

Municipal Data for Air Quality Policy

A Health–Economic Framework from Emilia-Romagna

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Outline

- 1 Motivation and Contribution
- 2 Data Architecture
- 3 Methods
- 4 Results
- 5 Decision Support and ASA Theme
- 6 Conclusions

Why municipal data matter for air-quality policy

- ▶ Air-quality policy requires evidence connecting **exposure, population, mortality and welfare consequences** .
- ▶ The relevant information already exists, but it is produced by different institutions under different territorial units, coding systems, access regimes and reference periods.
- ▶ Aggregate regional indicators can conceal substantial **within-region heterogeneity** in exposure and health burden.
- ▶ Municipal evidence is therefore useful for locating preventable damage and supporting territorial prioritisation.

Core question

How can fragmented public-sector data be transformed into **spatially granular, reproducible and reusable municipal evidence** for air-quality policy?

Research objectives and contribution

Three objectives

- 1 Build a documented workflow linking municipal exposure, population, mortality and economic data.
- 2 Estimate mortality that could have been avoided if annual concentrations had met the **2021 WHO Air Quality Guideline values**.
- 3 Translate pollutant-specific health impacts into **VSL- and VOLY-based welfare measures**.

What the paper adds

- ▶ 330 harmonised municipalities.
- ▶ 2016–2023 municipality-year structure.
- ▶ Municipal granularity preserved from inputs to outputs.
- ▶ Regional totals produced only after municipal calculations.
- ▶ Reusable for ex-post monitoring and ex-ante scenarios.

Main novelty

The contribution is **methodological and operational rather than epidemiological** : established concentration–response and valuation methods are embedded in a transparent municipal administrative-data architecture.

Research gap and paper aim

Dimension	Typical approach	This paper
Health-impact assessment	National, regional or city-level applications	Municipality-level implementation across Emilia-Romagna
Economic valuation	Aggregate VSL/VOLY estimates	Dynamic regional calibration with municipal health impacts
Policy relevance	Limited territorial targeting	Spatially explicit avoidable mortality and welfare evidence
Data integration	Institutional sources analysed separately	Bottom-up integration with stable municipal identifiers

Aim

Build a **policy-oriented municipal framework** that converts fragmented administrative data into health and welfare indicators for air-quality policymaking.

Integrated administrative-data architecture

Component	Source	Municipal input and analytical role
Exposure	ARPAE + NINFA	Annual population-weighted PM ₁₀ , PM _{2.5} and NO ₂ concentrations
Population	ISTAT	Residents aged 30+ and municipality-year denominators
Mortality	ISTAT Causes of Death	Natural-cause mortality, ICD-10 A00–R99, municipality-year baseline rates
Economic calibration	ISTAT + Eurostat	GDP per capita, PPS and inflation for VSL/VOLY transfer
Analytical module	WHO AirQ+	Counterfactual exposure, RR, avoidable mortality, YLL and valuation

Bottom-up design

Each calculation is performed at municipal level.

Regional aggregates are a **reporting step**, not the original analytical scale.

FAIR orientation and interoperability

Findable and Accessible

- ▶ documented institutional provenance;
- ▶ stable municipal identifiers;
- ▶ public or controlled-access procedures appropriate to each source.

Interoperable and Reusable

- ▶ common territorial codes and annual reference periods;
- ▶ consistent population denominators;
- ▶ transparent assumptions and formulas;
- ▶ modular analytical workflow.

Important point

A FAIR-oriented design does **not** require unrestricted release of confidential mortality data.

Reusability can be preserved through metadata, provenance, access conditions and transparent aggregation procedures.

Environmental exposure: monitors and NINFA

- ▶ ARPAE operates **47 fixed monitoring stations** providing validated point observations.
- ▶ NINFA provides annual concentrations on a **1 × 1 km grid**.

Why population weighting? It better represents residential exposure than a simple territorial mean over the municipal surface.

- ▶ Modelled fields cover municipalities without monitoring stations.
- ▶ Municipal exposure uses **population-weighted aggregation**.

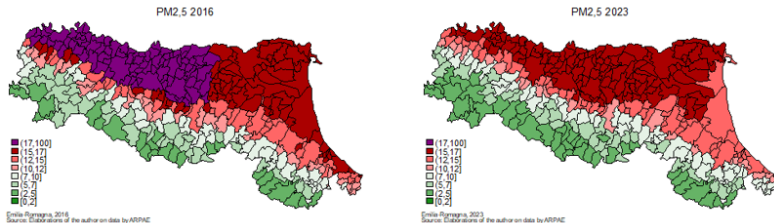


Figure: Municipality-level PM_{2.5} concentrations, 2016 and 2023.

Source: Authors' elaboration on ARPAE data.

Population, mortality and economic inputs

Population

- ▶ ISTAT resident population;
- ▶ residents aged 30+;
- ▶ municipality-year denominators.

Mortality

- ▶ ISTAT Causes of Death Registry;
- ▶ natural causes, A00–R99;
- ▶ annual municipal baseline mortality rates.

Economic data

- ▶ regional and EU GDP per capita;
- ▶ purchasing-power standards;
- ▶ HICP inflation.

Linkage key

Stable ISTAT municipal identifiers align exposure, population, mortality and economic information across years and sources.

Methodology: analytical workflow

- 1 Harmonise municipal identifiers, years and population denominators.
- 2 Construct population-weighted annual exposure for PM_{10} , $PM_{2.5}$ and NO_2 .
- 3 Apply WHO AirQ⁺ concentration–response functions by municipality, year and pollutant.
- 4 Estimate avoidable mortality relative to WHO 2021 counterfactuals.
- 5 Translate health impacts into YLL, VOLY and VSL welfare measures.
- 6 Aggregate municipal outputs afterwards for regional reporting.

Interpretation boundary

The framework estimates **counterfactual population impacts**.

It does not identify specific deaths caused by pollution and it does not identify the causal effect of a particular past policy.

Methods I: concentration–response coefficients

AirQ⁺ reports pollutant-specific relative risks for a concentration increment ΔC_p . The corresponding log-linear coefficient is:

$$\beta_p = \frac{\ln(RR_p)}{\Delta C_p} \quad (5)$$

For a 10 $\mu\text{g}/\text{m}^3$ increment:

$$\beta_p = \frac{\ln(RR_p)}{10} \quad (6)$$

Pollutant	RR per 10 $\mu\text{g}/\text{m}^3$	β per 1 $\mu\text{g}/\text{m}^3$	95% CI
PM ₁₀	1.04	0.003922	0.002956–0.005826
PM _{2.5}	1.08	0.007696	0.005826–0.008618
NO ₂	1.02	0.001980	0.000995–0.003922

Sources: WHO AirQ+ release 2.2; Chen & Hoek (2020); Huangfu & Atkinson (2020).

Methods II: WHO counterfactual and relative risk

For municipality i , year t , and pollutant p , exposure above the policy counterfactual is:

$$\Delta C_{i,t,p} = \max(C_{i,t,p} - C_{0,p}, 0) \quad (7)$$

The corresponding relative risk is:

$$RR_{i,t,p} = \exp[\beta_p \Delta C_{i,t,p}] \quad (8)$$

WHO 2021 annual counterfactuals

- ▶ PM_{2.5}: 5 $\mu\text{g}/\text{m}^3$
- ▶ PM₁₀: 15 $\mu\text{g}/\text{m}^3$
- ▶ NO₂: 10 $\mu\text{g}/\text{m}^3$

Why the max operator?

When observed concentration is already at or below the guideline, excess concentration and estimated avoidable burden are set to zero.

Methods III: avoidable fraction and avoidable deaths

The municipality-specific avoidable fraction is:

$$AF_{i,t,p} = \frac{RR_{i,t,p} - 1}{RR_{i,t,p}} \quad (9)$$

The corresponding number of avoidable deaths is:

$$AD_{i,t,p} = AF_{i,t,p} \times I_{i,t} \times \frac{Pop_{i,t}}{100,000} \quad (10)$$

Baseline mortality

$I_{i,t}$ is the annual natural-cause mortality rate per 100,000 residents aged 30+.

Population at risk

$Pop_{i,t}$ is the corresponding resident population aged 30+.

Repeated municipal implementation

The calculation is carried out separately for all **330 municipalities**, every year from 2016 to 2023, and each pollutant.

Methods IV: regional aggregation

The regional avoidable fraction is a baseline-death-weighted average of municipal fractions:

$$AF_{t,p}^{ER} = \frac{\sum_{i=1}^M AF_{i,t,p} I_{i,t} Pop_{i,t}}{\sum_{i=1}^M I_{i,t} Pop_{i,t}}, \quad M = 330$$

Equivalent interpretation

Because the factor 100,000 cancels, this is equivalent to total regional avoidable deaths divided by total regional baseline natural-cause deaths among residents aged 30+.

Why this matters

Regional aggregation occurs only after municipal calculations.
Spatial heterogeneity remains available for territorial targeting and scenario analysis.

Methods V: welfare-benefit aggregation

The framework maps municipal health impacts into two alternative welfare metrics.

VSL-based benefit:

$$B_{p,t}^{VSL} = \sum_{m=1}^M \Delta M_{p,m,t} VSL_{ER,t} \quad (1)$$

VOLY-based benefit:

$$B_{p,t}^{VOLY} = \sum_{m=1}^M \Delta YLL_{p,m,t} VOLY_{ER,t} \quad (2)$$

VSL

Welfare value of small mortality-risk reductions aggregated across the exposed population.

VOLY

Monetary valuation of changes in expected life years through Years of Life Lost.

Non-additivity

VSL and VOLY are complementary perspectives and must not be added together.

Methods VI: Years of Life Lost and VOLY calibration

Aggregate Years of Life Lost are calculated as:

$$YLL_{p,t} = \sum_{i=1}^M AD_{i,t,p} \times AYL \quad (11)$$

with:

$$AYL = 10.3 \quad (12)$$

so that:

$$YLL_{p,t} = AD_{p,t} \times 10.3 \quad (13)$$

The transferred VOLY is:

$$VOLY_j = VOLY_{ref} \left(\frac{GDP_{pcj}}{GDP_{pcEU}} \right)^{\beta}, \quad \beta = 0.8 \quad (14)$$

$VOLY_{ref}$ = EUR 70,000 in 2016 prices. The YLL measure is an aggregate proxy, not an age-specific remaining-life-expectancy calculation.

Methods VII: dynamic VSL calibration

To avoid overloading a single expression, the calibration is shown in two transparent steps.

Step 1 – cumulative inflation adjustment

$$I_t = \prod_{k=2016}^{t-1} (1 + \inf_{k \rightarrow k+1}) \quad (15a)$$

Step 2 – income-adjusted regional VSL

$$VSL_{ER,t} = VSL_{EU,2016} I_t \left(\frac{GDPpc_{ER,t}^{PPS}}{GDPpc_{EU,t}^{PPS}} \right)^{\beta} \quad (15b)$$

Baseline parameters

- ▶ $VSL_{EU,2016}$ = EUR 3.6 million;
- ▶ $\beta = 0.8$;
- ▶ inflation and PPS-adjusted GDP per capita vary by year.

Calibration outcome

Regional VSL increases from approximately **EUR 4.17 million in 2016** to **EUR 4.97 million in 2023**.

OECD (2025) is used as an updated plausibility benchmark rather than mechanically substituted into the original baseline.

Methods VIII: extension to a complete cost–benefit analysis

The current application estimates the **health-benefit side**.

A complete policy appraisal would additionally require intervention-specific costs.

Total social cost of scenario s

$$C_{s,t} = C_{inv,s,t} + C_{op,s,t} + C_{adm,s,t} \\ + C_{soc,s,t} + C_{health,s,t}^- \quad (3)$$

Net Present Value

$$NPV_s = \sum_{t=0}^T \frac{B_{s,t} - C_{s,t}}{(1+r)^t} \quad (4)$$

Benefit–Cost Ratio

$$BCR_s = \frac{PV(B_s)}{PV(C_s)}$$

where $PV(B_s)$ and $PV(C_s)$ denote the discounted present values of benefits and costs.

Current status

The paper is a **CBA-ready health-benefit module**, not a complete CBA:

intervention costs, discounting and scenario-specific NPV/BCR are not estimated in the present application.

Result 1: PM_{2.5} avoidable mortality remains substantial

Year	AF (%)	Avoidable deaths	per 100,000
2016	8.19	3,901	87.7
2017	10.69	5,215	116.9
2018	8.38	4,037	90.5
2019	8.27	4,037	90.4
2020	8.78	5,047	113.7
2021	7.30	3,853	87.2
2022	7.89	4,141	93.3
2023	6.67	3,403	76.3

Main result

The PM_{2.5}-specific burden remains substantial throughout 2016–2023, although the 2023 estimate is lower than the 2017 peak.

Interpretation

The temporal decline is descriptive and does not identify the causal effect of a specific air-quality or transport policy.

Result 2: regional improvement does not imply uniform local gains

Persistent heterogeneity.

Higher burdens remain visible in several lowland municipalities, while many Apennine municipalities record lower estimated rates.

Illustrative changes.

Ferrara: 116.2 → 106.8;
Reggio Emilia: 92.8 → 80.2;
Bologna: 86.8 → 83.6;
Codigoro 2023: 120.6.

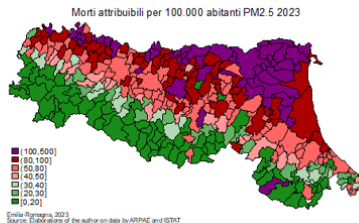
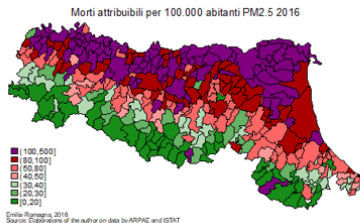


Figure: PM_{2.5} avoidable mortality per 100,000 residents aged 30+, 2016 and 2023.

Source: Authors' elaboration on ARPAE and ISTAT data.

Result 3: separate pollutant-specific mortality scenarios

Pollutant	Annual minimum	Annual maximum	Peak year
PM _{2.5}	3,403	5,215	2017
PM ₁₀	1,404	2,429	2017
NO ₂	412	993	2017

Do not sum pollutant-specific deaths

PM_{2.5}, PM₁₀ and NO₂ are estimated through separate single-pollutant concentration–response functions.

Because exposures are correlated, their mortality effects may overlap.

Why can PM_{2.5} exceed PM₁₀?

The estimated burden reflects pollutant-specific coefficients, exposure distributions and counterfactual concentrations, not only the physical relationship between particulate fractions.

Result 4: YLL and VOLY-based valuations

Years of Life Lost

Year	PM _{2.5}	PM ₁₀	NO ₂
2016	40,180.3	17,067.1	9,960.1
2017	53,714.5	25,018.7	10,227.9
2020	51,984.1	22,371.6	7,560.2
2023	35,050.9	14,461.2	4,243.6

VOLY valuation – million EUR

Year	PM _{2.5}	PM ₁₀	NO ₂
2016	3,257.95	1,383.86	807.60
2017	4,328.88	2,016.27	824.27
2020	4,022.24	1,730.99	584.97
2023	2,805.65	1,157.55	339.68

Interpretation

PM_{2.5} produces the largest pollutant-specific YLL and VOLY estimates in every displayed year.

Its VOLY valuation ranges from approximately

EUR 2.81 to 4.33 billion per year.

Pollutant-specific estimates are separate scenarios and are not additive.

Result 5: VSL-based welfare valuations are economically large

Annual ranges.

PM_{2.5}: EUR 16.3–21.9 bn;

PM₁₀: EUR 6.9–10.2 bn;

NO₂: EUR 2.0–4.2 bn.

Interpretation.

PM_{2.5} corresponds to approximately **8.7–13.8% of regional GDP**:

a welfare benchmark, not a budgetary expenditure or accounting GDP loss.

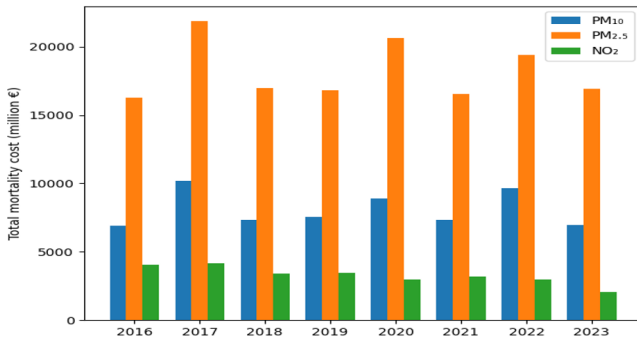


Figure: Pollutant-specific VSL-based valuation, 2016–2023.

Source: Authors' calculations based on ARPAE, ISTAT and Eurostat data.

How should the estimates be interpreted?

What the framework can support

- ▶ repeated ex-post monitoring;
- ▶ municipal priority identification;
- ▶ explicit ex-ante exposure scenarios;
- ▶ health-benefit valuation;
- ▶ geographically targeted appraisal;
- ▶ transfer to other regions with comparable sources.

What it does not currently provide

- ▶ causal evaluation of a specific intervention;
- ▶ complete intervention costs and NPV;
- ▶ morbidity and healthcare-use impacts;
- ▶ productivity and distributional effects;
- ▶ individual-level exposure or subgroup analysis.

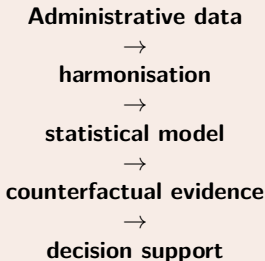
Two non-additivity rules

Do not add VSL to VOLY, and do not add pollutant-specific burden estimates to obtain a single combined pollution total.

From municipal evidence to “Statistical Intelligence”

- ▶ The analytical value does not come from one complex algorithm alone.
- ▶ It comes from making heterogeneous data **interoperable**, assumptions **explicit**, counterfactuals **transparent** and outputs **usable at the decision scale**.

From data to aware decisions



Interpretation for ASA 2026

The paper is an example of **statistical intelligence**: data become useful for public decisions only when provenance, comparability, uncertainty and scale of analysis are explicit.

A possible next layer: Artificial Intelligence

Current study

The current application does not use Artificial Intelligence.

Data intelligence

- ▶ anomaly detection;
- ▶ data-quality diagnostics;
- ▶ record-linkage support;
- ▶ metadata checks.

Predictive intelligence

- ▶ spatio-temporal exposure prediction;
- ▶ forecasting;
- ▶ nonlinear scenario emulation;
- ▶ uncertainty-aware comparison.

Decision intelligence

- ▶ interactive municipal scenarios;
- ▶ territorial pattern discovery;
- ▶ policy dashboards;
- ▶ natural-language exploration.

Principle

AI can extend the framework, but it should build on – not replace – a validated statistical architecture.

Limitations and further research

Current limitations

- ▶ annual rather than daily exposure resolution;
- ▶ population-weighted municipal exposure rather than individual exposure;
- ▶ restricted subgroup analysis;
- ▶ mortality only: no morbidity or healthcare use;
- ▶ no causal effect of a specific intervention.

Next extensions

- ▶ morbidity and healthcare utilisation;
- ▶ intervention-specific cost data;
- ▶ full ex-ante CBA;
- ▶ replication across other regions;
- ▶ richer spatial and predictive modelling.

Conclusions

- 1 A harmonised municipal architecture can transform fragmented environmental, demographic, mortality and economic sources into **reusable policy evidence**.
- 2 Air-pollution-related avoidable mortality remains substantial, while municipal estimates reveal **persistent territorial heterogeneity** concealed by regional averages.
- 3 VSL and VOLY translate health effects into welfare measures, but valuation metrics and pollutant-specific scenarios are **non-additive**.
- 4 The framework is **CBA-ready**: intervention-specific costs can be added without abandoning municipal granularity or the documented workflow.

Take-home message

Statistical intelligence is valuable when it turns fragmented data into transparent, reproducible and decision-ready evidence.

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Thank you for your attention

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