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Real-World Combustion Emissions, Engine Size and Vehicle Mass Versus Euro-Class Access Criteria in Low-Emission Zones

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Abstract

Low-emission zones, known in Poland as clean transport zones, grant or deny access according to a vehicle's Euro standard, age and fuel. These administrative labels, however, are only loosely connected to what an internal combustion engine (ICE) actually emits on the road. The founding assumption of a Euro-based zone is that the Euro stage is a usable proxy for the mass a vehicle emits, so admitting newer classes lowers the fleet emission inventory, the activity-weighted sum of class emission factors defined as the product of fleet frequency, in-zone activity and emission factor. This paper tests that assumption directly. A paradox follows: a newer, compliant, large and heavy vehicle can release more carbon dioxide (CO_2), nitrogen oxides (NOx) and particulate matter (PM) than an older, smaller vehicle that the same rule turns away. We develop a reproducible emission-accounting framework that pairs real-world emission factors, resolved by Euro standard, fuel, engine displacement and mass, with a mass-dependent treatment of non-exhaust particles. Given the number of petrol, diesel, liquefied-petroleum-gas (LPG) and electric vehicles in a fleet and the areas of the city and the zone, the model returns daily emissions and their density per square kilometre before and after a rule is applied. For a fleet parameterised on Polish statistics, the Warsaw and Kraków criterion removes about 80% of zone NOx, because the oldest vehicles are also the high-NOx diesels; the same rule, however, removes only about 40% of CO_2 and 48% of PM, and it shifts the admitted fleet toward heavier vehicles that produce more non-exhaust PM. Emission-based, fuel-based and hybrid criteria deliver larger and fairer reductions at the same level of stringency. Aligning zone access with real combustion emissions is therefore both more effective and more equitable, and it supports the wider goals of sustainable, low-carbon urban mobility.

Keywords: internal combustion engine emissions; low-emission zone; clean transport zone; Euro emission standards; real-driving emissions; NOx; particulate matter; non-exhaust emissions; vehicle mass; alternative fuels; emission factors; urban air quality

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1. Introduction

Road transport remains the dominant source of nitrogen dioxide (NO_2) at urban traffic sites and a major contributor to particulate pollution, even after decades of progressively tighter engine regulation [1]. The associated health burden is large and falls unevenly across the population, and it is this burden that gives cities the public-health case for keeping the most-polluting vehicles out of the most exposed streets [1,2]. What a zone can act on is the mass of pollutants its traffic emits and the daily loading delivered to the urban airshed, rather than the ambient concentration that results from this. Concentration, and secondary pollutants such as ozone, depend on that mass loading, together with meteorology and background transport, and the public-health rationale for a zone is to keep the loading within what the airshed can carry without breaching air-quality limits. Throughout this paper, emissions denote this mass quantity, expressed per vehicle–kilometre or per day, so the metrics compare the mass a rule admits with the mass it excludes rather than any concentration. More than three hundred European cities have responded with low-emission zones, and this instrument is now spreading across Central and Eastern Europe; the first Polish clean transport zones were launched in Warsaw and Kraków [3,4].

In almost every scheme, the rule that decides whether a vehicle may enter is administrative rather than physical. Access is set by the Euro emission standard, usually together with the registration date and the fuel type [3,4]; the Polish legal framework for these zones is drawn in the same terms [5]. A petrol car older than Euro 4 or a diesel car older than Euro 6, for example, is refused entry, while anything at or above the threshold is admitted [3,4]. The design rests on one implicit assumption, namely that the Euro class is a reliable proxy for how much a vehicle actually pollutes on the road.

Two large bodies of evidence suggest that this assumption is fragile. The first is the gap between emissions measured during type approval and emissions produced in real driving, which is large and systematic for diesel NOx and for CO_2 [6–8], as confirmed by roadside and on-road measurement of whole fleets [9,10]. The second is the structure of the fleet itself, which has shifted sharply toward larger and heavier vehicles, often grouped together as sport-utility vehicles. Their extra mass and engine size raise fuel consumption and CO_2 [11,12] and, through tyre and brake wear, increase non-exhaust particulate emissions [13,14], and they do so largely regardless of the Euro class shown on the windscreen. Together these trends produce a policy paradox: because access is keyed to a label that does not track real emissions, the rule can exclude low-emitting older cars while admitting high-emitting new ones. A small, older petrol hatchback that fails an age or Euro test may emit far less NOx, CO_2 and non-exhaust PM than a recent, fully compliant large diesel SUV that passes without restriction. When this happens often across an actual fleet, the zone delivers less environmental benefit than its administrative stringency implies, while loading costs onto the owners of small, low-emitting vehicles. The problem is therefore one of effectiveness and of fairness at the same time [15,16], and both matter for the legitimacy and durability of the policy [2].

1.1. Low-Emission Zones: Principle, Access Criteria and Key Concepts

A low-emission zone (LEZ) is a geographically bounded area that a city closes to vehicles below a defined emission threshold, enforced by camera-based number-plate recognition or by a windscreen-sticker scheme. The instrument acts directly on the traffic source of urban pollution: instead of pricing congestion or distance, it filters the fleet by an emission proxy. In practice, that proxy is almost always the Euro emission standard set out in Regulation (EC) No 715/2007 and its successors, which fixes type-approval limits for NOx, particulate mass and number, carbon monoxide and hydrocarbons for each successive vehicle generation [17]. Because the Euro stage is recorded on the registration document, and the registration date stands in for it where the stage is not stated, the rule can be enforced automatically and at low cost [18]. Most zones gate access on three administrative attributes, the Euro stage, the registration date and the fuel, and tighten the threshold on a published schedule; the most ambitious schemes move over time toward zero-emission zones that admit only battery–electric and, in some designs, fuel-cell vehicles [2,19]. The zero-emission label is, however, a tailpipe convention rather than a life-cycle statement: a

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battery–electric vehicle has no exhaust, yet its manufacture and electricity supply carry embodied and upstream emissions, and it still generates non-exhaust particles from tyre, brake and road wear that, as shown below, rise with its mass. It is therefore read here as zero tailpipe emission, and such vehicles are credited with no combustion emissions but not with zero particulate emissions.

To keep the later analysis precise, the central concepts are defined as follows:

- Low-emission zone (LEZ), ultra-low-emission zone (ULEZ) and zero-emission zone (ZEZ) are successive levels of stringency of the same instrument. In Poland, the legal term is the clean transport zone (CTZ, polish: "strefa czystego transport"), in Germany these areas are called Umweltzonen, and in France they are called low-emission mobility zones (zones à faibles émissions, ZFE).
- The Euro emission standard is the European type-approval limit class (Euro 1 to Euro 6d, with Euro 7 forthcoming) that a vehicle met when first certified. It is intended to represent a vehicle in service, but it constrains emissions measured over a single standardised laboratory cycle rather than across the full range of real-world operation.
- Real-driving emissions (RDE) testing and portable emissions measurement systems (PEMS) are the on-road procedure and the on-board instruments that measure tailpipe emissions during normal driving. They provide the evidence that on-road emissions can exceed type-approval values, though not necessarily the legal limits, since the real-driving-emissions procedure permits a conformity factor above the laboratory limit and much off-cycle operation is not separately capped [10,20].
- Exhaust and non-exhaust emissions are distinct. Exhaust (tailpipe) emissions are products of combustion and after-treatment, whereas non-exhaust emissions are particles from tyre, brake and road-surface wear and from the resuspension of road dust. The latter scale with vehicle mass and are not regulated by the Euro standard [14,21].
- The conformity factor is the ratio of on-road to laboratory emissions, and a value above one quantifies the type-approval gap between certified and real-world performance [6,22].

This vocabulary makes the design question explicit: a zone gates access by the Euro class, yet the quantities it aims to reduce, namely real-world CO_2, NOx and total PM, depend on fuel, after-treatment, engine size and mass as much as on the Euro stage.

1.2. Diffusion Across Countries and the Polish Context

Low-emission zones began in a small number of Western European cities and have since become a mainstream urban air-quality tool, with several hundred schemes now in operation and the instrument spreading eastward [3,19]. The designs vary in geography, stringency and the precise gating rule, but they share the same logic of filtering the fleet by an emission label. Table 1 summarises representative schemes across several countries together with their access criteria, illustrating both the diversity of implementation and the common reliance on the Euro standard, the fuel and the vehicle age.

Poland is a recent and instructive entrant. The 2023 amendment of the act on electromobility and alternative fuels widened the legal basis for clean transport zones, so that a large number of cities, reported to be of the order of several dozen, may introduce them over the coming years [5]. Warsaw and Kraków were the first to act, and the Katowice conurbation has legislated along similar lines [3,4]. The criteria adopted in Poland are exactly of the kind examined here: at the mature stage of their schedules, petrol cars are admitted from Euro 4 and diesel cars from Euro 6. Krakow applies these thresholds from the start of its zone in 2026, whereas Warsaw phases them in, requiring Euro 3 petrol and Euro 5 diesel from 2026 and reaching the Euro 4 and Euro 6 thresholds in 2028; the criterion modelled below is the mature rule on which both cities converge [3,4]. The wider policy environment reinforces the direction of travel, because the revised Ambient Air Quality Directive adopted at the end of 2024 sets a long-term objective of near-zero pollution by mid-century and brings interim limit values closer to the World Health Organization guidelines from 2030 [5].

Table 1. Examples of low-emission, ultra-low-emission and clean transport zones across selected countries, with their access criteria.

City (Country)	Since	Type	Vehicles Covered	Access Criterion
London (UK)	2019, 2023	ULEZ	Cars, vans, lorries	Petrol Euro 4 and above, diesel Euro 6 and above; daily charge otherwise [23,24]
German cities (DE)	2008	Umweltzone	Cars, vans, lorries	Coloured windscreen sticker by Euro stage and fuel [25]
Paris (FR)	2015	ZFE (Crit'Air)	Cars, two-wheelers, vans	Crit'Air sticker by Euro stage, fuel and age, on a tightening schedule [26]
Brussels (BE)	2018	LEZ	Cars, vans	Minimum Euro stage by fuel, tightened annually [16,27]
Milan (IT)	2008, 2019	Area C, Area B	Cars, vans	Euro stage and fuel thresholds, with a charge in the central area
Madrid (ES)	2018	ZBE	Cars	National environmental label by Euro stage and fuel [28]
Warsaw (PL)	2024	CTZ	Cars, vans	Petrol Euro 4 and above, diesel Euro 6 and above, tightening schedule [3]
Kraków (PL)	2026	CTZ	Cars, vans	Petrol Euro 4 and above, diesel Euro 6 and above (revised scope) [4]

The case for acting is strong, and in the Polish context it is stark. Ambient NO_2 is governed by fleet composition, traffic intensity, driving behaviour, cold-start emissions and street geometry rather than by regulatory class alone [1]. Exposure to traffic-related pollution is linked to respiratory and cardiovascular disease and to impaired cognition, and the burden falls hardest on poorer communities, which often face higher NO_2 concentrations while owning fewer cars [2]. A 2023 measurement campaign in Kraków found that none of forty-four monitoring locations met the World Health Organization recommendation for NO_2, and that the European limit value that will apply from 2030 was met at only three of them [4]. This evidence base motivates strong local action; whether a given restriction delivers on that promise, however, depends on the criterion it uses.

1.3. Research Gap, Questions and Novelty

The relevant studies rarely meet at the point where they matter most, namely, the design of the access criterion. Effectiveness studies establish whether zones improve air quality but treat the criterion as given [27,29]. Emissions studies document the type–approval gap [6,10] and the drift toward heavier vehicles [11] without asking what either means for a zone's entry rule. Work on non-exhaust emissions [14] and on cold starts [30,31] shows that large parts of the problem are invisible to a Euro-based shorthand, yet stops short of the policy instrument. Equity studies map who bears the cost [15,16] and how access restrictions reshape opportunity [32], but seldom trace either back to the gating variable. What is missing is a single framework that asks how faithfully the access criterion tracks real internal-combustion-engine emissions, and what alternative criteria would achieve. This study sets out to close that gap, and is organised around three questions as follows:

1. How well does the gating variable used by low-emission zones, the Euro class together with age and fuel, predict the real-world CO_2, NOx and exhaust and non-exhaust PM of the vehicles it admits and excludes?

2. How large is the resulting paradox on a modelled fleet, and how does it differ between a pollutant that scales with engine after-treatment and fuel (NOx) and pollutants that scale with mass and size (CO_2 and non-exhaust PM)?
3. What would emission-based, mass-based and fuel-based access criteria achieve, at matched stringency, in terms of effectiveness and equity, and does a hybrid criterion outperform any single rule?

The novelty of this work is in its treating the access rule itself as the object of study. To our knowledge, this is the first analysis to evaluate a low-emission-zone criterion as a classifier scored against real-world internal-combustion-engine emissions, and to do so with a reproducible model parameterised on a national fleet. Four contributions follow. First, we build an emission-accounting framework that maps a vehicle matrix of Euro standard, fuel, displacement and mass onto real-world urban emissions of CO_2, NOx and exhaust and non-exhaust PM, using inventory databases [33,34] calibrated with on-road PEMS and remote-sensing measurement [10]. Second, we define a set of paradox metrics that quantify how poorly age and Euro criteria track those emissions. Third, we carry out a descriptive variance decomposition of the assigned emission factors, showing how little of their variance the Euro class accounts for once fuel, displacement and mass are present. Fourth, we compare four families of access criteria on a modelled city fleet, where the fuel-based option provides a direct bridge to the alternative-fuels theme of this Special Issue. The remainder of the paper is organised as follows. Section 2 reviews related work; Section 3 sets out the materials and methods and the methodological basis of the framework; Section 4 reports the case-study results for a fleet parameterised on the Polish clean transport zones; Section 5 discusses the findings; and Section 6 concludes by answering the research questions and stating the contribution to the literature.

2. Literature Review

The evidence that low-emission zones improve air quality is real but heterogeneous, and the size of the effect depends strongly on how the zone is designed and how demanding its vehicle criteria are. Where zones are ambitious, the measured improvements can be large: nitrogen dioxide fell by about 30% in Antwerp and about 37% in Brussels within five years of introduction, and a systematic review reported cardiovascular health benefits across several of the schemes it examined [27,35]. German cities have seen reduced pharmaceutical spending for cardiovascular and respiratory conditions, with savings in the tens of millions of Euros per year [36], a natural-experiment study in Madrid found measurable air-quality gains and wider social benefits in the early years of its zone [28], and hourly analyses of German station data show that the reductions concentrate in traffic-related pollutants during peak hours, which points to a genuine traffic mechanism rather than a background trend [37].

Other evaluations report only modest effects, especially where the criteria are weak. A large analysis of seventeen German cities found that restricting the most-polluting vehicles cut ambient nitrogen oxides by no more than about 4%, with most of the achievable benefit coming from removing the very oldest vehicles and little extra gain from admitting only higher Euro classes [25]. London tells the same story at the scale of one scheme. The municipal authority reported that the 2023 expansion of the Ultra Low Emission Zone lowered car and van nitrogen oxide emissions in outer London by roughly 13–14% and exhaust fine-particle emissions by more, relative to a counterfactual without the expansion, alongside lower measured nitrogen dioxide across the capital [23,24]. An independent academic evaluation that built a control from other British sites was more cautious, finding no statistically significant change in nitrogen dioxide or nitrogen oxide once wider trends were accounted for [29]. The contrast between the official and the independent assessment is the point: the benefit of a scheme is not guaranteed by its administrative reach, and the access criterion is where effectiveness is won or lost. That makes it worth asking whether the gating variable reflects real emissions at all.

The discrepancy between certified and on-road emissions is one of the best-documented findings in vehicle-emissions research, and it cuts straight through the link between the Euro label and real pollution. Most Euro 5 and Euro 6 diesel cars exceed their type-approval NOx limits in real driving [38]. Compilations of on-road and portable-measurement data put average Euro 6 diesel NOx at several times the 80 mg/km limit [6,10], with only a small minority of models compliant on the road and the worst exceeding the limit by an order of magnitude [22]. Independent campaigns confirm the pattern: across 149 Euro 5 and Euro 6 cars, the average urban NOx emission factor of Euro 6 diesels was about 0.44 g/km, roughly eleven times the 0.04 g/km measured for petrol cars, so petrol vehicles emitted some 86–96% less NOx than diesels [7]. Roadside plume measurements of a real fleet found real-world NOx nearly seven times the Euro 6 diesel limit and particle-number emissions about two orders of magnitude above it [9]. Real-world updates to national emission factors place several older diesel families well above the laboratory limits, with retrofit vehicles and the newest cars carrying effective selective catalytic reduction as the main exceptions [8,39]. For CO_2 the certified-to-real gap grew from under 10% in 2001 to roughly 40% by the mid-2010s, so that recent cars consumed and emitted about 40% more than advertised [6].

Two consequences follow for the design of an access rule. First, because the Euro standard is fixed on a test cycle that under-represents real driving, two cars in the same Euro class can have very different real-world CO_2 and NOx. Second, the ranking of vehicles by fuel does not match the ranking by Euro class: the highest-emitting petrol Euro 6 family has been found to have NOx comparable to the lowest-emitting diesel family, so a single label conceals differences that matter for air quality [22]. The newest diesels certified under the real-driving-emissions procedure perform markedly better than earlier ones [8], so any framework must resolve the fleet finely enough to capture that improvement, instead of treating a Euro class as homogeneous.

While engines have become cleaner per unit of work on the regulatory cycle, the vehicles they power have grown larger and heavier, so that the mass rate of their real-world emissions has risen even as the regulated intensity has fallen. Sport-utility vehicles reached about 48% of global car sales in 2023 and, at some 200–300 kg more than a medium car, emit on the order of 20% more CO_2 [11]. The aggregate is enormous: the global SUV fleet emits close to one billion tonnes of CO_2 a year, which would rank it among the largest national emitters were it a country [12]. New-vehicle analyses estimate that car CO_2 could have fallen substantially had vehicle size held constant, and that the rise in heavier, less efficient models continues to slow fleet-efficiency progress [26,40]. The spread within the passenger-car category is wide: a small hatchback or compact crossover may emit around 130–150 g/km of CO_2 while a large petrol SUV exceeds 260 g/km [41]. Engine displacement and vehicle mass are not part of the Euro classification, so a model can advance through Euro stages while becoming heavier and more carbon-intensive in absolute terms [40].

A regulatory mechanism reinforces the physical one, and it is itself a paradox directly relevant to the present argument. European CO_2 standards for new passenger cars set each manufacturer a target adjusted by its fleet's average mass, so a heavier fleet receives a more lenient target through a mass-based limit–value curve [42,43]. The slope used for 2020–2024 allows roughly an extra 3.33 g/km of CO_2 for every additional 100 kg of vehicle mass [43]. Analysts argue that this adjustment now rewards heavier vehicles and weakens the standard by several grams per kilometre, and that it should be removed or replaced by a footprint parameter [42,44]. The criterion used by low-emission zones and the parameter used in the CO_2 standard share a common weakness: both can reward attributes that do not reduce, and may even increase, the quantity the policy intends to limit.

A further mechanism widens the paradox and is almost wholly invisible to a Euro-based criterion. Particulate matter from tyre wear, brake wear and road abrasion, together with resuspended road dust, scales with vehicle mass and driving dynamics and is essentially independent of the Euro standard, which regulates only exhaust particulate matter [14,21]. As exhaust particles have fallen with the spread of diesel particulate filters, non-exhaust emissions have become a growing share of traffic PM and now equal or exceed exhaust emissions in many settings [14]. Brake wear can contribute a large fraction of urban non-exhaust PM where braking is frequent [21,45], on-road measurements show brake and tyre particle emissions rise with vehicle mass and braking intensity [46,47], and estimates suggest that the additional tyre particulate from heavier vehicles can be of a magnitude comparable to the regulated tailpipe limit [13]. Heavier vehicles therefore emit more non-exhaust PM however new or clean their engine is certified to be. The projection that non-exhaust fine-particle emissions from passenger vehicles will rise by about half by 2030, driven mainly by increased mileage, shows that a mass-blind criterion will miss a growing part of the problem [14,48]. The shift to gasoline direct injection has also reversed the historical roles of petrol and diesel for particles, since direct-injection petrol engines can be significant particle emitters, which further undermines a fuel-and-Euro shorthand [47,49].

Urban operating conditions amplify exactly the emissions a zone is meant to reduce. A large share of urban trips begin with a cold engine and a cold after-treatment system, and the warm-up phase produces disproportionate emissions. For light-duty gasoline vehicles, the cold-start phase has been found to contribute on the order of two-thirds of the trip carbon monoxide and hydrocarbons and well over half of the trip NOx, while adding only a few percent of trip CO_2 [20,30]. On a real-driving route the cold-start phase, lasting only a few minutes, accounted for about 40–44% of the NOx of the much longer urban section [50]. At low ambient temperature, the effect grows sharply: a gasoline vehicle has shown a roughly thirtyfold increase in NOx over an urban cycle at -7 °C relative to a mild temperature [51]. The relevance to urban policy is direct, because city trips are short. More than half of car-driver trips in the United Kingdom are under five miles, and the average car journey in inner London is only about 1.5 miles, often too short for the after-treatment system to reach full effectiveness [52]. The start-up of a diesel engine is in itself a distinct operating state with elevated emissions and accelerated wear, as examined in detail in the dedicated literature [31]. Bottom-up urban-traffic models and the wider real-world literature treat cold-start excess and ambient temperature as first-order variables, and they show that ignoring cold starts can badly understate the exposure of pedestrians, cyclists and bus users near roads [53,54]. A framework that compares vehicles for zone design must therefore evaluate them under urban driving with a realistic cold-start share, not under a steady-state catalogue value.

Fairness is not a secondary concern, because it shapes both the legitimacy and the welfare consequences of the policy. Access-based mobility interventions tend to impose higher relative costs on households with limited choice and few adaptive resources [15]. Reviews of low- and zero-emission zones conclude that the socio-economic impact is central, that poorer households often own fewer or older cars, and that exemptions and financial support should be targeted at those who genuinely need a vehicle and could not otherwise afford to switch [2,19]. Well-designed support helps: in London, a larger share of scrappage grants reached the most-deprived boroughs than the least-deprived, and in Brussels, lower-income households made up the largest share of those moving from private cars to a mobility budget [16]. At the same time, qualitative work documents that a zone's

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burden can extend beyond its boundary and beyond the owners of non-compliant vehicles, affecting social participation and the affordability of replacement vehicles, and that the views of those who are most affected are not always heard [15]. Spatial analyses show that access restrictions can cut job accessibility unevenly across occupational groups and locations [32]. A criterion that excludes low-emitting small and older cars while admitting high-emitting new ones is regressive in a specific, measurable sense, because it asks owners of modest vehicles to bear the cost for little environmental return, with the qualification that a vehicle's absolute contribution also depends on how far it is driven, so a car with high per-kilometre factors but low annual mileage may contribute less in absolute terms than its factors alone suggest.

These studies are seldom connected to the access criterion itself. Effectiveness studies ask whether zones work [23,25]; emissions studies document the real-world gap [6,7] and the drift to heavier vehicles [11]; non-exhaust and cold-start studies show what a Euro shorthand misses [14,30]; equity studies show who pays [15,16]. No one asks how well the criterion tracks real ICE emissions, or what an alternative would achieve. The present paper addresses that gap by quantifying the mismatch between criterion and emissions and by comparing emission-based, mass-based and fuel-based alternatives, the last of which connects the analysis to the alternative-fuels theme of this Special Issue.

3. Materials and Methods

The framework treats a zone's access rule as a binary classifier that admits or excludes vehicles, and it scores that classifier against the real emissions the policy intends to reduce. This framing borrows three established methodologies. The emission accounting is the bottom-up, activity-times-emission-factor approach of the EMEP/EEA Air Pollutant Emission Inventory Guidebook and of the inventory models built on it, HBEFA and COPERT, which resolve emissions by vehicle category, Euro standard, fuel and traffic situation [33,34]. The evaluation of the rule follows the logic of diagnostic and classifier assessment: an admitted vehicle that out-emits an excluded one is treated as a misclassification, and each candidate rule is compared against an emission-optimal rule of equal stringency, in the spirit of comparing operating points on a common scale. The criterion comparison itself follows the policy-evaluation principle of holding stringency constant, with each alternative calibrated to exclude the same fleet share, so that effectiveness and equity are compared on a like-for-like basis rather than confounded with how many vehicles each rule happens to remove.

The analysis proceeds through connected stages. A vehicle classification matrix is defined; each class is assigned a vector of real-world emission factors; the factors are evaluated under representative urban operating conditions; metrics compare the admitted and excluded sets produced by a rule framework when applied to a synthetic city fleet parameterised from Polish marginal statistics; and alternative rules are compared at a common stringency. The whole chain is deliberately transparent and reproducible, so the same calculations can be repeated as newer emission-factor releases and real-driving datasets appear. Figure 1 summarises this workflow, from the vehicle classification matrix through the calibrated emission factors and urban operating conditions to the paradox metrics, the variance decomposition and the comparison of access criteria.

The unit of analysis is a vehicle class defined by four attributes: the Euro emission standard, from Euro 3 to Euro 6d and, prospectively, Euro 7; the fuel and powertrain, covering port-injection petrol, direct-injection petrol, diesel, LPG, compressed natural gas and biomethane, hybrid electric and, as a reference, battery electric; the engine-displacement band; and the kerb-mass band, expressed through vehicle segment (small, medium, large, SUV). The matrix is deliberately two-dimensional, separating the regulatory attribute, the

Euro class, from the physical attributes of fuel, displacement and mass. That separation is what lets the central question be posed: how do emissions vary across the physical attributes within a single Euro class?

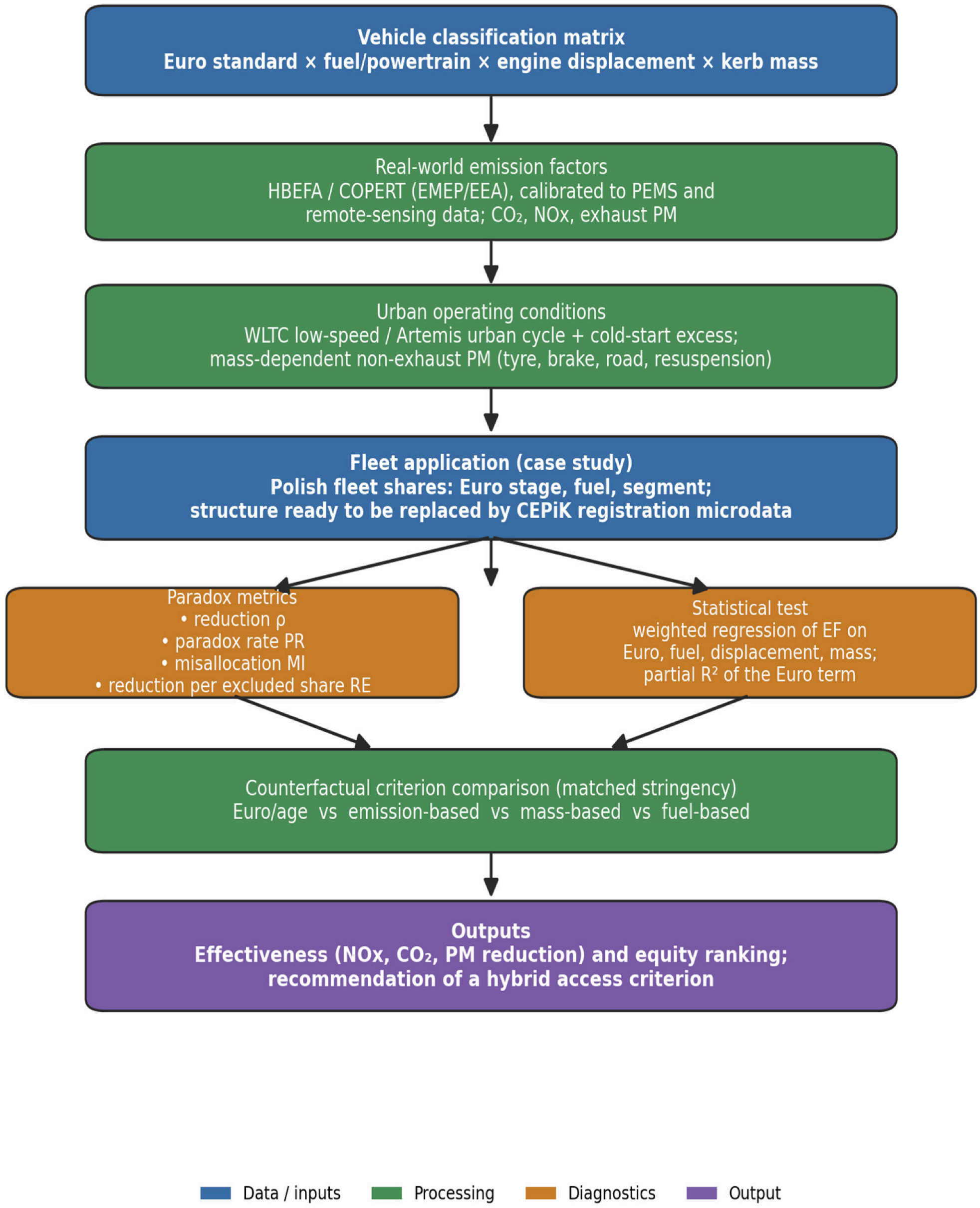

Figure 1. Workflow of the analytical framework, from the vehicle classification matrix (Euro standard, fuel, displacement and mass), through real-world emission factors calibrated to on-road PEMS and remote-sensing data and evaluated under urban operating conditions, to the paradox metrics, the regression test and the matched-stringency comparison of access criteria.

Emission factors are taken from the European inventory models HBEFA and COPERT, the latter based on the EMEP/EEA methodology, at the level of vehicle category, Euro standard, fuel and traffic situation [33,34]. Because both models, particularly their earlier versions, can under-represent on-road diesel NOx, the factors are calibrated to real-world evidence using published portable-measurement [7,22] and remote-sensing datasets [8,9]. The calibration applies conformity factors derived from those datasets to the inventory NOx values, so that the analysis reflects on-road rather than laboratory behaviour. Exhaust PM uses the inventory values for the relevant after-treatment configuration; CO_2 is derived from real-world fuel consumption, and where only a type-approval value is available, the documented certified-to-real gap is applied [6]. All factors are reported in Table 2, along with their source and calibration, which keeps the analysis auditable and updatable with newer HBEFA and COPERT releases and newer real-driving data.

Table 2. Real-world urban emission factors and key model parameters for representative vehicle classes. Values are derived from the inventory models (HBEFA, COPERT) calibrated to on-road PEMS and remote-sensing data, with conformity factors applied to NOx and the certified-to-real gap to CO_2, and combined with mass-dependent non-exhaust factors. They are model parameters to be replaced by measured values where available.

Representative Class	CO_2 (g/km)	NOx (g/km)	Exhaust PM (mg/km)	Non-Exhaust PM (mg/km)	Kerb Mass (kg)	Source
Petrol, Euro 3, small	165	0.20	2	28	1080	[33,34,38]
Petrol, Euro 4, small	150	0.10	2	30	1150	[33,34]
Petrol PFI, Euro 6, medium	150	0.04	2	34	1350	[7,50]
Petrol GDI, Euro 6, medium	155	0.06	3	35	1380	[47,49,55]
Petrol GDI, Euro 6, large SUV	235	0.08	4	48	1760	[11,47]
Diesel, Euro 5, medium	160	0.55	3	36	1450	[38,39]
Diesel LNT, Euro 6b, medium	150	0.44	2	36	1480	[6,38]
Diesel SCR, Euro 6d, medium	145	0.10	2	38	1520	[8,38]
Diesel SCR, Euro 6d, large SUV	190	0.16	3	52	1900	[11,14]
LPG bi-fuel, Euro 6, medium	155	0.05	2	33	1320	[50]
CNG/biomethane, Euro 6, medium	130	0.06	2	33	1380	[50]
Battery-electric, medium	0	0	0	40	1700	[14,48]

Because non-exhaust PM is independent of the Euro standard and increasingly important, it is estimated separately and added to the exhaust component. Tyre wear, brake wear and road abrasion are estimated with the mass-dependent approach of the EMEP/EEA methodology [21], combined with the mass and driving-dynamics sensitivities reported in the dedicated literature [13,47]. This captures the fact that heavier vehicles and those operated with more frequent braking produce more non-exhaust PM, and it stops the framework from crediting a heavy but Euro-compliant vehicle with low particulate emissions simply because its exhaust filter is effective. This mass-dependent treatment is a first-order approximation and is treated as one. Non-exhaust particulate originates in brake wear, tyre wear, road-surface abrasion and the resuspension of deposited dust, and because these sources respond to different drivers a single mass term cannot reproduce their individual behaviour. It is, in particular, unable to represent regenerative braking, which lowers brake-wear particles on hybrid and battery-electric vehicles even as their greater mass raises tyre and road wear, so for those vehicles the mass term is likely to overstate the non-exhaust total. The non-exhaust results below therefore indicate the direction and approximate scale of a mass effect rather than a resolved balance between components; the uncertainty this leaves is carried through the non-exhaust sensitivity range, and separating the components and testing an explicit regenerative-braking assumption is identified in Section 5 as a priority extension.

Class factors are evaluated under urban conditions representative of driving inside a zone: a low average speed, frequent stops and a realistic cold-start share. Two driving representations are used and compared. The first uses standard urban sub-cycles, such as the low-speed phase of the worldwide harmonised light vehicles test cycle and the urban part of the Artemis cycle. The second uses a real-world trajectory derived from recorded urban driving for the case-study city and processed with the project's existing computational toolchain [56]. Cold-start excess emissions are added using the contributions reported in the cold-start literature [30,50], and ambient temperature is treated as a scenario variable in the sensitivity analysis, because both the cold-start share, which is high on the short trips typical of city driving [52], and the ambient temperature [51] strongly influence urban NOx and particle emissions [53]. Evaluating vehicles under these conditions rather than under a steady-state catalogue value is essential, because the differences between fuels and after-treatment systems are largest precisely during the urban and cold phases a zone is meant to address.

The emission accounting underlying every metric is defined first. For a set of vehicle classes the emission of a pollutant is the activity-weighted sum of the class emission factors (Equation (1)); where the index runs over vehicle classes, the frequency term is the fleet share of a class, the activity term is its mean in-zone distance in vehicle–kilometres, and the emission-factor term is its real-world factor for that pollutant, so that in Equation (1), $E_p(S)$ is the total emission of pollutant p over the class set S, i indexes the classes, f_i is the fleet share of class i, d_i its mean in-zone distance in vehicle-kilometres and $EF_{p,i}$ its real-world emission factor for pollutant p.

$$E_p(S) = \sum_{i \in S} f_i d_i EF_{p,i} \tag{1}$$

An access rule partitions the classes into an admitted set A and an excluded set X, whose union is the whole fleet F. The fractional reduction in pollutant p achieved by rule R, written $\rho_p(R)$, that is, the share of fleet emission the rule removes, is given by Equation (2), in which A, X and F are the admitted, excluded and whole-fleet class sets.

$$\rho_p(R) = 1 - \frac{E_p(A)}{E_p(F)} \tag{2}$$

Three diagnostic metrics build on this accounting. The paradox rate (Equation (3)) is the fleet-weighted share of admitted and excluded class pairs in which the admitted vehicle is the higher emitter; the indicator equals one when the admitted class out-emits the excluded one, so a value near zero means the rule is well aligned with real emissions and a larger value means a stronger mismatch. In Equation (3), $PR_p(R)$ is the paradox rate, f_a and f_x are the fleet shares of an admitted class a and an excluded class x, and the indicator $1[\cdot]$ equals one when $EF_{p,a}$ exceeds $EF_{p,x}$.

$$PR_p(R) = \frac{\sum_{a \in A} \sum_{x \in X} f_a f_x \, 1\left[EF_{p,\,a} > EF_{p,\,x}\right]}{\sum_{a \in A} \sum_{x \in X} f_a f_x} \tag{3}$$

The emission-misallocation index (Equation (4)) compares the in-zone emission admitted by the rule with that admitted by an emission-optimal rule of equal stringency. The reference rule, marked with an asterisk, excludes the same fleet share but selects the admitted set so as to minimise in-zone emission, which amounts to excluding the highest-emitting classes up to that share; a value of zero marks an emission-optimal criterion and a larger value indicates more avoidable emissions admitted. In Equation (4), $MI_p(R)$ is the emission-misallocation index and A^* is the admitted set of the equal-stringency emission-optimal rule.

$$MI_p(R) = \frac{E_p(A) - E_p(A^*)}{E_p(F)} \tag{4}$$

The reduction per unit excluded fleet share (Equation (5)) measures efficiency, with the excluded share being the summed frequency of the excluded classes. A rule that is both effective and fair achieves a large reduction per unit of excluded share, removing emissions while turning away as few vehicles as possible. In Equation (5), $RE_p(R)$ is the reduction per unit of excluded share and s(R) is the excluded fleet share, the summed frequency of the excluded classes.

$$RE_p(R) = \frac{E_p(F) - E_p(A)}{s(R)} \quad (5)$$

As a descriptive variance decomposition of the assigned emission factors, the real-world factors are regressed on the regulatory and physical descriptors across the vehicle classes, weighted by fleet frequency (Equation (6)), with the Euro term entered as an ordinal stage, the fuel term as a set of indicators, and displacement and mass as continuous variables. In Equation (6), β_0 is the intercept, β_1 to β_4 are the coefficients at the Euro stage, fuel, engine displacement and kerb mass, and ε_i is the residual for class i.

$$EF_{p,\,i} = \beta_o + \beta_1 Euro_i + \beta_2 fuel_i + \beta_3 disp_i + \beta_4 mass_i + \varepsilon_i \quad (6)$$

The adequacy of the gating variable is then measured by the partial coefficient of determination of the Euro term (Equation (7)), the explained variance lost when the Euro term is dropped from the full model. In Equation (7), ΔR^2_{Euro} is that partial coefficient of determination of the Euro term, and R^2_{full} and $R^2_{no\ Euro}$ are the coefficients of determination of the full model and of the model without the Euro term.

$$\Delta R^2_{Euro} = R^2_{full} - R^2_{no\ Euro} \quad (7)$$

A small value indicates that, for a given pollutant, the Euro class adds little to the explained variance once fuel, mass and displacement are present; the within-class dispersion of the emission factor is reported alongside this. The hypothesis is that the Euro class alone explains only a modest fraction of the variance in real-world CO_2 and NOx, with fuel, mass and displacement carrying most of it. If it holds, the variable used to gate access is a weak predictor of the quantity the zone targets, which is the formal statement of the paradox. The expectation is consistent with the finding that CO_2 rises systematically with engine size while NOx depends more on fuel and after-treatment than on displacement [57]. Two points of interpretation must be stated plainly. First, this regression is not an independent empirical test, because the real-world factors of Table 2 are themselves assigned from the same descriptors that appear on the right-hand side; the coefficients and the explained variance therefore describe the internal structure of that factor assignment rather than a newly measured relationship, and the regression is used only as a transparent consistency check on how the assigned variance is distributed across the regulatory and physical attributes. An independent test would regress directly measured emissions, which is the purpose of the on-road measurement extension set out in Section 5. Second, a partial R^2 below about 0.10, that is, fewer than ten percentage points of the explained variance recovered by the Euro term, is treated here as negligible when judging the gating variable, since a term that shifts the explained variance by less than this cannot, on its own, separate high- from low-emitters across the fleet.

The class-level framework is applied to a case-study city fleet. In the base case the fleet is parameterised from published aggregate statistics, namely the national age structure [58] and the fuel and engine shares [59,60], with the LPG share taken from market data [61], and the method is built so that vehicle-registration microdata from the Polish central register can be substituted directly for the parameterised table when available. The approach applies to Warsaw, Kraków or the Katowice conurbation, each of which already operates or has legislated a clean transport zone with criteria based on the Euro standard, age and fuel [3,4]. Each vehicle is mapped to a class, assigned the corresponding emission-factor vector, and combined with an estimate of in-zone activity in vehicle–kilometres to yield total and per-passenger-kilometre emissions of CO_2, NOx and PM before and after the rule.

The Polish case is informative on two counts: the Warsaw and Kraków criteria admit petrol cars from Euro 4 and diesel cars from Euro 6, exactly the kind of rule examined here [3,4], and the registration document records the Euro norm or production date while the central register supports automatic plate-based verification, so the data needed for the analysis match the data actually used to enforce the policy [18].

On the same fleet, four families of access rules are compared, each calibrated to exclude a comparable share of vehicles so that stringency is held constant. The first is the conventional Euro-and-age criterion, including the current and announced stages of the case-study zone. The second is an emission-based criterion that admits vehicles by a real-world threshold in grams of NOx and CO_2 per kilometre, derived from the calibrated factors. The third is a mass- or displacement-based criterion, in the spirit of the vehicle taxes indexed to mass and to emissions used in Norway and France [26]. The fourth is a fuel-based criterion that admits vehicles by energy carrier and rewards low-carbon, low-pollutant alternative fuels (renewable diesel, compressed natural gas and biomethane, LPG, hydrogen and electricity), which connects this analysis to the alternative-fuels theme. The rules are ranked by total emission reduction, by reduction per excluded vehicle, and by an equity indicator comparing the number of low-emitting small and older vehicles excluded with the number of high-emitting vehicles admitted.

The robustness of the conclusions is tested against the assumptions the literature flags as influential: the cold-start share and ambient temperature, the urban speed and congestion level, the choice of emission-factor database and its calibration, the rate of fleet renewal, and the progressive tightening of the Euro criterion over time. Results are reported as ranges, and the qualitative conclusions are checked for stability across these assumptions so that the central findings do not hinge on a single set of parameter choices.

4. Results

The case study is a model parameterised on published statistics. The fleet class frequencies are reconstructed from the Polish age structure reported by PZPM and from the fuel and engine shares reported by Samar and GUS, and the emission factors are real-world values synthesised from HBEFA and COPERT and calibrated with the portable-measurement and remote-sensing literature cited above. Every reported figure is a reproducible output of the supplementary model script. The point estimates should be read as informed model estimates, to be confirmed by replacing the fleet table with vehicle-registration microdata.

The fleet represents a Polish city fleet of the kind subject to the Warsaw and Kraków zones. The marginal shares of Euro classes are reconstructed from the PZPM age structure, in which cars of four years or younger make up about 11% of the fleet, cars of five to ten years about 17%, cars of eleven to twenty years about 49%, and cars older than twenty years about 23%, and these shares are mapped to the Euro introduction years [58]. The fuel composition follows the published structure, with petrol comprising about 53% and diesel about 32% [59], LPG cars about 12% [61], and a small but growing hybrid and battery-electric share about 3% of the total [60]. The model resolves 92 non-empty vehicle classes defined by Euro standard, fuel and segment, each assigned a representative kerb mass, engine displacement and real-world urban emission factors from the calibrated factors of Section 3 and the mass-dependent non-exhaust treatment of the same section. The resulting fleet has a mean kerb mass of about 1450 kg, consistent with an old and mixed fleet. Annual distance is held uniform across classes in the base case. Because vehicle-kilometres vary with age, fuel and use, with diesel and LPG cars typically covering more distance and the oldest cars covering less distance, this assumption attributes too much in-zone activity to the oldest classes and too little to the diesel fleet, and the consequences for the estimated reductions are set out in the limitations. The same caveat applies to the fleet itself, which is reconstructed to match the observed marginal shares of age, fuel and segment but not necessarily their exact joint distribution, a limitation that registration microdata would remove. Table 3 shows the composition of the fleet in the modelled case study.

Table 3. Composition of the modelled case-study fleet. Shares approximate the Polish passenger-car fleet and are the single inputs to be replaced by vehicle-registration microdata (CEPiK). Summary values are computed by the model.

Attribute	Category	Share (%)
Fuel	Petrol	53
Fuel	Diesel	32
Fuel	LPG (bi-fuel)	12
Fuel	Hybrid and battery–electric	3
Euro stage	Euro 3 and older	23
Euro stage	Euro 4	29
Euro stage	Euro 5	20
Euro stage	Euro 6 and 6d	28
Segment	Small	35
Segment	Medium	42
Segment	Large and SUV	23
Summary	Mean kerb mass	1450 kg
Summary	Vehicle classes resolved	92
Summary	Share excluded by the Warsaw/Kraków criterion	≈39

Table 4 contrasts representative real-world urban emissions for an admitted newer large diesel SUV of the Euro 6 standard and an excluded older small petrol car that falls below the Euro 4 threshold petrol it must meet when following a rule of the kind operating in Warsaw and Kraków [3,4]. The admitted diesel car is the higher emitter of NOx by about a factor of three [7], the higher emitter of CO_2 through its greater mass and displacement, and the higher emitter of non-exhaust PM because tyre and brake wear scale with mass [13,47]. The vehicle the rule excludes is therefore the lower emitter on every pollutant considered.

Table 4. Representative real-world urban emissions for two contrasting vehicles, compiled from the cited measurements.

Vehicle	Euro and Age	Admitted	CO_2 [g/km]	NOx [g/km]	Non-Exhaust PM
Small petrol hatchback	Euro 3, older	No	about 160 [7,41]	about 0.15 [7]	low, light vehicle [13]
Large diesel SUV	Euro 6, newer	Yes	about 220–260 [7,41]	about 0.44 [7]	elevated, heavy vehicle [13,47]

The full fleet shows the same pattern across all classes. Figure 2 plots the real-world urban NOx and CO_2 of every class against its Euro standard, with point colour denoting fuel and point size proportional to mass. For NOx the diesel classes sit far above the petrol classes at every Euro stage, so an admitted Euro 6 diesel near 0.44 g/km lies above an excluded older petrol class near 0.15 g/km. For CO_2 the within-class spread is driven by size and mass rather than by Euro stage, and the classes overlap heavily between adjacent stages. The figure is the visual signature of the paradox: the gating variable does not separate the high-emitters from the low ones.

The urban factors already reflect urban operation, in which the warm-up phase contributes a large fraction of trip NOx for petrol vehicles [30,50] and the gap between fuels is the widest [51,52]. An explicit decomposition of the cold-start contribution at a chosen ambient temperature would widen the petrol-to-diesel gap further, and it is part of the measurement extension described in Section 5.

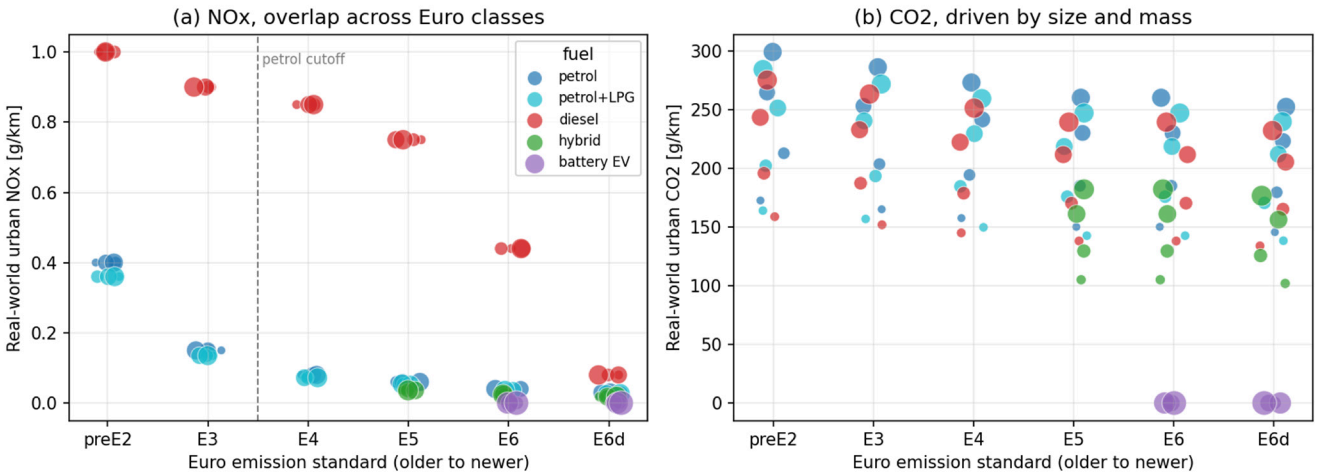

Figure 2. Real-world urban NOx (panel (**a**)) and CO_2 (panel (**b**)) versus Euro class for the modelled fleet. Point colour denotes fuel and point size is proportional to vehicle mass.

The Warsaw and Kraków rule admits petrol and LPG cars from Euro 4 and diesel cars from Euro 6, and on the modelled fleet it excludes a fleet share of about 0.39. Every metric follows by substituting the modelled classes into the definitions of Section 3. Equation (1) is evaluated for each pollutant, with the unrestricted fleet emission normalised to one, so the in-zone emission of the admitted set and of the equal-stringency reference set read directly as shares of the total fleet: for NOx about 0.199 was admitted against about 0.123 for the reference, for CO_2 about 0.602 and 0.519, and for PM about 0.520 and 0.463.

The paradox rate of Equation (3) counts the admitted and excluded pairs in which the admitted class is the higher emitter, its denominator being the product of the admitted and excluded shares:

$$\sum_{a \in A} \sum_{x \in X} f_a f_x = s_A \, s_X = \; 0.609 \; \times \; 0.391 \approx 0.238 \tag{8}$$

so that for NOx, where the higher-emitter pairs carry a weight of only about 0.011, the rate is small:

$$PR_{NOx} = \frac{0.011}{0.238} \approx 0.046 \tag{9}$$

while the same construction gives much larger values for CO_2 and PM.

$$PR_{CO_2} \approx 0.476 \; PR_{PM} \approx 0.318 \tag{10}$$

The paradox rate is therefore only about 5% for NOx but about 48% for CO_2 and about 32% for total PM. The low NOx value reflects a real and useful alignment: the oldest vehicles are also the high-NOx diesels, so the age-and-Euro criterion happens to target them well. The high CO_2 and PM values reflect the opposite, because those pollutants track mass and size, which the criterion ignores.

The fractional reduction in Equation (2) follows from the same shares. For NOx,

$$\rho_{NOx} = 1 - \frac{E_{NOx}(A)}{E_{NOx}(F)} = 1 - \frac{0.199}{1.000} \approx 0.80 \tag{11}$$

and for CO_2 and PM,

$$\rho_{CO_2} \approx 0.40 \; \rho_{PM} \approx 0.48 \tag{12}$$

The rule removes about 80% of fleet NOx while excluding 39% of vehicles, a strong result for NOx, yet only about 40% of CO_2 and about 48% of total PM are removed for the

https://doi.org/10.3390/en19153692

same exclusion. The emission-misallocation index of Equation (4) subtracts the reference-set emission from the admitted emission. For NOx,

$$MI_{NOx} = \frac{E_{NOx}(A) - E_{NOx}(A^*)}{E_{NOx}(F)} = \frac{0.199 - 0.123}{1.000} \approx 0.076 \quad (13)$$

and for CO_2 and PM,

$$MI_{CO_2} \approx 0.083 \; MI_{PM} \approx 0.057 \quad (14)$$

so about 8% of fleet emissions for both NOx and CO_2 and about 6% for PM are avoidable, in the sense that a rule of equal stringency selecting by real emissions would not admit them.

A variance decomposition of the assigned factors points the same way; because those factors are constructed from these very attributes, it serves as a consistency check rather than an independent estimate. The regression of Equation (6) and the partial coefficient of determination of Equation (7) quantify what the Euro class adds. For NOx the Euro class alone explains about 19% of the fleet-weighted variance in the real-world emission factor, the model without the Euro term reaches about 75%, and the full model about 90%, so the Euro term recovers only about 15 percentage points of the explained variance:

$$\Delta R^2_{Euro}(NOx) = R^2_{full} - R^2_{no\ Euro} = \ 0.90 - 0.75 \ \approx 0.15 \quad (15)$$

while for CO_2 the Euro class alone explains only about 3% of the variance and the full model about 99%, leaving its partial contribution smaller still.

$$\Delta R^2_{Euro}(CO_2) = 0.99 - 0.95 \ \approx 0.04 \quad (16)$$

Within the Euro 6 and Euro 6d classes alone, real-world NOx spans roughly an order of magnitude across fuels and configurations, and CO_2 spans from about 100 to about 260 g/km across segments. By the ten-percentage-point threshold adopted here the Euro contribution is negligible for CO_2, at about four points, but not for NOx, at about fifteen; even for NOx, however, it is far smaller than the diesel and after-treatment contribution, so the gating variable remains a weak predictor of the quantity the policy targets, most acutely for CO_2, which is the formal statement of the paradox. Table 5 reports the regression coefficients and the partial contribution of the Euro term for both pollutants.

Table 5. Fleet-weighted regression of real-world emission factors on vehicle attributes (standardised coefficients). The Euro term is a weak predictor once fuel, displacement and mass are included; diesel dominates NOx, while mass and displacement dominate CO_2. Because the emission factors are assigned from these same attributes, the table partitions the variance of the assigned factors rather than reporting an independently estimated relationship, and the significance markers describe fit within that decomposition.

Predictor	NOx (Standardised β)	CO_2 (Standardised β)
Euro stage (newer)	−0.39	−0.07
Diesel (vs. petrol)	+0.74	−0.05
Engine displacement	+0.10	+0.45
Kerb mass	+0.12	+0.66
R^2 of full model	0.90	0.99
R^2 without Euro term	0.75	0.95
Partial R^2 of Euro term	0.15	0.04

Because non-exhaust PM scales with mass and is independent of the Euro standard, the criterion cannot reduce it through the Euro label and may even raise it [14,21]. In the modelled fleet, the mean non-exhaust particulate emission is about 38.5 mg/km for the whole fleet and about 38.9 mg/km for the fleet admitted by the Warsaw and Kraków rule, and the admitted-fleet mean kerb mass rises from about 1450 to about 1470 kg. The stricter Euro criterion thus shifts the admitted fleet toward newer, heavier and larger vehicles, while the admitted-fleet non-exhaust burden barely moves, from about 38.5 to about 38.9 mg/km. A change of this size is within the resolution of a mass-based treatment and should not be read as a net effect of electrification: the mass-dependent factor does not resolve brake, tyre and road wear separately and does not credit the brake-wear reduction that regenerative braking delivers, so for the growing electric and hybrid share, the net direction is indeterminate under the present model. The robust conclusion is the negative one, that a Euro-based criterion cannot reduce non-exhaust PM because that burden tracks mass rather than the Euro standard, not that a stricter criterion raises it; the size of any mass effect still depends on how the brake, tyre and road components are apportioned, which the non-exhaust sensitivity range reflects. The effect is modest in the base case, but its direction is the opposite of the policy intent, and it grows with the share of heavy and electric vehicles, so it becomes more important as fleets renew [14,48]. Panel b of Figure 3 shows that only the mass-based criterion lowers the admitted-fleet non-exhaust particulate emission materially, to about 34 mg/km, while the Euro and fuel criteria leave it at or above the whole-fleet level.

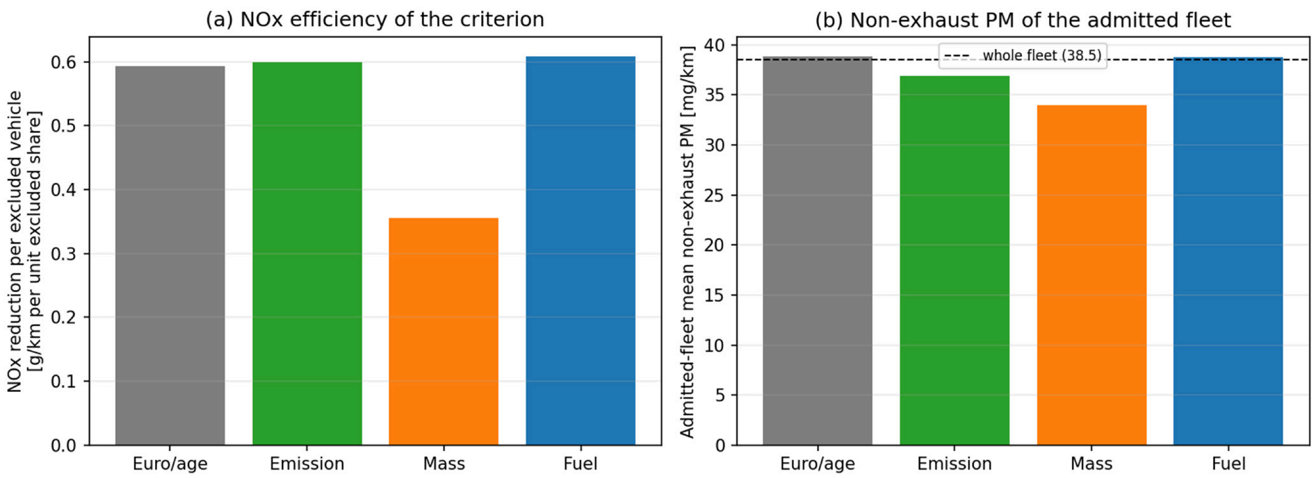

Figure 3. Criterion comparison on the modelled fleet at matched stringency. Panel (**a**) shows NOx reduction per excluded vehicle. Panel (**b**) shows the admitted-fleet mean non-exhaust particulate emission, with the dashed line marking the whole-fleet value.

Table 6 compares the four families of criteria at a matched excluded share of about 39–42%. The emission-based criterion dominates the Euro-and-age criterion on every pollutant, with larger reductions in NOx, CO_2 and PM while excluding fewer low-NOx petrol and LPG cars and admitting a lighter fleet. The fuel-based criterion, which removes diesel vehicles below the cleanest standard first, achieves the largest NOx reduction at about 88% and excludes the fewest low-NOx petrol cars, making it the most effective and most equitable for NOx. The mass-based criterion is the weakest for NOx, because mass does not identify diesel emissions, yet it is the only criterion that lowers the admitted-fleet mass and non-exhaust PM and it gives the largest CO_2 reduction. No single simple criterion is the best on every dimension, and this central design finding motivates a hybrid criterion combining a real-world emission threshold for NOx and CO_2 with a mass or footprint component for non-exhaust PM and a fuel adjustment that rewards low-pollutant alternative fuels. Results show that the Euro-and-age rule is matched or beaten on NOx, CO_2 and PM by at least one alternative of equal stringency, and that it turns away the largest share of low-NOx petrol and LPG cars, about 9.5% against 6.6% for the emission-based and 5.8% for the fuel-based rule, so its weakness is one of effectiveness and of equity at once.

Table 6. Criterion comparison on the modelled fleet at matched stringency. Reduction values are percentages of whole-fleet emission. The final column is the share of the fleet, made up of low-NOx petrol and LPG cars, that the rule excludes.

Criterion	Excluded [%]	NOx Reduction [%]	CO_2 Reduction [%]	PM Reduction [%]	Admitted Mean Mass [kg]	Admitted Non-Exhaust PM [mg/km]	Low-NOx Petrol Excluded [%]
Euro and age (Warsaw, Kraków)	39	80	40	48	1472	38.9	9.5
Emission-based	41	84	44	52	1397	36.9	6.6
Mass-based	39	48	45	47	1276	34.0	16.5
Fuel-based	42	88	42	50	1469	38.8	5.8

Because the headline figures are model estimates, their robustness was tested by varying the main assumptions one at a time around the base case. Table 7 reports the resulting ranges for the fleet NOx reduction and for the paradox rates of CO_2 and non-exhaust PM. The qualitative conclusion is stable across every variation: the NOx reduction stays high, between about 0.76 and 0.85, while the paradox remains small for NOx and large for the mass-driven pollutants, with the CO_2 paradox rate between about 0.45 and 0.52 and the non-exhaust PM paradox rate between about 0.28 and 0.37. The variables that move the results most are the diesel NOx conformity factor for the NOx reduction, and the share of heavy and sport-utility vehicles and the non-exhaust coefficient for the particulate paradox, which is consistent with the mechanism the paper identifies. Annual distance, held uniform across classes in the base case, is varied in a further scenario that gives diesel and LPG cars higher annual distance and the oldest classes lower distance (Table 7). Because the paradox rates compare emission factors pairwise, independently of the distance travelled, they are unchanged by this reweighting; only the fleet NOx reduction moves, falling by a few percentage points because the high-mileage diesel fleet contributes on both sides of the rule. The asymmetry between NOx and the mass-driven pollutants, which is the central finding, is therefore not an artefact of a particular parameter choice. The principal residual uncertainties, namely, the representativeness of the calibrated emission factors, the maturity of the non-exhaust factors and the use of parameterised rather than measured fleet shares, are revisited in the limitations.

Table 7. Sensitivity of the headline metrics to the main assumptions, from one-at-a-time variation around the base case. The reduction is the fleet NOx reduction; the paradox rate is the share of admitted-versus-excluded vehicle pairs in which the admitted vehicle is the higher emitter. In the class-dependent-mileage row, the paradox rates are unchanged from the base case because they are independent of the distance travelled, and the NOx-reduction range is indicative, to be confirmed on the full vehicle-class model.

Assumption Varied	Range Tested	NOx Reduction	CO_2 Paradox Rate	PM Paradox Rate
Base case	reference	0.80	0.48	0.32
Diesel NOx conformity factor	±30%	0.74–0.85	0.47–0.49	0.31–0.33
Cold-start share of urban trip	10–40%	0.78–0.82	0.47–0.49	0.31–0.33
Ambient temperature	−7 to +23 °C	0.79–0.83	0.47–0.49	0.31–0.34
Non-exhaust coefficient	±40%	0.80	0.48	0.28–0.36
Heavy and SUV share	±10 pp	0.78–0.81	0.45–0.52	0.29–0.37
Fleet Euro and fuel shares	±10 pp	0.76–0.83	0.45–0.51	0.30–0.35
Class-dependent mileage (VKT)	diesel/LPG higher, oldest lower	0.76–0.80	0.48	0.32

5. Discussion

The effectiveness literature shows that zones can improve air quality but that the gains are often modest and design-dependent [25,27]. The framework here locates one reason in the access criterion itself. Because the Euro class and the registration age are decoupled from real-world CO_2, NOx [7,9] and non-exhaust PM [13], an administratively strict rule can still admit high absolute emitters and exclude low ones. The case study makes this concrete and reveals an asymmetry the qualitative paradox alone does not show. The Warsaw and Kraków criterion reduces fleet NOx strongly, by about 80%, because the oldest vehicles in the Polish fleet are the high-NOx diesels, so for NOx the criterion is reasonably well-aligned with the source. For CO_2 and PM, the same criterion is poorly aligned, admitting the higher emitter in about 48% and 32% of vehicle pairs respectively, because these pollutants track mass and size rather than age. Two structural trends documented by others, the real-world emissions gap [6,7,22] and the shift toward heavier, larger vehicles [11,12,40], explain why the proxy succeeds for one pollutant and fails for the others. The lesson is not that zones are ineffective, but that a substantial part of their potential benefit, in carbon and in particles, is forgone when the access criterion is keyed to a label that does not reflect those emissions.

London makes this point sharply. The municipal authority attributes meaningful reductions in NOx and exhaust fine PM to the most recent ULEZ expansion [23,24], while an independent evaluation built on other British sites found no statistically significant change in nitrogen dioxide or nitrogen oxide once wider trends were considered [29]. Both could be partly right: a scheme that removes a small number of the very oldest vehicles while admitting a fleet that has grown heavier and more diesel-intensive at the upper end can deliver only a limited net change. This is consistent with the German finding that most of the benefit comes from removing the oldest vehicles and that admitting only higher Euro classes adds little [25]. The criterion is the mechanism through which that limited change arises, and it is therefore the natural place to intervene.

The variance decomposition formalises a well-supported intuition, and although it partitions factors that were themselves assigned from these attributes rather than independently measured, the split it produces is consistent with the on-road literature: the two quantities the policy cares about are governed by different physical attributes. CO_2 rises systematically with engine size and mass, whereas NOx depends far more on fuel and after-treatment than on engine size [7,57]. A single Euro class captures neither; the within-class dispersion of real-world emissions is correspondingly large [9,22]. The differences are amplified by the urban context, because the warm-up phase dominates urban NOx and many urban trips are too short for the after-treatment system to warm up, so the gap between a clean small petrol car and a large diesel is widest under exactly the conditions a zone addresses [51]. Two consequences follow for criterion design. Vehicles should be evaluated under urban driving with a realistic cold-start share rather than under a steady-state catalogue value, because the catalogue value understates the differences that matter. Additionally, the benefit of a given criterion depends on local trip patterns and climate, so a criterion that performs adequately in a temperate setting with longer trips may perform worse in a colder one with shorter trips. That is an argument for criteria tailored to local conditions rather than transferred uncritically between cities.

The trend toward heavier vehicles connects the analysis to a wider debate about how emission regulation is designed. The extra mass that raises CO_2 also raises non-exhaust PM, a component largely independent of the Euro standard and growing in relative importance as exhaust PM falls [14,21]. A striking parallel sits in the European CO_2 standard for new cars, whose manufacturer target is adjusted by fleet mass, so heavier fleets receive a more lenient target. Analysts say this mechanism now rewards heavier vehicles and should be replaced by a footprint parameter or removed [42,44]. The criterion used by a low-emission zone and the parameter used in the CO_2 standard share the same weakness: both can reward an attribute that does not reduce, and may increase, the quantity the policy intends to limit. For zone design, the implication is that a criterion ignoring mass misses both the non-exhaust and the carbon dimensions, and that a mass or footprint component would address what a Euro label alone cannot.

The criterion comparison is reported with the results in Section 4, so what matters here is what its ranking implies for design: no single simple rule is best on every dimension, and that is the design finding rather than a caveat to it. The fuel-based criterion ties the analysis to the alternative-fuels theme of this Special Issue: admitting vehicles by energy carrier, and rewarding renewable diesel, compressed natural gas and biomethane, LPG, hydrogen and electricity, offers a transparent route to lower combustion emissions in the zone, provided the real-world performance of each fuel is used rather than a nominal label. A hybrid criterion that combines a real-world emission threshold with a mass or footprint component and a fuel adjustment is therefore the practical recommendation, because a single Euro label cannot capture the pollutant, carbon and non-exhaust dimensions at once.

That recommendation rests on combustion detail, because the real-world ranking of fuels is governed by combustion and after-treatment behaviour rather than by the Euro label. Spark-ignition engines running on petrol, LPG or compressed natural gas hold their three-way catalyst near stoichiometric conditions and emit little NOx once warm, whereas a diesel must keep its selective catalytic reduction or lean-NOx trap above the light-off temperature to control NOx, which urban driving and cold starts frequently prevent [38,50]. Compressed natural gas and biomethane lower CO_2 and particulate mass, and bi-fuel LPG vehicles show low NOx, although natural gas can raise NOx relative to gasoline depending on calibration [50]. Renewable diesel and biomethane reduce the carbon intensity of the same engine without changing its NOx signature, so a fuel-aligned criterion must reward measured rather than nominal performance. Two combustion mechanisms deserve particular weight in an urban zone. First, gasoline direct injection has reversed the historical particle ranking, so direct-injection petrol cars without a filter can emit high particle numbers [47,49] and need a gasoline particulate filter to match the port injection, which most new direct-injection petrol cars now carry [55]. Second, the cold start and the warm-up dominate urban emissions, since for spark-ignition engines the first minutes contribute most of the trip NOx, carbon monoxide and hydrocarbons [20,30], and the effect worsens sharply at low ambient temperature [51], while the diesel start-up is itself a distinct high-emission and high-wear state [31]. A criterion that scores vehicles on real urban, cold-inclusive emissions captures these mechanisms, whereas a Euro-and-age label does not.

Such a criterion is also easier to reconcile with the equity evidence. Poorer communities are exposed to more pollution while owning fewer cars [2], and access restrictions impose higher relative costs on households with fewer adaptive resources [15]. A criterion that excludes low-emitting small and older cars while admitting high-emitting new ones is regressive in a specific sense, transferring the cost to owners of modest vehicles for little environmental return. In the case study the Euro-and-age criterion excludes a larger share of the low-NOx petrol and LPG fleet than a fuel-based criterion of equal stringency, about 9.5% against 5.8%, and that gap quantifies the regressive effect. Targeted support helps, as the London scrappage grants and the Brussels mobility budget show [16], but the present analysis suggests the criterion itself can be made fairer, not only the support around it, because an emission- or fuel-aligned rule matches the burden more closely to the actual contribution to pollution. This connects the engineering analysis to the broader literature on the acceptability and legitimacy of clean transport zones, where procedural fairness and the perception that costs are justly distributed are decisive for public support [15,32].

Several limitations qualify the conclusions. The analysis depends on the quality and representativeness of the emission factors and on their real-world calibration, and both the inventory models and the real-driving datasets keep evolving, with the newest diesels certified under the real-driving-emissions procedure performing markedly better than earlier ones, an improvement the class resolution must capture [8]. A related caveat is that the model relies on class-average emission factors rather than vehicle-specific measurements, so the within-class spread of real-world behaviour enters only through the calibration; this is the main input-data uncertainty, and it propagates most strongly to diesel NOx, which is why the NOx conformity factor is explicitly varied in the sensitivity analysis. The in-zone activity by class, in vehicle–kilometres, is estimated and carries uncertainty. The case-study fleet is reconstructed from aggregate marginal statistics rather than from vehicle-registration microdata, so it reproduces the observed shares of age, fuel and segment but may not capture their exact joint distribution, and the base case assumes uniform annual mileage across classes. These are examined in the sensitivity analysis, where the mileage assumption is varied directly (Table 7) and departures of the joint distribution from the observed marginals are bounded by the fleet-share sensitivity and by an additional test that pushes the age-fuel-segment correlation to a plausible extreme. A joint distribution that departs from the observed marginals would alter the mix of mass and Euro stage within the admitted set, while class-dependent mileage would raise the weight of the diesel fleet, which drives NOx, relative to the oldest classes, which drive neither CO_2 nor mass. The first effect bears on the paradox metrics and the second chiefly bears on the NOx reduction, so the asymmetry between NOx and the mass-driven pollutants is unlikely to be reversed by either, though its magnitude would move. Both simplifications would be removed by substituting the vehicle-registration microdata that the model already accepts. The non-exhaust factors are less mature than the exhaust factors, and the literature reports a wide range of values depending on method and conditions [14,21]. Resolving the non-exhaust burden into its brake, tyre, road-abrasion and resuspension components, and testing an explicit regenerative-braking credit for hybrid and battery–electric vehicles so that the drivetrain effect is separated from the mass effect, is the priority extension of the model and the natural next step once component-level factors are adopted. The framework is a static emission accounting and does not model behavioural responses to the rule, such as fleet renewal, vehicle substitution or the displacement of trips, which would need a complementary fleet-turnover or equilibrium model and which other authors identify as important for the welfare and accessibility effects of zones [15,32]. Finally, the case study reflects the fleet and conditions of one city, so the metrics are transferable but the magnitudes are not, and the results for a Polish city should not be assumed to hold where the fleet composition and climate differ.

Several extensions would strengthen the analysis. The most valuable would add primary on-road measurements with a portable emissions measurement system for a sample of vehicles representative of the local fleet, replacing the calibration of inventory factors with direct evidence and reinforcing the combustion dimension of the work. A second would couple the static accounting with a fleet-turnover model to estimate how an emission-aligned criterion would shape vehicle purchases over time. A third would integrate the criterion comparison with a model of public acceptability and equity, so the design recommendation accounts for both environmental and social objectives. A fourth would apply the framework to several cities with different fleets and climates, testing the transferability of the metrics and identifying criteria that are robust across contexts.

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6. Conclusions

Low-emission zones gate vehicle access chiefly by the Euro emission standard and the registration age, yet a large body of real-world evidence shows these labels are weakly connected to the actual emissions of internal combustion engine vehicles. The gap between certified and on-road emissions is large for diesel NOx and for CO_2, and engine size and vehicle mass, which both raise CO_2 and non-exhaust PM, are not part of the classification. The result is a measurable paradox in which newer, compliant, large vehicles can out-emit excluded older, smaller ones.

This paper set out an emission-accounting framework, set of paradox metrics, a descriptive variance decomposition of the assigned emission factors and a counterfactual comparison of emission-based, mass-based and fuel-based access rules on a modelled fleet, with the Polish clean transport zones of Warsaw and Kraków as a concrete, current case. A model parameterised on published Polish fleet statistics and on real-world emission factors quantifies the mechanism. The Warsaw and Kraków criterion reduces fleet NOx by about 80%, because the oldest vehicles are high-NOx diesels, but admits the higher emitter in about 48% of vehicle pairs for CO_2 and about 32% for PM; the Euro class alone explains only about 3% of the variance in real-world CO_2; and the stricter criterion slightly raises the non-exhaust particulate burden of the admitted fleet. At matched stringency, emission-based and fuel-based criteria reduce more of every pollutant while excluding fewer low-emitting small cars, and a mass or footprint component is needed for non-exhaust PM, which is why a hybrid criterion is recommended. The figures are model estimates parameterised on published statistics and should be confirmed with vehicle-registration microdata, which the supplied model accepts directly. Designing zone access around real combustion emissions, rather than around a regulatory label, is a low-cost, high-leverage way to align the instrument with its own objective, and it connects the engineering of internal combustion engine emissions to the design of the urban policies that increasingly govern where those engines may operate.

Returning to the three research questions, the analysis gives clear answers. First, the gating variable is a weak predictor of the emissions a zone targets: the Euro class explains only about 3% of the fleet-weighted variance in real-world CO_2 and recovers about 15 percentage points of explained variance for NOx, while real-world NOx and CO_2 each span roughly an order of magnitude within a single Euro class. Second, the paradox is strongly asymmetric across pollutants. It is small for NOx, where the admitted fleet contains the higher emitter in only about 5% of vehicle pairs, but large for the mass-driven pollutants, reaching about 48% for CO_2 and about 32% for non-exhaust PM, so a criterion that succeeds for NOx fails for carbon and particles. Third, at matched stringency the emission-based and fuel-based criteria dominate the Euro-and-age rule on every pollutant while excluding fewer low-emitting small cars, the mass-based criterion alone lowers the non-exhaust burden of the admitted fleet, and no single simple rule is best on every dimension, which is why a hybrid criterion that combines a real-world emission threshold for NOx and CO_2 with a mass or footprint component for non-exhaust PM and a fuel adjustment is the recommended design.

Contribution to the Literature: This study connects four bodies of work that are usually pursued separately, namely the evaluation of low-emission zones, the measurement of the type–approval gap, the analysis of non-exhaust and cold-start emissions, and the equity of access restrictions, and it joins them by making the access criterion itself the object of analysis. Its specific contributions are a reusable emission-accounting framework that scores a zone criterion as a classifier against real-world internal-combustion-engine emissions; a set of transparent paradox metrics, namely reduction, paradox rate, misallocation and reduction per excluded share, that make the mismatch quantifiable and comparable across

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cities; and a like-for-like comparison of emission-based, mass-based and fuel-based criteria that turn the critique into a concrete design recommendation. By grounding the case study in Polish clean transport zones and in real-world emission factors, and by releasing the model in a form that accepts registration microdata, the work offers both a method and a baseline that other studies can extend to different fleets, climates and policy designs.

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