Evaluation of real-world vehicle emissions in Warsaw

Authors: Kaylin Lee, Yoann Bernard, Tim Dallmann, Uwe Tietge, Izabela Pniewska, Isabel Rintanen

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

EXECUTIVE SUMMARY

Motor vehicles are a significant source of air pollution emissions in Warsaw, Poland, and contribute to the air quality challenges the city faces. The Real Urban Emissions (TRUE) Initiative conducted an emissions testing study in Warsaw in Fall 2020 to provide detailed information about the real-world emissions of the vehicle fleet and support the city's efforts to address poor air quality. The study analyzed over 220,000 measurements from 147,777 unique vehicles collected using remote sensing technology.

This report provides a detailed assessment of the real-world emissions of vehicles in Warsaw and offers policy recommendations to improve the environmental performance of the city's fleet. In particular, we examine the distribution of vehicles in the city and their emissions to identify ways in which Warsaw can reduce traffic-related pollution. This also includes a timely analysis for the city as it begins its discussions around a clean transportation zone, for which the framework has recently been set by the Electromobility and Alternative Fuels Act. We also investigate emissions from imported second-hand vehicles, whose use is widespread in Poland, and suggest ways in which Warsaw can address the relatively high emissions from these vehicles. As a case study, we compare the results from Warsaw with a TRUE study concurrently conducted in Brussels to help to further understand how different policies in the two cities have impacted emissions from light-duty vehicles, taxis, and buses.

The main findings of the TRUE Warsaw real-world vehicle emissions study are summarized below. We also provide specific policy recommendations regarding a clean transportation or low-emission zone in Poland, emissions from imported second-hand vehicles, and liquified petroleum gas conversions.

- The real-world nitrogen oxide (NO_x) emissions from Warsaw's diesel passenger cars not subject to Real Driving Emissions (RDE) type-approval requirements, namely Euro 2 to Euro 6c, all exceeded regulatory limits, echoing the findings from previous TRUE studies in Europe. More specifically, these vehicles have average NO_x emissions 1.6 to 4.3 times the regulatory limits. Vehicles certified to standards requiring RDE testing, Euro 6d-TEMP and Euro 6d, show mean distance-specific NO_x emissions below the RDE not-to-exceed requirements, but higher than the emissions standard laboratory limit.
- Post-Euro 4 vehicles equipped with diesel particulate filters (DPFs) emit 80% less PM emissions than the average Euro 4 level but other factors, such as poor maintenance and tampering, can lead to elevated levels of particulate matter (PM) emissions for individual DPF-equipped diesel vehicles. We find that 0.2 %–1.5% of diesel passenger cars and 0.4%–2.9% of diesel light commercial vehicles certified to Euro 5 standards and above show emission levels that exceed the 1.5g/kg threshold, implying that DPF malfunction or tampering could be a more widespread problem for light commercial vehicles.
- Approximately 83% of all passenger cars in Warsaw for which valid mileage information was available operate outside the existing regulatory emission durability requirements. The proposed Euro 7 provisions aim to ensure the emissions performance of vehicles certified to successive standards up to 15 years or 240,000 km. However, approximately 30% of in-use vehicles in Warsaw had ages and mileages exceeding these requirements. This calls for reassessment of the newly suggested emission durability requirements of Euro 7 and establishment of provisions sufficient to cover the average lifetime of vehicles in European cities.
- Imported second-hand vehicles make up 32% of the total light-duty vehicle measurements. The average age of imported second-hand vehicles is 13 years, more than double that of domestic vehicles, and their average mileage is approximately 223,000 km, or 1.5 times that of domestic vehicles. The average fuel-specific emissions from these vehicles are at least double those from domestic vehicles for all pollutants studied. The higher average emissions of imported vehicles are largely attributable to the high share of older and more polluting vehicles in the imported fleet.
- The Influx of old, polluting vehicles can be prevented by a nation-wide policy that puts a limit on the age of imported vehicles. Other measures, such as scrappage programs, tax benefits, and other financial incentives, can supplement such a policy to discourage the purchase of these vehicles. Locally, emissions from imported second-hand

vehicles can be addressed by restricting vehicles based on age or emission standards.

- A vehicle access restriction policy, like the suggested clean transportation zone, based on age or emission standard would remove the highest-emitting passenger cars from the Warsaw fleet. Restricting the use of diesel and petrol vehicles certified to below Euro 4 standards would remove diesel passenger cars responsible for 18% and 37% of the total NO_x and PM emissions, respectively, while accounting for only 6% of the fleet. It would further affect petrol passenger cars that are responsible for 38% of CO and 35% of HC emissions while only making up 11% of the passenger car fleet.
- Progressive access restrictions that expand to diesel vehicles certified to Euro 4 and Euro 5 and petrol vehicles certified to Euro 4 are strongly recommended to further reduce the NO_x and PM emissions. Diesel passenger cars in these groups account for 27% of the total NO_x and 28% of the total PM emissions, while making up only 13% of the total measurements. The petrol Euro 4 vehicle group alone is responsible for 14% and 10% of the current total CO and HC emissions, respectively.
- Despite the lower number of diesel vehicles, the fleet-average fuel-specific NO_x and PM emissions of the Warsaw light-duty vehicle fleet are 7% and 25% higher than those of the Brussels light-duty vehicle fleet, respectively. This is mainly attributable to the presence of diesel vehicles certified to emission standards lower than Euro 4, which are scarcely found in the Brussels fleet due to the low-emission zone currently in place.
- The Warsaw fleet-average CO and HC emissions are nearly two and three times those of the Brussels fleet, respectively, due to the prevalence of older petrol vehicles in the Warsaw measurements. The higher levels of CO and HC emissions of pre-Euro 5 petrol vehicles in Warsaw compared with those in Brussels may indicate some impacts of liquified petroleum gas conversions, which tend to emit more of CO and HC emissions than conventional petrol-fueled engines.
- The average age of vehicles in Warsaw's taxi fleet is seven years, while that of Brussels' taxis and ride-hailing vehicles is four years. Overall, the Warsaw taxis emit more of all pollutants studied. Warsaw diesel taxis emit NO_x and PM emissions 1.8 and 4.1 times the respective emissions from diesel taxis and ride-hailing vehicles in Brussels. If the 7-year age limit for taxis and ride-hailing vehicles currently in place in Brussels were to be implemented in Warsaw, 43% of the taxi fleet that is responsible for 58% to 87% of current emissions of all pollutants would be removed from the Warsaw fleet.
- Over 80% of city buses measured in Warsaw are certified to below Euro VI standards. The Warsaw city buses certified to Euro VI perform significantly better than those certified to preceding standards; their NO_x and PM emissions show levels approximately 35% and 70% of the respective emissions from the Euro V city buses. Thus, limiting the use of pre-Euro VI buses would be highly beneficial and further replacing these buses with electric buses could achieve a greater emissions reduction.

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INTRODUCTION

Poland suffers from one of the poorest air qualities in Europe. According to the World Health Organization, 36 of the 50 most polluted cities in the European Union (EU) in 2018 were in Poland and some of these cities had particulate matter ($PM_{2.5}$) levels far exceeding the EU's limits.[1] In the same year, approximately 12% of all premature deaths caused by airborne $PM_{2.5}$, ozone (O_3), and nitrogen dioxide (NO_2) exposure in EU-28 were in Poland.[2]

Warsaw is one of the most polluted cities in Poland. In 2019, the urban area of Warsaw recorded an annual average $PM_{2.5}$ level of 21 µg/m^3 which greatly exceeds the World Health Organization guidelines.[3] Warsaw was also one of the four cities in Poland greatly exceeding the EU annual NO_2 limit in 2018, primarily due to road transportation.[4] The health-related social costs of air pollution in Warsaw are estimated to be €4.2 billion every year, and they increase with more transport activities.[5] Warsaw shows one of the highest vehicle ownership rates in Europe and has further seen a growing influx of vehicles commuting from outside of the city.[6]

Despite the growing concern and public demand for action, the efforts to address air pollution have been meager in Warsaw. The implementation of a clean transportation zone, a concept equivalent to a low-emission zone, is now permitted in the country, set forth by the newly passed Electromobility Act, but Warsaw has yet to announce a detailed implementation plan. With many of the initiatives to improve air quality in their nascent stage, policymakers in Warsaw can greatly benefit from understanding the city's motor vehicle emissions.

A remote sensing measurement campaign was conducted by The Real Urban Emissions (TRUE) Initiative in Warsaw in Fall 2020 to provide the technical information necessary to support policies that can effectively reduce on-road transport emissions. This study presents the real-world emissions of vehicles in the city and the role imported second-hand vehicles (ISVs) play in Warsaw's fleet emissions. We provide additional context through a comparative study of emissions measurements collected in Warsaw and Brussels to identify city-specific characteristics that are important to consider in policy making and to evaluate policies that could be transferable between cities.

This paper first provides background information about the Warsaw fleet and transport-related policies that guided the analysis. Then, it identifies the fleet distribution of Warsaw and assess the real-world emissions of the Warsaw passenger car fleet, which offers critical policy implications for emissions control measures, including a clean transportation zone. The next section discusses the emissions trend from imported second-hand vehicles in Warsaw, followed by a comparative study using the TRUE Brussels study. In the latter, we also present detailed findings on taxi and bus emissions. We conclude with policy recommendations for reducing the impacts of vehicle emissions in Warsaw.

BACKGROUND

This section provides background information on the vehicle fleet in Poland, including policies and practices that guided this analysis and policy evaluation. Information is provided on the establishment of clean transportation zones in Poland, the country's second-hand vehicle import market, and the widespread practice of liquified petroleum gas (LPG) conversions.

CLEAN TRANSPORTATION ZONE

Poland introduced the Act on Electromobility and Alternative Fuels (here after the E-mobility Act) in January, 2018, with the aim of implementing the European Directive on the development of alternative fuel infrastructure, minimizing the dependence on crude oil, and decarbonizing the road sector.[7] The E-mobility

1 World Bank Group, "Air Quality in Poland, What Are the Issues and What Can Be Done?," Fall 2019, http://documents.worldbank.org/curated/en/426051575639438457/pdf/Air-Quality-in-Poland-What-are-the-Issues-and-What-can-be-Done.pdf.

2 European Environment Agency, "Poland - Air Pollution Country Fact Sheet," EEA country fact sheets, n.d., https://www.eea.europa.eu/themes/air/country-fact-sheets/2021-country-fact-sheets/poland.

3 European Environment Agency, "Poland - Air Pollution Country Fact Sheet"; World Health Organization, "What Are the WHO Air Quality Guidelines?," September 22, 2021, https://www.who.int/news-room/feature-stories/detail/what-are-the-who-air-quality-guidelines.

4 Supreme audit office (NIK), "Air Protection in Poland - Summary of the Most Important Findings," Audit report (Poland, October 2018), https://www.nik.gov.pl/plik/id,18506.pdf.

5 Sandra de Bryun, "Health Costs of Air Pollution in European Cities and the Linkage with Transport" (CE Delft, October 2020), https://cedelft.eu/wp-content/uploads/sites/2/2021/03/CE_Delft_190272_Health_costs_of_air_pollution_in_European_cities_and_the_linkage_with_transport_Def.pdf.

6 Michiel Modijefsky, "Warsaw Announces Mobility Measures to Improve Air Quality," Eltis, November 27, 2019, https://www.eltis.org/in-brief/news/warsaw-announces-mobility-measures-improve-air-quality.

7 Bartosz Pilecki, "The Development Of Electromobility In Poland Under The Act On Electromobility And Alternative Fuels," Conference paper (Austria: University of Szczecin, January 2019), https://www.researchgate.net/publication/338622761.

Act consists mainly of incentives for electric vehicles, including the abolition of excise taxes on electric and plug-in hybrid cars, exemption from parking fees, and development of an infrastructure network for alternative fuels. As part of the measure to stimulate the electric vehicle market, it permits cities to establish clean transportation zones, which limit access to the zones to primarily only electric-, hydrogen-, and natural gas-powered vehicles. A clean transportation zone pilot project was implemented in Krakow but was discontinued after nine months. If successfully implemented, however, such a restriction policy could be effective in reducing air pollution in the zone, as has been demonstrated by other European cities.

Recently passed Amendments to the E-mobility Act set a legal framework for a clean transportation zone to permit cities to effectively limit the use of polluting vehicles, with limited details on the area, implementation timeline, and types of vehicles subject to and exempted from the restrictions. However, efforts to address urban air pollution have gained widespread support from cities and residents alike. The governments of 12 cities in Poland, including Warsaw, endorsed the idea of clean transportation zones.[8] A survey by YouGov further shows that the residents of Warsaw demand strong action from the mayor to tackle on-road air pollution (84%) and promote the use of public transportation (72%), and want an emission-free city by 2030 (59%).[9] Another recent survey of five large Polish cities revealed that 67% of the city residents support the banning of old diesel vehicles.[10]

SECOND-HAND VEHICLE IMPORTATION

Poland was the 14th largest importer of cars world-wide in 2019, with the total imported vehicle market amounting to $11 billion.[11] In the same year, twice as many used cars were imported as new ones sold in the country.[12] Although second-hand vehicles provide an economical mobility option in Poland, the influx of high-emitting imported used vehicles add to Poland's existing old fleet. Poland has one of the oldest vehicle fleets in Europe, with an average age of in-use passenger cars of 14 years, compared to the European average of 11 years.[13] According to the Samar Automotive Market Research Institute, the average age of imported cars in 2020 was 11 years old.[14] Older vehicles, particularly those over 15 years old and certified to standards that predated to Euro 4, emit disproportionate amounts of air pollutants that cause great health concern. However, there is currently no restriction which limits the age of imported vehicles.

Most of these vehicles are imported from Western Europe; in 2020, four of the five top exporters of cars to Poland were Germany, France, Belgium, and the Netherlands.[15] Many of these imported vehicles are old, diesel-powered vehicles that have a limited market in the exporting countries since the "Dieselgate" scandal. In the first three quarters of 2020, 48% of all imported vehicles in Poland were diesel vehicles. Moreover, in many Western European cities, these vehicles often do not meet the emission standard requirements of low-emission zones while they are mostly not regulated in Eastern European countries. In addition to the lack of a low-emission zone, the difficulty of regulating the flow of vehicles within the EU also contributes to the influx of imported used vehicles into Poland.

LIQUIFIED PETROLEUM GAS CONVERSIONS

Poland has one of the largest liquefied petroleum gas (LPG)-powered vehicle fleets in the world. Backed by high gasoline prices and a high rate of private car ownership, Poland's LPG market underwent a rapid

8 Polish Alternative Fuels Association (PSPA) and Union of Polish Metropolises, "Declaration of the City Coalition for the development of Clean Transport Zones," September 21, 2021, https://www.wroclaw.pl/zielony-wroclaw/deklaracja-polskich-samorzadow-na-rzecz-rozwoju-stref-czystego-transportu.

9 CleanCities, "What European City-Dwellers Want From Their Mayors: Post-COVID Survey," Survey, May 2021, https://cleancitiescampaign.org/wp-content/uploads/2021/05/CCC-survey-briefing_final.pdf.

10 Polish Smog Alert, "ZACHOWANIA TRANSPORTOWE MIESZKAŃCÓW DUŻYCH MIAST," March 2021, https://polskialarmsmogowy.pl/wp-content/uploads/2021/06/Raport_zachowaniatransportowe_miasta_0706_3.pdf.

11 The Observatory of Economic Complexity (OEC), "Cars in Poland," OEC World, n.d., https://oec.world/en/profile/bilateral-product/cars/reporter/pol#:~:text=Imports%20In%202019%2C%20Poland%20imported,%2C%20and%20Spain%20(%24749M).

12 Maria Wilczek, "Polish Imports of Used Cars Rebound after Pandemic and Ahead of Anticipated Tax Rise," *Notes from Poland* (blog), October 9, 2020, https://notesfrompoland.com/2020/10/09/polish-imports-of-used-cars-rebound-after-pandemic-and-ahead-of-anticipated-tax-rise/.

13 European Automobile Manufacturers' Association, "Average Age of the EU Vehicle Fleet, by Country," European Automobile Manufacturers' Association, February 1, 2021, https://www.acea.auto/figure/average-age-of-eu-vehicle-fleet-by-country/.

14 Samar Automotive Market Research Institute, "Imports Are Growing Rapidly - September 2020," October 5, 2020, https://www.samar.pl/__/3/3.a/109719/3.sc/11/Wrzesie%C5%84-2020---Import-gwa%C5%82townie-ro%C5%9Bnie.html?locale=pl_PL.

15 Samar Automotive Market Research Institute. "Imports Are Growing Rapidly - September 2020."

expansion in the late 1990s.[16] With today's prices, fueling costs for LPG vehicles are approximately 40% less than comparable petrol vehicles per 100km.[17] Liquified petroleum gas now accounts for approximately 9% of the total road fuel in Poland and nearly 15% of passenger cars in Poland are equipped with LPG installations.[18]

Many LPG-powered cars in Poland are converted from imported used cars with gasoline engines. This is because LPG can easily be installed to engines with multipoint fuel injection, a common type of engines in old petrol vehicles, at a relatively low cost.[19] In 2019, approximately 25% of all petrol-powered cars in Poland were retrofitted with LPG system.[20]

Although LPG is sometimes referred to as a clean fuel, LPG-powered vehicles still emit other air pollutants that are detrimental to human health. Previous studies demonstrated that LPG-powered vehicles emit multiple times the carbon monoxide (CO) and hydrocarbon (HC) emissions during road testing than are emitted by petrol vehicles.[21] Since LPG conversions are usually retrofitted on older vehicles whose emission control systems may not function properly, they can show higher emissions than newer LPG vehicles or vehicles built for LPG.

METHODOLOGY

DATA COLLECTION

The TRUE Initiative conducted a remote sensing emissions testing campaign between September 24 to October 9, 2020. In order to measure real-driving exhaust emissions, the testing was conducted at six different locations selected to cover a range of vehicle types and driving conditions representative of the Warsaw fleet. The selected locations are shown in Figure 1.

Opus Remote Sensing Europe (Opus RSE) was contracted to perform the emissions testing, and an Opus AccuScan™ RSD5500 instrument was used to measure the exhaust emissions of vehicles as they drove past the device. An example of the setup of the equipment during the study is shown in Figure 2. The remote sensing instrument measures tailpipe emissions of the pollutants CO, HC, NO, and NO_2, in addition to plume opacity, which is an estimate of particulate matter (PM). Registration information and measurements of its speed and acceleration were merged with the emissions and weather conditions data to provide a complete dataset.

DATA PROCESSING AND ANALYSIS

The methods used to prepare and analyze the Warsaw remote sensing data follow those developed and applied for previous TRUE studies in other European cities. During the Warsaw study, 220,484 valid measurements were collected from 147,777 unique vehicles. License plate numbers for these vehicles were matched against a registration database to extract basic technical information, including fuel type, emission standard, make, model, build year, and age. Due to gaps in the database, the complete set of technical information was not available for each vehicle. While these gaps, in some cases, limit the detail of analysis which can be pursued, the data can still be useful for characterizing the real-world emissions of the Warsaw fleet and would introduce bias if excluded completely. For example, we include over 51,000 records with no vehicle class information in certain analyses as:

- Over 50% of these records have technical specifications, such as registration date, build year, make, model, and age, and valid emission data usable for analysis;
- These vehicles show relatively high levels of emissions, without which the emission trends of Warsaw may be understated; and
- Over 75% of these records are for imported second-hand vehicles, and excluding them would result in a less accurate picture of the emissions of imported vehicles in Warsaw.

16 M Buczaj and A Sumorek, "Analysis of the Market of LPG as an Alternative Vehicle Fuel in Poland in 2005–2016," *ECONTECHMOD : An International Quarterly Journal on Economics of Technology and Modelling Processes* 06, no. 04 (October 24, 2017): 47–54.

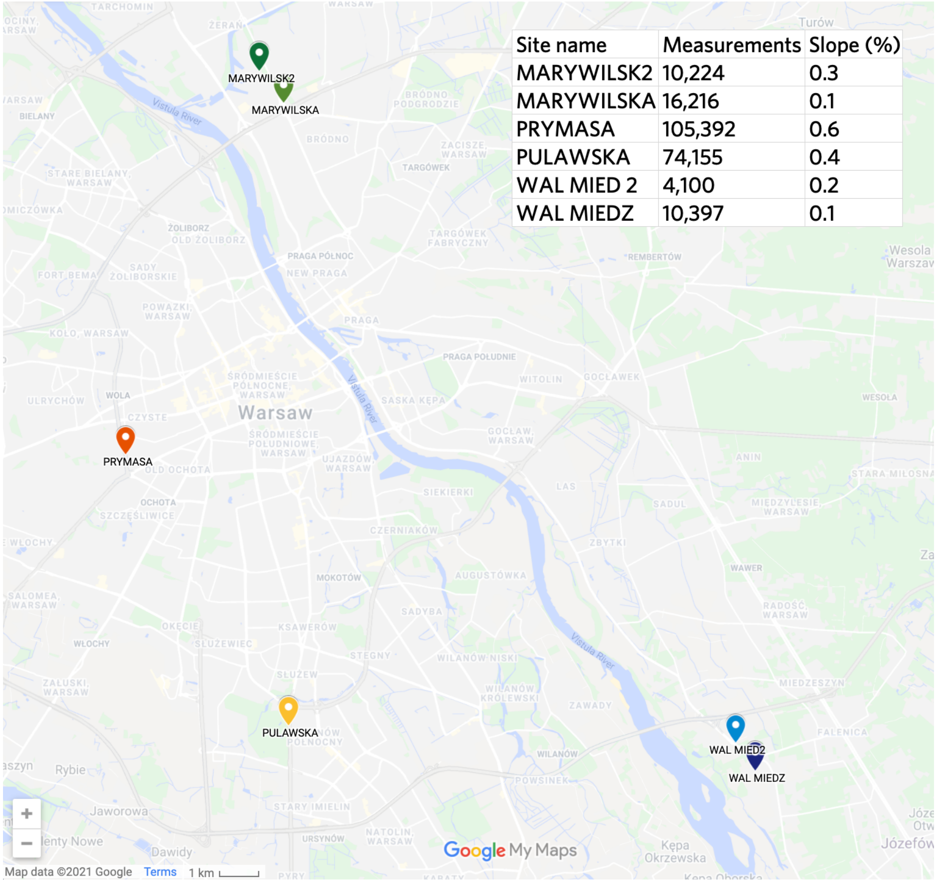
17 The estimate is calculated based on the fuel prices in Poland recorded between July 2021 and October 2021, taking into account overconsumption of fuel by LPG vehicles by 15% relative to petrol vehicles . Source: https://www.globalpetrolprices.com/Poland/lpg_prices/

18 World LPG Association, "Autogas Market Trends," Autogas.net, n.d., https://auto-gas.net/government-policies/autogas-incentive-policies/poland/.;

19 Samar Automotive Market Research Institute, "Cars with LPG - condition of the park at the end of 2019," July 10, 2020, https://www.samar.pl/__/3/3.a/108876/3.sc/11/Auta-z-LPG---stan-parku-na-koniec-2019-roku.html?locale=pl_PL.

20 Samar Automotive Market Research Institute. "Cars with LPG - condition of the park at the end of 2019."

21 Jerzy Merkisz and Jacek Pielecha, "Gasoline and LPG Vehicle Emission Factors in a Road Test," 2009, https://doi.org/10.4271/2009-01-0937.; Bruce Organ et al., "A Remote Sensing Emissions Monitoring Programme Reduces Emissions of Gasoline and LPG Vehicles," *Environmental Research* 177 (October 2019): 108614, https://doi.org/10.10x16/j.envres.2019.108614.



Site name	Measurements	Slope (%)
MARYWILSK2	10,224	0.3
MARYWILSKA	16,216	0.1
PRYMASA	105,392	0.6
PULAWSKA	74,155	0.4
WAL MIED 2	4,100	0.2
WAL MIEDZ	10,397	0.1

Figure 1. Six testing sites selected for the 2020 Warsaw emissions testing campaign, their slopes, and numbers of valid measurements made at each site.

Figure 2. Examples of remote sensing instrument set-up in the 2020 Warsaw remote sensing campaign.

It is important to note that LPG conversions were not identified in the database since only the original fuel type of the vehicle is listed in registration data. Therefore, we infer the presence of LPG conversions in Warsaw only from the recently available sources and the exact number of such vehicles was not identifiable.[22]

22 Samar Automotive Market Research Institute, "Cars with LPG - condition of the park at the end of 2019."

Consistent with previous TRUE analyses, we filtered the data for valid speed and positive vehicle specific power to obtain valid emission values. All emission values are expressed in fuel-specific values, in g/kg, and those of passenger cars were further converted to distance-specific values, a unit consistent with the European regulatory limits, using the method developed in earlier TRUE publications.[23]

All light-duty vehicles (LDVs) are used for the analysis of imported second-hand vehicles and the comparison with the TRUE Brussels remote sensing data, given the reasons listed above. For records where vehicle class information was not available, LDVs were identified by applying curb weight (<3,000 kg and > 600 kg) and engine displacement (<10,000 cm^3 and >500 cm^3) thresholds. Depending on the pollutant, the number of measurements for LDVs with valid emission data ranged from 144,871 to 161,691.

WARSAW FLEET CHARACTERISTICS

FLEET COMPOSITION

The Warsaw remote sensing campaign collected a sample of 220,484 valid measurements from 147,777 unique vehicles, including those with invalid emissions and limited vehicle specifications. To provide a complete picture of the vehicle fleet in Warsaw, the entirety of the sample is used to examine the fleet composition.

Passenger cars were most common in the sample, accounting for 68% of measured vehicles, followed by vehicles with no identifiable class (23%), light commercial vehicles (8%) and buses (1%). No emission standards were assigned to the vehicles in which no vehicle class information was available. Other vehicle classes, such as motorcycles, heavy-duty trucks, and forestry or agricultural tractors, made up less than 0.5% of the entire fleet measured.

Figure 3 summarizes the distribution of fuel type and emissions standard for the four most common vehicle classes found in the Warsaw dataset. The most

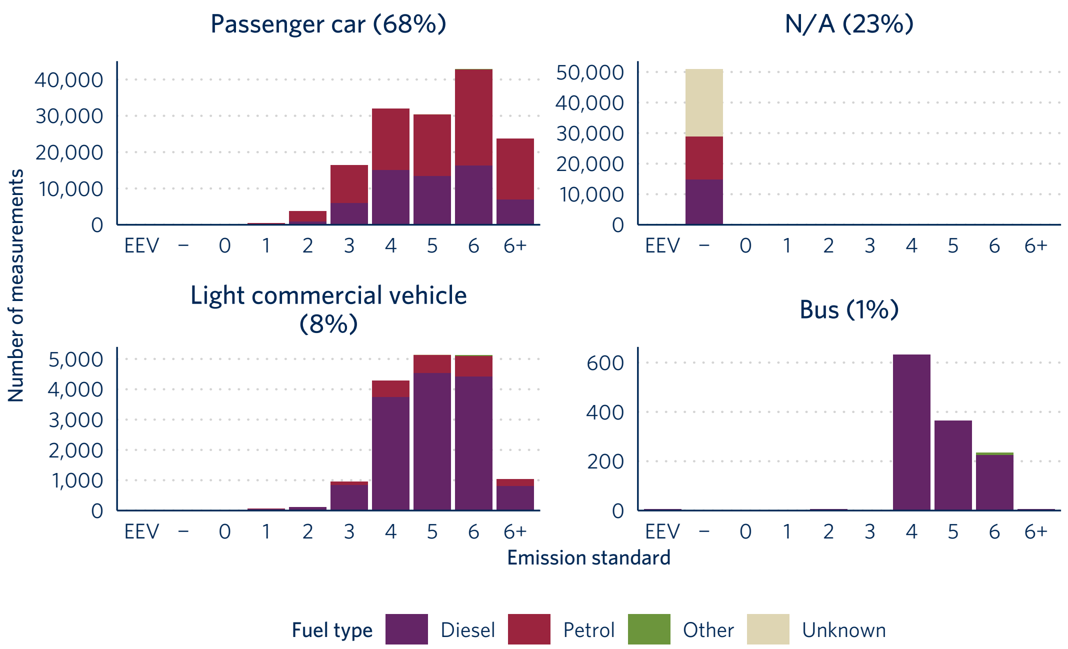


Figure 3. Fuel type and emission standard distribution for major vehicle classes represented in the Warsaw remote sensing sample. Vehicle classes that make up less than 0.5% are excluded. Euro 6 refers to Euro 6 standards up to 6c and Euro 6+ refers to the succeeding standards, Euro6-d-TEMP and 6d, combined.

23 Yoann Bernard et al., "Determination of Real-World Emissions from Passenger Vehicles Using Remote Sensing Data" (Washington, D.C.: TRUE Initiative, June 5, 2018), https://theicct.org/publication/determination-of-real-world-emissions-from-passenger-vehicles-using-remote-sensing-data/.

Table 1. Warsaw passenger car characteristics and testing conditions by emission standard.

	Measurements	Avg. vehicle age at time of measurement (years)	Avg. road grade	Certified CO_2 emissions (g/km, NEDC)	Avg. ambient temperature (°C)	Avg. vehicle specific power (kW/ton)	Avg. speed (km/h)	Avg. acceleration (km/h/s)
Diesel 3	5,547	16	0.5	146	24.8	11.3	43	1.4
Petrol 3	9,643	17	0.4	162	24.8	10.9	43	1.5
Diesel 4	13,986	12	0.5	154	24.7	11.3	43	1.4
Petrol 4	15,858	12	0.5	159	24.7	10.9	43	1.5
Diesel 5	12,471	7	0.5	137	24.5	11.6	43	1.6
Petrol 5	15,741	7	0.5	142	24.5	11.1	43	1.6
Diesel 6	15,410	3	0.5	126	24.2	11.8	43	1.7
Petrol 6	24,922	3	0.5	133	24.4	11.4	43	1.7
Diesel 6d-TEMP	6,063	1	0.5	137	24.1	11.8	43	1.8
Petrol 6d-TEMP	14,029	1	0.5	138	24.3	11.3	43	1.7
Diesel 6d	539	0	0.5	137	23.8	11.6	43	1.8
Petrol 6d	1,948	0	0.5	110	24.0	11.6	44	1.7

prevalent fuel type for passenger cars was petrol (60%) and most of the remaining vehicles measured were powered by diesel engines (39%). Diesel was the most common fuel type for both light commercial vehicles and buses, making up 87% and 99%, respectively, of the total measurements. The fuel type of 43% of the measurements for which no vehicle class was identified is unknown, but diesel and petrol made up respective measurement shares of 30% and 27%.

Vehicles certified to Euro 4 through Euro 6c standards made up 70% of the passenger cars, 87% of the light commercial vehicles, and 99% of the buses in the sample. Older passenger cars certified to Euro 3 and below and newer vehicles certified to Euro 6d-TEMP and Euro 6d accounted for similar shares of 14% and 16%, respectively.

WARSAW PASSENGER CAR CHARACTERISTICS AND TESTING CONDITIONS

A detailed assessment of passenger cars shows that petrol vehicles are more commonly found in Warsaw than diesel vehicles. In the sample, petrol vehicles show a consistently higher share than diesel vehicles across different emission standards, as shown in Table 1. Particularly, vehicles certified to Euro 6, 6d-TEMP, and 6d are predominantly petrol-powered.

The testing conditions of the Warsaw measurement campaign are also summarized in Table 1. The average ambient temperature at the time of measurement was around 24°C, which was over 5°C higher than the average daily maximum temperature in September in Warsaw. The average speed of the vehicles measured

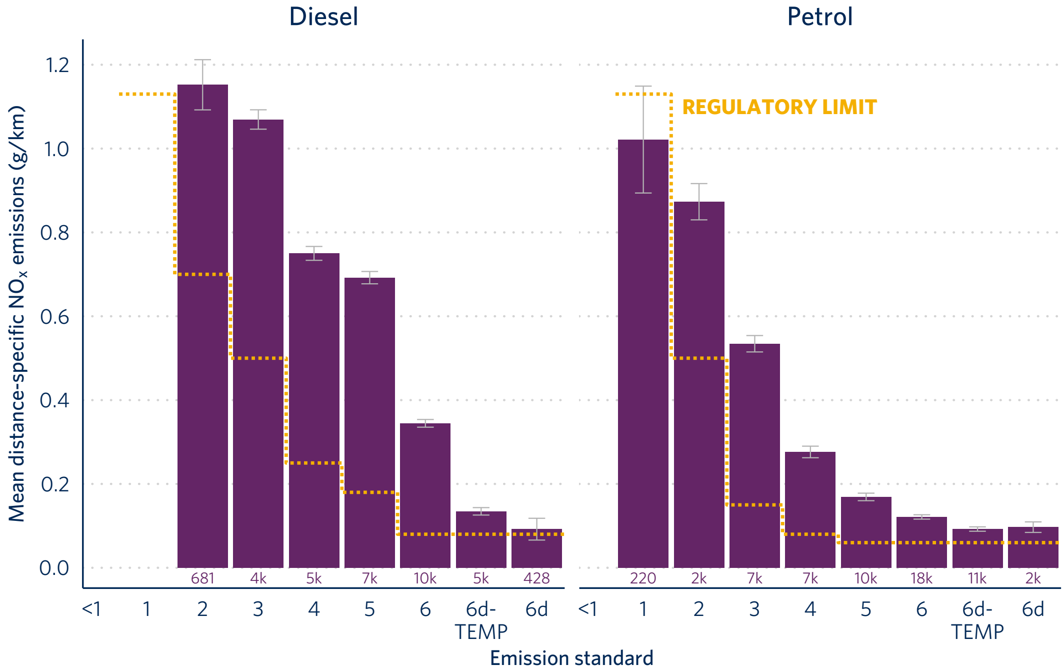


Figure 4. Average distance-specific NO_X emissions from diesel and petrol passenger cars by emission standard for the 2020 Warsaw remote sensing campaign. Whiskers represent the 95% confidence interval of the mean. Only results for groups of over 100 measurements are shown.

was 43km/h, a level notably higher than the average speed in previous TRUE studies, likely due to the selection of sites with reasonably smooth traffic flow and a speed limit of 50km/h–70 km/h.[24]

The type-approval CO_2 emissions of petrol vehicles show a downward trend with newer emission standards. Those of 6d petrol vehicles are particularly low; they show CO_2 emissions that are approximately 20% lower than those of the preceding standard, Euro 6d-TEMP, and are notably lower than those from the diesel equivalent. The improved emission performance of Euro 6d petrol vehicles can be partially explained by the fact that 6d vehicles were registered in 2020, when the EU set new, more ambitious mandatory type approval CO_2 targets for new passenger cars.[25] These targets have been driving a higher rate of hybridization technologies, mostly implemented on petrol vehicles.

PASSENGER CAR EMISSIONS

REAL-WORLD PASSENGER CAR EMISSIONS

Passenger cars made up 68% of the vehicles tested during the Warsaw emissions measurement campaign.[26] This section presents the distance-specific nitrogen oxide (NO_X), particulate matter (PM), carbon monoxide (CO), and hydrocarbons (HC) emissions by vehicle emission standard of passenger cars in the Warsaw dataset.

NO_X EMISSIONS

As shown in Figure 4, the average distance-specific NO_X emissions of passenger vehicles in Warsaw dataset show a trend consistent with past TRUE studies in other European cities.[27] The average distance-specific NO_X

24 OPUS Remote Sensing Europe, "TRUE Warsaw 2020 Fieldwork and Methodology Report" (Gaztambide 45, 28015, Madrid, Spain: Opus RS Europe SL, June 15, 2021), https://theicct.org/wp-content/uploads/2022/03/OpusRSE-ICCT_Fieldwork_Warsaw_25-08-2021.pdf

25 Sandra Wappelhorst et al., "Europe's CO_2 Emission Performance Standards for New Passenger Cars: Lessons from 2020 and Future Prospects" (Washington, D.C.: International Council on Clean Transportation, September 15, 2021), https://theicct.org/publication/europes-co2-emission-performance-standards-for-new-passenger-cars-lessons-from-2020-and-future-prospects/.

26 The sample of passenger cars used in this section only includes records where vehicle class information was available.

27 Yoann Bernard et al., "Evaluation of Real-World Vehicle Emissions in Brussels" (Washington, D.C.: TRUE Initiative, November 22, 2021), https://theicct.org/publications/true-brussels-emissions-nov21; Tim Dallmann et al., "Remote Sensing of Motor Vehicle Emissions in Paris" (Washington, D.C.: International Council on Clean Transportation, September 10, 2019), https://theicct.org/publication/remote-sensing-of-motor-vehicle-emissions-in-paris/.

emissions from petrol vehicles decrease with more stringent standards but those from diesel vehicles show little improvement prior to the introduction of Euro 6. Nevertheless, we observe that diesel Euro 6 vehicles certified to up to 6c emit three times more NO_x than their petrol equivalent. Only Euro 6d-TEMP and Euro 6d diesel vehicles show NO_x emission levels comparable to their petrol equivalents.

Vehicles of all emission standards above Euro 1 show average distance-specific NO_x emissions exceeding the regulatory laboratory limits when tested in real-driving conditions. In particular, diesel Euro 2 to Euro 6 passenger cars have real-world NOx emissions 1.6 to 4.3 times the respective regulatory limits. We find that the most common passenger car groups in Warsaw (i.e. those with > 10,000 records), namely diesel Euro 6 and petrol Euro 5, 6, and 6d-TEMP, all show emission levels above the laboratory limits. Particularly, the average real-world NO_x emissions of the diesel Euro 6 group and the petrol Euro 5 group, that together make up over 20% of the total measurements shown, are 4.3 times and 2.8 times the regulatory limits, respectively. The data, however, indicate that Euro 6d-TEMP and Euro 6d vehicles, which are subject to an additional on-road emission regulation, emit within their on-road thresholds of 2.1 times and 1.43 times the laboratory limits, respectively.

PM EMISSIONS

As shown in Figure 5, the data collected on PM emissions in Warsaw also echo the findings from studies in other European cities; pre-Euro 5 diesel vehicles that are not equipped with diesel particulate filters (DPFs) emit PM emissions at levels 4 to 11 times those of petrol equivalents. Furthermore, a significant improvement with DPFs is demonstrated by the PM emission performance of diesel Euro 5 vehicles, which emit 80% less compared with diesel Euro 4 vehicles. The relatively high levels of PM emissions observed for petrol vehicles certified to Euro 1 through Euro 3 standards is also noteworthy, as these older petrol vehicles are more common in the Warsaw vehicle fleet than older diesel vehicles.

The fuel-specific emission values (g/kg) obtained from instantaneous remote sensing emission readings can be used to detect individual high-emitting vehicles. Even though average PM emissions from post-Euro 4 diesel vehicles are drastically reduced with the application of DPFs, poor maintenance, aging, deliberate tampering, or removal of DPFs can lead to high levels of PM emissions for individual vehicles. To assess DPF malfunction and tampering in the Warsaw fleet, we applied the same emissions threshold used in the TRUE Brussels study, which was developed based on previous research

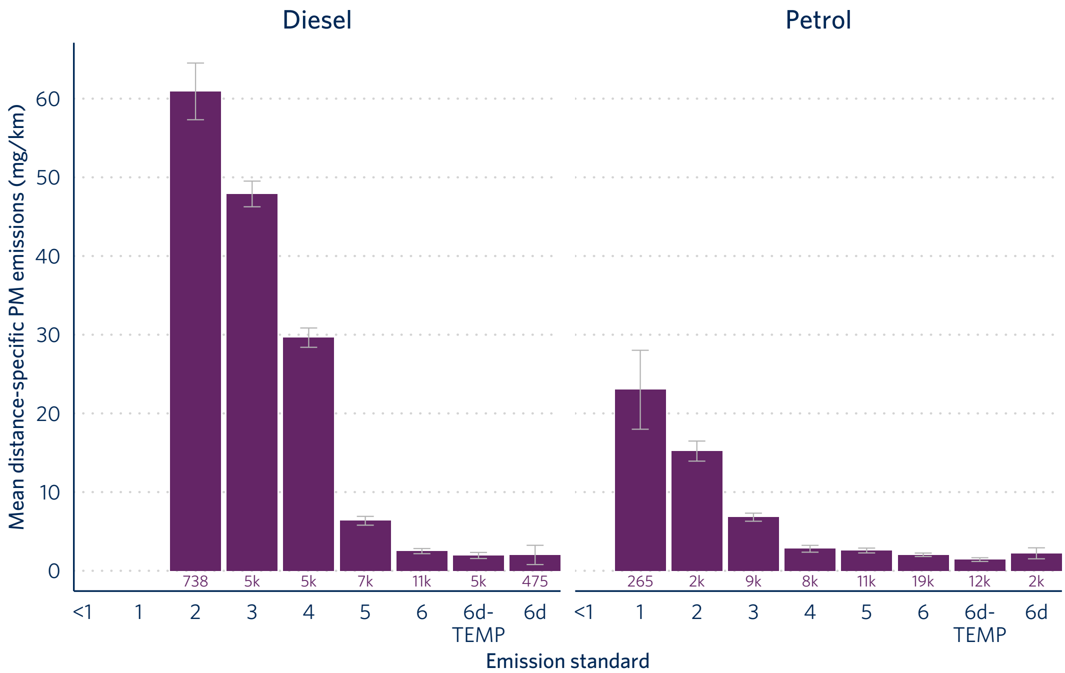


Figure 5. Average distance-specific PM emissions from diesel and petrol passenger cars by emission standard for the 2020 Warsaw remote sensing campaign. Whiskers represent the 95% confidence interval of the mean. Only results for groups of over 100 measurements are shown.

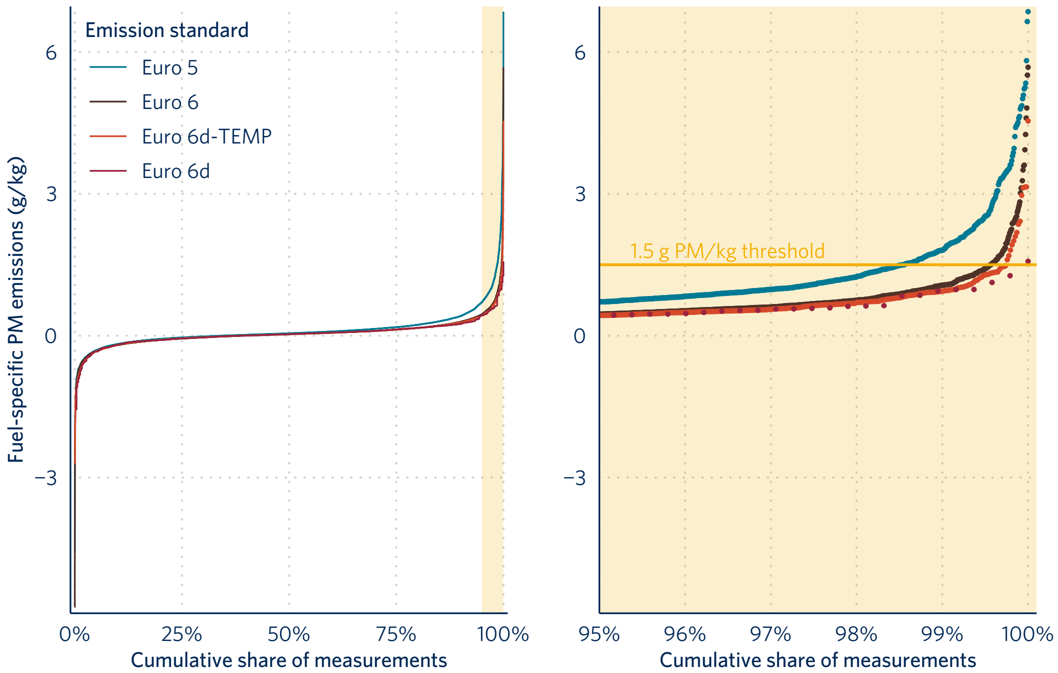


Figure 6. Cumulative distribution of diesel passenger cars and fuel-specific PM emissions by emission standard for vehicles certified to Euro 5 or above in Warsaw. Left panel shows the full range and the right panel shows a close-up of the 95th – 100th percentile range.

showing that PM emissions from DPF-equipped vehicles rarely exceed 1.5g PM per 1 kg of fuel burned.[28]

Figure 6 demonstrates that a relatively small share of DPF-equipped diesel vehicles in Warsaw show PM emissions exceeding the 1.5g/kg threshold. As shown in the right panel, only 1.5% of diesel vehicles certified to Euro 5, 0.4% of those certified to Euro 6, 0.3% of those certified to Euro 6d-TEMP, and 0.2% of those certified to Euro 6d were above this level. However, this should not downplay the importance of rigorous monitoring and inspection, as these vehicles accounted for 32%, 23%, 16%, and 9% of the total PM emissions within the respective emission standard groups.

In Warsaw, the shares of LCV measurements that exceed the 1.5g/kg PM threshold were almost double for Euro 5 (2.9%) and Euro 6 (0.9%) vehicles, suggesting that DPF tampering or malfunction may be a more widespread problem for LCVs than passenger cars. Further particulate number (PN) testing could be complemented with periodic technical inspection (PTI) programs to more accurately screen for individual high-emitting vehicles and identify DPF malfunctions for both passenger cars and LCVs.[29]

CO EMISSIONS

As shown in Figure 7, data from the Warsaw passenger fleet demonstrate that petrol vehicles certified to below Euro 6d-TEMP emit higher distance-specific carbon monoxide (CO) emissions than their diesel counterparts. Pre-Euro 5 Warsaw petrol vehicle groups emit two to nine times more CO emissions than the oldest diesel vehicle group, with three out of four of those groups showing real-world emissions above regulatory limits. Petrol vehicles certified to Euro 5 or above, on the other hand, show average distance-specific CO emissions below the regulatory limits and the newer standards, such as 6d-TEMP and 6d, show emission levels similar to those of equivalent diesel vehicles.

HC EMISSIONS

Similar to CO emissions, we find that average distance-specific HC emissions from petrol vehicles certified to below Euro 6 are higher than those of their diesel counterparts. Currently, regulatory limits on HC emissions only apply to petrol vehicles. Figure 8

28 Mridul Gautam and Donald Stedman, "Correlation of the Real-Time Particulate Matter Emissions Measurements of a ESP Remote Sensing Device (RSD) and a Dekati Electronic Tailpipe Sensor (ETaPS) with Gravimetrically Measured PM from a Total Exhaust Dilution Tunnel System," n.d., 61.

29 See Bernard et al., "Evaluation of Real-World Vehicle Emissions in Brussels."

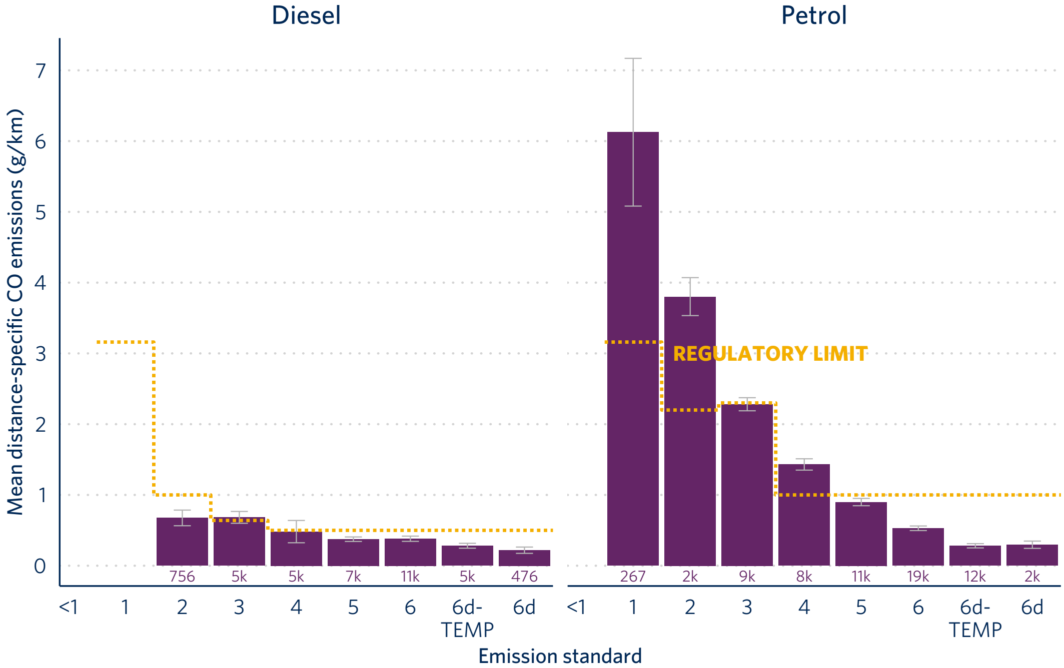


Figure 7. Average distance-specific CO emissions from diesel and petrol passenger cars by emission standard for the 2020 Warsaw remote sensing campaign. Whiskers represent the 95% confidence interval of the mean. Only results for groups of over 100 measurements are shown.

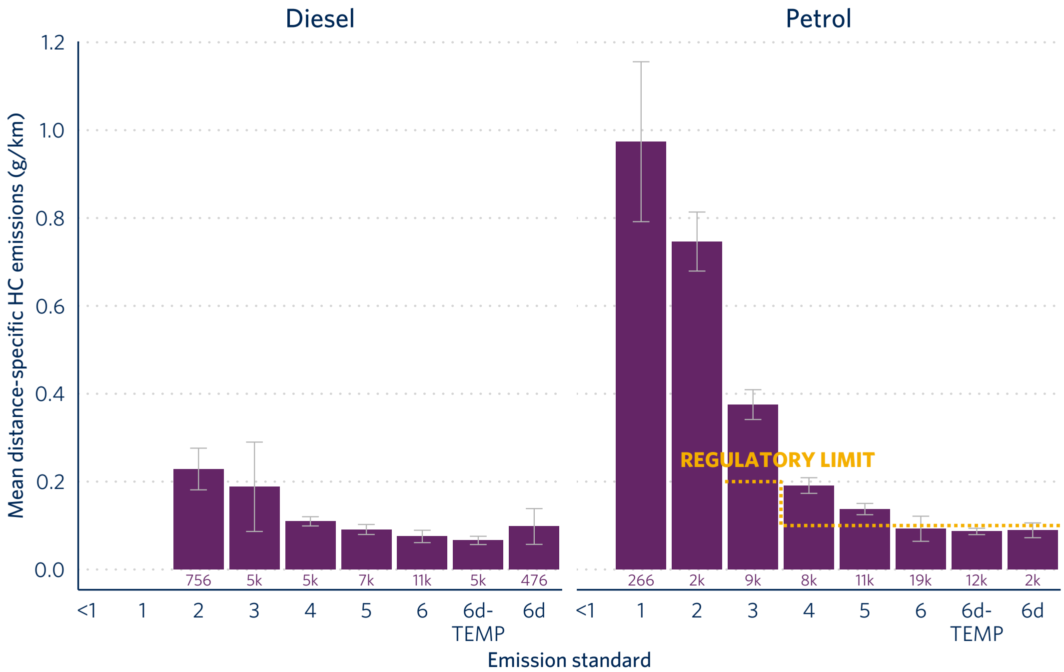


Figure 8. Average distance-specific HC emissions from diesel and petrol passenger cars by emission standard for the 2020 Warsaw remote sensing campaign. Whiskers represent the 95% confidence interval of the mean. Only results for groups of over 100 measurements are shown.

further suggests that in real-driving conditions, pre-Euro 6 petrol vehicles show mean distance-specific HC emissions exceeding their respective regulatory limits. In addition, vehicle groups that are not subject to emissions testing, such as Euro 1 and 2, emit levels of HC emissions three to four times the emissions level of the worst performing diesel vehicle group, Euro 2.

EVALUATION OF EMISSION SHARES OF WARSAW PASSENGER VEHICLE GROUPS

Estimation of vehicle activity and emission shares can help to identify vehicle groups that contribute disproportionately to emissions. This information can inform the development of policies, like the clean transportation zone currently under discussion in Warsaw. In this section, we use measurement shares as a proxy for vehicle activity shares and estimate emission shares using distance-specific emission estimates for each vehicle group.

Figure 9 shows that diesel Euro 2 to Euro 5 groups and petrol Euro 2 and Euro 3 groups have NO_X emission contributions disproportionate to their activity shares. Particularly, diesel cars certified to Euro 5 and below account for 45% of the total NO_X emissions while making up less than 20% of the passenger car fleet in Warsaw. Diesel Euro 3 and Euro 4 groups are also responsible for more than 50% of total passenger car PM emissions, while accounting for only 10% of the total measurements. Petrol cars certified to Euro 4 or below are responsible for over 50% of CO emissions and 45% of HC emissions while making up less than 20% of the fleet.

The results demonstrate the benefits that could result from phasing out the highest-emitting vehicle groups

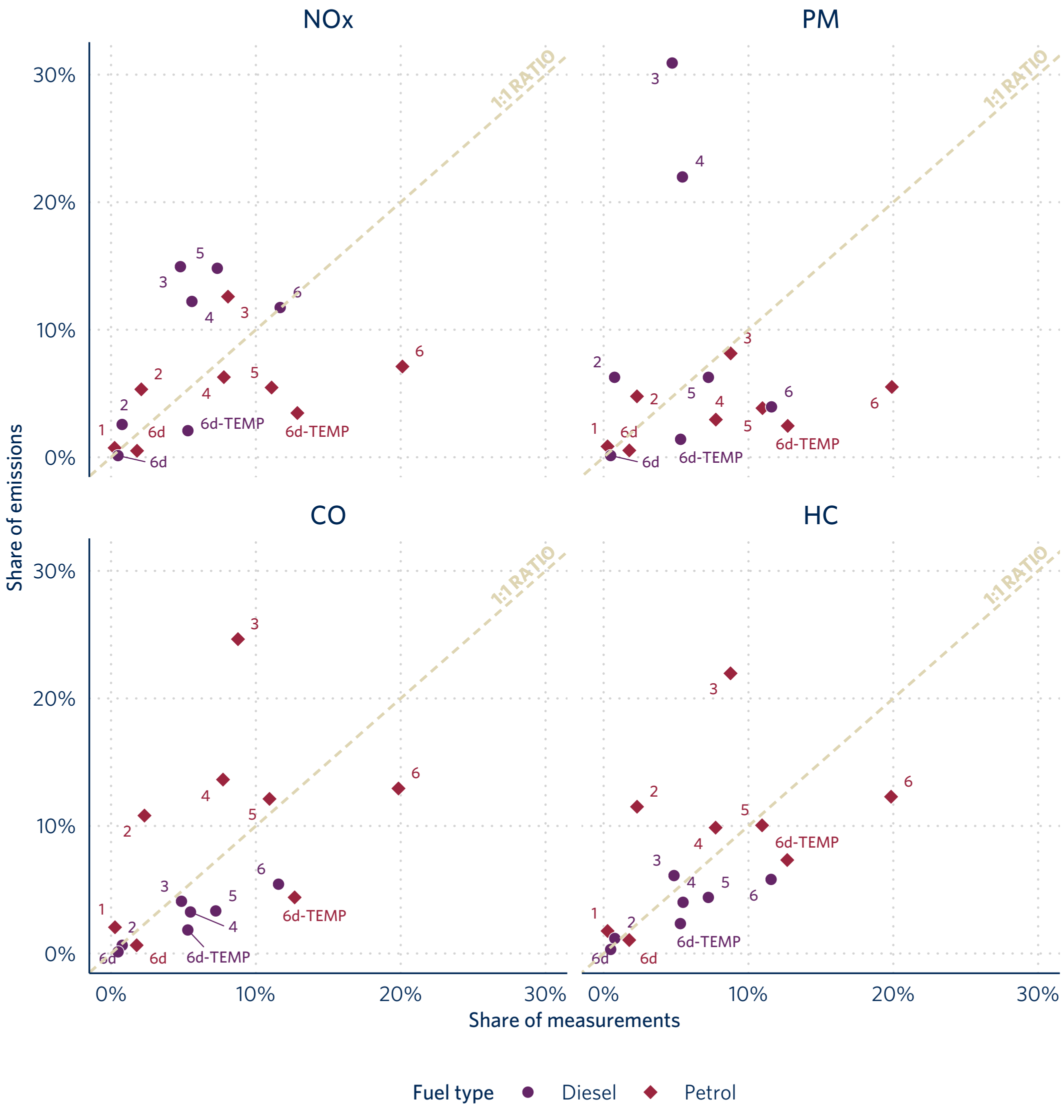


Figure 9. Measurements shares and estimated shares of NO_X, PM, CO, and HC emissions of passenger cars in Warsaw by fuel type and emissions standard. Only groups with over 100 measurements are shown.

from the Warsaw fleet. For example, our findings suggest the city can achieve great reductions in passenger car NO_X and PM emissions by restricting access of diesel vehicles certified to Euro 5 or below, which make up a small portion of the measurements but contribute disproportionately to total emissions. In addition, the results for CO and HC in older vehicles have important implications for restricting the use of petrol vehicles certified to Euro 1 to Euro 4 standards.

It is, however, important to note that these findings only reflect the passenger car fleet in Warsaw and other high-usage vehicle categories, such as buses and trucks, may show a different emission and activity trend. For Warsaw to establish a comprehensive transportation policy, a more thorough analysis that includes all types of vehicles should be considered.

IMPACTS OF MILEAGE ACCUMULATION

The degradation of emission control system over time and with accumulated mileage is shown to have a substantial impact on the emissions of in-use vehicles. Studies have shown evidence of increased NO_X, CO, and HC emissions of petrol vehicles with higher mileage and age.[30] These findings are also reflected in the European Monitoring and Evaluation Programme and Environmental Energy Agency air pollutant emissions guidebook that supports the reporting of emission data.[31]

To better ensure the emission performance of vehicles throughout their useful lifetime, two emission durability requirement provisions have been put forth by EU regulations. In-service conformity defines a period during which in-use vehicles are subject to conformity testing. Introduced from the Euro 3 standard, in-service conformity is checked from 6 months or 15,000 km, and up to 5 years or 80,000 km for Euro 3, 5 years or 100,000 km for Euro 4, and 5 years or 160,000 km for Euro 5 and Euro 6. The durability demonstration provision aims to verify the durability of emission control systems up to a useful lifetime at type-approval and is defined only by accumulated mileage. Similar to the in-service conformity requirements, the durability demonstration requirement has increased over time with the implementation of new standards: 80,000 km for Euro 2 to Euro 4 and 160,000 km for Euro 5 and Euro 6.

The vehicle registration database accessed for this study contained mileage data for passenger cars and enabled investigation into the impact of mileage on real-world emissions, a topic which has not been studied in previous TRUE studies. We used a sample of 96,458 diesel and petrol passenger cars of all emission standards whose mileage information was available. Mileage is recorded at the timing of periodic technical inspection. Currently in Warsaw, inspection of vehicles during which the mileage is recorded is required three and five years after the vehicle purchase, and every year thereafter. Therefore, the data used may underestimate milage, as it is outdated by one year on average.[32]

As the data used here provides a snapshot of one remote sensing campaign that took place in a limited period of time, it is not suitable for assessing the deterioration rates of vehicles.[33] Instead, we focus on real-world emissions as a function of accumulated mileage. To show the mileage distribution of the Warsaw passenger cars, measurements with mileages that are below the 5th percentile and above the 95th percentile are excluded from the analysis and the remaining measurements were grouped into mileage bins of equal ranges of 10,000km.

Figure 10 presents the distribution of vehicle age and recorded mileage for the Warsaw passenger car sample. Our data shows that only 17% of all unique vehicles with validated emission standards in Warsaw were operating within the two durability requirements, whichever comes first. Given the presence of old vehicles with unidentifiable class, we note that the actual share of

30 Jens Borken-Kleefeld and Yuche Chen, "New Emission Deterioration Rates for Gasoline Cars – Results from Long-Term Measurements," *Atmospheric Environment* 101 (January 2015): 58–64, https://doi.org/10.1016/j.atmosenv.2014.11.013; Yoann Bernard et al., "TRUE U.S. Database Case Study: Emissions Deterioration of U.S. Gasoline Light-Duty Vehicles and Trucks" (Washington, D.C.: TRUE Initiative, October 30, 2020), https://theicct.org/publications/true-us-database-emissions-deterioration-oct2020; Tao Zhan et al., "An Analysis of Real-World Exhaust Emission Control Deterioration in the California Light-Duty Gasoline Vehicle Fleet," *Atmospheric Environment* 220 (January 2020): 117107, https://doi.org/10.1016/j.atmosenv.2019.117107.

31 European Environment Agency, "1.A.3.b.i-Iv Road Transport 2019," in *EMEP/EEA Air Pollutant Emission Inventory Guidebook 2019* (European Environment Agency, 2019), https://www.eea.europa.eu/publications/emep-eea-guidebook-2019/part-b-sectoral-guidance-chapters/1-energy/1-a-combustion/1-a-3-b-i.

32 The average distance travelled by car in Poland in 2020 was 7,500km. Source: Change in distance travelled by car. https://www.odyssee-mure.eu/publications/efficiency-by-sector/transport/distance-travelled-by-car.html

33 For an example of the use of longitudinal remote sensing data used to define emission deterioration rates, see the TRUE study on the emission deterioration of U.S. gasoline light-duty vehicles and trucks. https://theicct.org/publication/true-u-s-database-case-study-emissions-deterioration-of-u-s-gasoline-light-duty-vehicles-and-trucks/

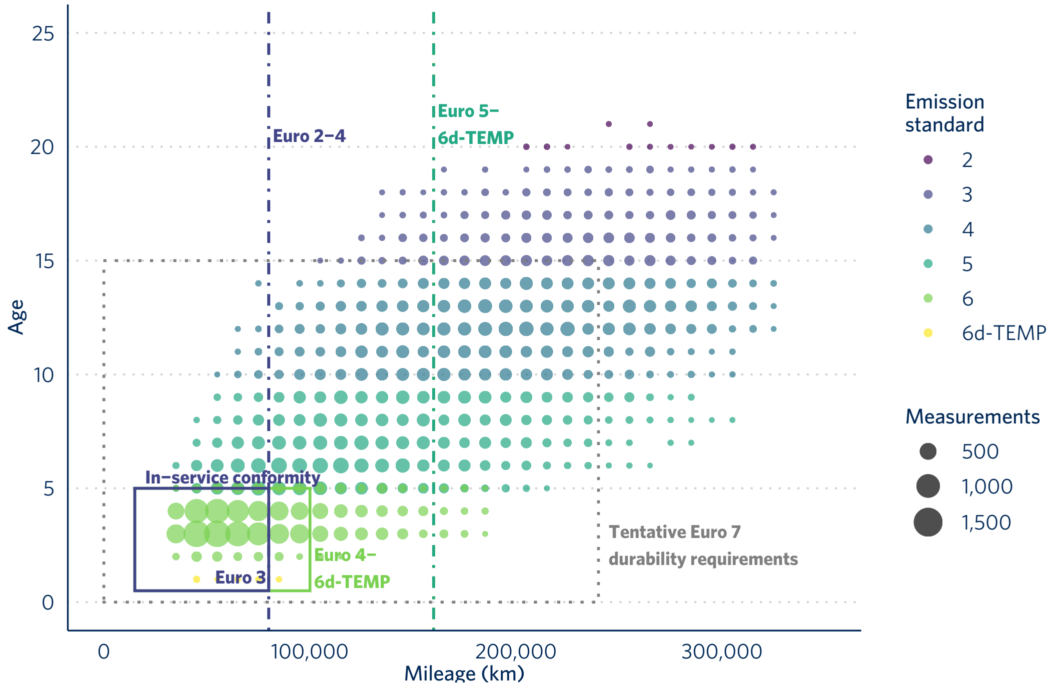


Figure 10. Distribution of mileages and ages of the Warsaw passenger cars. Rectangles indicate the in-service conformity requirements for different emission standards. Vertical dash-dotted lines indicate emission durability demonstration periods defined by mileage. The emission durability requirements of Euro 7 are currently under discussion. Only data points of over 50 measurements are shown.

those operating within the durability requirements is likely lower. This means that the majority of in-use vehicles in Warsaw have mileages and ages that exceed the useful lifetime defined in EU regulations for in-service conformity and durability demonstration.

To assess the impact of mileage accumulation on emissions by emissions standard, we investigated fuel-specific emissions as a function of recorded mileage at the time of the campaign. The mileage values are compared against the durability demonstration requirements to show if the Warsaw passenger cars are still operating within this regulatory useful lifetime. In the analysis, passenger cars certified to pre-Euro 3, Euro 6d-TEMP, and Euro 6d standards are excluded due to insufficient data.

Our analysis finds that emissions increase with accumulated mileage both within and outside the durability demonstration period. Figure 11 shows an upward trend of average fuel-specific emissions of NO_X, CO, and HC with increasing mileage of petrol vehicles in Warsaw.

The average emissions for Euro 6 vehicles measured in Warsaw are shown for mileage bins between 5,000 km and 135,000 km, a range within the emission durability demonstration period (160,000 km). The average emissions of vehicles in the lowest mileage group are greater than those in the highest mileage group by 21% for NO_X, 14% for HC, and by a factor of over two for CO. Most of the vehicles certified to Euro 3 and Euro 4 standards in Warsaw had mileages beyond the durability requirement of 80,000 km and, therefore, the emission trends seen here can indicate the possible long-term impacts of mileage on emissions. For the Euro 4 and Euro 5 groups, the average emissions of all three pollutants from the highest mileage group were larger than those from the lowest mileage group by a factor ranging from 2.7 to 7.6. For passenger cars certified to Euro 3, all measurements presented in Figure 11 recorded mileages exceeding the mileage specified in the durability demonstration period by at least 45,000 km. The average emissions of the highest mileage group are 1.5 to 3.2 times those of the lowest mileage group, indicating that emissions can continue to increase at mileages beyond the durability demonstration period. The PM emission results for all petrol vehicles did not produce any noticeable trend.

Currently, there is limited knowledge on the real-world emission deterioration of diesel engines. One study found that the emission levels of diesel vehicles do not

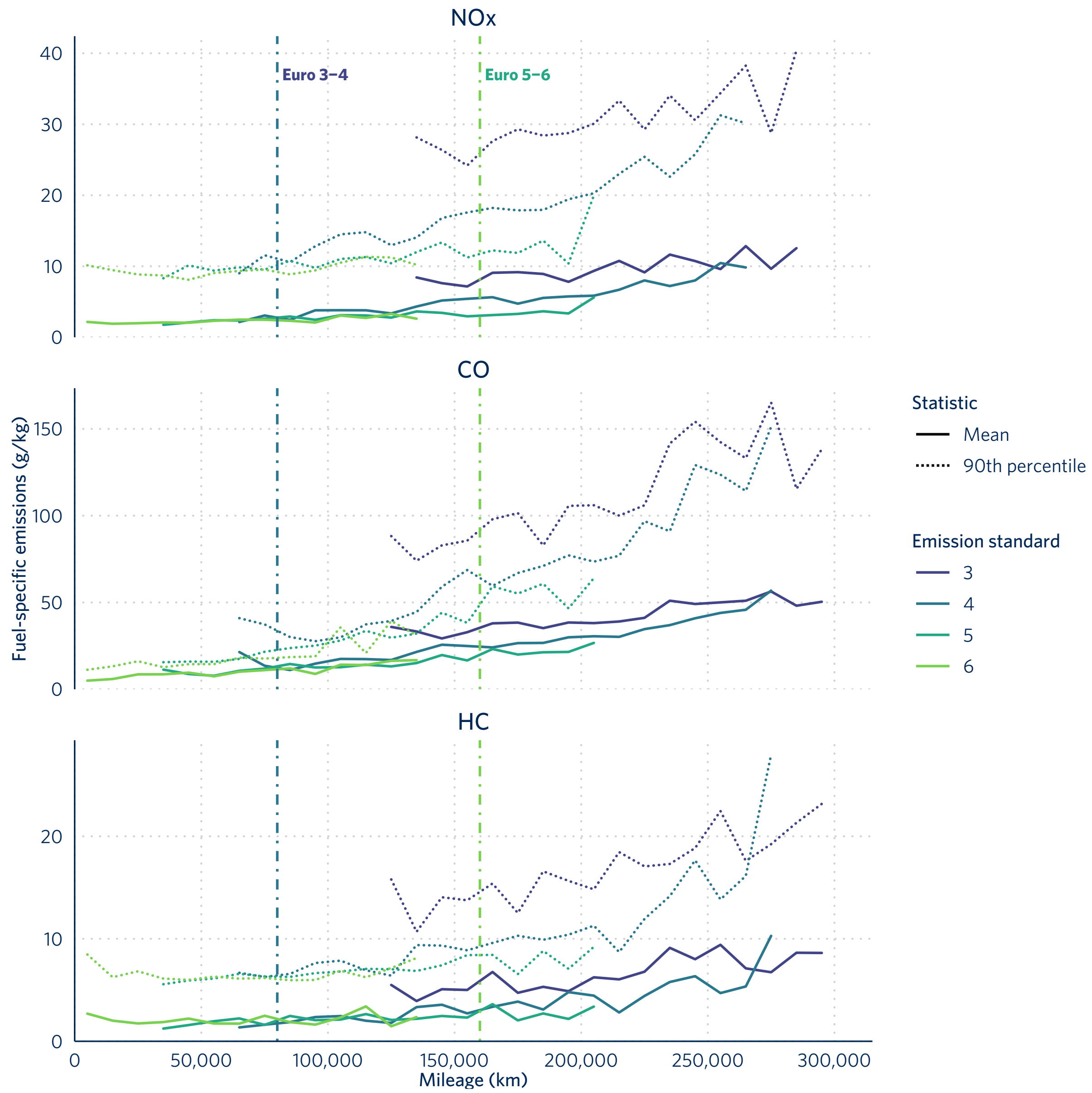


Figure 11. Impacts of mileage accumulation on the emissions of NO_x, CO, and HC from petrol vehicles in Warsaw. Vertical dash-dotted lines indicate emission durability demonstration periods defined by mileage. Only results for data points with over 200 measurements are shown.

stay stable throughout their lifetime by demonstrating increasing NO_x emissions of passenger cars certified to Euro 2 and Euro 3 standards using longitudinal data obtained over 15 years.[34]

While the data used in this study offers only a snapshot, our findings provide some insights into the impacts of mileage on the NO_x emissions of diesel vehicles. As shown in Figure 12, for all emission standards studied, the average NO_x emissions show an increase between the lowest and the highest mileage groups. The Euro 6 group shows the biggest increase of over 15%, followed by Euro 4 and Euro 5 (10%) and Euro 3 (4%). A slight upward trend of NO_x emissions from Euro 3 vehicles suggests that, although small, mileage still has an impact on NO_x emissions from diesel engines long after the vehicles surpass the durability requirements. The results for PM, CO, and HC did not show any noticeable trends.

34 Yuche Chen and Jens Borken-Kleefeld, "NOx Emissions from Diesel Passenger Cars Worsen with Age," *Environmental Science & Technology* 50, no. 7 (April 5, 2016): 3327–32, https://doi.org/10.1021/acs.est.5b04704.

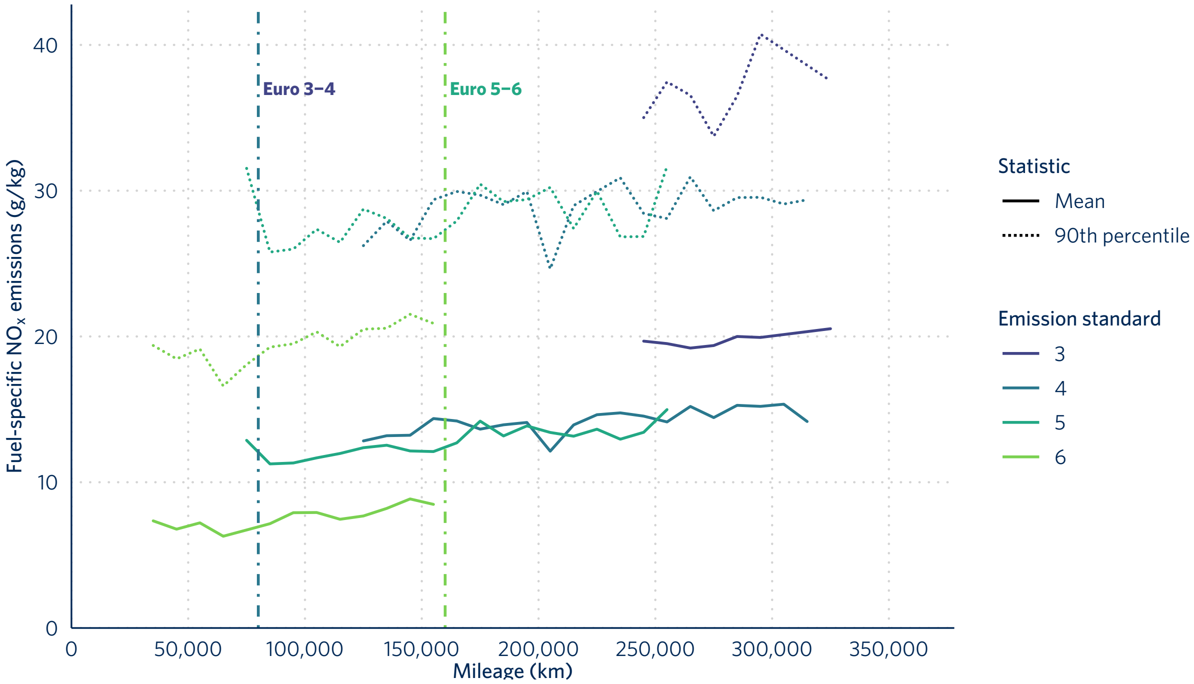


Figure 12. Impacts of mileage accumulation on NO_x emissions from diesel vehicles in Warsaw. Vertical dash-dotted lines indicate emission durability demonstration periods defined by mileage. Only results for data points with over 200 measurements are shown.

The findings indicate that the in-service conformity and emission durability demonstration periods defined in regulatory standards are not sufficient to cover the actual useful lifetimes of the majority of vehicles in the Warsaw passenger car fleet. Our measurements show that at least 83% of in-use vehicles in Warsaw had mileages or ages greater than these requirements. It is expected that the upcoming Euro 7 standard will extend the in-service conformity testing period to 15 years or 240,000 km, and the durability demonstration period to 240,000 km.[35] These requirements should better represent actual in-use lifetimes of European passenger cars. However, our findings show approximately 30% of the passenger cars observed in Warsaw had mileages or ages exceeding these levels, suggesting longer useful lifetimes may be needed to accurately represent the usage of passenger cars in European cities. We recommend aligning age and mileage requirements for in-service conformity testing with the useful life period for durability demonstration and setting these to levels representative of the complete useful life of the EU fleet. As a point of reference, 90% of Warsaw passenger cars observed in this study were less than 20 years old and had mileages under 320,000 km. Compiling similar data for fleets in other European cities would help to inform the definition of more representative useful life periods in emissions regulations.

EMISSIONS FROM IMPORTED SECOND-HAND VEHICLES

Poland's vehicle fleet is characterized by a large number of imported second-hand vehicles which we were able to examine using registration information available in the Warsaw dataset. In the following analysis, imported second-hand vehicles were distinguished by the existence of foreign registration dates as well as domestic registration dates acquired from the registry data. Their foreign registration dates all preceded their domestic registration dates, which indicates that these vehicles were originally registered elsewhere and imported to Poland. Of these vehicles, 99.95% had mileages of over 50 km. Despite nearly 40% of the imported second-hand vehicles in the sample not having identifiable vehicle classes, we were able to group most of them into light-duty vehicles (LDVs), using thresholds for curb weight and engine displacement

35 CLOVE Consortium, "Additional Technical Issues for Euro 7 LDV" (Advisory Group on Vehicle Emission Standards (AGVES), Brussels, April 27, 2021), 7, https://circabc.europa.eu/w/browse/f57c2059-ef63-4baf-b793-015e46f70421.

(see methodology). Therefore, the analysis is expanded to all LDVs in the following sections.

FLEET CHARACTERISTICS OF LIGHT-DUTY VEHICLES IN WARSAW

We first examine the fleet characteristics of all LDVs used in the following analysis, which may look slightly different from those of passenger cars due to the inclusion of light commercial vehicles and vehicles with unknown classes. As detailed in the methodology, these vehicles with unknown vehicle classes were not excluded because they had vehicle information useful for a detailed analysis, such as registration date, fuel type, engine displacement, and emission data. The LDV sample used had 193,187 measurements from 125,896 unique vehicles.

The average age of the measured Warsaw LDV fleet is 8 years. However, as shown in Figure 13, vehicles that belong to the three vehicle classes that constitute the LDV sample show different age distributions: light commercial vehicles have the lowest average age of 6 years with two peaks around 1–2 years and 10 years, and passenger cars show an average age of 7 years with a peak around age 1 year. Lastly, light-duty vehicles with unknown classes show an average age of 15 years with a peak around 16 years and significantly increase the average age of the Warsaw LDV fleet.

Nearly 80% of these vehicles were identified as imported second-hand vehicles.

FLEET CHARACTERISTICS OF IMPORTED VEHICLES

The Warsaw LDV sample contained 61,571 measurements from 40,747 imported second-hand vehicles, which made up almost a third of all LDVs. The majority of the imported vehicles were passenger cars (61%), followed by those with unknown classes (35%) and light commercial vehicles (4%).

The remaining sample consisted of domestic vehicles, which we define as all other vehicles that were registered only in Poland but were not necessarily manufactured in Poland. Domestic vehicles made up 68% of all LDV measurements (131,616 measurements from 85,149 unique vehicles). Passenger cars were the most predominant vehicle class, accounting for 85% of the measurements, followed by light commercial vehicles (11%). The vehicle class of the remaining 4% of the measurements could not be identified.

Due to the lack of the vehicle class information and the different phase-in timings of emission standards for light commercial vehicles and passenger cars, this analysis focuses on age rather than emission standard. Imported second-hand vehicles are older and have

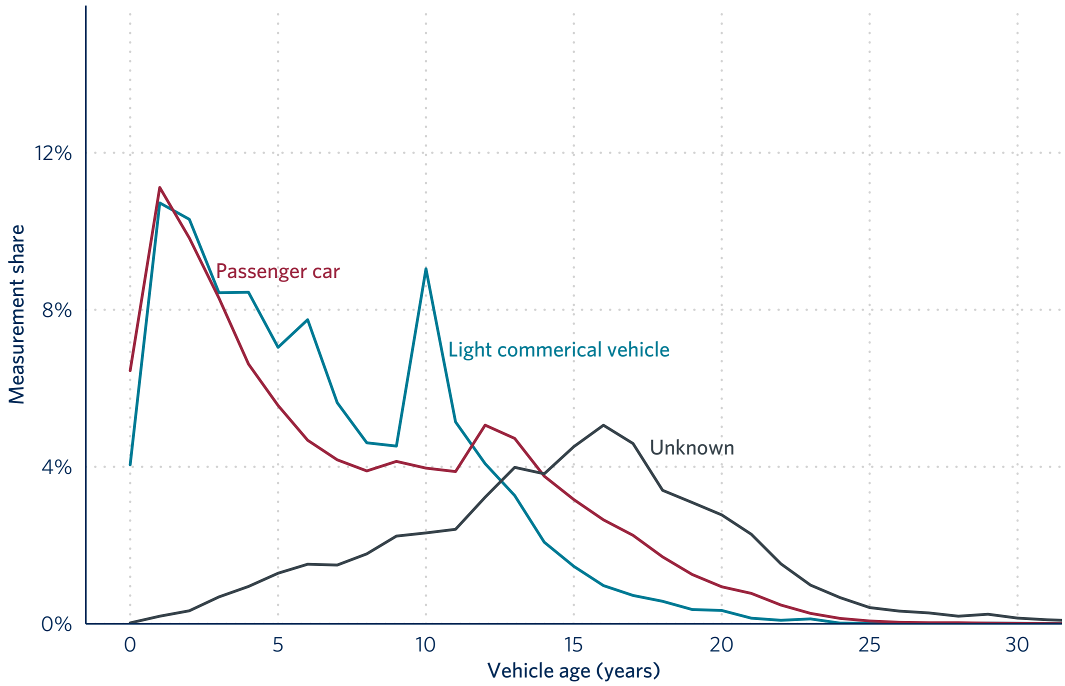


Figure 13. Age distribution of different vehicle classes that constitute the Warsaw light-duty vehicle sample.

higher mileages than domestic vehicles in Warsaw. The average age of imported second-hand vehicles (13 years) was more than double that of domestic vehicles (6 years). Figure 14 presents the distribution of ages and mileages of imported and domestic vehicles in Warsaw. Imported second-hand vehicles show a distribution shifted more towards older vehicles than domestic vehicles, with a peak around 15 years. Older vehicles also tend to have higher mileages; the average mileage of domestic vehicles was 144,365 km, whereas that of imported second-hand vehicles was 222,767 km. Both the average and the median mileage values of imported second-hand vehicles were over 1.5 times those of domestic vehicles.

The composition of fuel types also differed for domestic and imported second-hand vehicles in Warsaw, as shown in Figure 15. More domestic vehicles are petrol-powered (58%) than diesel-powered (42%). In contrast, more than half (53%) of the imported second-hand vehicles run on diesel. The more dominant share of diesel-powered imported second-hand vehicles is not unexpected, given that most of imported second-hand vehicles in Poland come from Western European countries where diesel vehicles are more common than petrol vehicles.

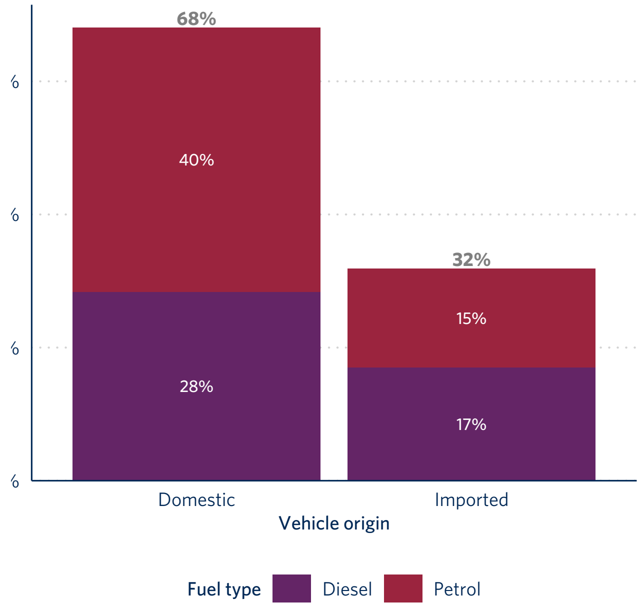


Figure 15. Distribution of fuel types by import status.

EMISSIONS OF IMPORTED SECOND-HAND VEHICLES

This section investigates the emissions of NO_X, PM, CO, and HC from imported second-hand vehicles in Warsaw. The results are shown for all domestic and imported LDVs and by fuel type.

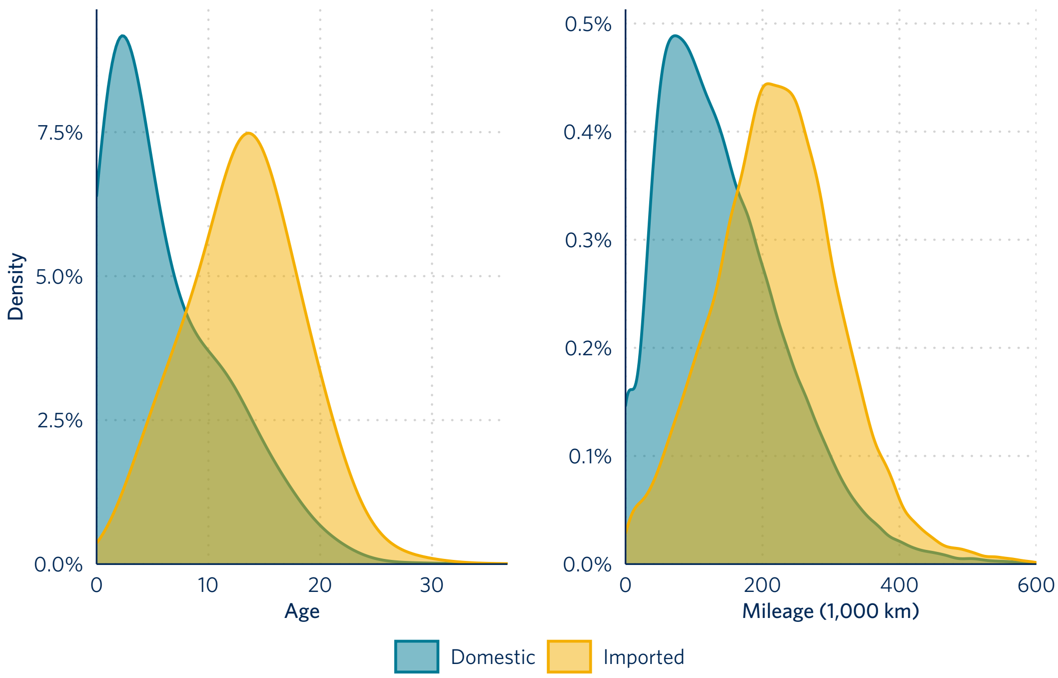


Figure 14. Age and mileage distribution of imported and domestic light-duty vehicles in Warsaw. Note that the scales of the y-axes for two density plots are different.

The results demonstrate that imported second-hand vehicles are more polluting than domestic vehicles in Warsaw. More specifically, Figure 16 shows that the emission performance of imported second-hand vehicles is consistently worse than that of domestic vehicles across all pollutants. The fleet-average fuel-specific NO_x and PM emissions from imported second-hand vehicles are more than double and triple those from domestic vehicles, respectively. The trend is similar across fuel types, with both imported diesel and petrol vehicles showing large mean fuel-specific emissions. The fleet-average emissions from imported second-hand vehicles are also nearly double those from domestic vehicles for CO and HC.

We examined whether other variables contributed to the significantly higher emission rates observed for imported second-hand vehicles relative to domestic vehicles. We found no significant difference in the influence of vehicle specific power and ambient temperature on emissions from the two groups. Similarly, no significant impacts were observed for vehicle weight, make, and model that could explain the large emission gap.

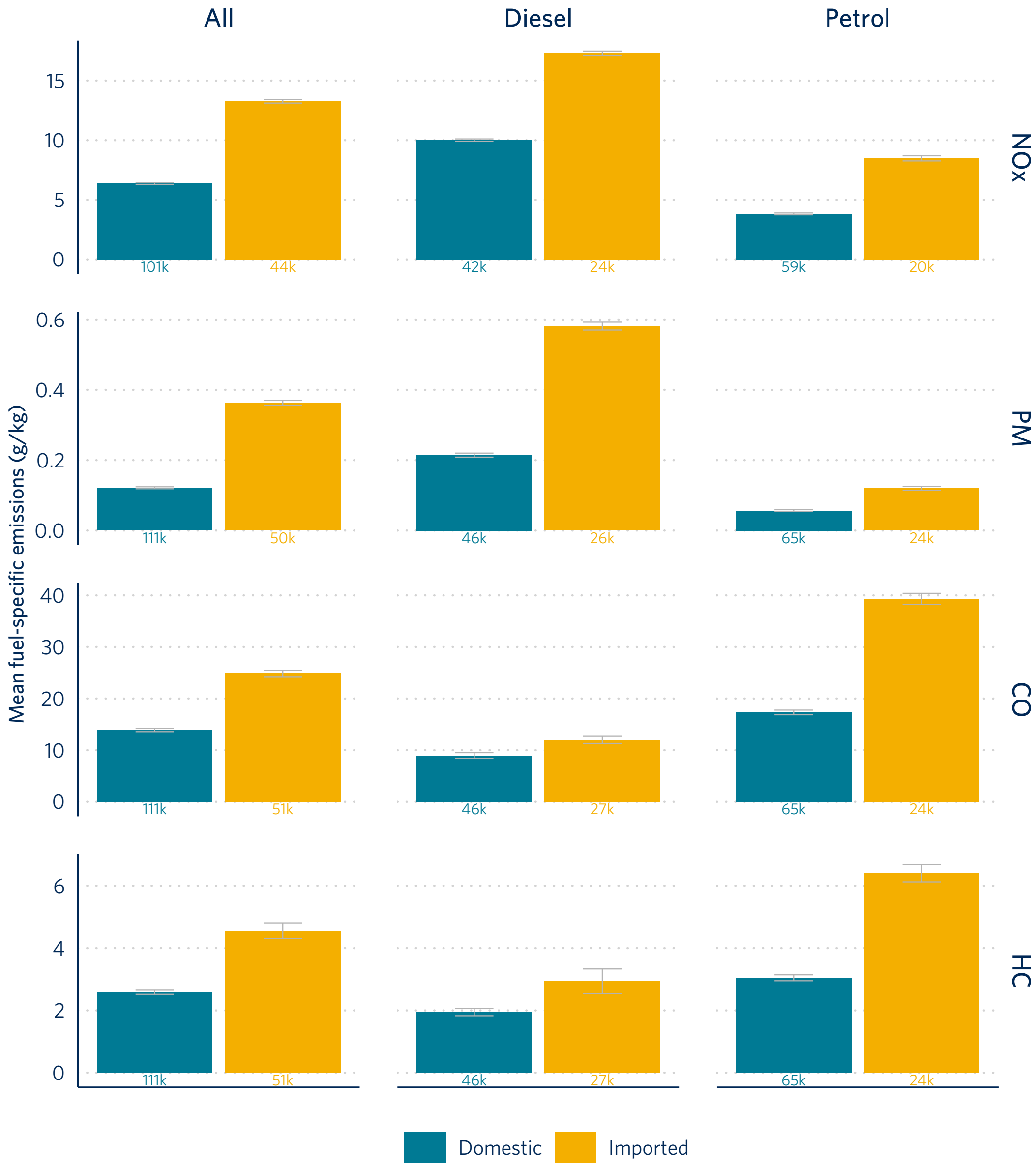


Figure 16. Average fuel-specific emissions of NO_x, PM, CO, and HC from domestic and imported vehicles in Warsaw. Whiskers indicate the 95% confidence interval of the mean.

The average fuel-specific emissions for all pollutants were explored by age for comparison on a more granular level. Figure 17 compares the average fuel-specific emissions of domestic and imported second-hand vehicles by age and fuel type. Although the results for NO_x emissions from diesel vehicles show a slight variance within the age groups, the domestic and imported second-hand vehicles of the same age generally show comparable levels of emission for all other pollutants.

The notable difference is seen in the number of old vehicles present in the two samples. Older vehicles were more commonly found in the imported second-hand vehicle group while there were more younger vehicles in the domestic group. Particularly, the larger presence of old vehicles of age 20 years and above, which also show among the highest mean fuel-specific emissions, is visible in the imported second-hand vehicle group. While these vehicle measurements accounted for less than 2% of domestic measurements, over 10% of all measurements of imported second-hand vehicles were over 20 years old.

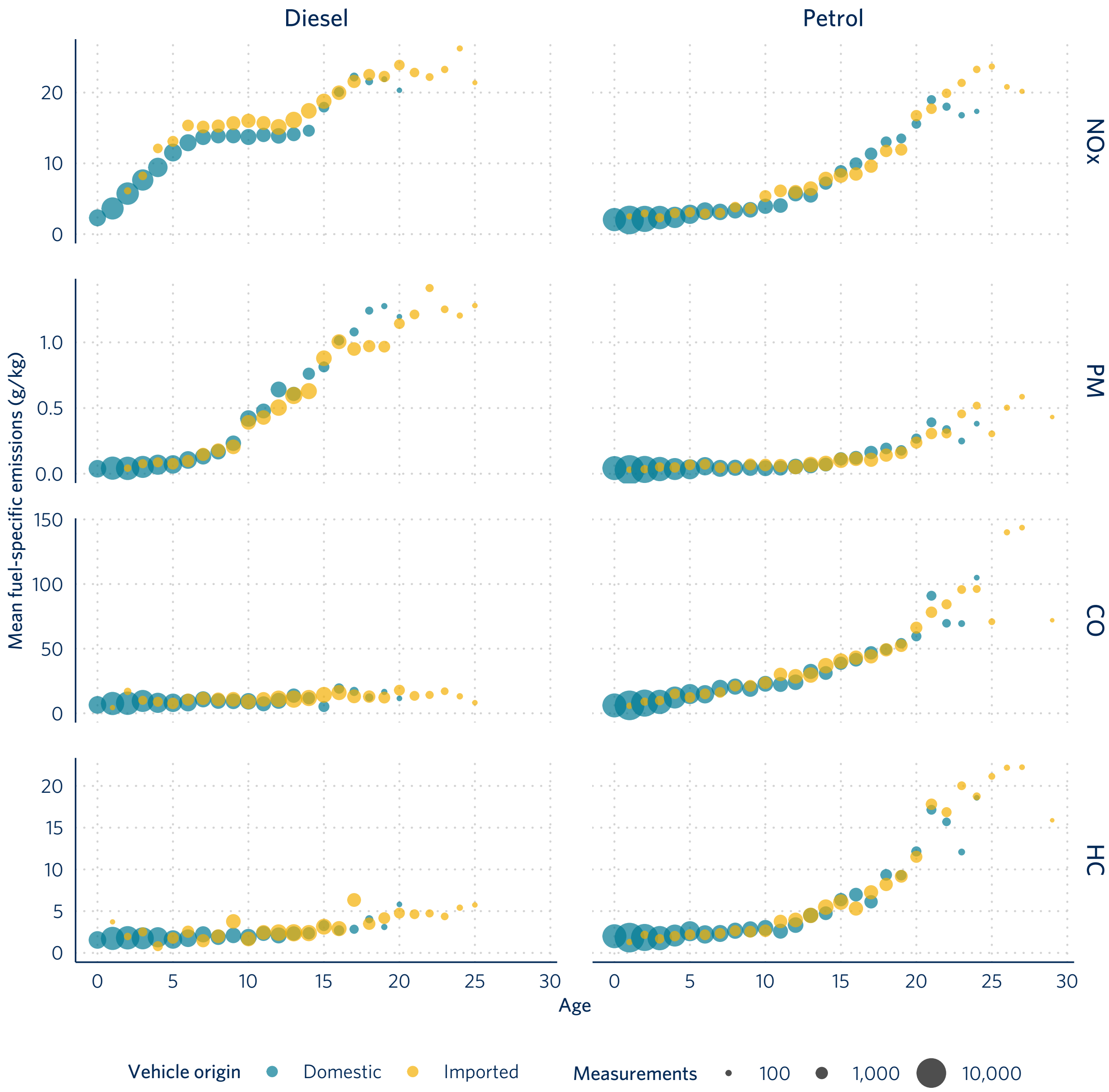


Figure 17. Average fuel-specific emissions for NOx, PM, CO, and HC from domestic and imported vehicles by fuel type. Size of data points indicate the measurement numbers. Each point shown has at least 50 measurements.

POLICY IMPLICATIONS

Imported second-hand vehicle market is large in Poland for a number of reasons: 1) these vehicles provide an affordable mobility options in areas where the public transportation infrastructure is poor; 2) petrol vehicles of age 12 and older, or those certified to below Euro 5, can easily be converted to run on LPG and, therefore, are in high demand; and 3) old diesel vehicles are common exports from markets that limit the use of diesel vehicles due to policies in many Western European cities. Currently, there are no regulations that limit the importation of old, polluting vehicles in Poland.

Limiting the emissions from imported second-hand vehicles is possible at the national level through various programs. One direct way is to impose import restrictions, commonly with an age limit, similar to the prohibition of the importation of vehicles of over 3 years in some North African countries.[36] Considering the challenge of implementing such restrictions within the same EU jurisdiction, other policies, such as taxation and scrappage programs, would be more effective in promoting earlier retirement of older vehicles and incentivizing the purchase of cleaner, newer vehicles. Strengthening and enforcing inspection and maintenance programs to ensure that imported second-hand vehicles undergo rigorous testing and repair for quality assurance can also be implemented nation-wide.[37]

At the city level, Warsaw can reduce the number of old imported second-hand vehicles within the city boundary by requiring on-road vehicles to meet certain emission standard requirements. Restricting the use of vehicles certified to below Euro 4 standard, which are currently 17 years old or older, would remove the vehicles identified as the highest emitters in the imported second-hand vehicle group. A progressive implementation of such restrictive policy would further deter vehicle owners from purchasing imported second-hand vehicles in the long-term, as they would anticipate further restrictions in the future.

In Warsaw, vehicles whose vehicle classes and emission standards were unidentifiable tended to be older and have high average emissions. Therefore, in order to present a more accurate picture of emissions from all vehicles and address them more comprehensively, it is important that these vehicles are accounted for in the registry database.

36 Jorge Macias et al., "Policy Handbook for the Regulation of Imported Second-Hand Vehicles," Working Paper (Mexico, D.F.: Global Fuel Economy Initiative, June 2013).

37 Macias et al. "Policy Handbook for the Regulation of Imported Second-Hand Vehicles."

CASE STUDY: COMPARISON OF THE REAL-WORLD EMISSIONS OF THE WARSAW AND BRUSSELS FLEETS

This section compares the findings of a previous TRUE study evaluating the real-world emissions of the Brussels fleet with the Warsaw fleet emissions. The Brussels study provides an important point of comparison particularly because, while Brussels has a fleet structure largely representative of Western Europe, it shares the same emission regulations for new vehicles as Warsaw under the EU rules, which makes direct comparison possible. In addition, Brussels has implemented various policies addressing traffic-related pollution, such as a low-emission zone (LEZ) and a maximum age limit for taxis, which could serve as a benchmark for Warsaw's transportation policy.

TESTING CONDITIONS AND FLEET CHARACTERISTICS

Table 2 compares the testing conditions and general fleet characteristics of light-duty vehicles from the two remote sensing campaigns. Both the Warsaw and Brussels campaigns measured comparable numbers of unique vehicles around the same time using similar remote sensing instruments. However, the average ambient temperature during the Warsaw testing campaign was 5°C higher than during the Brussels testing campaign. Additionally, the LDVs measured in Warsaw show a vehicle specific power 1kW/t higher than that of the LDVs measured in Brussels due to the average speed of LDVs measured in Warsaw being nearly 10km/h higher than that of the Brussels LDVs.

The younger average age of the Brussels LDVs can be largely attributable to the LEZ that has been in place in Brussels since 2018. At the time of the campaign, the LEZ restrictions covered diesel vehicles certified to below Euro 4 and petrol vehicles certified to below Euro 2, and few of these vehicles are found in the Brussels LDV sample. The restrictions are currently being expanded to include diesel Euro 4, with further access regulations across all vehicle types expected until 2035.

EMISSIONS FROM LIGHT-DUTY VEHICLES

The real-world emissions from the light-duty vehicle samples of Warsaw and Brussels were investigated for NO_X, PM, CO, and HC. All LDVs, rather than only passenger cars, were explored to provide a more comprehensive picture of the fleet. Light-duty vehicles powered by fuels other than diesel and petrol made up less than 0.1% of the fleet and were there for excluded from the analysis. Figure 18 gives an overview of the average emissions of the LDVs in both cities by fuel type.

An investigation of the fleet-average emissions and emissions by fuel type offers insight into how the fleet composition influences emissions in Warsaw and Brussels. We find that the fleet-average emissions from the Warsaw LDVs are higher across all pollutants, with the biggest differences shown for CO and HC emissions.

Table 2. Comparison of testing conditions and general fleet characteristics for the Warsaw and Brussels light-duty vehicle fleets.

	Warsaw	Brussels
Campaign dates	September – October 2020	October – November 2020
Number of sampling locations	6	8
Remote sensing instrument	Opus AccuScan™ RSD5500	Opus AccuScan™ RSD 5000 & RSD 5500
Number of measurements and unique vehicles	193,187 from 125,896 unique vehicles	254,017 from 125,510 unique vehicles
Dieselization rate	45%	65%
Average vehicle age (at the time of measurement)	8 years	6 years
Average ambient temperature	24.4°C	19.2°C
Average vehicle specific power	11.1 kW/t	9.6 kW/t

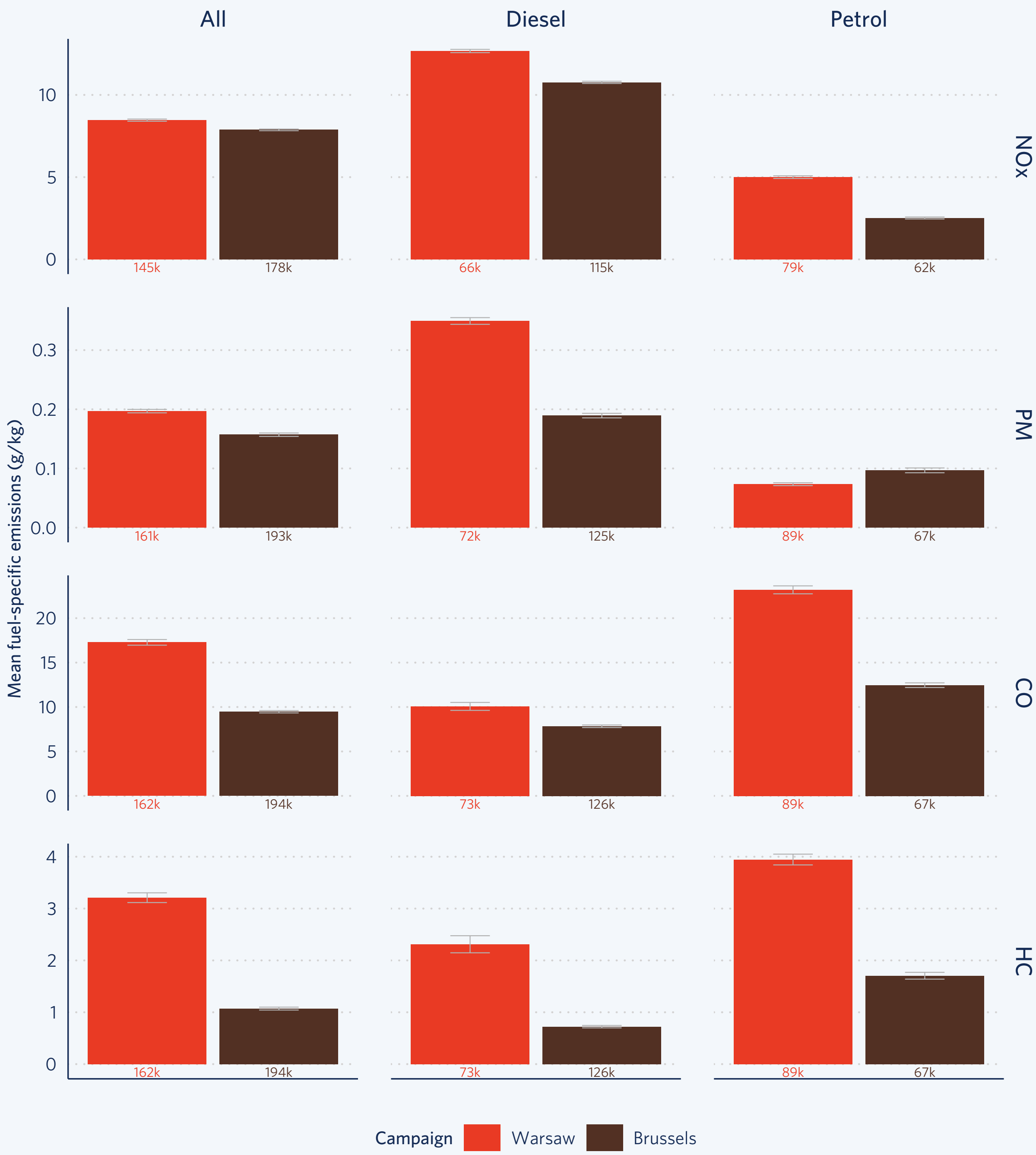


Figure 18. Average fuel-specific emissions of NO_x, PM, CO, and HC from light-duty vehicles in Warsaw and light-duty vehicles in Brussels. Whiskers indicate the 95% confidence interval of the mean.

The fleet-average NO_x emissions of Warsaw, however, are only 7% higher than those of Brussels despite both petrol and diesel vehicles in Warsaw emitting 1.2 and 2 times, respectively, the average NO_x emissions of their Brussels counterparts. This is mainly because the share of diesel vehicles present in the Brussels LDV sample is 20% higher than that of the Warsaw sample. Diesel vehicles in Brussels emit double the emissions of the Warsaw petrol vehicles, the more prevalent fuel type in Warsaw.

Similarly, the Warsaw diesel vehicles have average fuel-specific PM emissions (0.35 g/kg) that are nearly double those of the Brussels diesel vehicles (0.19g/kg) but the gap is smaller for the fleet- average PM emissions, also mainly due to the higher share of diesel vehicles in Brussels' fleet. These findings demonstrate that the share of diesel vehicles in the fleet is an important factor for fleet-average NO_x and PM emissions.

The Warsaw LDV fleet, however, shows fleet-average fuel-specific CO and HC emissions that are nearly two and three times those of the Brussels LDV fleet, respectively. These results can be explained by the higher share of petrol vehicles in the Warsaw fleet, which tend to emit more CO and HC emissions.

Figure 19 presents the average fuel-specific emissions of all four pollutants from LDVs by emission standard, which elucidates further why the Warsaw vehicles have higher NO_x and PM emissions than the Brussels vehicles. High NO_x and PM emitters like diesel vehicles certified to below Euro 4 and petrol vehicles certified

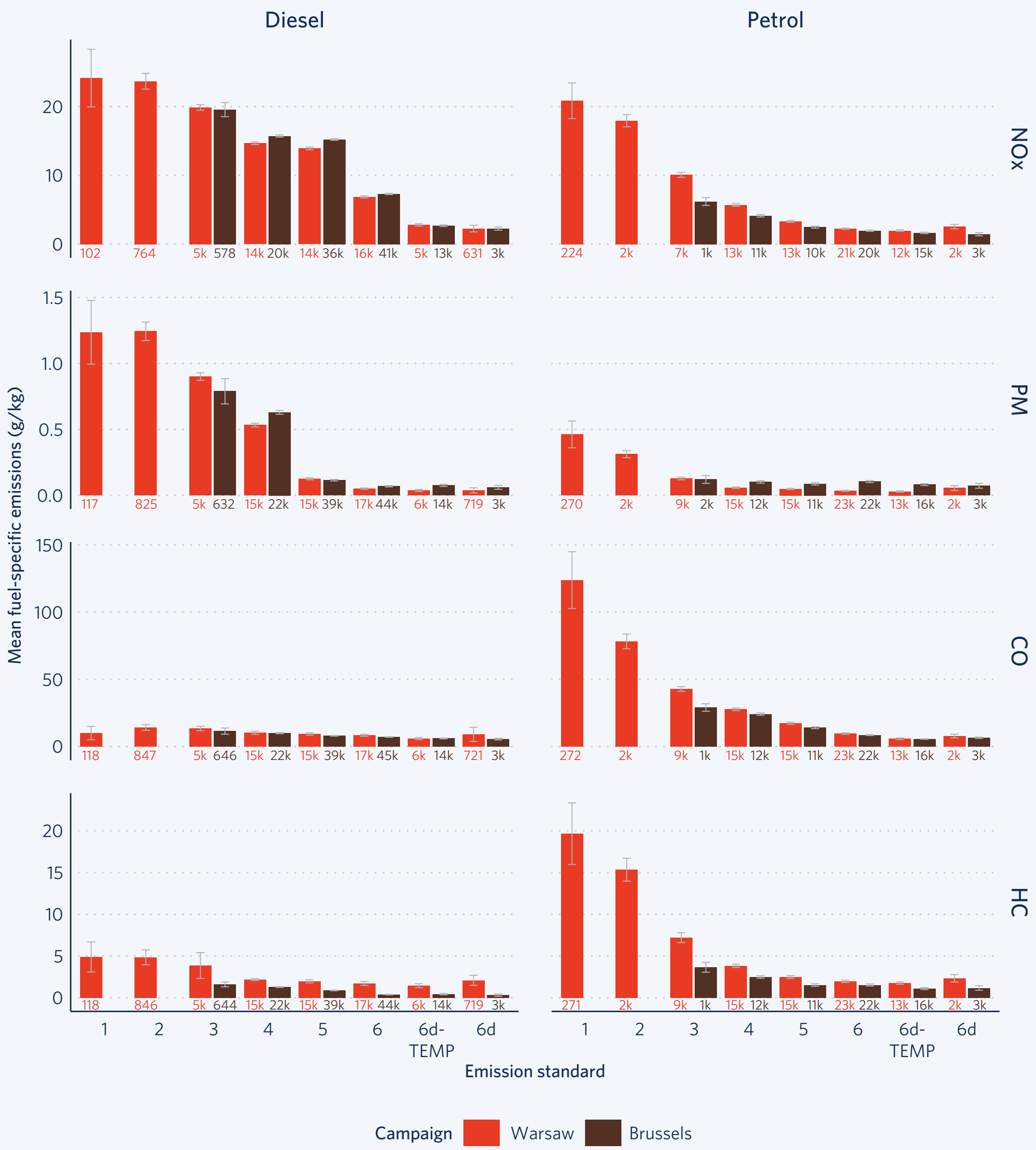


Figure 19. Average fuel-specific NO_x, PM, CO, and HC emissions of the Warsaw and Brussels fleets by fuel type and emission standard. Whiskers indicate the 95% confidence interval of the mean. Only the results with at least 100 measurements are shown.

to below Euro 2 are scarcely found in the Brussels fleet because of the LEZ restrictions. Additionally, petrol vehicles are not as prevalent as diesel vehicles in Brussels and most of the existing petrol vehicles are certified to Euro 4 or above, which, on average, have significantly lower NO_x and PM emissions compared to their diesel equivalents.

The finding that Warsaw's petrol vehicles certified to below Euro 5 generally show higher average NO_x emissions but lower average PM emissions than comparable vehicles in the Brussels fleet may indicate that there are some LPG conversions in the Warsaw petrol fleet. Studies have shown that LPG-powered vehicles emit higher levels of NO_x, CO, and HC emissions than petrol-powered vehicles.[38] In addition, LPG conversions that are built upon existing engine control design may lead to a suboptimal air fuel ratio within their three-way catalyst responsible for NO_x, CO, and HC emission control. However, the combustion of gas typically leads to lower PM mass emissions.

This assumption can be further corroborated by the higher levels of average CO and HC emissions of petrol vehicles certified to Euro 3 and Euro 4 in Warsaw compared to those in Brussels.[39] However, the differences in fleet-average CO and HC emissions between the two fleets are largely attributable to the presence of petrol vehicles certified to below Euro 3 in the Warsaw fleet which emit three and eight times more CO and HC emissions, respectively, than the poorest performing Euro 3 petrol vehicle group in the Brussels fleet. This demonstrates the importance of the Brussels LEZ, which likely played a large role in removing petrol Euro 1 vehicles that show the highest average HC and CO emissions from the Brussels fleet.

POLICY IMPLICATIONS

The comparison reveals that the low-emission zone implemented in Brussels can also be an effective policy tool to reduce vehicle emissions in Warsaw. Our results demonstrate that the LEZ in Brussels was effective in removing the highest emitting vehicle groups, such as pre-Euro 4 diesel and pre-Euro 2 petrol vehicles, from the fleet.[40] While the data shows some presence of diesel Euro 3 vehicles, whose average NO_x and PM emission are the highest in the Brussels fleet, an exceptionally low fraction of these vehicles makes their contribution to the total emissions rather minor.

In terms of NO_x and PM emissions, Warsaw could largely benefit from implementing similar restrictions, as old diesel vehicles contribute significantly to NO_x and PM emissions from LDVs in Warsaw. However, there remains a large number of petrol vehicles certified to older standards which emit disproportionate amounts of emissions. These vehicle groups also emit CO and HC emissions at the levels not found in any vehicle groups in Brussels. Therefore, prioritizing the phase-out of both petrol and diesel vehicles certified to below Euro 4 would be important for Warsaw's clean transportation zone policy.

Another important consideration for a clean transportation zone in Warsaw is to avoid exempting LPG conversions from its restrictions. An earlier proposal of the Amendments concerning clean transportation zones mentioned the possibility of expanding authorization to LPG-powered vehicles.[41] Although the exemption of LPG-powered vehicles is absent from the E-mobility Act, authority-designated exemptions are still possible. As old petrol vehicles can easily be retrofitted to LPG conversions at low costs in Poland, such an exemption can incentivize drivers to turn to old petrol vehicles rather than newer, cleaner vehicles.

TAXI EMISSIONS

This section presents a comparison of the emissions from taxis in Warsaw and taxi and ride-hailing vehicles in Brussels. The Warsaw LDV sample contains 5,208 measurements from 3,080 registered taxi vehicles but ride-hailing vehicles could not be identified and thus were not considered in the analysis. The number of taxi measurements accounts for 2.7% of the total LDV fleet, the same share as the Brussels taxis and ride-hailing vehicles in its fleet.

Taxis are an important source of emissions in cities because of their frequency of use and distance

38 Merkisz and Pielecha, "Gasoline and LPG Vehicle Emission Factors in a Road Test."

39 The share of LPG conversions in the Warsaw petrol vehicle sample is unknown, which leads to the uncertainty in the accurate amount of HC emissions measured by remote sensing techniques. The HC species emitted by LPG conversions tend be better captured by remote sensing than those emitted by petrol vehicles (OPUS's internal document, "Review of infrared response for various fuels and exhaust emissions")

40 Bernard et al., "Evaluation of Real-World Vehicle Emissions in Brussels."

41 "Draft Amendments to the Electromobility and Alternative Fuels Act," 908 Journal of Laws 2020 § Article 39 (2018), https://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU20180000317/U/D20180317Lj.pdf.

travelled. In both cities, taxis and ride-hailing vehicles measured had a younger average age than that of other vehicles. The average age of taxis in Warsaw was 7 years, over one year younger than other vehicles in Warsaw. However, they had an average mileage that is over 20,000 km higher than other LDVs in Warsaw, indicating that taxis are commonly used in the city. The right panel of Figure 20 shows that a higher share of taxis have mileage of over 300,000 km compared with other vehicles in Warsaw.

Taxis in Warsaw are also older compared with taxis and other ride-hailing vehicles in Brussels. The average age of taxis in Warsaw is three years older than those of Brussels, which is on average four years old. The young age of the Brussels taxi and ride-hailing fleet is likely attributable to the 7-year age limit the city introduced to limit emissions from these high-usage vehicles. In addition, the vast majority of taxis in Warsaw (77%) are petrol-powered, while 94% of the Brussels taxis are diesel-powered.

Figure 21 presents the results for emissions from taxis in Warsaw and taxis and ride-hailing vehicles in Brussels. Despite the much younger ages of taxis and ride-hailing vehicles in Brussels, the two cities show comparable levels of fleet-average NO_X and PM emissions. Although 96% of the Brussels taxis are certified to Euro 5 and above due to the age limit, the prevalence of diesel taxis in the fleet, which emit over 42% more NO_X and more than double the PM emissions than the petrol taxis in Warsaw, has a large impact on the fleet-average emissions.

Taxis in Warsaw, however, perform much worse by fuel type, largely due to their older age. The diesel taxis in Warsaw emit substantially higher NO_X and PM emissions, as most of them are certified to below the Euro 6 standard. Older petrol vehicles that are certified to below Euro 5, similarly, are responsible for among the highest CO and HC emissions from the Warsaw taxis. However, the significantly low level of average PM emissions from the Warsaw petrol taxis may indicate some presence of LPG conversions in the Warsaw petrol taxi fleet.

As most of high-emitting taxis in Warsaw are vehicles certified to older emission standards that are scarcely found in the Brussels taxi fleet, Warsaw could achieve significant emissions benefits by implementing the same age limit for its taxis. Figure 22 illustrates the estimated emissions impacts if the same 7-year age limit of Brussels were to be applied to taxis in Warsaw. Given that the fuel-specific emissions used in the analysis do not take into account differences in fuel efficiency, the results are presented by fuel type.

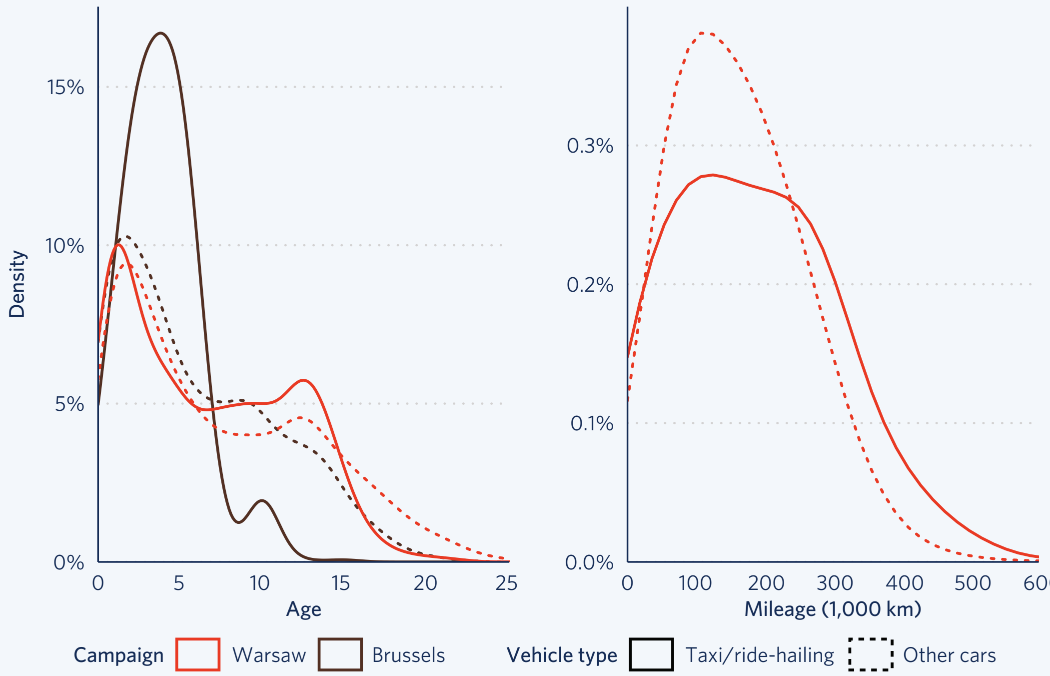


Figure 20. Age distribution of Warsaw taxis, Warsaw other vehicles, and Brussels taxis and ride-hailing vehicles (left) and distribution in density of mileage recorded for taxis and other vehicles in Warsaw (right).

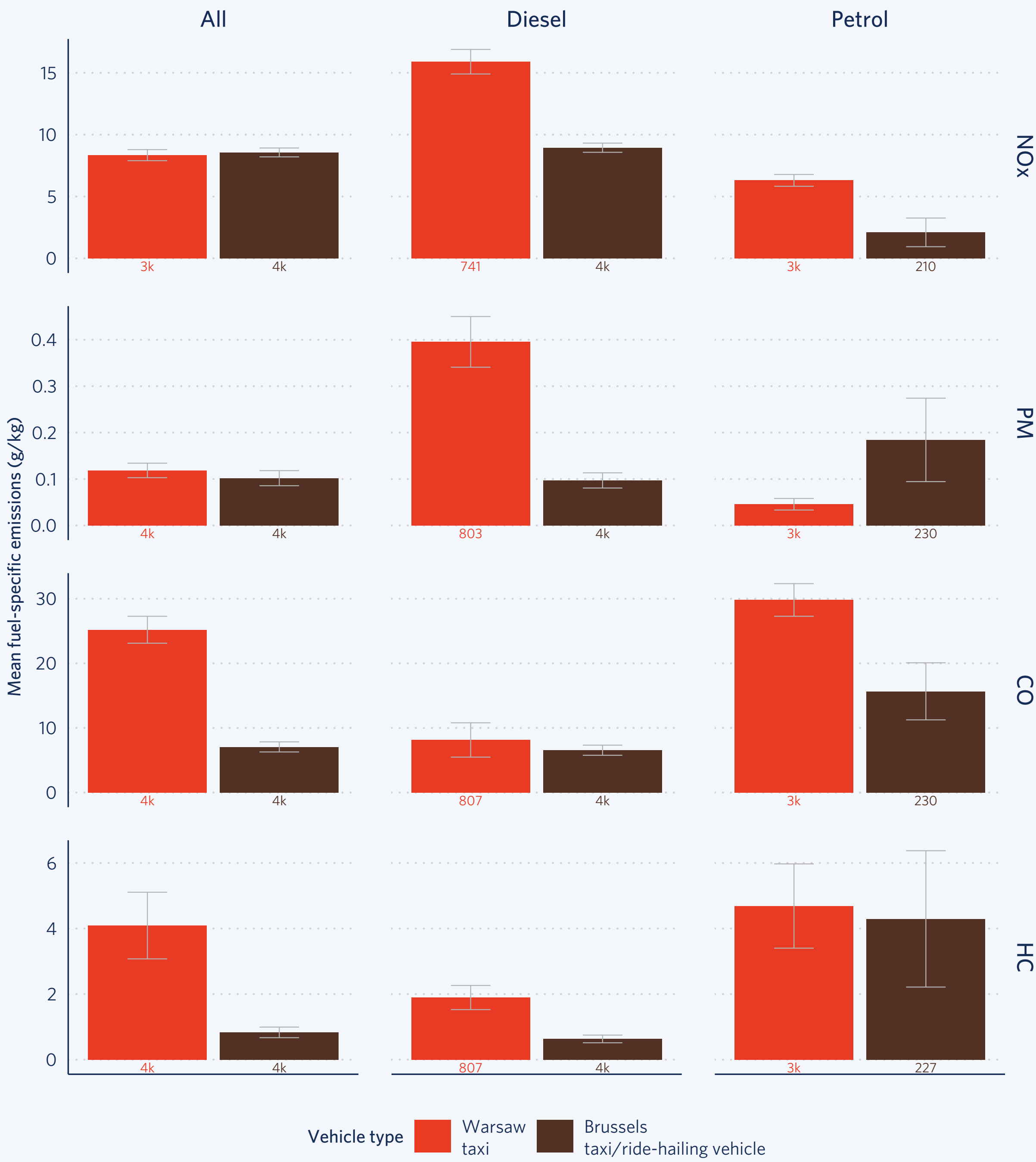


Figure 21. Average fuel-specific emissions of NO_x, PM, CO, and HC from taxis in Warsaw and taxis and ride-hailing vehicles in Brussels. Whiskers indicate the 95% confidence interval of the mean.

We show that if the same regulation was applied to taxis in Warsaw, 43% of the taxis which are currently responsible for a significant share of emissions would not be allowed to operate. If these vehicles were replaced with zero-emission alternatives, current emissions of all pollutants from taxis in Warsaw would decrease by, at minimum, nearly 60%. Replacing these vehicles with the best available petrol or diesel vehicles certified to Euro 6d would also lead to significant benefits.

As discussed above, implementing the age limit would affect over 40% of the current taxis in Warsaw and, therefore, such policy should be phased in progressively over a sufficient period of time. Supplementing this with other policies that provide taxi drivers financial support

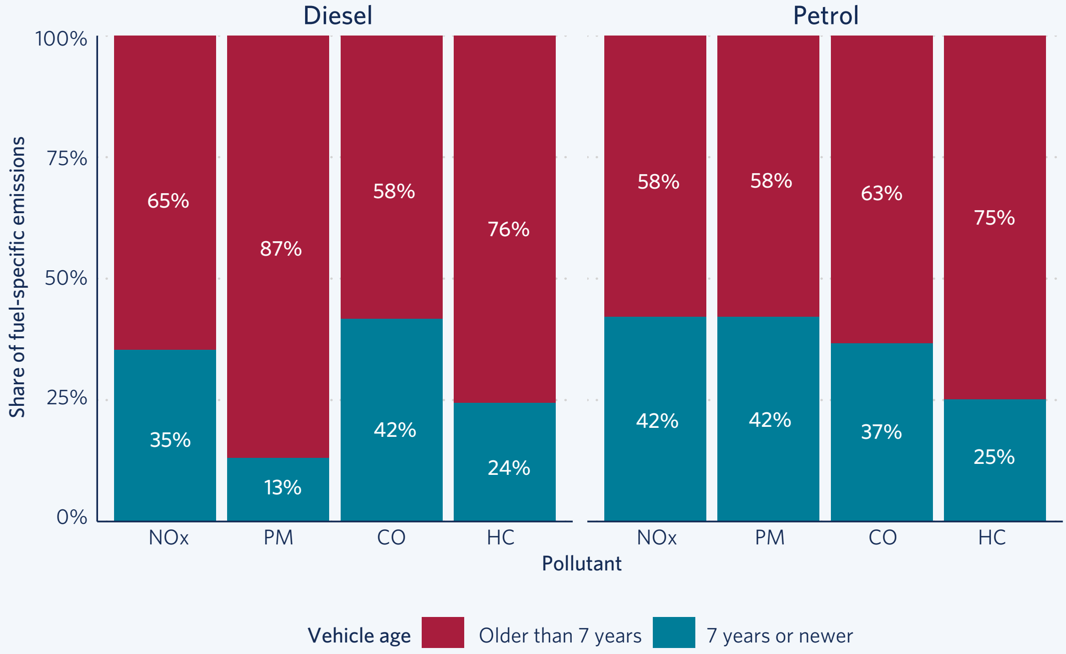


Figure 22. Maximum emission reduction potential for NO_x, PM, CO, and HC resulting from 7-year age limit on taxis by fuel type.

and adequate lead time could ensure the fairness of the implementation. London, for instance, gradually tightened the restriction of taxis of over 15 years to those of 12 years over three years, giving its taxi drivers sufficient time to comply with the policy.

BUS EMISSIONS

This section focuses only on the city buses measured in Warsaw and Brussels as approximately 95% of the Warsaw bus measurements were of city buses. City buses are an important target for emissions reduction not only because they are high-usage vehicles but also because their procurement is often made in large quantities and determined by few authorities.

The Warsaw campaign collected 1,178 measurements from 253 unique vehicles, a number comparable to the Brussels bus measurements of 2,067 from 230 vehicles. Only diesel-powered buses were investigated as they accounted for the entire bus fleet in Brussels and all but eight buses in Warsaw.

Figure 23 presents the shares of city buses by emission standard in Warsaw and Brussels. Nearly all city buses in the Brussels sample were certified to Euro VI, whereas the buses measured in Warsaw were spread across Euro IV, Euro V, and Euro VI. Warsaw city buses certified to Euro IV and V standards made up 83% of the measured fleet. However, it is important to note that the Brussels sample was not fully representative of the Brussels city bus fleet due to a sample bias; the main public transport operator of Brussels, Société des Transports Intercommunaux de Bruxelles (STIB), confirmed the presence of Euro IV and V buses operating in the city bus fleet.

Due to the possible bias of the city bus samples, this study does not compare the fleet-wide city bus emissions in the two cities. Figure 24 presents the emission performance of city buses certified to different emission standards. Most notably, it shows that Euro VI buses achieved a large reduction in emissions of both NO_x and PM from their precursors. The Warsaw Euro VI buses emit only approximately 35% of the NO_x emission and 70% of the PM emission levels emitted by the Euro V city buses.

The particularly high fraction of buses certified to below Euro VI in the Warsaw bus fleet and their outsized average NO_x and PM emissions call for measures to limit the use of these buses. Newer buses like Euro VI perform much better in terms of emissions but they are not comparable to zero-emission alternatives like electric buses. The recently passed Amendments to the E-mobility Act requires that all new buses procured in Polish cities with more than 100,000 residents be

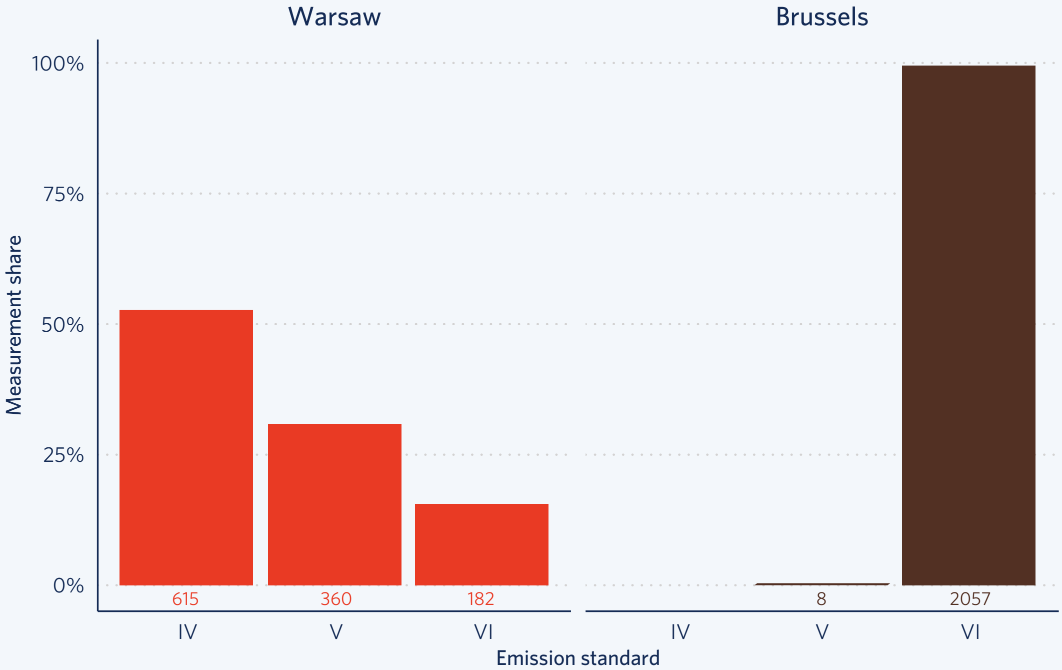


Figure 23. Measurement shares of buses by emission standard for Warsaw and Brussels in respective samples.

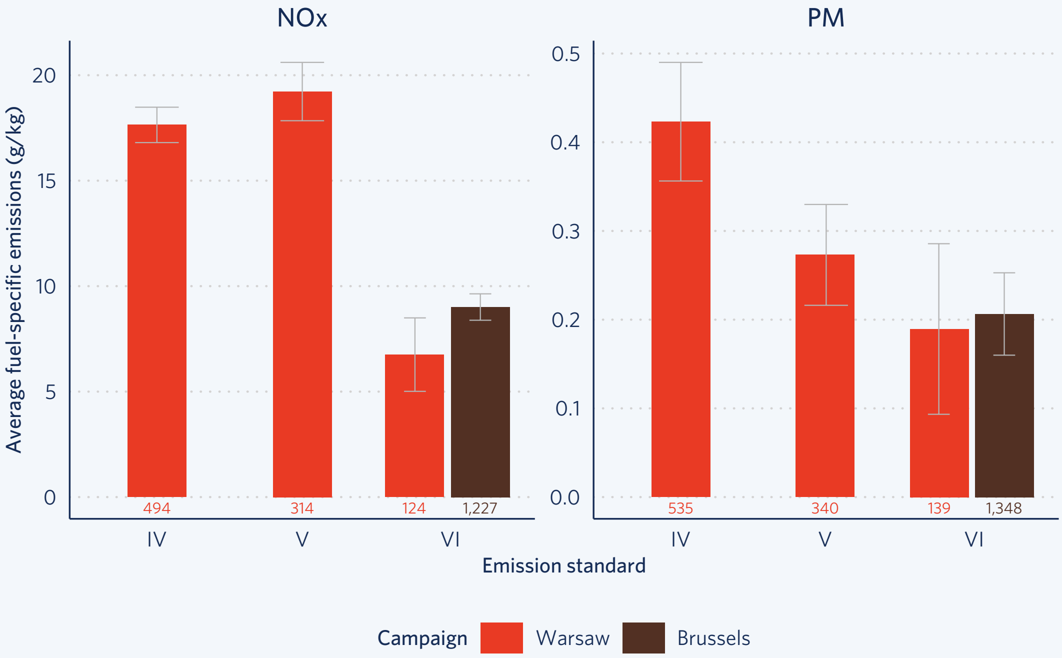


Figure 24. Average fuel-specific emissions of NO_x and PM of city buses in Warsaw and Brussels by emission standard. Whiskers indicate the 95% confidence interval of the mean. Only results for those with over 10 measurements are shown.

electric buses.[42] Furthermore, as the recovery and resilience plan of Poland sets an aim to expand the use of electric buses, replacing the high-emitting Euro IV and Euro V buses with electric buses is highly recommended for a longer-term solution.[43]

42 Draft Amendments to the Electromobility and Alternative Fuels Act.

43 Ministry of Funds and Regional Policy of Poland, "National Recovery and Resiience Plan," April 30, 2021, https://www.gov.pl/web/planodbudowy/kpo-wyslany-do-komisji-europejskiej.

POLICY IMPLICATIONS AND RECOMMENDATIONS

Understanding the real-world emissions of vehicles of a city can help identify important local trends, which in turn can inform relevant and effective policies to address traffic-related emissions. Based on our real-world emissions assessment, we suggest concrete policy recommendations for three specific areas: implementing a clean transportation zone that could accelerate the removal of the oldest, highest-emitting vehicles from the Warsaw fleet, addressing the disproportionate emission impact of imported second-hand vehicles, and limiting the risk of growing emission contributions from LPG conversions.

CLEAN TRANSPORTATION ZONE

Discussions regarding the establishment of a clean transportation zone are currently underway in Warsaw. The idea of clean transportation zone, however, is fairly new in the country and its details are not solidified. Our study examined the real-world NO_X, PM, CO, and HC emissions of Warsaw to identify high emitting vehicle groups that could be prioritized for restrictions.

Overall, an immediate phase-out of vehicles certified to below Euro 4 is strongly recommended, regardless of their fuel type. These vehicles are over 15 years old and emit emissions disproportionate to their vehicle share. The emissions reduction of CO and HC from restricting these vehicles would be particularly significant. Our analysis showed that petrol vehicles certified to Euro 3 standards and below emit 38% of the total CO emissions and 35% of the total HC emissions, while making up 11% of all measurements. Such policy would also ban the highest NO_X and PM emitting vehicle groups, diesel Euro 1 to diesel Euro 3, that are currently responsible for 18% of NO_X and 37% of PM emissions.

The benefits of limiting the use of old vehicles could be further augmented, as their old age means that they are operating beyond their emission durability requirement period. Our findings show that vehicles operating outside of the durability requirements have elevated levels of emissions and their emission performance further deteriorates with accumulated mileage. Furthermore, such restrictions would likely generate a bigger emission reduction than anticipated in the study, as the LDVs with unidentifiable vehicle types and elevated emissions are most likely old passenger cars that are not accounted for in this study.

By expanding the restrictions to include diesel Euro 4 and Euro 5 vehicles, Warsaw could further remove high NO_X and PM emitters from the fleet. Diesel vehicles certified to Euro 4 and Euro 5, which make up 13% of the total passenger car measurements, are two of the highest contributors of NO_X emissions; their combined NO_X emission share is 27%. Diesel Euro 4 also contributes disproportionately to PM emissions, accounting for over 20% of the total PM emissions alone. For comparison, LEZs in other European cities have already banned (London) or plan to ban (Brussels and Paris) diesel Euro 4 and Euro 5 vehicles by around 2025.

Vehicles converted to run on LPG, which are often pre-Euro 5 petrol vehicles, and other LPG-powered vehicles should not be exempted from the restrictions. Contrary to conventional knowledge, LPG-powered vehicles are not clean; they tend to emit less particulate matter emissions but may still emit high particulate number (PN) emissions that are detrimental to human health. Specifically, retrofitted LPG vehicles are observed to emit real-world PN emissions 3.7 times higher than the type-approval limit.[44] Furthermore, restricting LPG conversions could help reduce the number of pre-Euro 5 petrol vehicles that are often imported and converted to run on LPG.

LIMITING IMPORTED SECOND-HAND VEHICLES

Our data demonstrates that imported vehicles operating in Warsaw emit significantly higher levels of NO_X, PM, CO, and HC emissions than those that are not imported. Warsaw could address the emissions from imported second-hand vehicles by applying uniform restrictions based on emission standards to vehicles of all fuel types, including LPG, which would be a simpler and more expedited approach than nation-wide measures. Such policy could also partly address PN, CO, and HC emissions from LPG conversions, as petrol vehicles are often imported for LPG-retrofitted vehicles.

More comprehensive nation-wide policies, such as age restrictions for imported vehicles, scrappage programs, tax schemes, or financial incentives for cleaner vehicles, would help reduce the number of imported second-hand vehicles more directly. Such policies can also help promote fair transitions to low-emission or zero-

44 A. Kontses et al., "Particle Number (PN) Emissions from Gasoline, Diesel, LPG, CNG and Hybrid-Electric Light-Duty Vehicles under Real-World Driving Conditions," *Atmospheric Environment*, November 2019, 117126, https://doi.org/10.1016/j.atmosenv.2019.117126.

emission transportation by discouraging low-income populations from purchasing old second-hand vehicles and making them easier to replace their old vehicles with newer, cleaner vehicles.

LIQUID PETROLEUM GAS CONVERSIONS

Although the exact number of LPG-retrofitted vehicles in the Warsaw fleet is unknown, the elevated emissions of NO_X, CO, and HC observed in comparison with the emissions from the Brussels passenger car fleet as well as other sources corroborated some existence of LPG conversions in the Warsaw fleet. As the status of conversion is not recorded in the registry of Poland in practice, the accurate number of LPG-retrofitted vehicles was not available. In order to investigate the impact of LPG conversions on emissions, a tracking method, such as through the periodic technical inspection program, should be established and enforced.

THE REAL URBAN
EMISSIONS INITIATIVE

TRUE—The Real Urban Emissions Initiative
FIA Foundation, 60 Trafalgar Square, London WC2N 5DS, United Kingdom
For more information contact: **true@fiafoundation.org**
@TRUE_Emissions
www.trueinitiative.org