/\text{m}^3$) confirms that while the overall background pollution mass remains relatively stable, the internal spatial structure of emissions undergoes a major transformation.

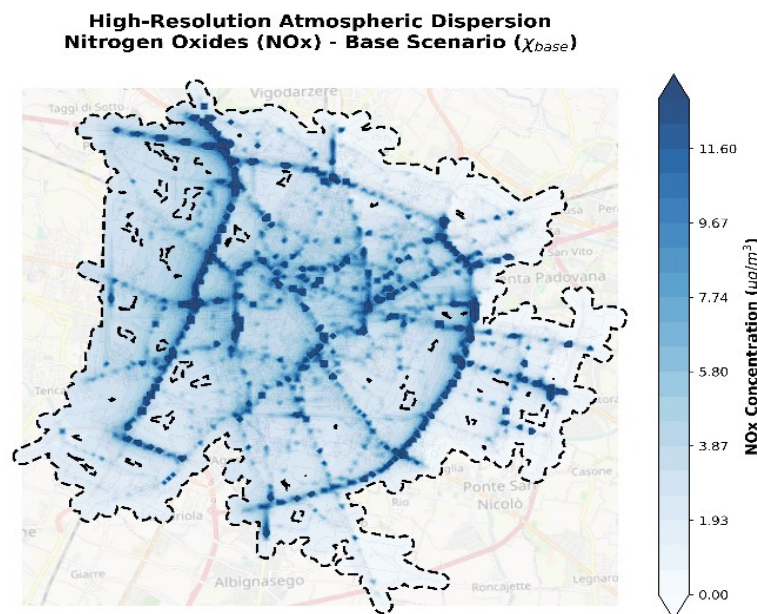


Figure 26 High-Resolution Atmospheric Dispersion of (NO_x) $\mu\text{g}/\text{m}^3$ for the Base Scenario

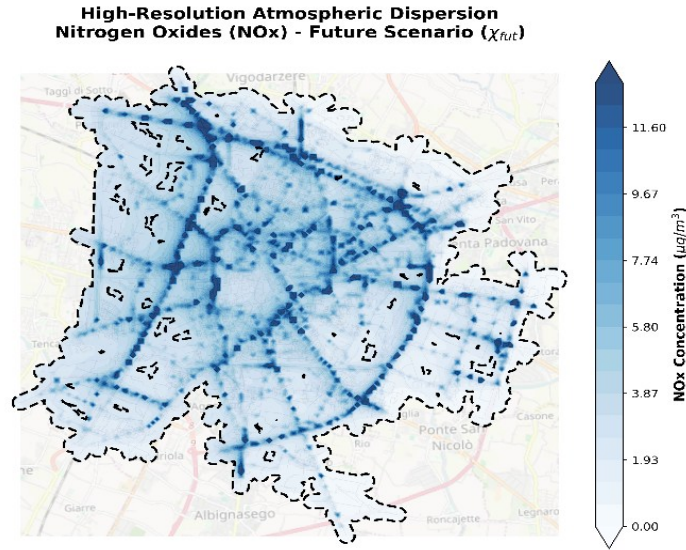


Figure 27 High-Resolution Atmospheric Dispersion of (NO_x) $\mu\text{g}/\text{m}^3$ for Future Scenario.

To rigorously isolate the spatial impact of the policy, dispersion shifts are quantified via the Absolute Difference and Relative Percentage Difference maps using a diverging color gradient anchored strictly at zero (0.00).

The Absolute Difference map isolates the physical mass shifts at human breathing height (1.8m). Within the central LEZ boundary, the restriction of non-compliant diesel passenger vehicles produces distinct improvements. While the absolute mass reduction at the link level is modest (approximately -1.0g/hr), the localized absolute dispersion difference achieves maximum drops of $-45.18\mu\text{g}/\text{m}^3$ directly on restricted central corridors (captured visually in the deep blue scale below $-4.00\mu\text{g}/\text{m}^3$). Conversely, 72.92% of simulation receptors register net increases. Displaced traffic circulates onto the bypass corridors and outer ring roads, generating massive diversion penalties. Link-level emissions surge by up to +34.0g/hr on the periphery, translating to absolute dispersion additions that peak at $+26.26\mu\text{g}/\text{m}^3$.

**High-Resolution Atmospheric Dispersion
Nitrogen Oxides (NO_x) - Absolute Difference ($\Delta\chi$)**

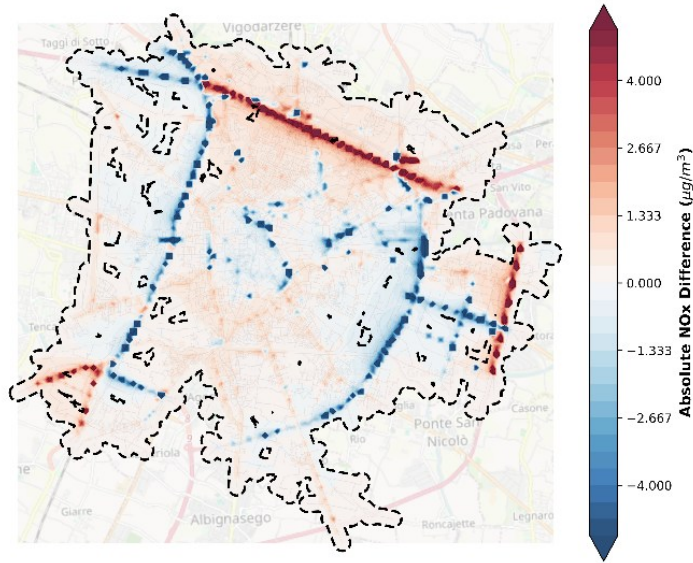


Figure 28 High-Resolution Atmospheric Dispersion of (NO_x) Absolute Difference ($\mu\text{g}/\text{m}^3$)

**High-Resolution Atmospheric Dispersion
Nitrogen Oxides (NO_x) - Relative Percentage Difference ($\%\Delta\chi$)**

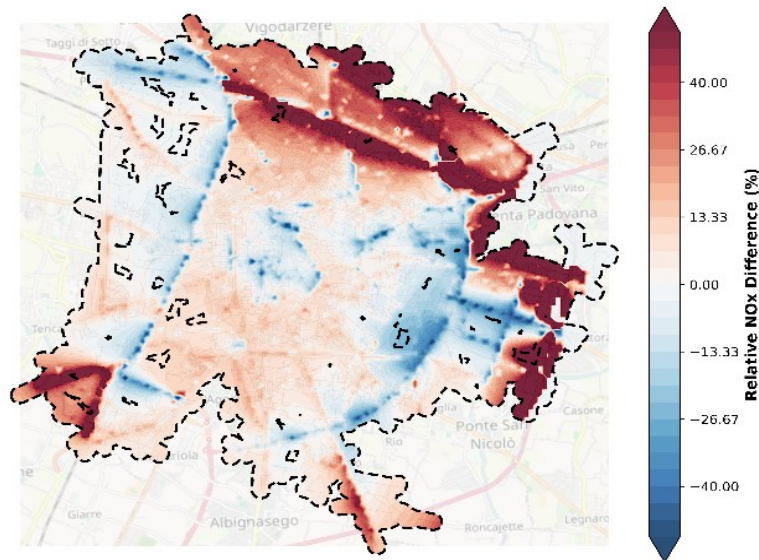


Figure 29 High-Resolution Atmospheric Dispersion of (NO_x) Relative Percentage Difference (%).

The Relative Percentage Difference map confirms this systemic trade-off. In the urban core, the LEZ delivers relative emission improvements of up to -97.0%, yielding localized dispersion concentration differences down to -72.89%. However, the peripheral corridors bear the severe burden of the diverted circulation. Because displaced internal combustion vehicles travel longer detour distances at higher constant cruising speeds, engine load and unit emissions increase

significantly along outer bypasses. Consequently, the peripheral ring system experiences relative emission surges up to +145.0%, which saturate the visual scale of the dispersion map (solid red zones exceeding +40.00%).

This spatial divergence highlights a critical environmental engineering insight for the Padova domain: while passenger-targeted LEZ measures successfully clear micro-particulates (PM) and Carbon Monoxide (CO) from the historical center, they inadvertently penalize the urban periphery by displacing and intensifying NO loading along external residential and transit bypasses.

5. CONCLUSIONS AND POLICY RECOMMENDATIONS

5.1. Overall Policy Effectiveness

The implementation of the hypothetical Low Emission Zone (LEZ) in the municipality of Padova yields a highly complex and divergent environmental outcome. The fundamental conclusion of this spatial and mathematical simulation is that highly localized urban traffic policies involve significant environmental tradeoffs, successfully mitigating certain localized pollutants while inadvertently exacerbating total atmospheric loading elsewhere.

Effectiveness in Mitigating Particulate Matter and Carbon Monoxide The policy was unequivocally successful in mitigating Particulate Matter (PM) and Carbon Monoxide (CO). The network-wide mass of PM dropped by a massive 83.69% (yielding an absolute negative difference of 3,832.80 g/hr), and CO decreased by 27.43%. As established in the fleet redistribution matrix, the LEZ strictly banned all Euro 0 spark-ignition vehicles and all standard diesel engines from the central urban core. By purging these high-emitting older vehicles and compression-ignition engines from the center, the policy effectively cleaned the historic urban core and restricted CO and PM accumulations strictly to the periphery.

The NO_x Penalty and Traffic Displacement Effect

However, the critical anomaly discovered in this study is the severe spatial penalty regarding Nitrogen Oxides (NO_x). Despite the inner-city improvements, total network NO_x emissions actually increased by 45.05%, adding an absolute mass of 58,565.09 g/hr to the urban network.

This severe NO_x penalty is directly tied to the physical traffic rerouting of the banned V3 fleet and the structural realities of the local vehicle registry. Because standard diesels represent a massive 45.8% of the local combustion fleet, assigning them a 0.00% allowance inside the LEZ forced enormous volumes of diesel vehicles into peripheral detour routings. As this displaced, diesel-heavy fleet was pushed onto longer peripheral arterial networks to bypass the center, their travel distances increased. Furthermore, the higher speeds and sustained engine loads required on these arterial corridors trigger massive, exponential NO_x emission spikes, as defined by the EMEP/EEA Tier 3 mathematical formulas.

5.2.Limitation of the study

The scope of this environmental inventory is strictly limited to passenger cars moving on the projected geographic road network within and directly adjacent to the proposed Padova LEZ boundary. This scenario study does not consider heavy-duty vehicles, commercial cargo trucks, and two-wheelers. The simulated LEZ intervention is based on a stringent hypothetical framework wherein access is restricted exclusively to zero-emission vehicles, hybrid technologies, and advanced Euro-standard spark-ignition engines (Euro 2 through 6), effectively banning all standard compression-ignition (diesel) engines from the inner cordon. Emission calculations are mathematically constrained to the boundaries of the EEA Tier 3 guidebook parameters, focusing exclusively on direct tailpipe exhaust. Finally, due to the absence of a fully equipped on-site meteorological tower within Padova's immediate historic center, atmospheric dispersion physics are driven by surface and upper-air data systematically assimilated and validated from the closest monitoring station (Venezia Tesserà).

5.3.Final Conclusions and Policy Recommendations

Ultimately, the simulation confirms a significant "spillover effect": the LEZ successfully protects the central population from PM and CO exposure, but it drastically displaces and magnifies the NO_x burden onto the peripheral road network and surrounding communities. The data proves that localized LEZs, without comprehensive regional fleet upgrades, can inadvertently increase the total urban NO_x burden.

To optimize future urban mobility policies and mitigate this peripheral penalty, the following interventions are recommended based on the data:

- **Comprehensive Fleet Modernization:** Because merely diverting "dirty" vehicles around a central zone displaces rather than eliminates pollution, regional policies must prioritize permanent fleet modernization. Specifically, transitioning the local diesel fleet away from the highly-emitting 'Euro 6 Old (a/b/c)' profiles is required to lower the baseline network NO_x.
- **Peripheral Interception Infrastructure:** To prevent the massive NO_x spikes caused by the V3 fleet driving extended detours, the municipality must intercept these vehicles

before they circulate the periphery. Establishing robust Park-and-Ride facilities outside the city limits would eliminate the extended combustion-heavy detours entirely.

- **Phased Implementation Strategies:** Banning 100% of standard diesels (including modern Euro 6 models) immediately created a drastic traffic shock. A phased or tiered implementation could prevent sudden peripheral congestion and the resulting NOx spikes while the local fleet naturally modernizes.

6. REFERENCES

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Table 5 CO Emission Coefficients for Spark-Ignition (Petrol) Engines

Euro Standard	Alpha (α)	Beta (β)	Gamma (γ)	Delta (δ)	Epsilon (ϵ)	Zeta (ζ)	Eta (η)
Euro 0	0.000007	-0.000786	-0.01681	4.962271	0.000001	-0.000228	0.016879
Euro 1	0.000029	-0.002770	0.13400	2.550000	0.000023	-0.002820	0.094000
Euro 2	0.000020	-0.001640	0.08250	0.000000	0.000023	-0.002820	0.094000
Euro 3	0.000000	-0.000133	0.01783	0.768600	0.000257	-0.038140	1.838000
Euro 4	0.000000	-0.000329	0.05109	0.000000	0.000181	-0.052780	3.750000
Euro 5	0.000000	-0.000212	0.04616	0.000000	0.000030	-0.009770	1.058000
Euro 6	0.000000	-0.000212	0.04616	0.000000	0.000030	-0.009770	1.058000

Table 6 CO Emission Coefficients for Compression-Ignition (Diesel) Engines

Euro Standard	Alpha (α)	Beta (β)	Gamma (γ)	Delta (δ)	Epsilon (ϵ)	Zeta (ζ)	Eta (η)
Euro 0	0.000000	0.040000	1.55000	3.720000	0.000000	0.080000	0.730000
Euro 1	0.000000	-0.030000	1.53000	0.000000	0.000000	0.000000	1.540000
Euro 2	0.000000	-0.030000	1.57000	0.000000	0.000000	0.000000	1.750000
Euro 3	0.000000	0.000000	0.26000	1.680000	0.000000	0.000000	1.530000
Euro 4	0.000000	-0.010000	1.00000	0.880000	0.000000	0.040000	2.880000
Euro 5	0.000000	0.210000	-0.74000	0.720000	0.030000	1.510000	0.000000
Euro 6	0.000000	0.210000	-0.74000	0.720000	0.030000	1.510000	0.000000

Table 7 NO_x Emission Coefficients for Spark-Ignition (Petrol) Engines

Euro Standard	Alpha (α)	Beta (β)	Gamma (γ)	Delta (δ)	Epsilon (ϵ)	Zeta (ζ)	Eta (η)
Euro 0	0.008736	1.534685	175.190196	9.428662e-13	-1.777507e-16	6.870565e-14	118.052693
Euro 1	0.000545	-0.058221	3.055056	-3.245593e-12	-6.535298e-16	7.621797e-14	5.822050
Euro 2	0.000383	-0.029202	0.952859	-3.491486e-10	0.001489	-0.078634	3.360416
Euro 3	0.000018	-0.004181	0.260843	6.562127e-12	0.000111	-0.034237	2.806281
Euro 4	0.000039	-0.008580	0.577346	1.306531e-12	2.701764e-17	-1.307669e-13	5.430520
Euro 5	-0.000315	0.103057	0.239057	-0.339279	0.034536	1.986013	1.263763
Euro 6	-0.000315	0.103057	0.239057	-0.339279	0.034536	1.986013	1.263763

Table 8 NO_x Emission Coefficients for Compression-Ignition (Diesel) Engines

Euro Standard	Alpha (α)	Beta (β)	Gamma (γ)	Delta (δ)	Epsilon (ϵ)	Zeta (ζ)	Eta (η)
Euro 0	0.000356	-0.049357	3.236414	8.291176e-11	4.577175e-16	-3.821760e-13	3.525506
Euro 1	0.000436	-0.006387	3.199254	5.434279e-12	-0.000520	0.145920	1.033482
Euro 2	0.000129	-0.012481	2.580261	3.957738e-11	-0.000538	0.082526	1.075962
Euro 3	-0.000770	0.111214	4.681975	1.151747e-09	-0.002377	0.329466	1.662394
Euro 4	0.000562	-0.076397	4.198823	6.248237e-10	4.612732e-15	-2.028038e-12	3.789552
Euro 5	0.000067	-0.011381	0.945952	1.923608	-0.000052	0.004264	1.000000
Euro 6	0.000067	-0.011381	0.945952	1.923608	-0.000052	0.004264	1.000000

Table 9 PM Emission Coefficients for Spark-Ignition (Petrol) Engines

Euro Standard	Alpha (α)	Beta (β)	Gamma (γ)	Delta (δ)	Epsilon (ϵ)	Zeta (ζ)	Eta (η)
Euro 0	0.000000	0.000000	0.003220	0.000000	0.000000	0.000000	1.000000
Euro 1	0.000000	0.000000	0.003220	0.000000	0.000000	0.000000	1.000000
Euro 2	0.000000	0.000000	0.003220	0.000000	0.000000	0.000000	1.000000
Euro 3	0.000000	0.000000	0.003220	0.000000	0.000000	0.000000	1.000000
Euro 4	0.000000	0.000000	0.003220	0.000000	0.000000	0.000000	1.000000
Euro 5	0.000000	0.000000	0.003220	0.000000	0.000000	0.000000	1.000000
Euro 6	0.000000	0.000000	0.003220	0.000000	0.000000	0.000000	1.000000

Table 10 PM Emission Coefficients for Compression-Ignition (Diesel) Engines

Euro Standard	Alpha (α)	Beta (β)	Gamma (γ)	Delta (δ)	Epsilon (ϵ)	Zeta (ζ)	Eta (η)
Euro 0	0.000174	- 0.025788	1.349384	-8.06966e-11	-7.769945e-15	9.348105e-13	2.998632
Euro 1	0.000084	- 0.008631	0.421547	1.098764e-12	-1.935170e-16	-5.987903e-15	3.704366
Euro 2	0.000074	- 0.009853	0.600890	-9.250021e-10	-8.712523e-13	8.035582e-11	6.938688
Euro 3	0.000050	- 0.005456	0.319281	-1.299964e-13	-3.073184e-16	2.970830e-14	6.199639
Euro 4	0.000012	- 0.001816	0.151591	2.443046e-14	-4.454560e-18	-3.279648e-15	3.368699
Euro 5	0.000000	0.000000	0.000137	0.000000	0.000000	0.000000	1.000000
Euro 6	0.000000	0.000000	0.000142	0.000000	0.000000	0.000000	1.000000