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CARES

CITY AIR REMOTE EMISSION SENSING

Deliverable D4.5 – Report on real-world emission factors and impact of low-emission zones

WP 4
Task 4.3
Deliverable 4.5

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CARES website: https://cares-project.eu/

Executive summary

Here we present three use cases for remote emission sensing as demonstrated by measurements in Krakow, Milan and Prague:

- Determine the emission performance by vehicle family,
- Identify high-emitting trucks and their extra emissions,
- Determine the impact from Low Emission Zones.

We find that average NO_X emissions from diesel cars have decreased significantly with RDE requirements, i.e., for Euro 6d-TEMP and Euro 6d emission stages. Most vehicle families perform well within the RDE limit, but a few shows higher emissions. These vehicle families are suggested to be chosen for follow-up testing to check on their in-use compliance.

Plume chasing measurements have collected reliable evidence on the fleet share and contribution from high NO_X emitting trucks: Almost 60% and more than 33% of Euro V and Euro VI trucks respectively are found with suspicious to high emissions. On average these malfunctioning vehicles double the NO_X emissions compared to a clean fleet. Demonstration with roadside inspection have shown that their identification is robustly possible.

Finally, the impact of low-emission zones and the extra contribution from high-emitting vehicles are estimated. Careful on-road measurement help determining those segments of the fleet that have smaller shares of the activity but high shares in the total pollutant emissions. Well-designed measures e.g. for Krakow are estimated to reduce NOx and PM emissions from the car fleet by about 20 to 25%, while affecting only 7% of the fleet.

Attainment of the objectives and explanation of deviations

Description of work related to deliverable as given in the DoW

The original DoW states: “Report on real-world emission factors by vehicle/engine family, on best/worst performing vehicle types, including Euro 6 and RDE emission standards, on meteorological influences, on high-emitter shares and on the impact of urban area low emission zones.”

Time deviation from original DoW

The original plan was to deliver month 33. However, the last measurement campaign in Prague had been postponed to September 2022. In accordance with the partners, we therefore also postponed this deliverable.

Content deviation from original DoW

No deviation from original work plan. However, the analysis of meteorological influences was found to be better placed in the reports for the individual campaigns (WP 3) and was hence moved there.

Table of Contents

1. Introduction

Remote sensing technology can measure emissions from in-use vehicles in real operation setting. Real-world emission measurements are critical to impactful policy making because emission discrepancies exist not only between vehicles on the testing bed and on the road but also across different cities and regions. In addition to real-world emissions information, remote sensing measurements, if measured in locations representative of the city, also provide insight into the composition and the activity of the city's fleet. Understanding the traffic and vehicle emissions characteristics of a particular city is key to effective transportation policy making.

Within the context of the City Air Remote Emissions Sensing (CARES) project, emissions testing was conducted using various remote sensing technologies in three European cities: Milan, Krakow, and Prague. Commercial remote emission sensing technology was deployed in all three cities, collecting a total of over 285,000 measurements. Remote sensing instruments from two different providers were deployed in three cities with various testing conditions, covering a range of weather conditions, topographies, and vehicle power demands. A data set of this scale can be used in aggregate to uncover vehicle emissions trends in the European regions and inform EU-level policies. On a more granular level, the city-specific data sets can be used to assess the effectiveness of current or planned local transportation policies.

This report presents the primary findings from the CARES city demonstration campaigns and the ways in which these findings are used to inform evidence-based policy. First, by focusing on NO_X emissions from various vehicle families we show that there still exist large discrepancies between emission levels from vehicles in real driving conditions and emission levels manufacturers claim their vehicles emit. Such discrepancies suggest that some manufacturers have not improved the emission performance of their vehicles previously type-approved to Euro 5 and Euro 6 (registered until September 2017 and required no on-road emissions testing) since the European Justice Court's rulings that prohibited the use of illegal defeat devices for manipulation of emissions[1]. For vehicles type-approved to the Euro 6d-TEMP and Euro 6d standards, additional real driving emissions (RDE) testing is required to ensure that emissions control systems operate effectively outside the test-cycle environment. The real-world emissions from these vehicles show that only very few vehicle families may be emitting excessive NO_X emissions, indicating the need for continued market surveillance.

The results from the remote sensing data gathered from each city can also be used to evaluate if local policies, more specifically low-emission zones, can effectively reduce excessive emissions from on-road vehicles. A low-emission zone is an area where the access of certain vehicle groups, typically defined by vehicle category and emission standard, is somehow restricted. There have been many and long-standing examples in Europe with different schemes[2]. Here we focus on the two cities of the CARES project that are in the process of implementing zones: Milan introduced a low-emission zone that covers 75% of the city in 2019, two years before the remote sensing measurements were collected, and Krakow recently announced its plan to implement a low-emission zone starting 2026. The CARES remote sensing measurements from the two cities were used to estimate the impacts of the low-emission zones on air pollutant emissions and additional policy recommendations are provided to enhance their LEZ implementation.

1.1. Objectives and scope of this report

Here we present a summary of the analysis with the focus on light-duty vehicles as measured by the commercial instruments by HEAT and OPUS. The purpose is to go beyond fleet and class average emissions and to compare emissions across vehicle manufacturers. This serves as example how RS can contribute to fleet monitoring and ISC testing by identifying vehicle classes, models, production years, etc., that stand out in terms of their emission performance.

[1] CJEU, Case C-693/18, Official Journal of the European Union (European Court of Justice 2020).

[2] https://urbanaccessregulations.eu/low-emission-zones-main

In addition, we present sample calculations for Milan and Krakow, using the real-world emission measurements, on the possible impact of policy measures. Both cities have plans to establish low-emission zones but with different stringency and specifications. This illustrates the use of RS measurements for informing local policy actions. All in all, we cover the following number of vehicles (Table 1). About 60% of all vehicles measured in Krakow, Milan and Prague are passengers certified to Euro 5 or younger emission standards. For background information on the individual measurement campaigns please refer to the dedicated CARES report3.

Table 1: Number of valid remote sensing records by measurement location and vehicle layer (=combination of propulsion fuel and Euro certification) collected in the CARES campaigns 2021 and 2022.

	propulsion	all valid records	PC Euro 5	PC Euro 6b,c	PC Euro 6d-TEMP	PC Euro 6d
Krakow (OPUS RSD 5500)	Diesel	42,069	7,590	8,190	1,791	934
	Gasoline	53,491	9,269	14,397	5,006	3,824
	LPG or CNG	24	2	2	6	0
Milan (HEAT)	Diesel	10,984	2,751	3,089	1,516	671
	Gasoline	15,568	2,666	3,757	2,713	1,702
	LPG or CNG	146	27	1	31	1
Prague (OPUS RSD 5500)	Diesel	60,571	11,769	13,159	5,803	4,334
	Gasoline	38,109	5,833	8,438	6,043	5,976
	LPG or CNG	930	86	94	142	266

Last but not least, the share and contribution from high-emitting vehicles is estimated: There have been enough plume chasing measurements conducted in combination with confirmatory road-side inspections. This allows first verifying the chosen approach and high-emitter thresholds; second, we can conclude on the share and extra contribution to total NOX emissions from trucks on highways.

2. NO_X emissions from diesel passenger car families

There is established evidence that vehicles, particularly those with diesel engines, emit high levels of NO_X emissions in real driving conditions[4,5,6]. The introduction of three-way catalysts in the early 1990s drastically reduced the emissions of nitrogen oxides (NO_X), carbon monoxide (CO), and hydrocarbons (HC) from petrol vehicles and their particulate matter (PM) emissions have always been low. Diesel vehicles, however, have known to have high levels of NO_X and PM emissions and in real driving conditions these emissions often increase, exceeding the regulatory emissions limits vehicles need to meet before being placed on the market.

Emissions in real operating conditions differ from type-approval limits, or regulatory limits, due to a number of reasons. At type-approval, vehicles are tested under a controlled environment which does not cover a range of power demands and speeds often seen in urban driving conditions. In cities, the distances that vehicles travel are usually limited, which leads to a common use of cold engines, a condition prone to excessive emissions. Malfunctions and poor maintenance of vehicles are also additional causes of high emissions.

The diesel exhaust emission scandal that broke in 2015 further revealed that some manufacturers were deploying auxiliary emissions strategies (AES) to limit NO_X emission controls in normal operating

[3] Bernard, Y., et al. (2023) CARES Deliverable D3.4 – Summary report on partner cities' measurements campaigns (https://cares-project.eu/).

[4] Norbert Ligterink, 'Real-World Vehicle Emissions', 2017-06, 2017, https://www.itf-oecd.org/sites/default/files/docs/real-word-vehicle-emisions.pdf.

[5] G.O. Duarte, G.A. Gonçalves, and T.L. Farias, 'Analysis of Fuel Consumption and Pollutant Emissions of Regulated and Alternative Driving Cycles Based on Real-World Measurements', *Transportation Research Part D: Transport and Environment* 44 (May 2016): 43–54, https://doi.org/10.1016/j.trd.2016.02.009.

[6] Lijun Hao et al., 'Remote Sensing of NO Emission from Light-Duty Diesel Vehicle', *Atmospheric Environment* 242 (1 December 2020): 117799, https://doi.org/10.1016/j.atmosenv.2020.117799.

conditions, leading to widespread excess emissions from diesel vehicles in real-world driving[7]. The disclosure of the use of so-called defeat devices prompted the assessment of vehicle emissions performance on the manufacturer level. In order to address the discrepancy between emissions in the real-world and the laboratory, the European Commission further adopted a regulation requiring real driving emissions (RDE) testing to complement laboratory testing from vehicles produced from September 2017 and onward. During RDE testing, these vehicles are subject to on-road emissions limits defined by the conformity factor, the factor by which the vehicle is allowed to emit above the type-approval limit.

This section focuses on the emissions performances of various vehicle families found in the emissions measurements conducted in Milan, Krakow, and Prague during the CARES project. **Vehicle families are defined by the combination of manufacturer group and engine displacement**, to account for the fact that emissions performance depends on the engine and grouped manufacturers have the same engine providers, as well as differences in engine performance by size. The manufacturer groupings are given in the Appendix: Manufacturer groupings.

The results are presented in distance-specific emissions per distance travelled (milligram NO_X per km. These values were converted from fuel-specific emissions (milligram NO_X per kg fuel consumed), the unit of emissions that remote sensing technology typically uses as follows: The type-approval CO_2 emissions, declared by each manufacturer and model, are proportional to the specific fuel consumption. This value is increased by the average gap factor accounting for the difference between type-approval test and real-world consumption[8]. Thus the average real-world fuel consumption is obtained and the product of emission in [g/kg] and fuel consumption in [g/km] gives the distance specific emission in [mg/km]. The following discusses first the NO_X emissions of modern pre-RDE vehicles and then that of post-RDE vehicles.

2.1. Euro 5 and pre-RDE Euro 6 cars

In the aftermath of the diesel exhaust emission scandal and the recent European Court of Justice's rulings prohibiting the use of auxiliary emissions strategies (AES) to circumvent emissions testing, vehicles with defeat devices were recalled. Most fixes were related to software updates on vehicles certified to Euro 5 and Euro 6. However, little was known about the specifics and effectiveness of those fixes[9]. Here we summarize the observed NO_X emission performance of Euro 5 and Euro 6 vehicle families in the three cities Krakow, Milan, and Prague., where CARES measurements were conducted.

All 26 Euro 5 diesel vehicle families identified in the aggregated CARES data show mean real-world NO_X emissions multiple times above the type-approval limit of 180 mg/km, though there is some variance between cities (Figure 1). The variance in emissions across cities is likely attributable to different measurement conditions: There were site differences in the three cities, such as road slope, vehicle speed and acceleration, and resulting power demand of the measured vehicles. Additionally, the three testing campaigns were conducted in different times of the year with the Krakow testing taking place in winter, which may explain some of the highest mean NO_X emissions from vehicle families measured in Krakow. The variance may also stem from differences in instrument performance, as the HEAT systems were used in Milan while the OPUS systems were used in Krakow and Prague.

[7] EP, 'REPORT on the Inquiry into Emission Measurements in the Automotive Sector (2016/2215(INI))', Final Report (Brussels, Belgium: European Parliament, Committee of Inquiry into Emission Measurements in the Automotive Sector, 2 March 2017).

[8] Yoann Bernard, Jan Dornoff, and David C. Carslaw, 'Can Accurate Distance-Specific Emissions of Nitrogen Oxide Emissions from Cars Be Determined Using Remote Sensing without Measuring Exhaust Flowrate?', *Science of The Total Environment*, November 2021, 151500, https://doi.org/10.1016/j.scitotenv.2021.151500.

[9] Yoann Bernard and Chelsea Baldino, 'Will the Future RDE Regulation Be Enough to Restore Trust in Diesel Technology?', *ICCT* (blog), 30 August 2017, https://theicct.org/will-the-future-rde-regulation-be-enough-to-restore-trust-in-diesel-technology/.

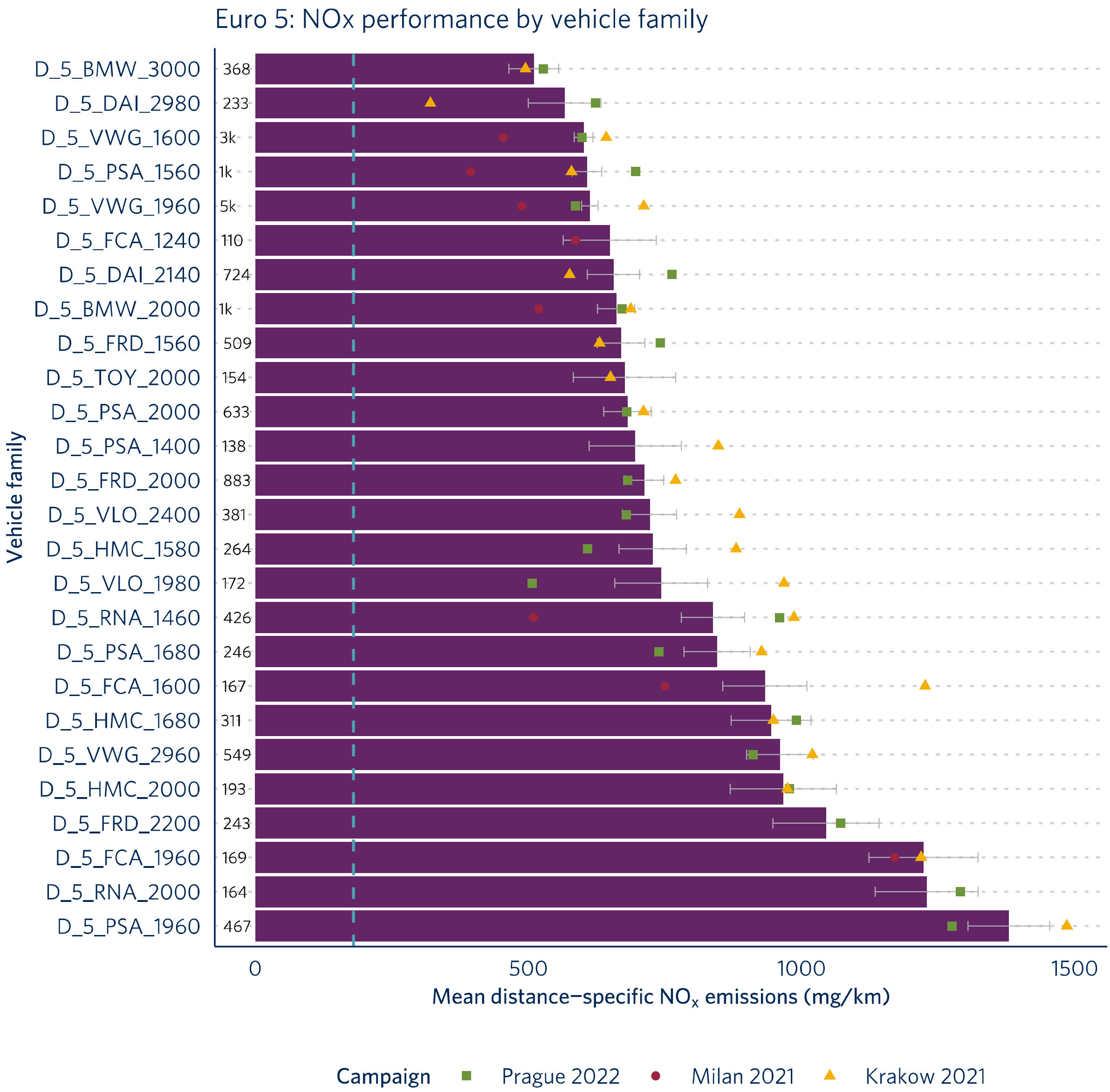

Figure 1. Mean distance-specific NOx emissions (mg/km) from diesel Euro 5 vehicle families identified in the three CARES remote sensing measurements. Individual cities are indicated in respective shapes. The blue dotted line refers to the type-approval limit of 180 mg/km. Whiskers indicate the 95% confidence interval of the mean. The number of observations is given at the y-axis; only vehicle families with 100 or more measurements are presented.

The highest-emitting vehicle families certified to Euro 5 were from PSA group, Renault-Nissan Automobiles, Fiat Chrysler Automobiles, and Ford (PSA 1950-1970cc engines, RNA 1990-2010cc engines, FCA 1950-1970cc engines, and Ford 2100-2300cc engines in Figure 1). Their mean real-world NO_X emissions were above 1000 mg/km, or over five times the regulatory limit. Fiat Chrysler Automobiles and Renault-Nissan are some of the manufacturers that claimed to have updated their software[10] to correct the defeat devices, but the real-world data from three major European cities puts the effectiveness of these updates into doubt.

32 vehicle families from pre-RDE Euro 6 diesel vehicles had enough RS records (≥100) measured in the three cities. Their average emission performance improved relative to the previous generation but still all 32 vehicle families showed mean NO_X emissions exceeding the type-approval limit of 80 mg/km (Figure 2). The highest emitting vehicle family was Hyundai Motor Company’s 2000cc and these vehicles show consistently high emissions in Krakow and Prague, the two cities where the

[10] Daimler, Opel, and Volvo being other manufacturers with software updates.

vehicle family was identified. It was followed by Renault-Nissan 1600cc (RNA), Daimler 1600cc (DAI), and Fiat Chrysler Automobiles (FCA) 1960cc, manufacturers of which allegedly introduced software fixes to lower their emissions. Again, these real-world measurements put the effectiveness of these updates into doubt.

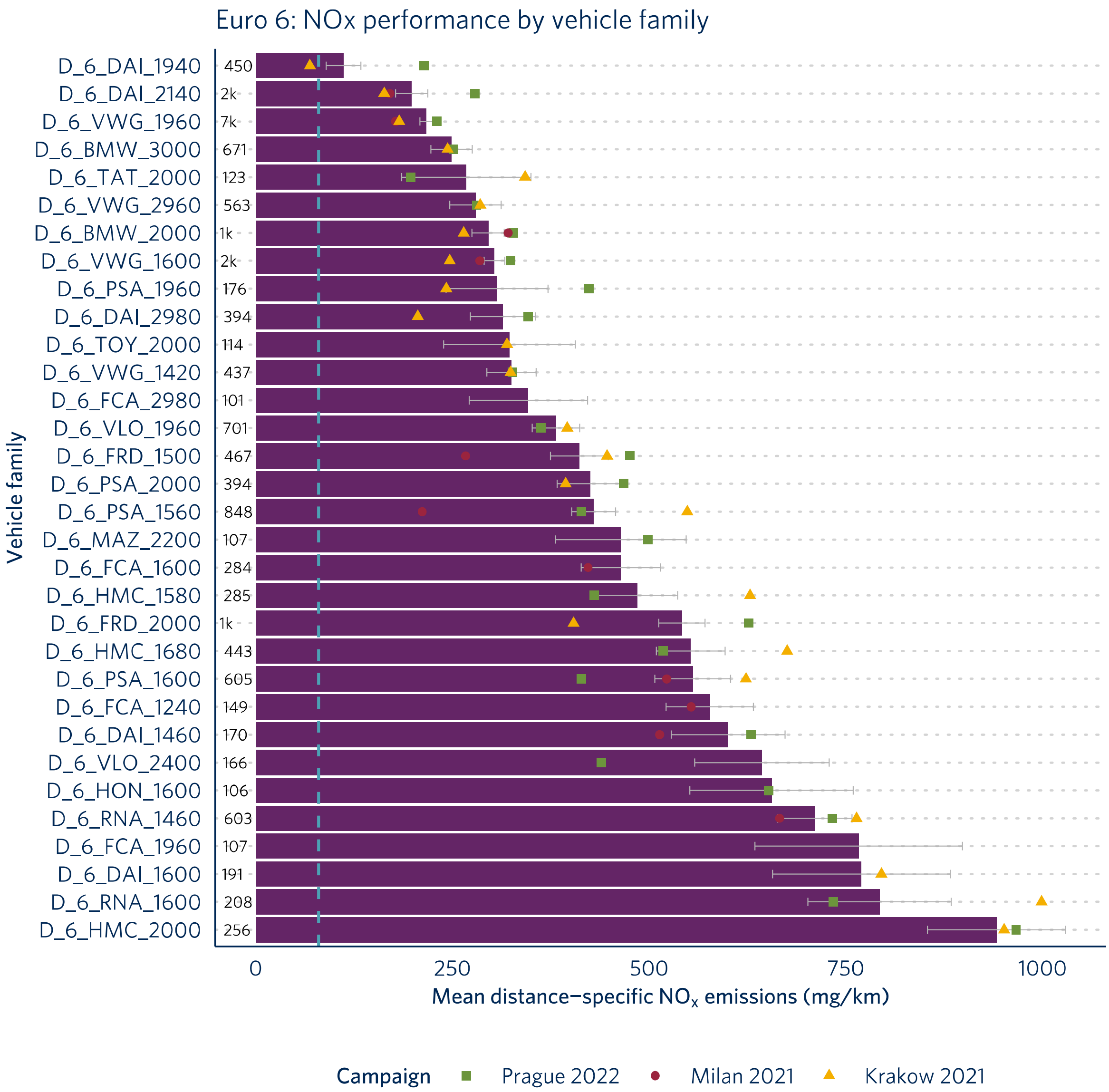

Figure 2. Mean distance-specific NOx emissions (mg/km) from diesel pre-RDE Euro 6 vehicle families identified in the CARES remote sensing measurements. Individual cities are indicated in respective shapes. Blue dotted line refers to the type-approval limit of 80 mg/km. Whiskers indicate the 95% confidence interval of the mean. Only vehicle families with 100 or more measurements are presented.

The best performing diesel vehicle family is equipped with the Daimler 1930-1950cc engines (D_6_DAI_1940); their mean NO_X emissions are only 40% above the type-approval limit and thus would already comply with the more stringent Euro 6d-TEMP emission standard. It is half the emission level of the runner-up, also from the Daimler family (2130-2150cc engines). However, good performance of some engines does not ensure equally good performance of other engines from the same manufacturer: The Daimler 1600cc engines and the Daimler 1460 cc engine belong to the ten worst engine families, that have NO_X emissions above 500 mg/km on average.

The NO_X results from the pre-RDE Euro 5 and Euro 6 vehicle families from the CARES sample demonstrate that diesel vehicles certified to Euro 5 and Euro 6 in Europe are still emitting excess NO_X emissions seven years after the “dieselgate” scandal. The results show that high levels of NO_X emissions are seen in vehicle families across the board, not only in certain vehicle families. Most of the vehicle families were emitting consistent levels of NO_X emissions across the three European cities, signaling that the problem of excess NO_X emissions from pre-RDE diesel vehicles is widespread across Europe.

Moreover, even vehicle families from the manufacturers that have announced recalls of vehicles with defeat devices or issued software updates, such as Volkswagen, Fiat Chrysler Automobiles, Daimler, and Renault Nissan Group, still were emitting NO_X emissions greatly exceeding the emissions limits, questioning the effectiveness of such fixes and the sufficiency of the enforcement following the updates.

Therefore, continued monitoring – and corrective actions – are recommended. In fact, those vehicle groups are known and easily traceable targets for reducing high-emissions.

2.2. Euro 6d-TEMP and Euro 6d (post-RDE) cars

Since 2017, type-approval for passenger cars in Europe includes the Real-Driving Emissions (RDE) test using on-board portable emissions measurement systems (PEMS)[11,12]. This was introduced to ensure that the vehicle is tested under conditions similar to normal, real-world operating conditions. During an on-road test, the vehicle must stay below a not-to-exceed limit, defined as the product of a conformity factor and the type-approval limit value of 80 mg/km. The conformity factors for Euro 6d-TEMP and Euro 6d norms are 2.1 and 1.43, respectively. This section examines the real-world NO_X emissions from vehicle families subject to RDE testing, namely Euro 6d-TEMP and Euro 6d, in comparison to the not-to-exceed RDE emission limits to shed light on the effectiveness of the RDE regulations.

The most modern vehicles are, naturally, not so abundant in the fleet: Only 14 Euro 6d-TEMP diesel vehicle families have been measured between 100 and 3000 times in the three cities. Overall, Euro 6d-TEMP diesel vehicles performed significantly better than Euro 6 diesel vehicles (Figure 3). 10 out of 14 Euro 6d-TEMP vehicle families were emitting NO_X at levels below the RDE limit of 168 mg/km. The variance appears high but is due to lower sample numbers and the much lower absolute emission level.

[11] Comision de Regulacion de la Union Europea, 'COMMISSION REGULATION (EU) 2016/427', 10 March 2016, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32016R0427&from=SL.

[12] Commission Regulation (EU) 2016/646, 'Commission Regulation (EU) 2016/646 of 20 April 2016 Amending Regulation (EC) No 692/2008 as Regards Emissions from Light Passenger and Commercial Vehicles (Euro 6)' (2016), http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2016.109.01.0001.01.ENG.

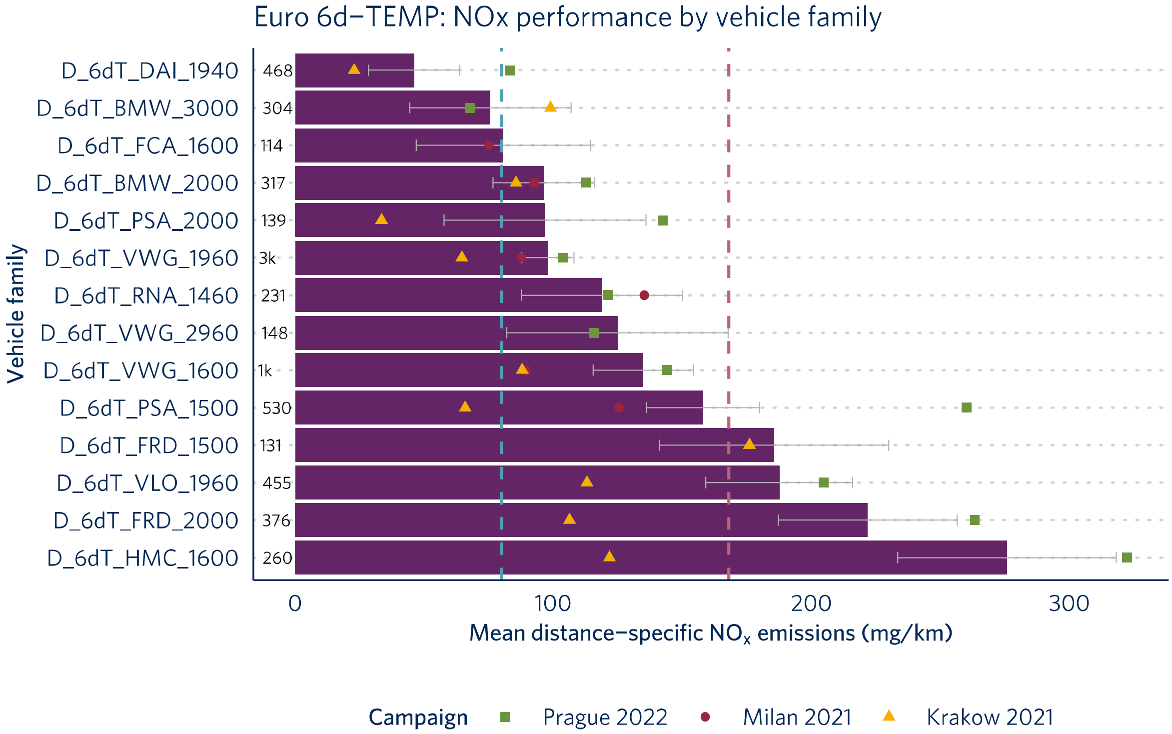

Figure 3. Mean distance-specific NOx emissions (mg/km) from diesel Euro 6d-TEMP vehicle families identified in the CARES remote sensing measurements. Individual cities are indicated in respective shapes. Blue dotted line refers to the type-approval limit of 80 mg/km and red dotted line to the RDE limit of 168mg/km. Whiskers indicate the 95% confidence interval of the mean. Only vehicle families with 100 or more measurements are presented.

The Daimler 1930-1950cc engine family is the best performing Euro 6d-TEMP vehicle family – as it was already among the Euro 6 families. Their mean NO_X emission is below the below the type-approval limit of 80 mg/km, i.e. without any conformity factor. Hyundai Motor Company with 1600 cc engine was again the manufacturer of the highest-emitting vehicle engine family, with mean NO_X emissions exceeding the RDE limit by around 65%; followed by the Ford 2000cc engine vehicle family. However, it is noteworthy that the RDE limit was complied with during the earlier measurements (outside CARES) in Krakow 2019.

The Euro 6d standard became mandatory in January 2021; therefore only 12 vehicle families had more than 100 measurements, and these come mostly from the campaign in Prague that took place in September 2022. 9 out of 12 vehicle families showed mean real-world NO_X emissions lower than the RDE limit of 114mg/km (Figure 4). Volkswagen 1960cc and again Daimler 1940cc families were the best performing vehicle families with relatively minor variance in emission performance across different cities. The Hyundai Motor Company 1600cc engine family showed (again) the highest mean NO_X emissions for Euro 6d diesel vehicles; however, the level of 170 mg/km is much lower than the previous generations. The bigger variance across the engine families reflects of low sample numbers and low absolute emission levels.

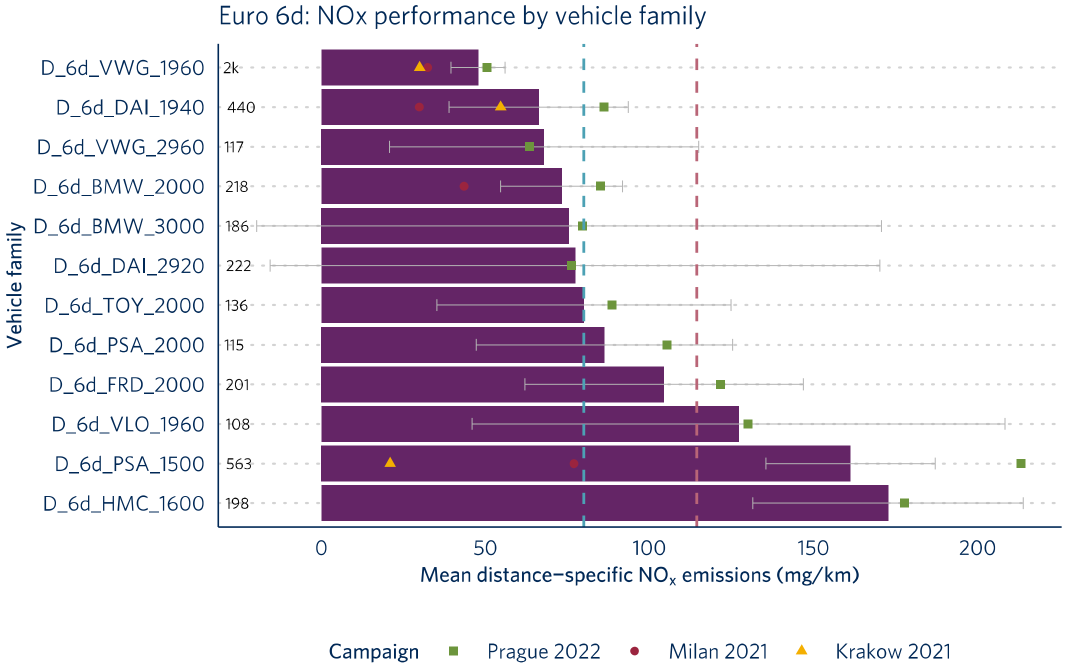

Figure 4. Mean distance-specific NOx emissions (mg/km) from diesel Euro 6d vehicle families identified in the CARES remote sensing measurements. Mean distance-specific NOx emissions (mg/km) from individual cities are indicated in respective shapes. Blue dotted line refers to the type-approval limit of 80 mg/km and red dotted line to the RDE limit of 114 mg/km. Whiskers indicate the 95% confidence interval of the mean. Only vehicle families with 100 or more measurements are presented.

The analysis of real-world NO_X emissions of post-RDE vehicles from the CARES data demonstrates that the RDE regulations helped greatly to improve the emission performance of diesel vehicles in real world operation. All but one vehicle family measured in Milan, Krakow, and Prague showed NO_X levels no higher than the RDE limit (within their respective uncertainty range) and quite a number of vehicle families even stayed at the nominal type-approval limit. However, there were some vehicle families, such as Hyundai Motor Company 1600cc, Peugeot 1500cc, and Volvo 1960cc engine families, that show recurring high levels of NO_X emissions exceeding RDE limits at least for some of urban driving conditions measured.

The evidence that some vehicle families are emitting NO_X at levels inconsistent with regulatory limits may suggest further investigation into the in-service conformity of these vehicle families. Moreover, it is crucial for improved air quality, that low emission levels are maintained throughout the lifetime of the vehicles and their emission control equipment. **This warrants some continuous but low intensity fleet monitoring for which standard RES instruments are perfectly suited.**

3. High-emitter shares: Trucks

CARES made progress in the characterisation of high-emitting vehicles. The ultimate proof is however the emission measurement of the vehicle by some accredited method – or the identification of an eventual defeat device. This has become possible in the last campaign with plume chasing of trucks on highways outside Prague: Plume chasing measurements identified trucks that were considered suspicious if not high-emitting. Some 20 of those trucks were pulled-over the Czech police. An emission control expert from the Danish police[13] undertook spot-checks of the OBD data to verify the reason for the observed high NO_X emissions. In 18 cases manipulations of the engine or emission control software were detected, or faulty sensors, or corrupted add-blue injection, or a sustained lack of maintenance

[13] Martin Kristensen was funded through own funds from TU Dresden.

(despite an active MIL lamp for a longer period of time). In two other the reason for high emissions was either a "cold" SCR system as the vehicle had been running empty and a missing software update.

These spot checks served to validate the approach for identifying high NO_X emitting trucks by plume chasing. Here we generalise the results as follows: All observed trucks are assigned to either of the three groups, "below limit value", "suspiciously elevated" and "above limit value". For Euro V trucks a high share of 42% and 18% respectively falls into the two highest classes with only 7% and 28% of the observed Euro VI trucks (Table 2). The average observed NO_X emission is calculated to each layer and the weighted sum then gives the average for Euro V and Euro VI trucks on highway driving. This average is about 120% and 80% higher than a clean Euro V and Euro VI truck fleet respectively. For both emission classes the relative increment from malfunctioning trucks to NO_X emissions is about equal. That is explained by the fact that the much fewer high-emitting Euro VI trucks have much higher elevated emissions – each compared to the Euro V observations.

		Share in observations	**EF [mg/kWh] Average per layer**
Euro V trucks	Below limit value	40%	1600
	Suspiciously elevated	18%	2900
	High: Above limit value	42%	5500
	Class average	**100%**	**3470 = 2.2 times a clean fleet @1600 mg/kWh**
Euro VI trucks	Below limit value	65%	600
	Suspiciously elevated	28%	1540
	High: Above limit value	7%	3940
	Class average	**100%**	**1100 = 1.8 times a clean fleet @600 mg/kWh**

Table 2: Share of Euro V and Euro VI trucks observed on Czech highways and their average emission rate per layer.

4. Assessment of low-emission zone policies in Milan and Krakow

Milan and Krakow, two cities that were chosen for CARES demonstration projects, have been in the process of introducing a low-emission zone (LEZ) in their inner-city areas. We here demonstrate how remote sensing measurements can be used to assess the effectiveness of the LEZ policy by providing insight into the vehicle activity and emissions characteristics. The sites selected for the CARES remote sensing campaigns were located in the (prospective) LEZs of the two cities.

4.1. Low-emission zones in Milan

The low-emission zone in Milan entered into force in 2019 to address air pollution and traffic problems. The LEZ is divided into two zones, Zone B that covers over 75% of the city and Zone C that is located in the inner city and that has more stringent regulations. It is planned to progressively expand travel restrictions with successive emission standards, with the aim of eventually banning all diesel vehicles from entering these zones by 2030. However, the implementation of more stringent restrictions was postponed due to parallel stress from COVID19 countermeasures in the year 2020. Therefore, contrary to original plans, no further step was introduced and the following minimum emission standards for accessing the Milan LEZ remained in force at the time of the remote sensing testing in 2021 (Figure 5):

- Zone B (i.e. including the measurements site at Via Cilea):
  - Petrol vehicles certified at least to Euro 2
  - Diesel vehicles certified at least to Euro 3 and equipped with diesel particulate filters
- Zone C (i.e. including the measurements site at Via Madre Cabrini):
  - Petrol vehicles certified at least to Euro 2
  - Diesel vehicles certified at least to Euro 4 and equipped with diesel particulate filters

Note, that there are no restrictions for the numerous vehicles powered with CNG and LPG.

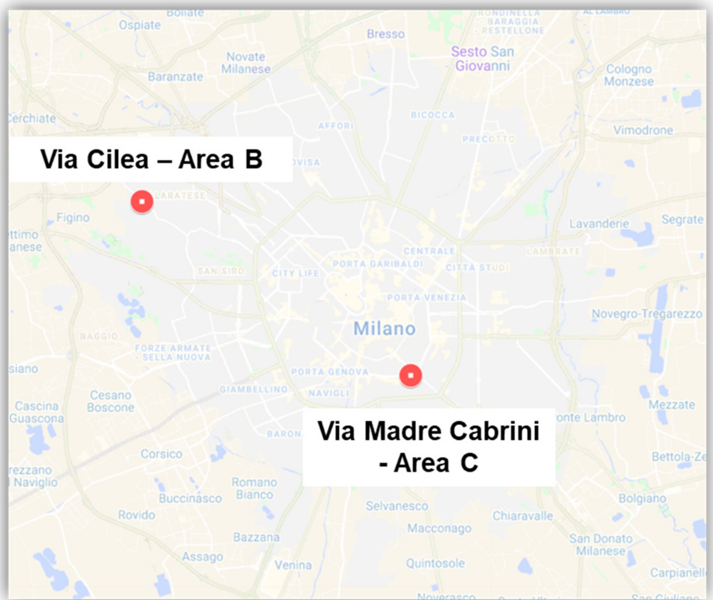

Figure 5: Indicative locations of the two measurement sites for the EDAR remote sensing measurement system, inside Area B and inside Area C. A third location, via Bazzoni in Area C, was only used for measurements with the point sampling instrument and is not discussed here.

The CARES project collected over 35,000 remote sensing measurements from Milan, which provide notable insights into the emissions characteristics of the alternative fuels that are exempted in the LEZ in Milan. One of the main findings from the remote sensing measurements collected in Milan is that **LPG and CNG vehicles emit more NOX and PM emissions than petrol vehicles**, contrary to the common belief. Emissions from LPG vehicles, or vehicles retrofitted to use LPG, are particularly important, as they are more commonly used in Milan relative to other European cities. For example, LPG vehicles made up over 15% of the passenger car measurements collected in Via Cilea, located in Zone B. The mean NO_X and PM emissions from LPG vehicles certified to Euro 4 and Euro 5 are around 30% higher than those from petrol counterparts. Therefore, modern petrol cars contribute less to total emissions than their share in driving, while LPG cars are not cleaner but contribute about as much to NOx and PM emissions as their share in driving (Figure 6). Of course, diesel cars having even higher unit emissions, contribute most to the total load from these two pollutants – therefore they have rightly been in the focus of restrictions so far.

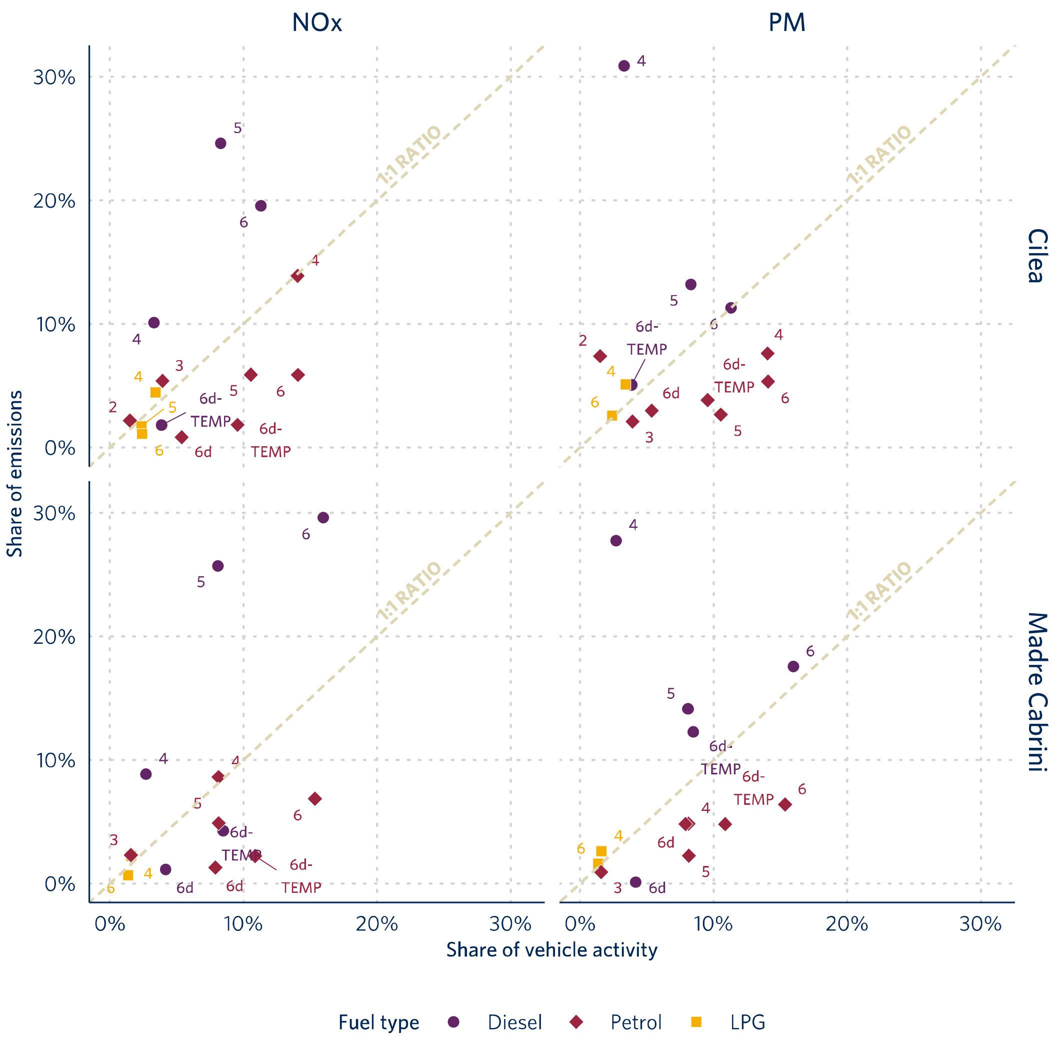

Figure 6. Share of vehicle activity and NOx and PM emissions based on CARES remote sensing measurements in Milan. Only fuel types and emission standards with vehicle activity and emission share of 1% of more are presented.

The remote sensing measurements from both sites also demonstrate that Milan's LEZ would reap much greater emission benefits from further restricting diesel vehicles from accessing the LEZ. For instance, Euro 4 diesel vehicles are still allowed to enter in via Cilea (Area B); they account for only 3% of the vehicle activity but for over 30% of all passenger car PM emissions. As these cars were not required to be originally equipped with a diesel particle filter their unit emissions are at least one order of magnitude higher than from all other passenger car classes running here. In Madre Cabrini (Area C with tighter requirements) 75% of Euro 4 diesel cars are even equipped with diesel particulate filters; however, they still contribute most to PM emissions due to the fact that restrictions only applied during the weekdays from 7:30 to 19:30. This derogation from access restrictions is currently put in place to protect businesses in the city but can be eliminated with adequate supplementary policies to support vehicle renewals of business fleets. The analysis shows that very specific measures affecting only a small number of vehicles – and thus likely only a small number of drivers - can bring disproportionately high emission benefits.

High contributions of Euro 5 and pre-RDE Euro 6 diesel vehicles to NO_X emissions further suggest that limiting the use of these vehicles can help achieving a significant reduction in NO_X (as well as direct NO_2) emissions in the city. The planned next step of the Milan LEZ is to ban Euro 5 diesel cars (and possibly also vans), which have high share of NO_X emissions in Madre Cabrini. Further high NO_X reductions can be achieved by restricting access for all other pre-RDE diesel vehicles. In other words, allowing only diesel light-duty vehicles certified to Euro 6d-TEMP and Euro 6d emission standards.

4.2. Low-emission zone in Krakow

Another CARES demonstration city, Krakow, recently announced the implementation schedule for its low-emission zone. It’s planned to enter into force from July 2024; the Krakow LEZ will provide some grace period for vehicles purchased before 2023 and gradually restrict all vehicles from 2026 onwards. The LEZ covers the area bordered by the administrative boundaries of the city of Krakow and will restrict all vehicles with petrol, diesel, hybrid, and LPG installations (Figure 7).

The requirements to enter the Krakow LEZ are as follows:[14]

- Starting July 2024:
  - Minimum standards allowed for vehicles registered before March 2023
    - Petrol and LPG vehicles certified to Euro 1 or later
    - Diesel vehicles certified to Euro 2 or later
  - Minimum standards allowed for vehicles registered after March 2023 or later
    - Petrol and LPG vehicles certified to Euro 3 or later
    - Diesel vehicles certified to Euro 5 or later
- Starting July 2026:
  - All vehicles regardless of the registration date
    - Petrol and LPG vehicles certified to Euro 3 or later
    - Diesel vehicles certified to Euro 5 or later

[14] Public Transport Authority in Kraków (ZTP). (n.d.). *LEZ requirements*. LEZ requirements – ZTP Kraków, https://ztp.krakow.pl/en/lez/lez-requirements

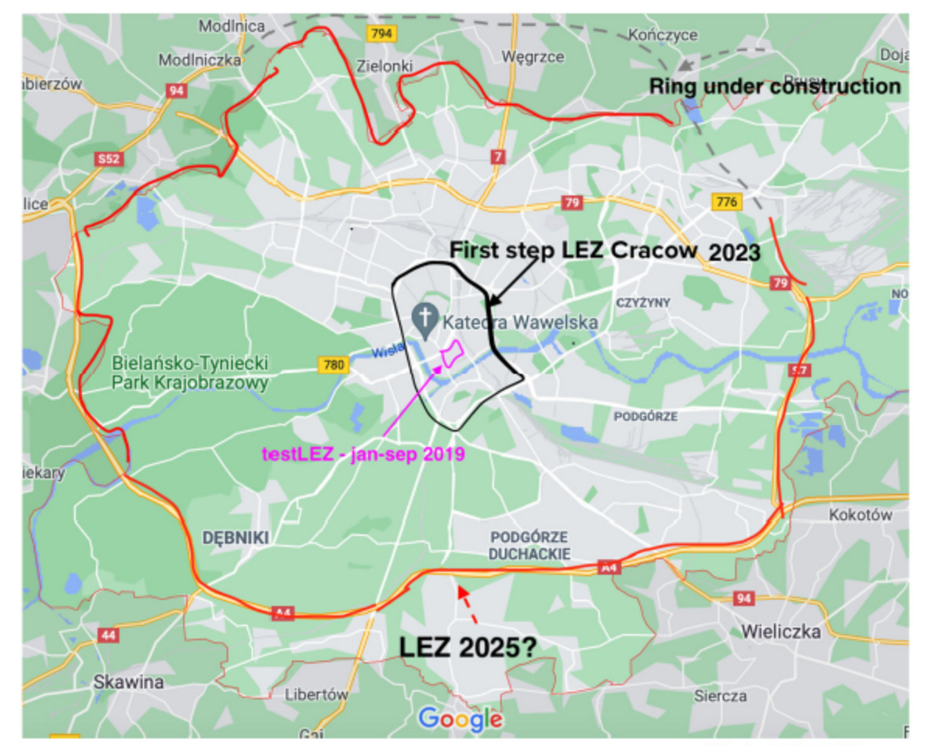

Figure 7: Indicative boundaries for the LEZ tested earlier (2019) and planned in future for Krakow.

To assess the impact the planned LEZ would have on drivers and vehicle emissions in Krakow, the vehicle composition was forecasted for 2026, the year the Krakow LEZ is planned to begin, based on over 128,000 remote sensing measurements collected in 2021. To more accurately estimate the impact the LEZ would have on drivers, it is important to account for the fleet renewal between our base year (2021) and the projected implementation dates in 2024 and eventually 2026. The fleet composition was projected for 2026, using the same age distribution of passenger cars identified from the CARES Krakow data, and the shares of vehicles that would not meet the restrictions listed above were estimated.

In 2021 more than 20% of cars would be older cars affected by the planned restrictions. However, as a consequence of foreseeable fleet renewal, there will be only 7% of all passenger cars certified to Euro 4 and Euro 2 standards for diesel and petrol/LPG cars, respectively, in 2026 (Figure 8). Old petrol cars certified to below Euro 3 are removed from the active vehicle fleet as they are replaced by new vehicles certified to Euro 6d or eventually Euro 7, depending on when they are introduced. The majority of diesel vehicles certified to Euro 3 and Euro 4 also retire when the LEZ begins, resulting in 7% of diesel vehicles whose use would be limited in Krakow.

Figure 8. Shares of passenger cars in Krakow affected by the proposed low-emission zone restrictions in 2021 and 2026. The 2026 passenger car fleet composition is based on the age distribution from the 2021 remote sensing data.

The CARES Krakow data were further paired with additional 100,000 remote sensing measurements from the summer of 2019 in Krakow to define emission factors of passenger cars reflecting not only winter but also summer emission characteristics of the Krakow passenger car fleet. Indeed, the remote sensing measurements collected in November–December of 2021 showed highly elevated PM emissions from both diesel and petrol vehicles. Particularly for petrol vehicles, the mean PM emissions were over 10 times the PM emissions from petrol vehicles measured in 2019, likely due to cold engines resulting from colder testing temperature. The petrol vehicles also included bi-fueled LPG vehicles, which may have further contributed to high levels of PM.

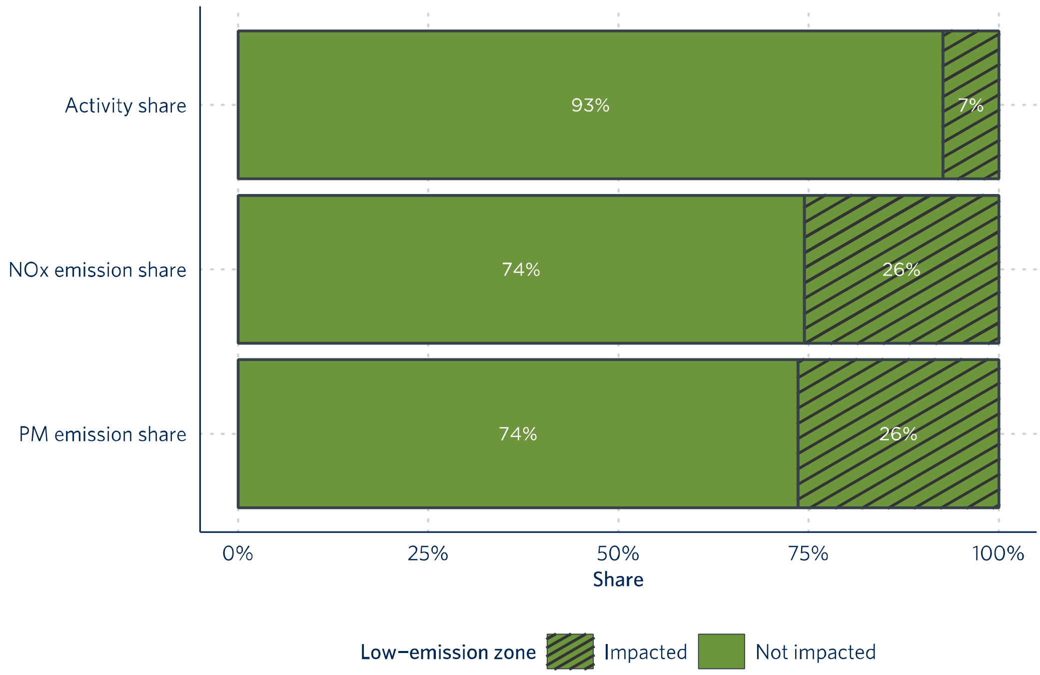

Figure 9. Share of passenger car activity affected by the low-emission zone in 2026 and their respective shares of NOx emissions, and PM emissions from the passenger car fleet.

The projected activity data is combined with the adjusted emission factors to derive an estimate of the emission shares affected: The 7% of vehicle potentially affected by access restrictions would emit about a quarter of NO_X and PM emissions in Krakow (Figure 9). In quantitative terms, the average emissions of the car fleet without and with LEZ are estimated as follows:

Average emissions [mg/km]	Average emissions in 2021	Average emissions in 2026 before LEZ	Average emissions in 2026 with LEZ*
NOx	337	216	164 / -24%
PM	9.7	7.0	5.5 / -21%

Table 3: Average car fleet emissions at the time of measurement and in the projection year 2026, without and with LEZ restrictions. *Assumption: All non-compliant cars replaced by Euro 6d of the same fuel type.

Here, remote sensing measurements were used to evaluate the impact and the effectiveness of the planned low-emission zone scheme in Krakow. In communicating restriction-based regulations, it is important to stress the disproportionate benefits the policy can generate while minimizing the burdens on vehicle drivers. Such policies should be complemented with options for clean and carbon friendly transportation like improved walking and cycling provisions and space/lanes, with high-quality public transport and potentially incentives for an accelerated transition to zero-emission vehicles, if private travel is to be fostered.

5. Appendix: Manufacturer groupings

The following table shows the taxonomy of vehicle families used in Section 1, including abbreviations of manufacturer groups and vehicle makes that belong to each manufacturer group.

Table 4: Association of individual vehicle makes (brands) to the producing (parent) company.

Manufacturer group abbreviation	Manufacturer group	Vehicle make
BMW	BMW	BMW
		Mini
DAI	Daimler	Mercedes
		Smart
FCA	Fiat Chrysler Automobiles	Abarth
		Alfa Romeo
		Chrysler
		Dodge
		Ferrari
		Fiat
		Jeep
		Lancia
		Maserati
FRD	Ford	Ford
GEM	General Motors	Cadillac
		Chevrolet
HMC	Hyundai Motor Company	Hyundai
		Kia
HON	Honda	Honda
MAZ	Mazda	Mazda
MH	Mitsubishi	Mitsubishi
PSA	Peugeot	Citroën
		DS
		Opel
		Peugeot
		Vauxhall
RNA	Renault-Nissan	Dacia
		Infiniti
		Nissan
		Renault
SA	Saab	Saab
SH	Subaru	Subaru
SUZ	Suzuki	Suzuki
TAT	Jaguar Land Rover	Jaguar
		Land Rover
TOY	Toyota	Daihatsu
		Lexus
		Toyota
VLO	Volvo	Volvo
VWG	VW Group	Audi
		Bentley
		Porsche
		SEAT
		Škoda
		VW