THE REAL URBAN EMISSIONS INITIATIVE

Assessment of real-world vehicle emissions from four Scottish cities in 2022

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FIA Foundation and the 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. TRUE will use a combination of measurement techniques to produce a granular picture of the on-road emissions of the entire vehicle fleet by make, model, and model year.

EXECUTIVE SUMMARY

Despite having achieved significant improvements in air quality in recent decades, Scotland still has air pollution hot spots in densely populated urban areas that pose a great health risk. In cities, road transport is the primary source of air pollution, largely responsible for the emissions of particulate matter (PM) and nitrogen oxides (NO_X). To address emissions from transport, Scotland has mandated low emission zones in four major cities, Aberdeen, Dundee, Edinburgh, and Glasgow, and committed to reducing car travel by 20% by 2030, among other measures.

Analyzing real-world vehicle emission data can help to enhance existing policies and identify opportunities for future action. As part of the Air Remote Sensing Project led by Transport Scotland, remote sensing technology was deployed in Aberdeen, Dundee, Edinburgh, and Glasgow in 2022 to measure emissions from on-road vehicles under real driving conditions. This was the second deployment of its kind; the first took place in Edinburgh and Glasgow in 2021.

The 2022 deployment resulted in around 660,000 vehicle emission measurements from the four cities, collected during six testing campaigns in April and September 2022. Based on our analysis, which included an emerging approach to defining an emissions threshold for identifying vehicles with tampered or malfunctioning emission control systems, we draw the following conclusions:

Ramping up low emission zone policies to restrict diesel Euro 6 cars and implementing age or mileage limits alongside emission standard-based policies could ensure greater air quality benefits. Real-world NO_X emissions from Euro 6 diesel cars are over 3 times higher than those from the successive standard, Euro 6d-TEMP, and over 30% higher than those from Euro 3 petrol vehicles which are subject to the current low emission zone restrictions. Pre-Euro 6d-TEMP diesel vehicles also showed a large variance in emission performance across ages and registration years, indicating the potential deterioration of emission control systems. Additional age or mileage caps alongside the low emission zone policy could reduce the risk of emission benefit slip from vehicle emission deterioration.

Policy measures to support taxi and private-hire drivers in the transition to cleaner fleets can result in outsized emission benefits relative to their share of the fleet. Taxis and private hires emit consistently higher NO_X than other passenger cars due to their higher mileage, with older taxis registered before 2016 emitting twice as much as other private cars of the same registration years. Consistent with the emissions testing conducted in 2021, the TX4 taxi manufactured by London Taxi Company (now London Electric Vehicle Company, LEVC) was again one of the highest-emitting Euro 5 and 6 taxis in Scotland. However, LEVC's newer plug-in hybrids and liquefied petroleum gas retrofit vehicles showed significantly lower real-world NO_X emissions. As an intermediate step toward a 100% battery-electric taxi fleet, Scottish cities could consider promoting the use of petrol hybrids or plug-in hybrids.

The use of remote sensing roadside inspection can be an effective long-term monitoring solution to catch vehicles that are tampered with or malfunctioning. An NO_X emission threshold of 24 g/kg maximizes the chance of identifying a defective or manipulated diesel truck with a single instantaneous emission measurement when used alongside roadside inspection. Collecting multiple emissions measurements increases the chance of correctly identifying such vehicles exponentially, given that normally behaving vehicles can sometimes exhibit high emissions. In this way, a long-term deployment of remote sensing for monitoring could effectively flag high emitters for inspection and repair and help to inform more effective and targeted policy in the future.

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CONTEXT

Although Scotland has achieved significant improvement in air quality in recent decades, air pollution remains highly concentrated in dense urban areas. Road transport continues to be the main source of pollutant emissions in the country.[1] Long-term exposure to nitrogen oxides (NO_X) and particulate matter (PM), of which internal combustion engines are leading emitters, is strongly associated with increased mortality due to cardiovascular diseases, respiratory diseases, lung cancer, and other health outcomes in Scotland.[2] Researchers have estimated that around 2,700 premature deaths can be attributed to air pollution across Scotland annually.[3]

The Scottish Government has put in place various measures to minimize the environmental and health impacts of the transport sector. In its 2018–2032 Climate Change Plan, updated in 2020, Scotland made an ambitious commitment to reduce car kilometers traveled by 20% by 2030.[4] The government also established low emission zones (LEZs)—a traffic intervention policy limiting access to a defined area by vehicles that do not meet specified emission standards—in the capital, Edinburgh, and three other major cities, Aberdeen, Dundee, and Glasgow. The Glasgow LEZ has been in force since June 2023, while LEZ enforcement in the three remaining cities is planned to begin in May and June 2024.[5] Continuous monitoring and measuring of emissions from on-road transport is part of the efforts.

Building on a previous The Real Urban Emissions (TRUE) Initiative study on real-world vehicle emissions in Edinburgh and Glasgow in 2021, this study examines real-world vehicle emissions data collected in Aberdeen, Dundee, Edinburgh, and Glasgow in 2022 as part of the Air Remote Sensing Project.[6] Led by Transport Scotland, in conjunction with the ICCT, Hager Environmental & Atmospheric Technologies (HEAT), and Environmental Resources Management (ERM), the Air Remote Sensing Project aims to establish a database of real-world emissions from the Scottish fleet and is the largest remote emission-sensing data collection project in Europe to date.

OBJECTIVES

Building on the 2021 TRUE Initiative report, this study analyzes real-world vehicular emission data collected in 2022 with the following objectives:

- To characterize various vehicle fleets in Aberdeen, Dundee, Edinburgh, and Glasgow, including heavy-duty vehicles, of which the sample size was relatively small in the 2021 measurement campaign.
- To assess the real-world emission performance and regulatory compliance of passenger cars registered since 2000, with a particular interest in the performance of newer diesel passenger cars certified to Euro 6d-TEMP and Euro 6d.
- To expand on the 2021 investigation of the emission performance of different taxi types, including hybrid and retrofit taxis.
- To evaluate the emission performance of buses and trucks with a focus on the new Euro VI-E standard.
- To explore ways to determine thresholds for the enforcement of NO_X high-emitters with potentially defective or tampered emission control systems using emission data from individual trucks measured five times or more during the 2021 and 2022 campaigns.

DATA COLLECTION

Emissions Detection and Reporting (EDAR) systems were deployed in Aberdeen, Dundee, Edinburgh, and Glasgow in 2022 to remotely measure tailpipe NO_X and PM emissions from passing vehicles using spectroscopy.[7] Emissions data were collected in all four cities in September and October 2022. Our study also examines data collected in April and May 2022 in Aberdeen and Dundee, where an EDAR

1 "Environmental Standards Scotland Air Quality Investigation - Scottish Government Improvement Plan," Scottish Government, March 27, 2023, http://www.gov.scot/publications/environmental-standards-scotland-air-quality-investigation-scottish-government-improvement-plan/.

2 Mary Abed Al Ahad, Urška Demšar, Frank Sullivan, and Hill Kulu, "Long-Term Exposure to Air Pollution and Mortality in Scotland: A Register-Based Individual-Level Longitudinal Study," *Environmental Research* 238 (1 December 2023): 117223, https://doi.org/10.1016/j.envres.2023.117223.

3 UK Health Security Agency, "Chemical Hazards and Poisons Report: Issue 28,' (June 16, 2022), https://www.gov.uk/government/publications/chemical-hazards-and-poisons-report-issue-28.

4 "20% Reduction in Car Km by 2030," Transport Scotland, accessed 24 November 2023, https://www.transport.gov.scot/our-approach/environment/20-reduction-in-car-km-by-2030/.

5 "How Low Emission Zones Work, "Low Emission Zones Scotland, accessed March 6, 2024, https://www.lowemissionzones.scot/about/how-lezs-work.

6 Kaylin Lee, Yoann Bernard, and Jonathan Cooper, "Assessment of Real-World Vehicle Emissions in Scotland in 2021: Emissions Testing Campaigns in Edinburgh and Glasgow," (Washington, DC: TRUE Initiative, 2023), https://theicct.org/publication/true-scotland-remote-sensing-jun23/.

7 A more detailed description of the methodology can be found in Lee, Bernard, and Cooper, "Assessment of Real-World Vehicle Emissions in Scotland in 2021: Emissions Testing Campaigns in Edinburgh and Glasgow."

Table 1. City, road and location, campaign month, road slope, and number of measurements from 2022 vehicle emission testing campaigns.

Site	City	Campaign month	Road (location)	Slope	Raw measurements
A	**Aberdeen**	April–May	Wellington Road (near harbor)	1.6%	186,965
B	**Dundee**	April–May	West Marketgait (near harbor)	1.7%	67,556
C	**Aberdeen**	September – October	Anderson Drive (city center)	4.5%	120,167
D	**Dundee**	September – October	A90 (highway)	5.9%	127,835
E	**Edinburgh**	September – October	Ferry Road (city center)	1.0%	138,165
F	**Glasgow**	September – October	Oswald Street (city center)	4.5%	19,397

deployment was initially scheduled for late 2021 but was postponed due to COVID-19.

In total, 660,085 raw measurements were collected during the six campaigns. Table 1 presents the location of testing sites, month the data were collected, road slopes, and the numbers of raw measurements for each campaign.

Figure 1 presents the characteristics of the fleet examined in our analysis. As discussed in greater detail below (see Sample overview), passenger cars were the most commonly found vehicle class, followed by light commercial vehicles, trucks, and buses. All campaign sites showed a vehicle class distribution loosely resembling this overall trend, but there was some variance due to the characteristics of each testing site. For instance, trucks and light commercial vehicles made up nearly 20% of all measurements in Sites A and D and 11% in Site B. This is largely because all three sites were frequented by commercial vehicles and long-haul trucks: Site A (in Aberdeen) and Site B (Dundee) were near harbors, while Site D (Dundee) was located on a highway connecting the city to other major cities in Scotland.

Sites C (Aberdeen) and E (Edinburgh) were located inside the city centers along busy streets with high volumes of passenger car and commercial vehicle traffic and showed similar vehicle makeup. Meanwhile, the measurements in Site F (Glasgow) were characterized by high shares of buses and diesel passenger cars, as the EDAR system was set up over a lane that only allowed buses. Diesel passenger vehicles captured in Site F were predominantly taxis that used the bus-only lane for pick-ups and drop-offs. Site F was located near Hope Street, the street with the highest nitrogen dioxide (NO_2) pollution in Glasgow, and the measurements from this site allowed us to assess emissions in a high-pollution zone.[8]

A high share of measurements with missing vehicle classes in the data is due to incomplete information from the Scottish Driver and Vehicle Licensing Agency database. The over 20% of vehicles with no available class information in Site A could be non-UK registered vehicles; vehicle information was not found in the Scottish Driver and Vehicle Licensing Agency database for 90% of those measurements. We were able to identify missing vehicle classes from the measurements using other vehicle specification information, adding around 4,300 truck measurements to the analysis.[9]

The EDAR system measured the driving conditions and emissions of passing vehicles simultaneously. Figure 2 shows the four ambient and driving conditions of all sampled vehicles. All four parameters were normally distributed, with median values of 14.2 °C (ambient temperature), 45.4 km/h (speed), -0.08 km/h/s (acceleration), and 5.2 kW/t (vehicle specific power, or engine power demanded by the speed, acceleration, and road grade). The median ambient temperature of our sample was milder than that of the 2021 remote sensing campaign, as the 2021 campaign took place earlier in the year. The median speed was similar to that of the 2021 sample, while median acceleration and vehicle specific power were both lower.

8 Gavin Thompsom, "Scotland's Most Polluted Streets in 2021," Friends of the Earth Scotland, 30 January 2022, https://foe.scot/scotlands-most-polluted-streets-in-2021/.

9 Additional identification of vehicle classes was possible using the available information about vehicles on the Scottish Driver and Vehicle Licensing Agency database. The combination of information on fuel type, gross weight, make, axle configuration, and engine displacement was compared with the prevalent trucks and buses in the European market.

Figure 1. Locations of selected sites and the composition of the fleet measured in each site.

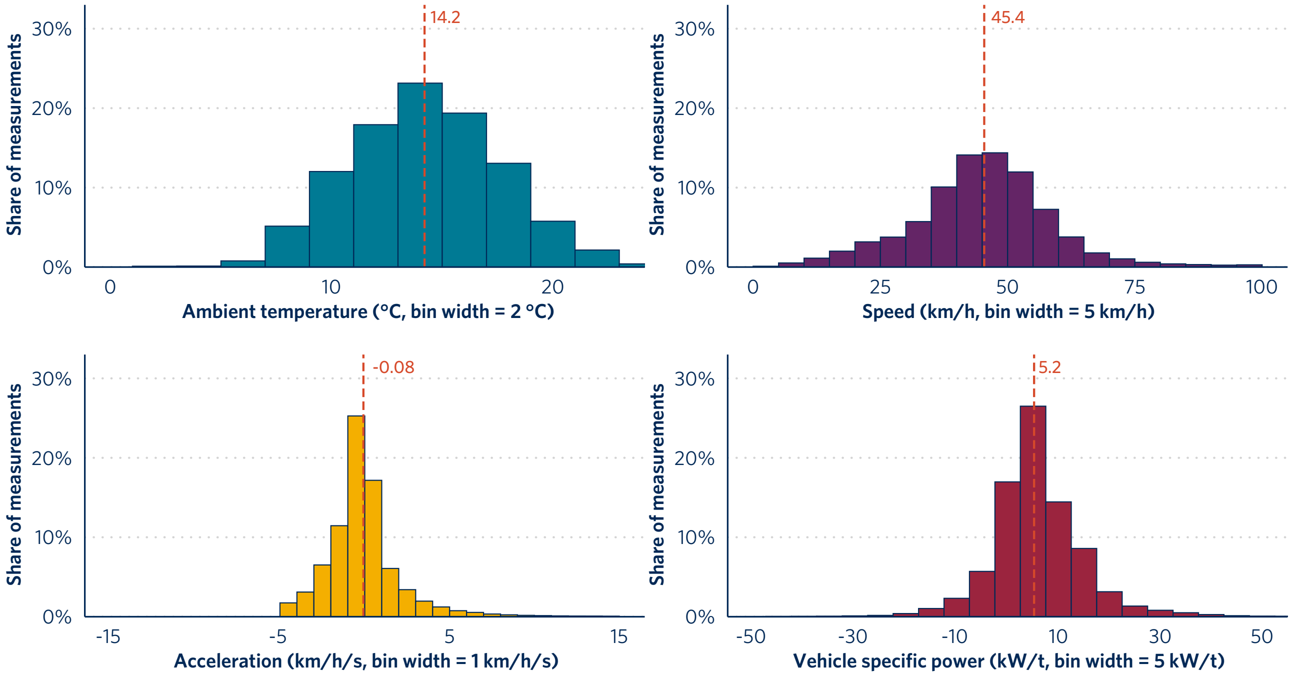

Figure 2. Distribution of driving and ambient conditions of all sampled vehicles. Red dotted lines represent median values.

SAMPLE OVERVIEW

Figure 3 disaggregates our sample of 660,085 raw measurements by vehicle class. The majority of measurements (73%) were from passenger cars, including taxis and private hires, followed by light commercial vehicles (12%). Despite accounting for just 5% of the sample, the presence of heavy-duty vehicles, or trucks and buses, in the sample is relatively high, with over 33,500 measurements.

For our emissions analysis, we filtered out all raw measurements that were determined by the EDAR system to be invalid or with vehicle specific power values less than or equal to zero. Table 2 summarizes our raw and valid measurements by vehicle class. As some vehicles were measured more than once, the number of unique vehicles is also presented.

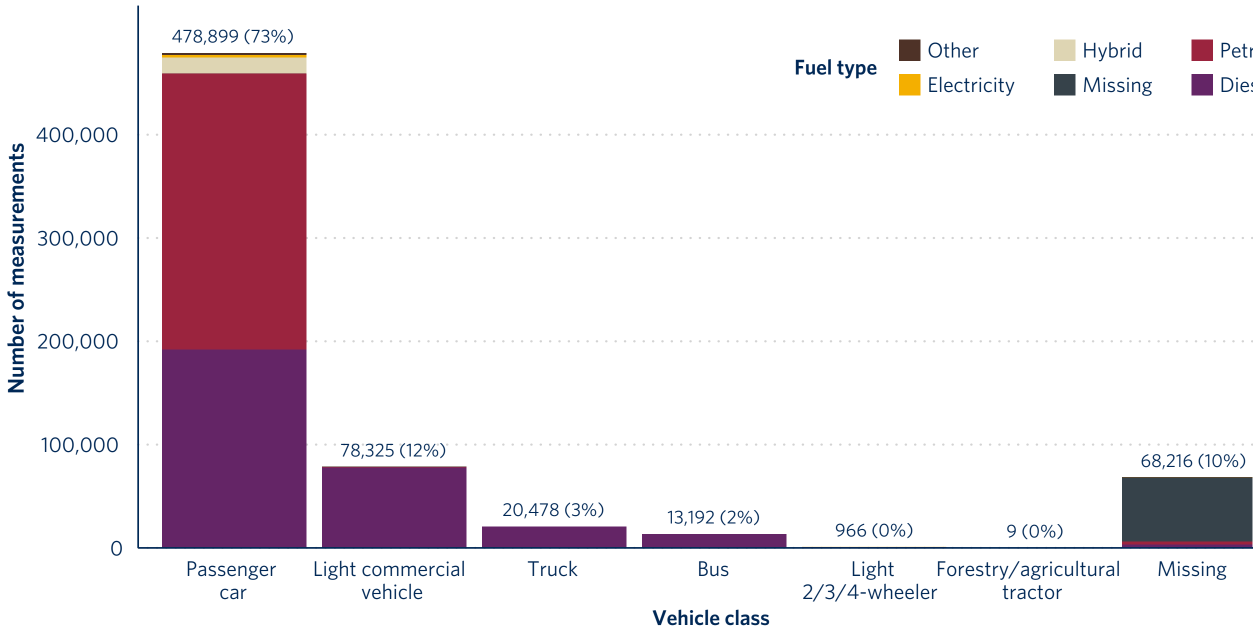

Figure 3. Fleet composition of all fleets measured in all six sites from the 2022 vehicle emission testing campaigns.

Table 2. Summary of raw and valid emission measurement numbers by vehicle class.

Vehicle class		Raw measurements	Valid emission measurements	Unique vehicles with valid emission measurements
Passenger car	**Total**	**478,899**	**303,003**	**142,882**
	Private car	465,739	296,162	140,333
	Taxi and private hire	13,160	6,841	2,550
Light commercial vehicle		78,325	48,289	22,456
Truck		20,478	15,746	5,876
Bus		13,192	8,475	1,198

FLEET CHARACTERISTICS

PASSENGER CARS

Nearly 97% of passenger cars across testing sites were powered by internal combustion engines (ICEs), with petrol and diesel vehicles making up 57% and 39% of the sample, respectively. For our analysis, we further categorized passenger cars into two groups, private cars and taxis or private hires, as taxis and private hires tend to have higher mileage, which can lead to the deterioration of emission control systems and contribute to disproportionate emissions.

Figure 4 shows the distribution of registration years and emission standards for petrol- and diesel-fueled private cars. Hybrid and electric cars together accounted for less than 4% of the sample and are therefore not presented. The dotted line indicates the mean age of vehicles powered by each fuel type. On average, petrol-fueled private passenger cars were slightly younger than diesel counterparts: among private passenger cars registered between 2017 and 2022, 62% run on gas, while 30% run on diesel. This reflects a trend of increased usage of petrol vehicles in Scottish cities in recent years.

Cars certified to Euro 6a–c (denoted as 6 in Figure 4) were the largest group for both petrol and diesel private cars,

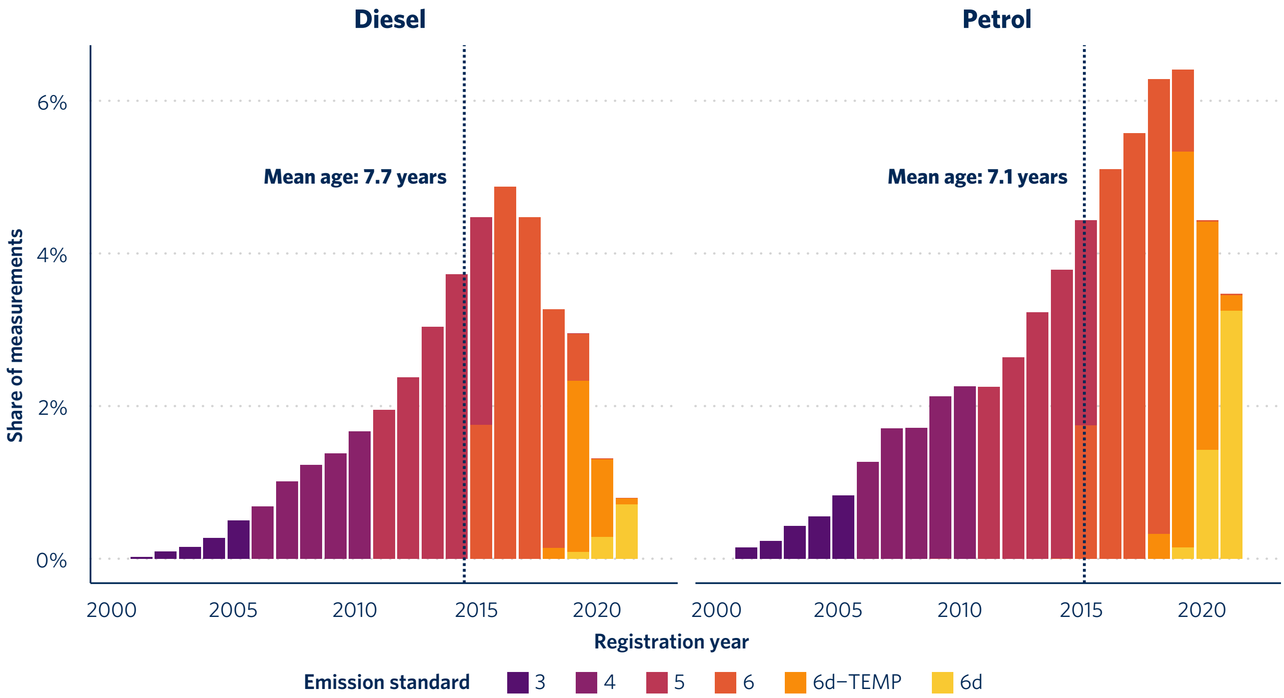

Figure 4. Distribution of registration years and emission standards, or Euro standards, of private passenger cars. Dotted lines mark the mean registration years, and the mean age is indicated above. Euro 6 refers to Euro 6a–c.

followed by Euro 5. Newer vehicles that are subject to Real Driving Emissions (RDE) testing, namely Euro 6d-TEMP and Euro 6d, accounted for around 20% of the private passenger car measurements.

Taxis and private hires from Dundee, Edinburgh, and Glasgow were identified based on taxi license plate data acquired by Transport Scotland from the three cities. Due to an inability to acquire taxi and private hire information for Aberdeen, however, taxis and private hires registered in Aberdeen were not disaggregated and were considered as private passenger cars throughout the analysis. Diesel was the most common fuel type for both taxis and private hires, accounting for almost 95% of the measurements, followed by petrol (5%).

Figure 5 illustrates the characteristics of taxis and private hires in our sample. The two vehicle types had a similar mean age, of 5.7 years (taxis) and 5.6 years (private hires), roughly two years younger than the mean age of diesel private cars. Euro 6 was the most prevalent emission standard for taxis and private hires, accounting for over 65% of both types, followed by Euro 5. A higher share of private hires was certified to Euro 6d-TEMP than taxis. Retrofit vehicles—vehicles retrofitted to run on liquified petroleum gas (LPG) or equipped with selective catalytic reduction (SCR) systems to reduce NO_X emissions—were found only in the taxi fleet and were all registered between 2010 and 2016.[10]

Notably, the average ages of taxis and private hires varied by city due to divergent policies limiting the use of old cars for taxis and private hires. Table 3 presents the mean ages of taxis and private hires in Dundee, Edinburgh, and

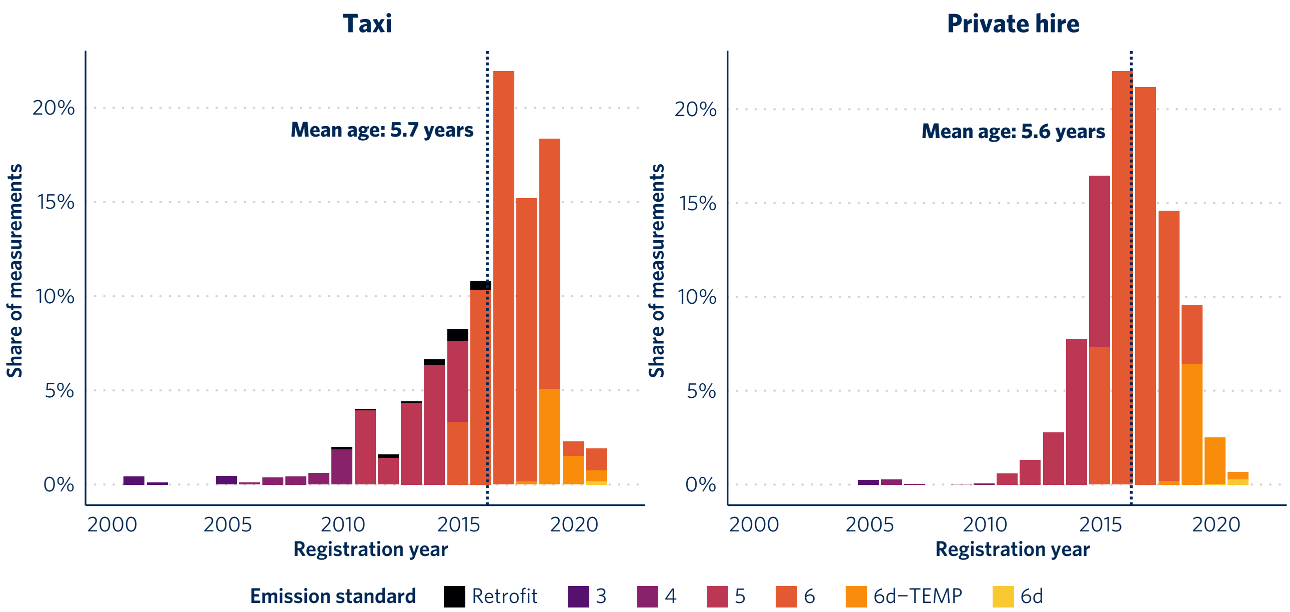

Figure 5. Distribution of registration years and emission standards, or Euro standards, of taxis and private hires measured during the 2022 vehicle emission testing. Dotted lines mark the mean registration years, and the mean age is indicated above. Euro 6 refers to pre-Euro 6d-TEMP vehicles, such as Euro 6a–c.

Table 3. Summary of mean ages of taxis and private hires and relevant policies in Dundee, Edinburgh, and Glasgow.

	Dundee		Edinburgh		Glasgow	
	Taxi	Private hire	Taxi	Private hire	Taxi	Private hire
Mean age	5.8	6.5	4.8	6.1	7.8	5.2
Policy targeting the fleet	New private hires must be electric vehicles from an approved list; for private hires of over 8 years old, 3 emission tests per year required.		10-year age limit for both taxis and private hires (from April 2022)		7-year age limit only for private hires	

10 A quarter of these vehicles were retrofitted to run on LPG and the remaining vehicles were additionally equipped with selective catalytic converters.

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Glasgow, alongside information on fleet age limit policies in each city. Glasgow, which does not limit the age of taxis but caps private hire vehicles to 7 years of age, had the oldest average taxi age but youngest mean private hire age.

BUSES

Almost 40% of bus measurements were collected in Glasgow, where the EDAR system was set up above a bus lane, while 27% were in Aberdeen. In our analysis, we did not distinguish between city buses and coaches. Over 99% of the buses measured were powered by diesel. As shown in Figure 6, retrofit buses made up the largest share of bus measurements with 43%. Originally certified to Euro IV or V, these buses are retrofitted with SCR systems to reduce NO_x emissions. The mean age of the bus sample was 7.8 years.

Most of the remaining buses were certified to Euro VI and Euro VI-D, which accounted for 38% and 11% of all bus measurements, respectively. Measurements of buses certified to Euro VI-E, the newest emission standard that was introduced in 2021, accounted for less than 1% of the bus sample.

TRUCKS

All but two measurements in the sample were from trucks fueled by diesel. Owing to the sites selected to collect these measurements, 87% of the trucks were captured in Aberdeen and Dundee. Among these, the majority (74%) of unique trucks belonged to the N3 vehicles category, defined as having a gross weight of 12–16 tons.

Figure 7 shows the distribution of registration years and emission standards for the measured trucks. The trucks had a mean age of 4.7 years, relatively younger than the mean ages of other fleets. Two-thirds of truck measurements were from vehicles that were registered after 2017. Euro VI was the leading standard for truck measurements (64%), followed by Euro VI-D (22%). Over 430 measurements were certified to Euro VI-E, which requires the evaluation of emissions at cold starts, enabling us to analyze the new standard's performance in the Scottish context.

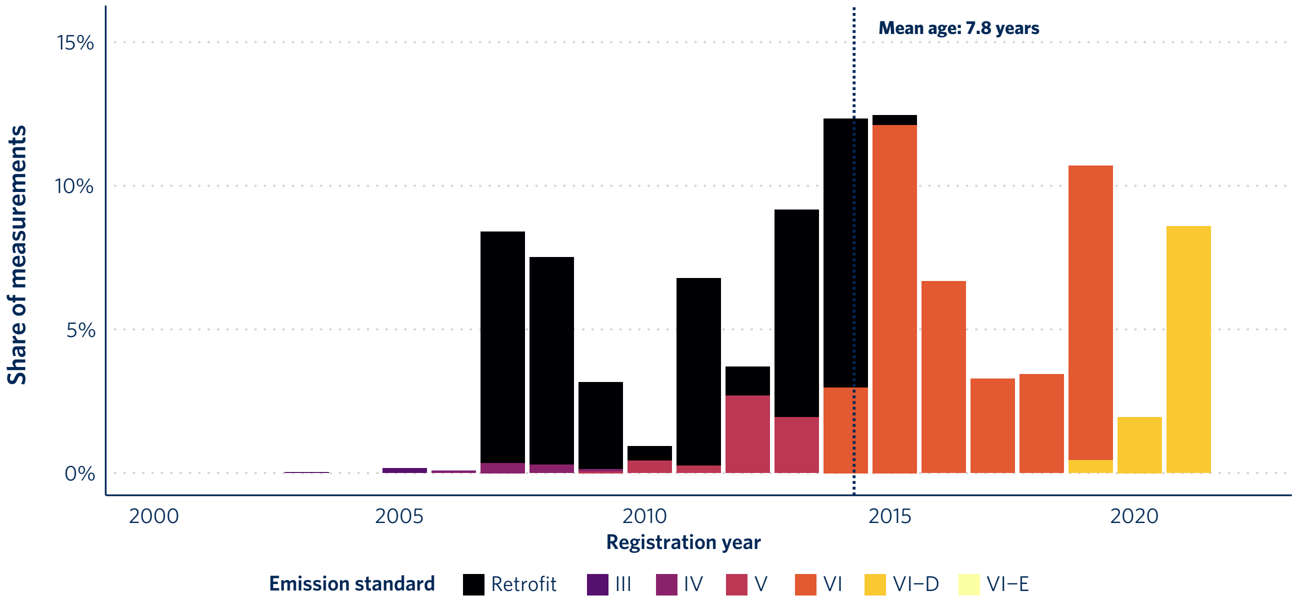

Figure 6. Distribution of registration years and emission standards, or Euro standards, of buses measured during the 2022 vehicle emission testing. Dotted lines mark the mean registration year and the mean age is indicated above. Euro VI refers to pre-Euro VI-D vehicles, such as Euro VI a, b, and c.

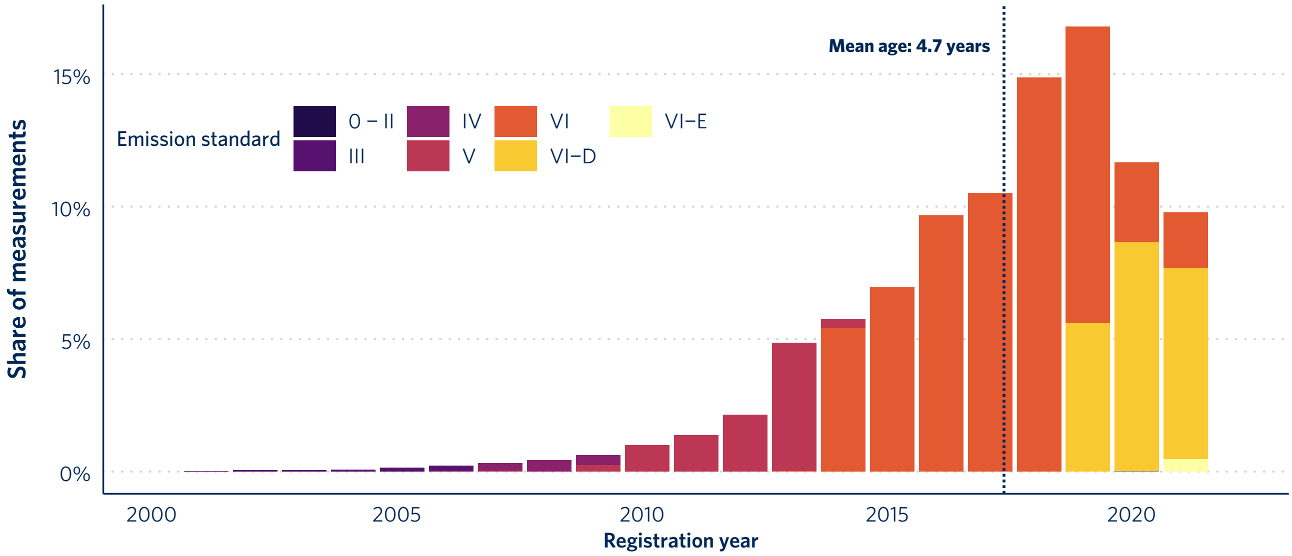

Figure 7. Distribution of registration years and emission standards, or Euro standards, of trucks measured during the 2022 vehicle emission testing. Dotted lines mark the mean registration years, and the mean age is indicated above. Euro VI refers to pre-Euro VI-D vehicles, such as Euro VI a, b, and c.

EMISSION CHARACTERISTICS

PASSENGER CAR EMISSIONS

NO_x and PM emissions from passenger cars were aggregated to depict the overall emission performance of the Scottish passenger car fleet. Applying a method used in previous TRUE studies, fuel-specific emission measurements generated by the EDAR systems were converted to distance-specific emission values.[11] Since the emission performance of a vehicle is primarily shaped by its age and the emissions standard to which it is certified, emissions results are presented by vehicle registration year and emissions standard.

As shown in Figure 8, NO_x emissions from both diesel and petrol passenger cars exhibited a clear downward trend from 2000 to 2022, driven by the progressive tightening of emission standards over time. The emissions reduction is more notable for diesel cars, which have exhibited a 95% reduction in NO_x emissions over the last two decades. Euro 6 brought the most significant improvement in emission performance: Euro 6 vehicles registered in 2019, for instance, showed mean emissions over 50% lower (at 257 mg/km) than Euro 6 vehicles registered in 2015 (568 mg/km). This is largely due to the introduction of the Worldwide harmonized Light vehicles Test Procedure (WLTP) in 2017, which included more dynamic driving cycles in emission testing than the New European Driving Cycle (NEDC) it replaced. RDE testing that required vehicles to be tested on-road became mandatory with Euro 6d-TEMP and Euro 6d, resulting in Euro 6d-TEMP and Euro 6d diesel vehicles registered after 2020 showing similar mean NO_x emissions to those of petrol cars certified to Euro 6.

Petrol cars showed significantly lower NO_x emissions than diesel vehicles across all emission standards, largely owing to the three-way catalytic converter, an effective NO_x reduction strategy that has been required with the introduction of Euro standards. Notably, however, petrol vehicles registered before 2017 had mean NO_x emissions that go beyond their interquartile range, hinting at the presence of a small number of high-emitting vehicles. This trend is more prominent for older petrol vehicles, which may indicate deterioration of the emission control systems in petrol engines, as previous studies have revealed.[12]

Figure 9 illustrates the emission performance improvements achieved through the adoption of more stringent emission standards. The most notable reduction

11 Jack Davison, Yoann Bernard, Jens Borken-Kleefeld, Naomi J Farren, Stefan Hausberger, Åke Sjödin, James E Tate, Adam R Vaughan, and David C Carslaw, "Calculation of Distance-Based Emission Factors from Vehicle Emission Remote Sensing Measurements," *The Science of the Total Environment*, 739 (October 15, 2020): 139688, https://pubmed.ncbi.nlm.nih.gov/32758932/.

12 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; Kaylin Lee, Yoann Bernard, Tim Dallmann, Uwe Tietge, Izabela Pniewska, and Isabel Rintanen, "Evaluation of Real-World Vehicle Emissions in Warsaw," (Washington, DC: TRUE Initiative, 2022), https://theicct.org/publication/true-warsaw-emissions-apr22/#:~:text=The%20analysis%20finds%20the%20real,4.3%20times%20the%20regulatory%20limits.

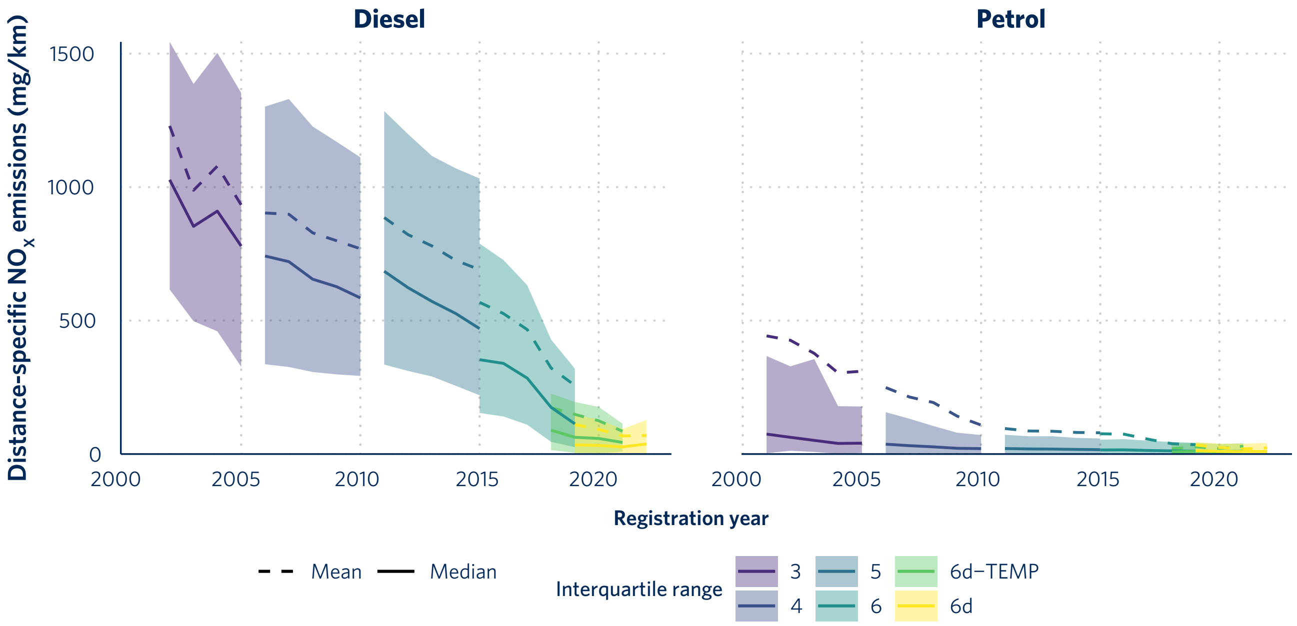

Figure 8. Evolution of mean and median distance-specific NOx emissions (mg/km) for all passenger car measurements. Shaded area represents the interquartile range (25th to 75th percentile range). Only registration years with 50 or more measurements are shown.

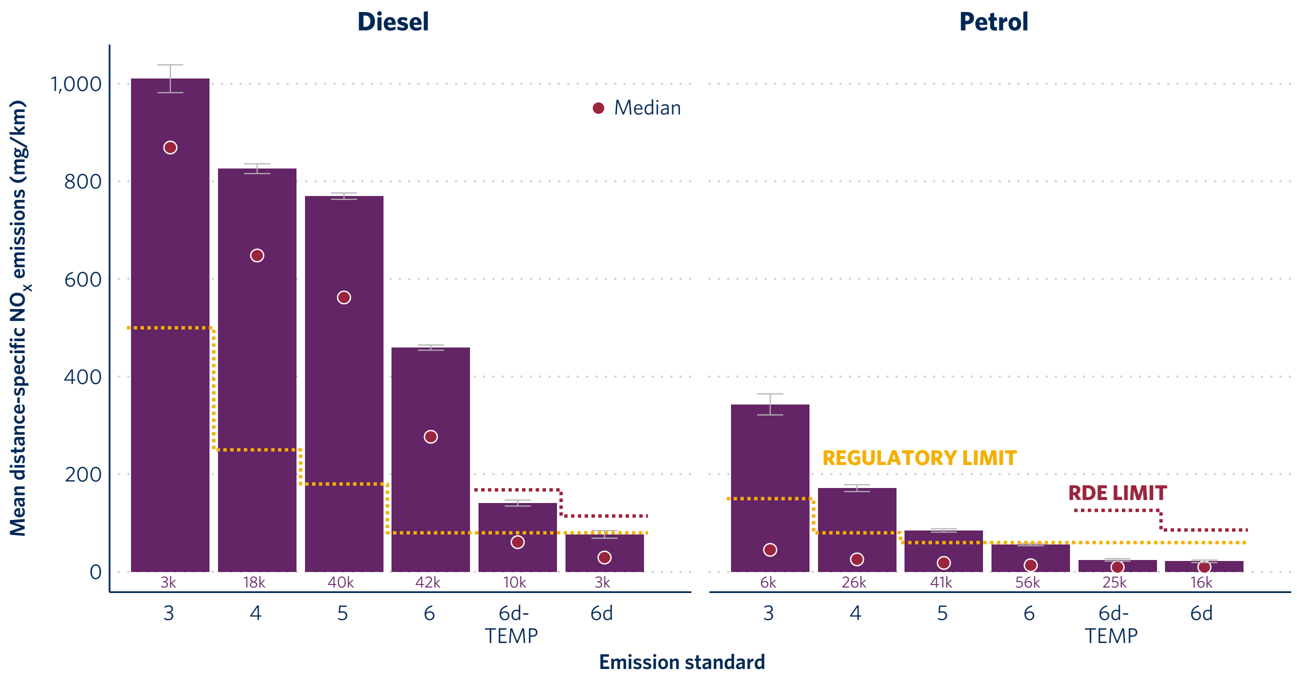

Figure 9. Mean and median distance-specific NOx emissions (mg/km) of passenger cars measured during the 2022 emission testing in Scotland by fuel type and emission standard. Whiskers represent 95% confidence interval of the mean and red point indicates the median NOx emissions (mg/km). Only measurements of over 100 are presented.

in NO_x emissions is seen for diesel Euro 6d-TEMP and Euro 6d vehicles, which had mean NO_x emissions 70% and 83% lower than diesel Euro 6 vehicles, respectively. Vehicles certified to Euro 6d-TEMP and Euro 6d also showed mean and median emissions below the RDE limit, indicating that the introduction of RDE testing with Euro 6d-TEMP was likely effective in reducing real-world emissions.

Petrol vehicles measured in this campaign showed lower NO_x emissions compared to those measured in 2021 and those measured under the TRUE Initiative in other

European cities, such as Warsaw and Brussels.[13] Notably, the median emissions of older petrol vehicles, such as Euro 3 and Euro 4, showed levels similar to, or even lower than, those of diesel Euro 6d-TEMP and Euro 6d vehicles. This highlights the importance of identifying and limiting the use of old vehicles with possible malfunctioning or broken emission control systems.

PM emissions from passenger cars showed trends similar to those of NO_X emissions.[14] For diesel vehicles, both mean and median PM emissions declined drastically for vehicles registered beginning in 2011, largely owing to the introduction of diesel particulate filters (DPFs) that became mandatory from Euro 5. PM emissions from diesel vehicles have since remained steady, as shown in Figure 10. PM emissions from petrol vehicles have improved over time and are significantly lower than those of diesel vehicles, with petrol vehicles registered in 2001 exhibiting median emissions in line with diesel vehicles registered in 2012. The results suggest that old diesel cars have an outsized contribution to PM compared to newer diesel vehicles or petrol vehicles.

Figure 11 illustrates the effectiveness of more stringent PM regulations and the widespread introduction of DPFs in diesel vehicles. Euro 5 diesel cars had mean PM emissions of 21.3 mg/km, one-third those of Euro 4 diesel vehicles (76.1 mg/km). Mean PM emissions from vehicles certified to successive standards, however, were slightly more elevated than the those certified to the same standards measured in other European cities, including Milan, Krakow, and Prague, and showed little improvement with RDE testing introduced with Euro 6d-TEMP.[15]

Mean PM emissions from petrol vehicles of all standards were lower than those of their diesel counterparts. However,

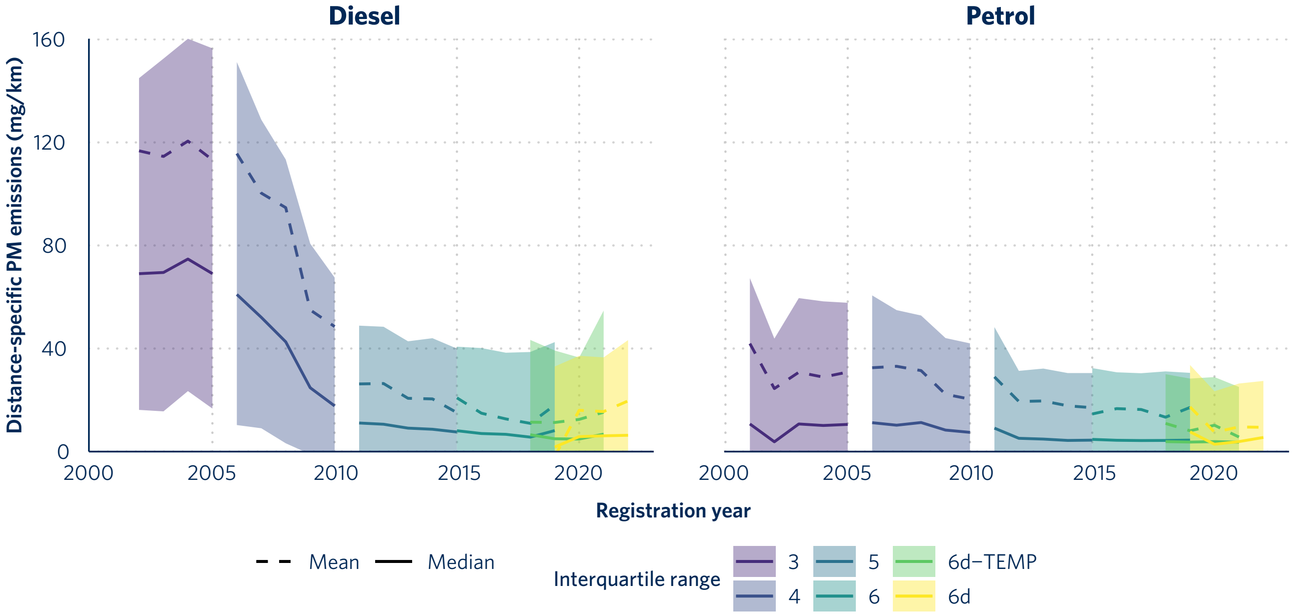

Figure 10. Evolution of mean and median distance-specific PM emissions (mg/km) for all passenger car measurements collected during the 2022 emission testing in Scotland. Shaded area represents the interquartile range (25th to 75th percentile range). Only registration years with 50 or more measurements are shown.

13 Yoann Bernard, Tim Dallmann, Kaylin Lee, Isabel Rintanen, and Uwe Tietge, "Evaluation of Real-World Vehicle Emissions in Brussels," (Washington, DC: TRUE Initiative, 2021), https://theicct.org/publication/evaluation-of-real-world-vehicle-emissions-in-brussels/.; Lee, Bernard, Dallmann, Tietge, Pniewska, and Rintanen, "Evaluation of Real-World Vehicle Emissions in Warsaw."

14 EDAR system measures particulate matter using the light scattering of particles at different wavelengths and reports result in terms of particulate number (PN) in nanomole PM per mole of CO_2. Here we assume a conversion factor of 3mg PM = 10^{12} PN is used in line with a study conducted by TNO, which may be adjusted for different fuel types. See: Nils Hooftman, Norbert E. Ligterink, and Akshay Bhoraskar, "Analysis of the 2019 Flemish remote sensing campaign," (TNO, 2020), https://publications.tno.nl/publication/34638150/2gBdxC/hooftman-2020-analysis.pdf

15 Yoann Bernard et al., "CARES Summary Report: Partner City Measurement Campaigns," EU Horizon 2020 Project Deliverable, City Air Remote Emission Sensing (CARES), April 2023, https://cares-project.eu/wp-content/uploads/2023/06/CARES-814966-D3.4-Summary-report-on-partner-cities-measurement-campaigns.pdf.

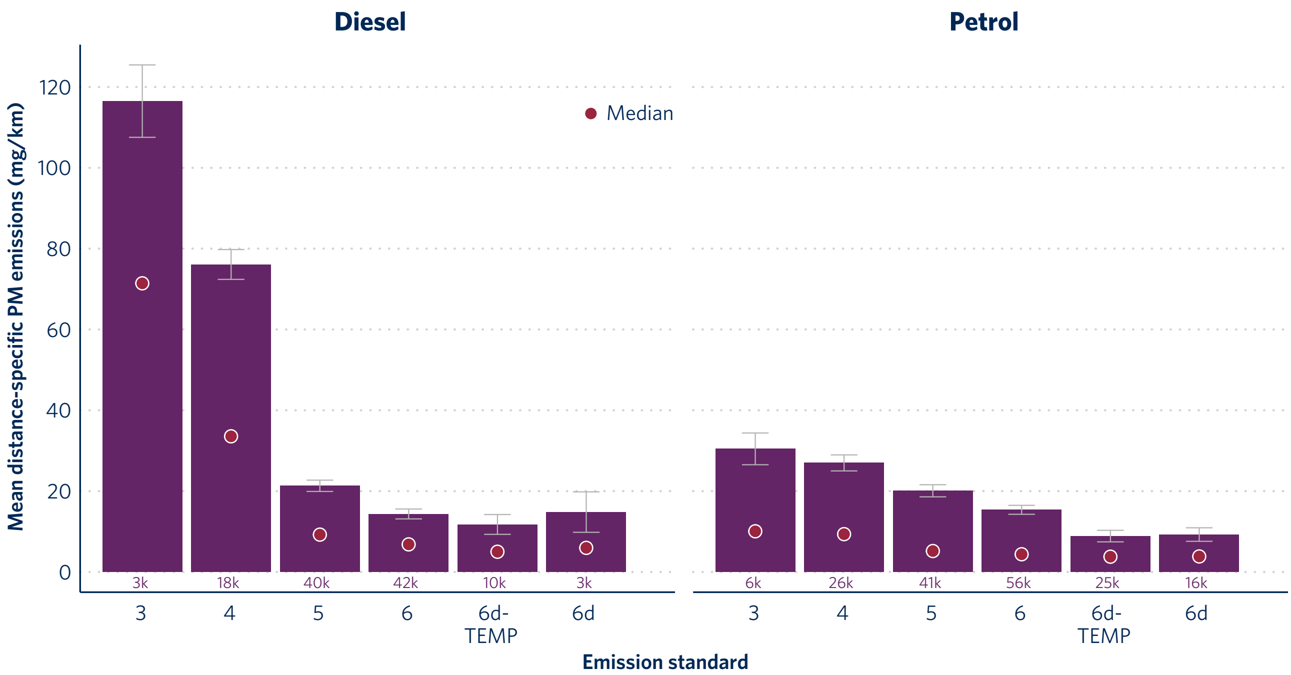

Figure 11. Mean and median distance-specific PM emissions (mg/km) of passenger cars measured during the 2022 emission testing in Scotland by fuel type and emission standard. Whiskers represent 95% confidence interval of the mean and red point indicates the median PM emissions (mg/km). Only measurements of over 100 are presented.

the mean PM emissions from the Scottish petrol vehicles were two to three times higher than levels seen in other European cities using alternative remote sensing methods.[16] The elevated PM levels seen for Euro 5 and Euro 6 petrol vehicles can be partly attributed to the use of gasoline direct injection to comply with these emission standards, which produces higher PM emissions than conventional port fuel injection.[17] However, new binding particulate number limits and additional on-road RDE testing introduced from 2017 helped to reduce PM emissions from Euro 6d-TEMP and Euro 6d petrol vehicles.[18]

16 The results were compared with the results from point sampling measurements of black carbon which constitutes the majority of vehicle exhaust emissions from the CARES project. See Bernard et al. "CARES Summary Report: Partner City Measurement Campaigns."

17 Omar I. Awad et al., 'Particulate Emissions from Gasoline Direct Injection Engines: A Review of How Current Emission Regulations Are Being Met by Automobile Manufacturers', *Science of The Total Environment* 718 (20 May 2020): 137302, https://doi.org/10.1016/j.scitotenv.2020.137302; Barouch Giechaskiel, Leonidas Ntziachristos, and Panagiota Dilara, "European Regulatory Framework and Particulate Matter Emissions of Gasoline Light-Duty Vehicles: A Review," *Catalysts* 9, no. 7 (July 2019): 586, https://doi.org/10.3390/catal9070586.

18 Another potential reason for elevated PM emissions seen for petrol vehicles of all emission standards is that the conversion factor of 3mg PM = 10^{12} PN (see footnote 21) used by the instrument provider may need to be further adapted to petrol vehicles.

EMISSION PERFORMANCE OF NEWER DIESEL VEHICLES

This section builds on the emission performance assessment of diesel Euro 6d-TEMP and Euro 6d vehicles measured in 2021.[19] A larger number of diesel Euro 6d-TEMP and Euro 6d cars present in the 2022 sample allowed us to update this assessment and compare with the earlier results.

We assessed the NO_X emission performance of different vehicle families, defined by both engine manufacturer and capacity, as engine capacity alone did not show a significant correlation with NO_X emissions. As Figure 12 illustrates, NO_X emissions within the same engine capacity category varied widely by manufacturer, with certain vehicle families repeatedly showing high real-world emissions. Notably, the vehicle families with the top four highest-emitting engines certified to Euro 6d-TEMP standards in this study, namely the 1500cc and 2000cc Ford engines, 1600cc Hyundai Motor Company engine, and 1960cc Volvo engine, were also among the highest-emitting vehicle families from the measurements collected

19 Kaylin Lee, Yoann Bernard, and Jonathan Cooper, "Assessment of Real-World Vehicle Emissions in Scotland in 2021: Emissions Testing Campaigns in Edinburgh and Glasgow," (ICCT: Washington, DC, 2023), https://theicct.org/publication/true-scotland-remote-sensing-jun23/

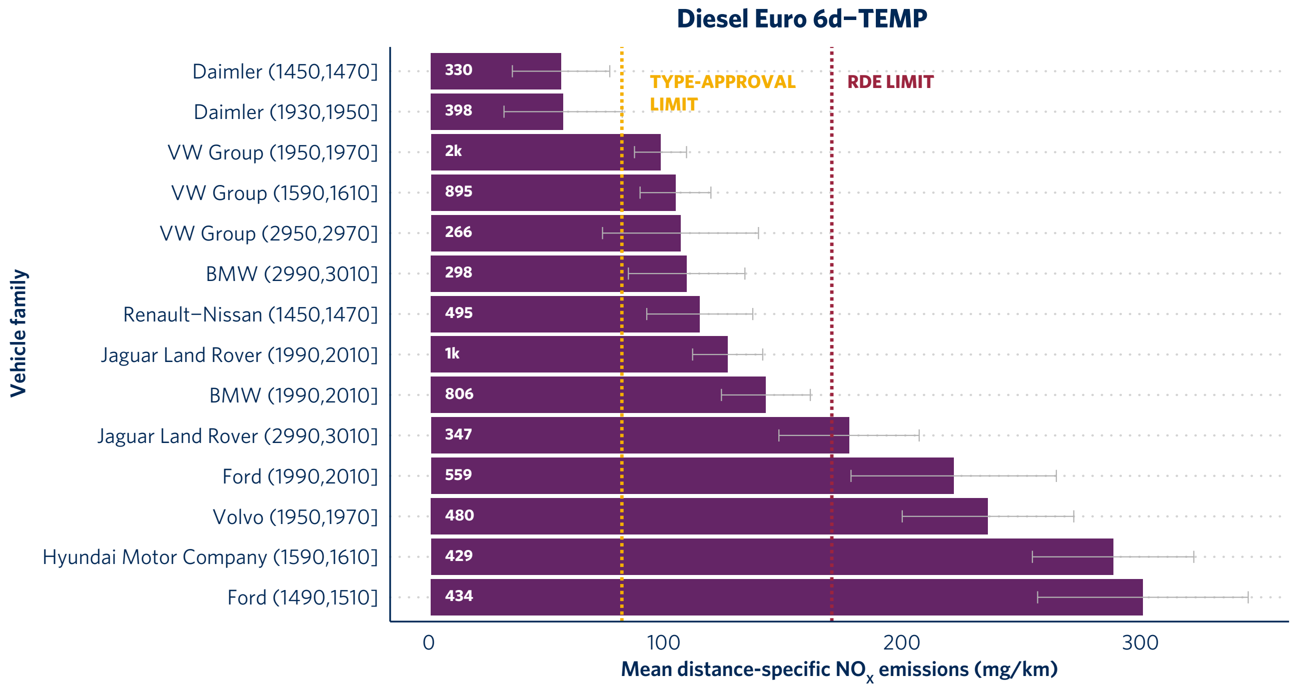

Figure 12. Mean distance-specific NO_x emissions from diesel passenger cars certified to Euro 6d-TEMP collected during the 2022 emission testing in Scotland by vehicle family. Whiskers represent 95% confidence intervals of the mean. Only measurements of over 100 are presented.

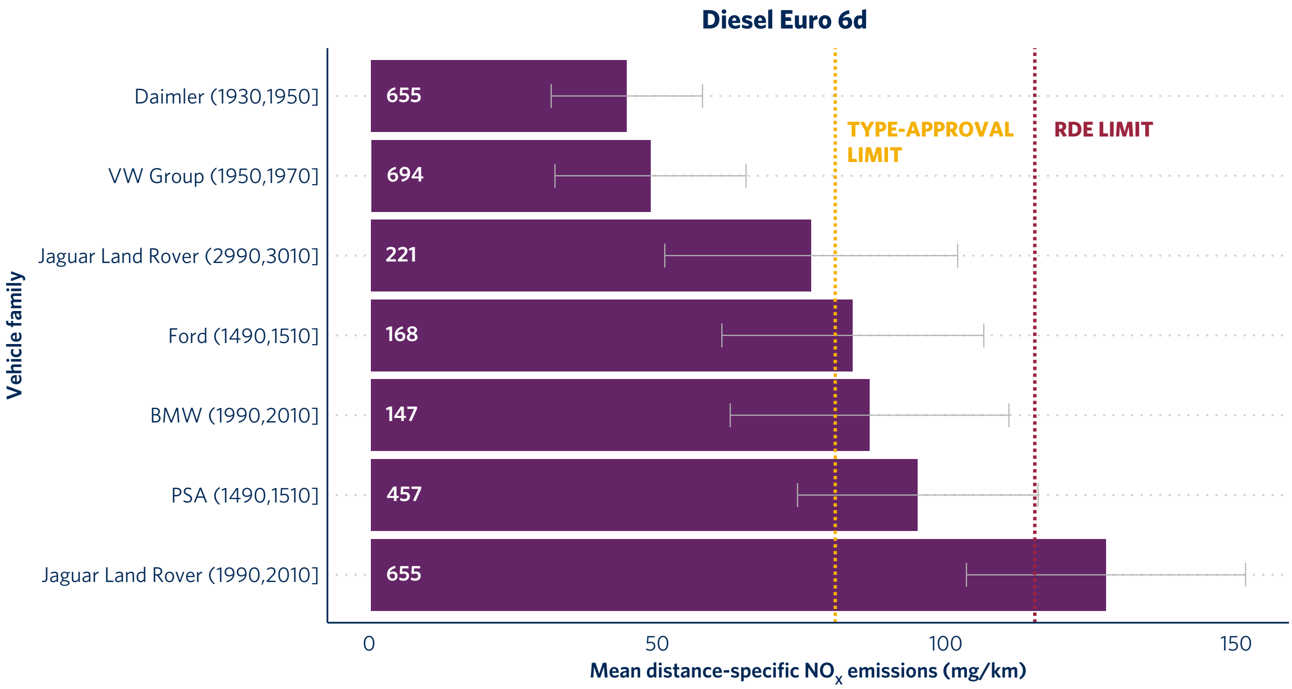

Figure 13. Mean distance-specific NO_x emissions from diesel passenger cars certified to Euro 6d collected during the 2022 emission testing in Scotland by vehicle family. Whiskers represent 95% confidence intervals of the mean. Only measurements of over 100 are presented.

in 2021 in Scotland. The results consistent with the 2021 study highlight that continuous evaluation of the emission performance of these diesel vehicles in real operating conditions can help identify high-emitting vehicle families and target any excess NO_x emissions that may not have been effectively controlled by RDE limits.

Figure 13 shows the mean distance-specific NO_x emissions of diesel Euro 6d vehicle families in the 2022 sample.

Similar to 2021, vehicles with the Daimler 1940cc, VW Group 1960cc, Ford 1500cc, PSA 1500cc, and Jaguar Land Rover 2000cc and 3000cc engines led in terms of absolute numbers of diesel Euro 6d measurements in 2022, although the sites where the samples were collected were different. Jaguar Land Rover 2000cc engines, which were one of the highest-emitting vehicle families from 2021, were the highest-emitting diesel Euro 6d engines in our sample, with mean NO_x emissions of 127 mg/km, above the RDE limit—although the lower bound of the 95% confidence interval was below the limit. A further breakdown by brand revealed that, more specifically, Jaguar vehicles were emitting higher levels of NO_x than Land Rovers on average, albeit with high variance in emission performance.

TAXI AND PRIVATE HIRE EMISSIONS

Figure 14 compares NO_x emissions from taxis and private hires with those from other diesel private cars. The results show that taxis and private hires consistently emit higher NO_x emissions than private cars across registration years. This gap is larger for older vehicles (those registered before 2016), and decreases for vehicles registered in more recent years, illustrating that older taxis, likely certified to Euro 5, may have been more prone to emission deterioration due to high usage.

Differences between the PM emissions from the three vehicle types were particularly stark. As shown in Figure 15, private cars had the lowest mean PM emissions among different vehicle types across almost all registration years. Median PM emissions from private cars—indicated by the dot in the bar—level off at levels below 10 mg/km from 2013, largely due to the introduction of DPFs in 2011, which became mandatory for all new vehicles in 2013. Taxis, meanwhile, showed highly elevated median PM emissions of over 20 mg/km until 2016, and do not show comparable emissions with private cars until 2019. This may suggest significant emission deterioration among taxis resulting from accrued mileage, while mean PM emissions of over 50 mg/km among taxis registered before 2017 further suggest that some taxis may have defective DPFs. Private hires, meanwhile, showed lower mean PM emissions than taxis but higher PM emissions than private passenger cars across most registration years, suggesting the possible impact of mileage on PM emissions.

We further assessed NO_x emissions from the primary makes for both taxi and private hire fleets. Figure 16 shows NO_x emissions from the top five highest-emitting taxi and private hire makes certified to Euro 5 and Euro 6. London Taxi Company (LTC)'s TX4 taxis and Mercedes taxis certified to Euro 5 showed the highest real-world mean NO_x emissions of 1,969 mg/km and 1,913 mg/km, respectively—

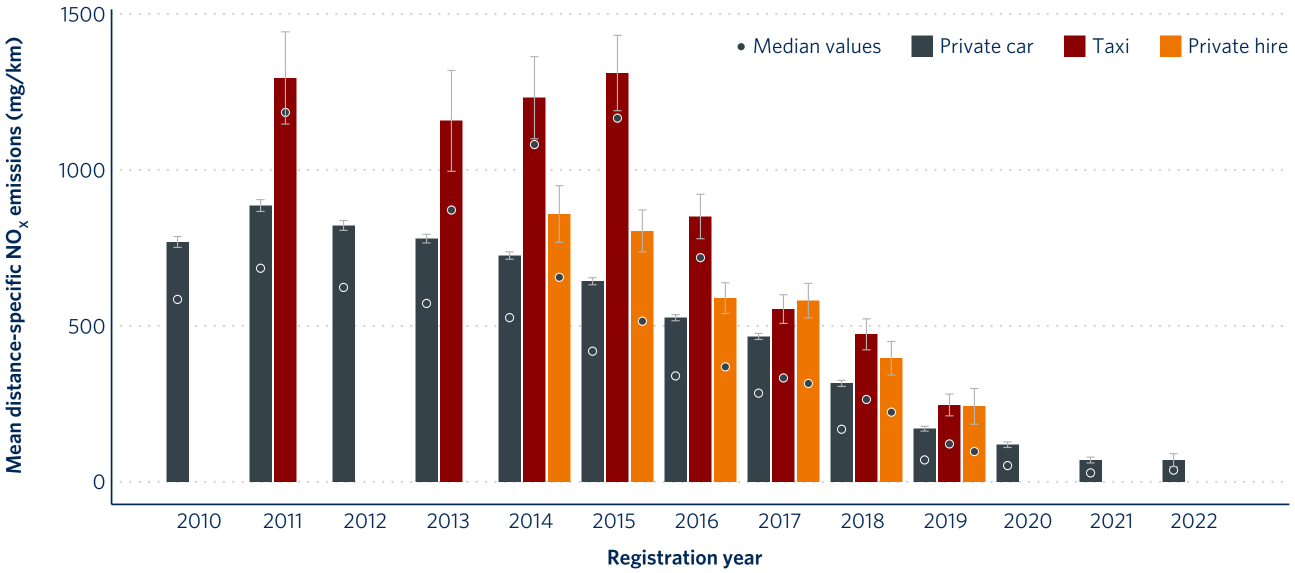

Figure 14. Mean and median distance-specific NO_x emissions from diesel private passenger cars, taxis, and private hire by registration year. Whiskers represent 95% confidence intervals of the mean. Dots indicate median emissions. Only measurements of over 100 are presented.

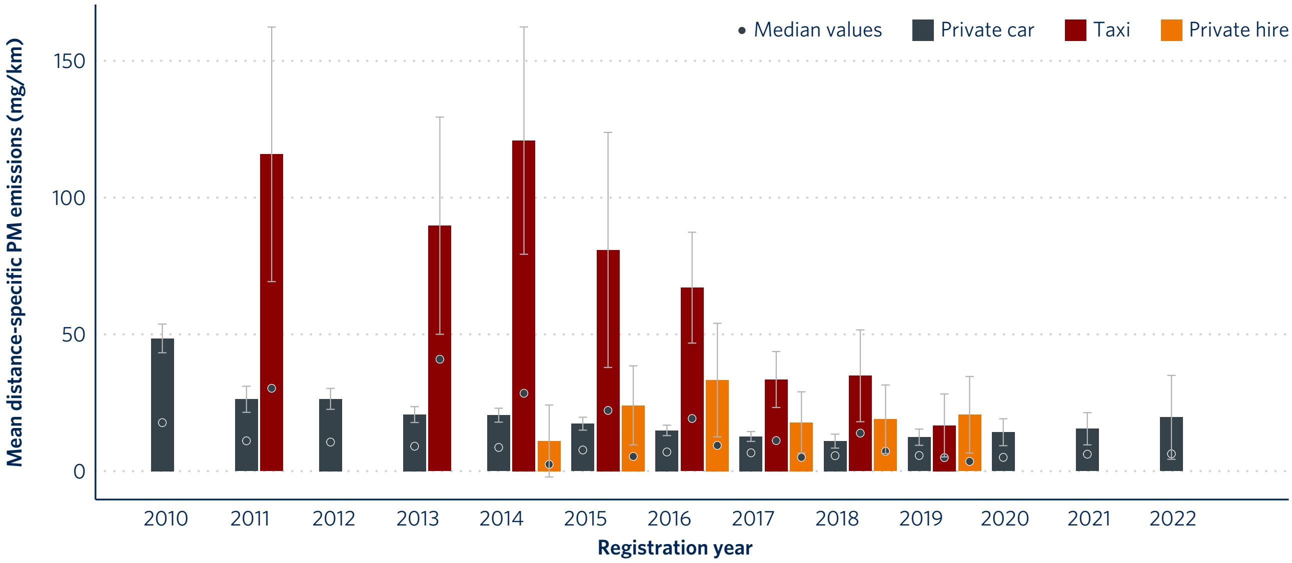

Figure 15. Mean and median distance-specific PM emissions from diesel private passenger cars, taxis, and private hire by registration year. Whiskers represent 95% confidence intervals of the mean. Dots indicate median emissions. Only measurements of over 100 are presented.

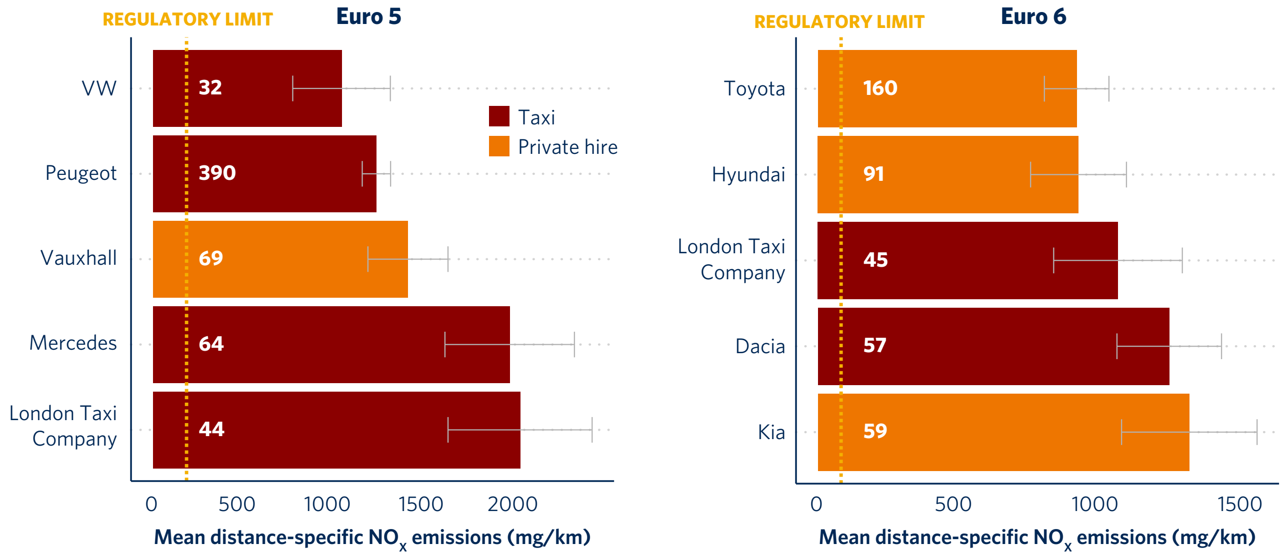

Figure 16. Mean distance-specific NO_x emissions from the top 5 highest-emitting taxis and private hire makes for Euro 5 and Euro 6. Whiskers represent 95% confidence intervals of the mean. Only measurements of over 30 are presented.

180mg/km.[20] The TX4 taxis also ranked third, behind Kia and Dacia, among the highest-emitting Euro 6 taxis and private hires, with mean real-world emissions of 1,038 mg/km, nearly 13 times the Euro 6 emission limit of 80mg/km. These results align with the findings of the previous TRUE analysis of emissions in Scotland, which found that LTC was among the highest-emitting Euro 5 and Euro 6 taxi makes.[21]

Vauxhall was the highest-emitting private hire make among Euro 5 vehicles, with mean emissions of 1,368 mg/km. Kia and Hyundai, meanwhile, were the highest-emitting Euro 6 private hire makes. The engines used in these two Euro 6 makes were the 1,582cc (D4FB) and 1,685cc (D4FD) manufactured by Hyundai Motor

20 London Taxi Company (LTC), the manufacturer of London's iconic black TX4 taxis, was renamed to London Electric Vehicle Company (LEVC) in 2017 with the launch of the new range-extended plug-in hybrid taxis (LEVC TX), certified to Euro 6d-TEMP and above. For the context of this study, LTC is used to refer to the make of the TX4 taxis certified to Euro 5 and Euro 6 and LEVC is used for the make of the LEVC TX taxis.

21 "Assessment of Real-World Vehicle Emissions in Scotland in 2021: Emissions Testing Campaigns in Edinburgh and Glasgow."

Company and both had average NO_x emissions over 800mg/kg, or over 10 times the Euro 6 regulatory limit. The finding is notable as Hyundai Motor Company was also the manufacturer of the Euro 6d-TEMP 1598cc engine that was in the highest-emitting Euro 6d-TEMP vehicles captured in Scotland in 2021 and 2022.[22] Although emissions deterioration stemming from accrued mileage of private hire vehicles could partially explain the trend, such large exceedances may warrant further investigation of Hyundai Motor Company's engine performance.

Figure 17 further explores the emission performance of TX taxis manufactured by LTC and London Electric Vehicle Company (LEVC, as the company has been known since 2017), which comprised around 10% of all taxi traffic measured in Scotland. To meet London's Ultra Low Emission Zone requirements, LTC retrofitted some of its Euro 4–5 taxis and has produced zero-emission capable plug-in hybrids, known as the LEVC TX, since 2017. The availability of retrofit and LEVC TX taxi measurements enabled assessment of the real-world emission performance of these vehicles. Due to the lack of CO_2 emissions information on different powertrain types, NO_x emissions are presented in grams of NO_x per kg of fuel burned (g/kg). Despite the limitations of comparing fuel-specific emissions for vehicles with varying CO_2 emissions and fuel economy, the results clearly show that LPG retrofit LTC taxis had lower NO_x emissions compared to their diesel counterparts. Their mean real-world NO_x emissions were 4.6 g/kg, around 80% lower than those of Euro 5 diesel taxis (21.8 g/kg) and over 50% lower than those of Euro 6 diesel taxis (10.5 g/kg).

LEVC TX taxis showed real-world NO_x emissions below 1 g/kg, significantly lower levels than any other types of LTC taxis.[23] Plug-in hybrids do not emit CO_2 emissions when they use electricity to power vehicles, and LEVC TX taxis are equipped with range extenders and are driven by electricity until the battery is depleted, at which point petrol is used. That any emissions were observed from these vehicles indicates that they were running on petrol at the time of measurement. As shown in Figure 17, nearly 50% of the captured LEVC TX taxis were not powered by their batteries at the time of measurement, much lower than the 90% approximate electric driving share corresponding to the type-approval conditions for these

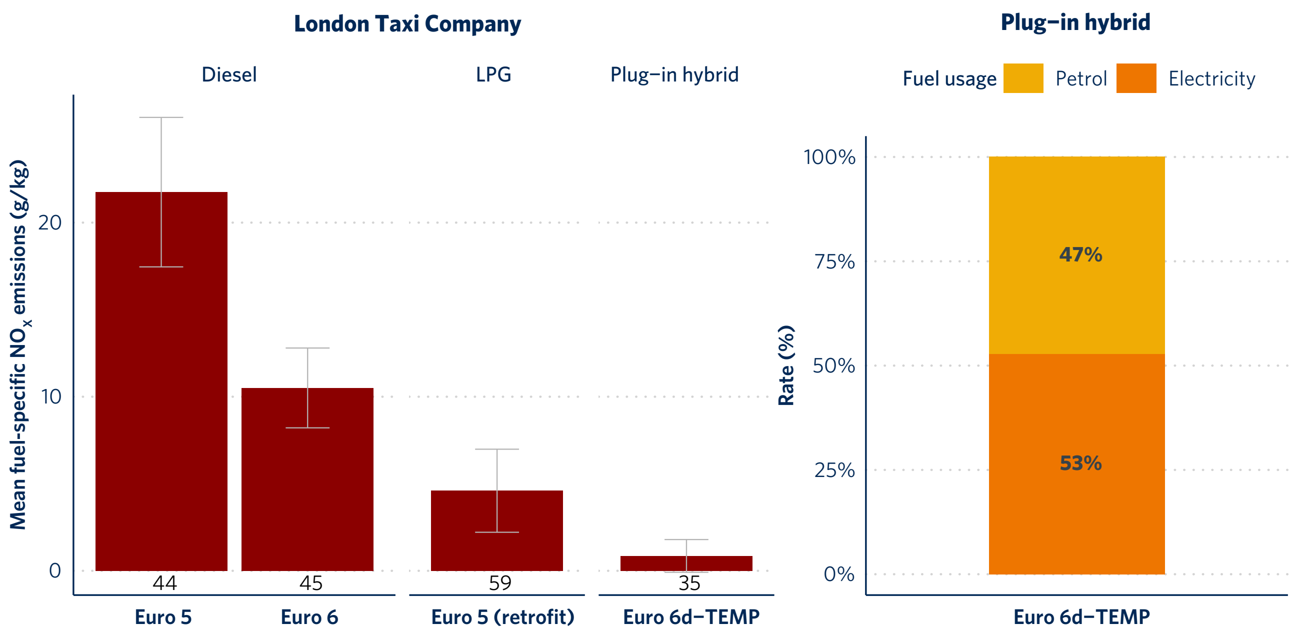

Figure 17. Mean fuel-specific NO_x emissions (g/kg) from London Taxi Company taxis of various fuel types and powertrain types (left) and validity rate of emission measurements from the Euro 6d-TEMP London Taxi Company taxis measured during the 2022 emission testing in Scotland.

22 See section on Emission performance of newer diesel vehicles.

23 Fuel-specific NO_x emissions from plug-in hybrids were calculated only for measurements with valid CO_2 plumes, or when the vehicles were running on petrol.

vehicles.[24] This gap raises the question of whether the LEVC TX taxis often have depleted batteries and do not run on electricity as much as anticipated in their type-approval procedure, though a larger sample would be necessary to determine the rate of battery use in plug-in hybrid taxis.

BUS EMISSIONS

To examine the overall performance of buses, we first analyzed bus NO_x emissions by registration year and emission standard regardless of where the measurements were collected. To allow comparison with regulatory limits, fuel-specific emissions were converted to the amount of NO_x emitted per energy produced (g/kWh) using the methodology deployed in the 2021 Scottish remote sensing study.[25]

Figure 18 shows the evolution of mean, median, and interquartile range of energy-specific NO_x emissions (g/kWh) for all valid bus measurements collected in 2022. For all buses certified to Euro V and above, NO_x emissions show a steady downward trend over time. The oldest Euro VI buses, introduced in 2014, cut their NO_x emissions by over half compared to the latest Euro V buses registered in 2013, likely owing to in-service conformity (ISC) testing, an additional measure introduced with Euro VI to reduce emissions from buses via testing emissions of in-use vehicles with an accumulated mileage of 25,000 km.[26] Median NO_x emissions from Euro VI and VI-D buses registered after 2016 were in line with the ISC limits, indicating that more than half of buses that were up to 6 years old at the time of measurements were emitting under the limit even in real-world driving conditions.

Meanwhile, older buses registered between 2007 and 2014 and retrofitted with SCR showed fluctuating NO_x emissions. Likely certified to Euro IV and V prior to retrofitting, these buses had mean NO_x emissions of 5.4 g/kWh—lower than those from non-retrofit Euro V (6.8 g/kWh) but up to 2.5 times those from the highest-

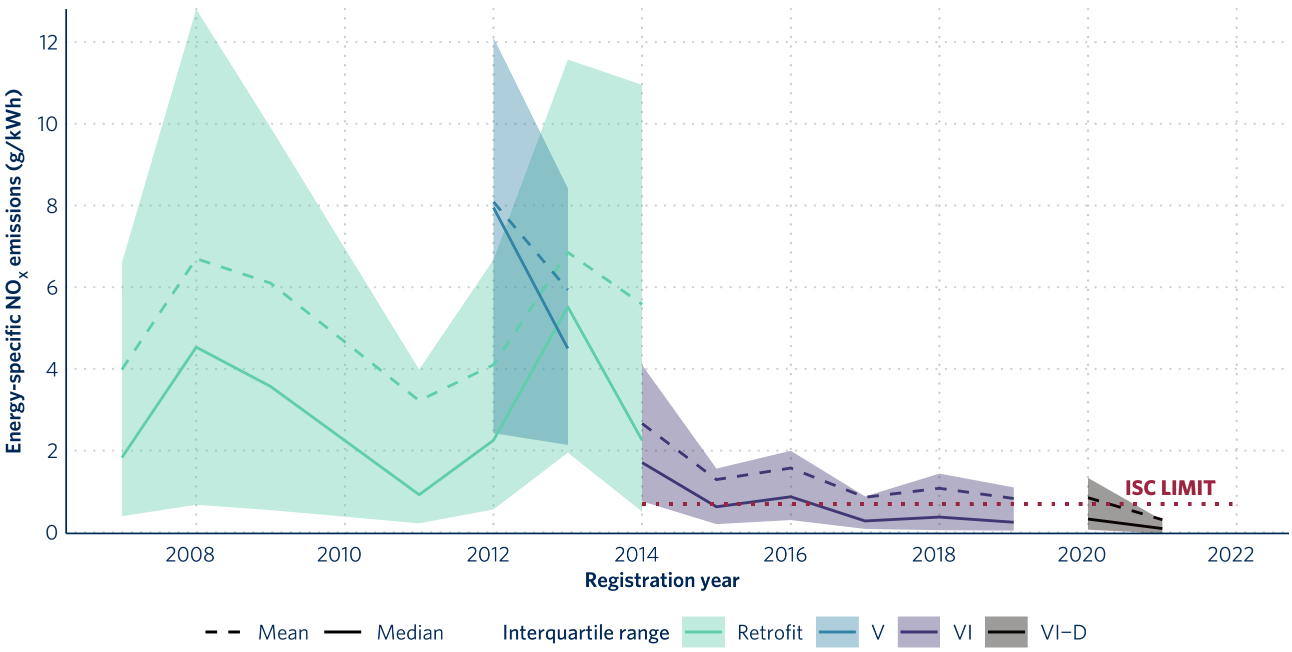

Figure 18. Evolution of mean and median energy-specific NOx emissions (g/kWh) for all bus measurements collected during the 2022 emission testing in Scotland. Shaded area represents the interquartile range (25th to 75th percentile range). Only registration years with 50 or more measurements are shown.

24 Patrick Plötz, Steffen Link, Hermann Ringelschwendner, Marc Keller, Cornelius Moll, Georg Bieker, Jan Dornoff, and Peter Mock, "Real-World Usage of Plug-in Hybrid Vehicles in Europe: A 2022 Update on Fuel Consumption, Electric Driving, and CO2 Emissions," (Washington, DC: ICCT, 2022), https://theicct.org/publication/real-world-phev-use-jun22/.

25 Sina Kazemi Bakhshmand, Eamonn Mulholland, Uwe Tietge, and Felipe Rodríguez, "Remote Sensing of Heavy-Duty Vehicle Emissions in Europe," (Washington, DC: ICCT, 2022), https://theicct.org/publication/remote-sensing-of-heavy-duty-vehicle-emissions-in-europe/.

26 In-service conformity testing requires that on-road PEMS testing be conducted on heavy-duty vehicles that have accrued a minimum of 25,000km within 18 months of first registration in a variety of conditions, including urban, rural, and motorway.

emitting non-retrofit Euro VI buses. Figure 19 compares the mean and median emissions of retrofit buses with non-retrofit buses of different emission standards. Buses retrofitted with SCR showed mean real world NO_x emissions over 4 times higher than those of Euro VI and 12 times higher than those of Euro VI-D buses. Furthermore, the emission performance of retrofit buses varied widely—much more than that of Euro VI vehicles—suggesting that the emission abatement capability of retrofit buses is not consistent.

Figure 20 examines the emission performance of buses certified to the most common emission standards at the city level. The results show that buses measured in Aberdeen show consistently higher NO_x emissions across all emission standards, with larger emission gaps seen for older buses, including retrofits. Specifically, retrofit buses and Euro V buses in Aberdeen showed real-world NO_x emissions of around 7.5 g/kWh, between 1.8 and 2.3 times those from buses of the same standards in Dundee, the city with the lowest-emitting bus fleet. Euro VI and Euro VI-D buses in Aberdeen, however, had emission performance comparable to those in other cities.

Such differences can be partly attributed to the prevalence of cold engines, likely due to the Aberdeen testing site's proximity to bus depots. Some of the highest emitting buses were found to belong to the operators whose bus depots are near the testing site. Indeed, even buses certified to the latest emission standards, such as Euro VI-D, in Aberdeen showed mean NO_x emissions at least double those of fleets from other cities, demonstrating that they are prone to elevated emissions at lower engine temperatures. Starting 2021, Euro VI-E added a cold-start requirement, but the emissions from Euro VI-E buses were not evaluated due to the lack of measurements.

In Edinburgh, the predominance of relatively lower-emitting Volvo buses—which comprised 90% of the buses measured in Edinburgh, and were one of the best-performing Euro VI and VI-D makes—appeared to have contributed to the low mean NO_x emissions. The variance in emission performance by make across the whole bus sample was assessed but deemed inconclusive as the influence of cold engine was not ruled out.

These results give a glimpse into how bus emissions may be influenced by the low emission zone policies that took effect in Glasgow in 2023 and are due to be implemented in Aberdeen, Dundee, and Edinburgh in 2024, and raises concerns about whether retrofit buses are delivering the

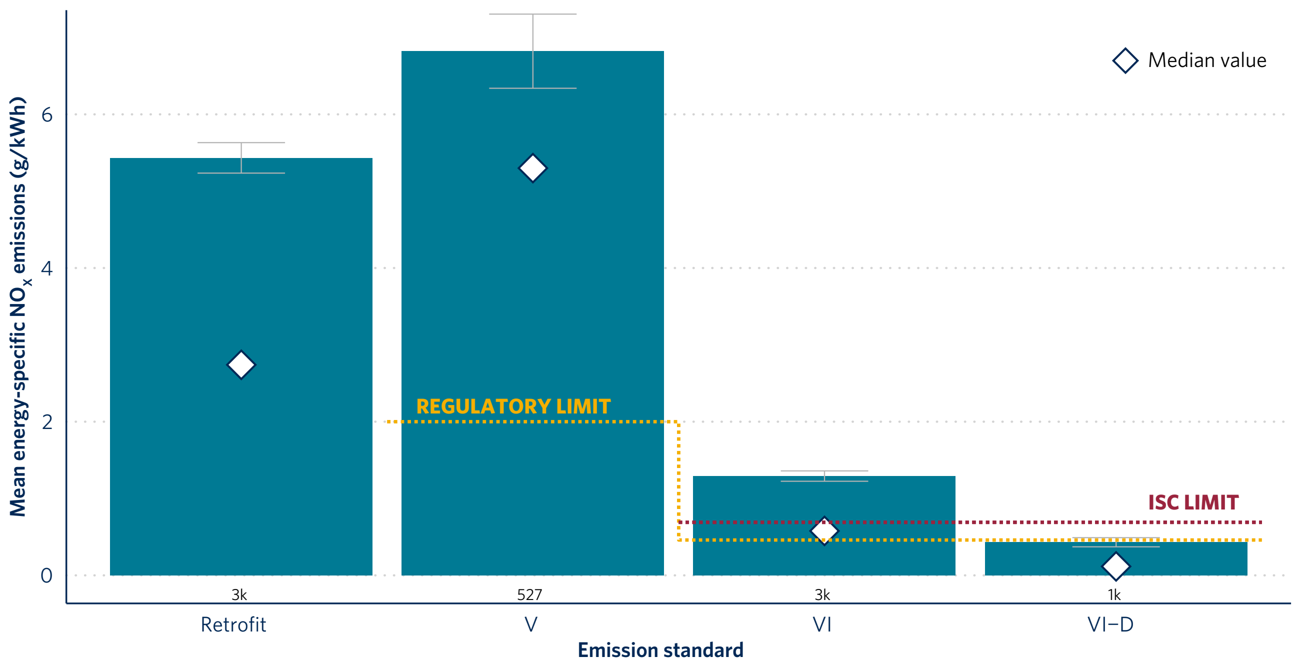

Figure 19. Mean and median energy-specific NOx emissions (g/kWh) of buses measured during the 2022 emission testing in Scotland by emission standard and retrofit status. Whiskers represent 95% confidence interval of the mean and diamond shape indicates the median NOx emissions (g/kWh). Only measurements of over 100 are presented.

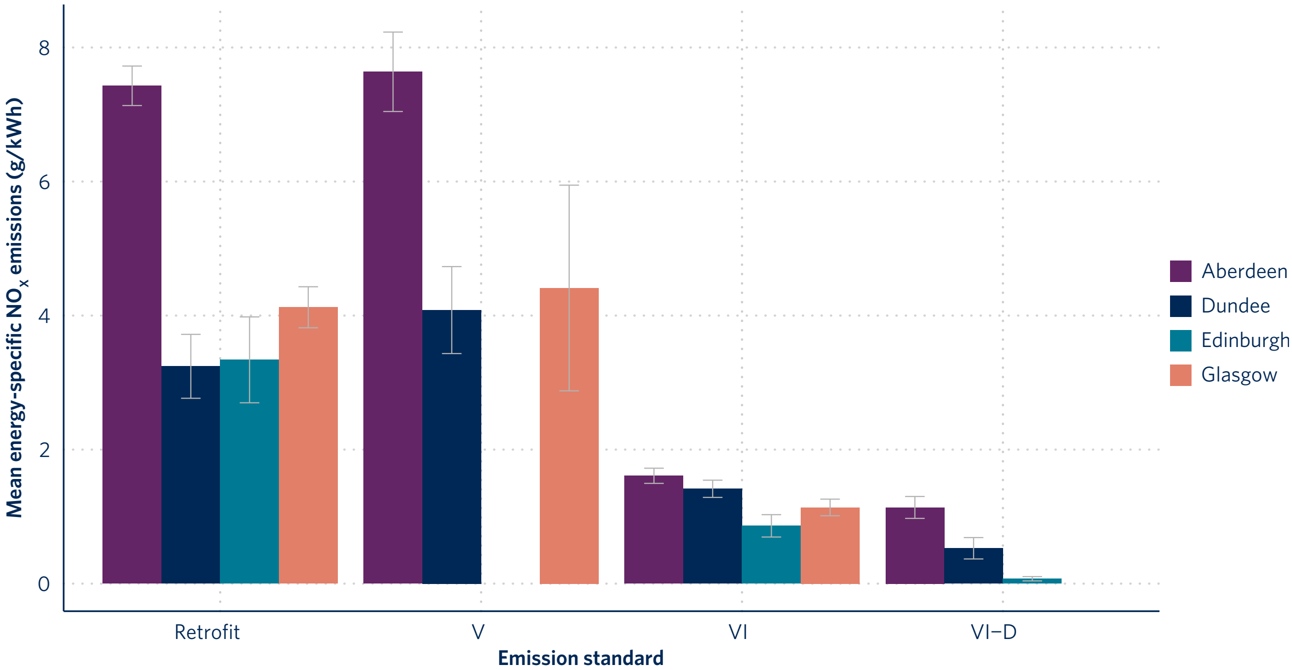

Figure 20. Mean energy-specific NOx emissions (g/kWh) of buses by emission standard and city. Only points with over 30 measurements are presented.

expected emission benefits.[27] The data suggest that Euro V buses in Aberdeen, Dundee, and Edinburgh that will be restricted from the zone starting in 2024 should be replaced by Euro VI buses rather than retrofitted if possible. This also calls for reevaluation of retrofit buses, as their performance may vary. Looking ahead, an evaluation of Euro VI-E bus performance in real-world settings will be important to ensure their consistency in emission performance.

TRUCK EMISSIONS

Most of the trucks measured during the 2022 emission testing campaigns were registered between 2008 and 2022, with emission standards spanning from Euro IV to Euro VI-E. As shown in Figure 21, NO_X emissions were drastically different for trucks registered before and after 2014, the year of the introduction of the Euro VI standard and ISC testing. Trucks registered after 2014 showed real-world NO_X emissions at least 50% lower than those registered before 2014, with a steady downward trend until 2022.

Despite the notable improvement in NO_X emission performance, however, even Euro VI trucks—including those certified to Euro VI-D and Euro VI-E—exceeded the ISC limit of 0.69 g/kWh during real-world driving, as shown in Figure 22. These results corroborate conclusions from previous studies indicating that Euro VI trucks show relatively high real-world NO_X emissions despite technological improvements and more stringent pollutant regulations.[28]

Gaps between ISC limits and real-world mean emissions decrease with newer emission standards, however. Improved emission performance by Euro VI-D trucks is largely because conditions included in ISC testing were widened to include lower power demand to account for the effect of urban driving on emissions. Trucks certified to Euro VI-E further reduced mean NO_X emissions by 20% from Euro VI-D despite exceeding the ISC limit by around 25%. Furthermore, median NO_X emissions from Euro VI-E trucks were below the ISC limit and even below the type-approval limit. This suggests that the additional emission testing that includes partial cold starts helped to reduce real-world NO_X emissions from trucks.

The data further show that a small portion of Euro VI a-d trucks emitted much more than the rest of the fleet. The top 10^{th} percentile trucks had real-world NO_X emissions 3.5 times and 5 times the median emissions for Euro VI a-c and Euro VI-D, respectively. The causes of excessive

27 The low emission zone enforcement requiring buses to be at minimum Euro VI will begin in the summer of 2024 in Aberdeen, Dundee, and Edinburgh. In Glasgow, the requirement has been in place since 2018. See: Low Emission Zones Scotland, https://www.lowemissionzones.scot/.

28 Theodoros Grigoratos, Barouch Giechaskiel, and Nikiforos Zacharof, "Real World Emissions Performance of Heavy-Duty Euro VI Diesel Vehicles," *Atmospheric Environment* 201 (15 March 2019): 348–59, https://doi.org/10.1016/j.atmosenv.2018.12.042.

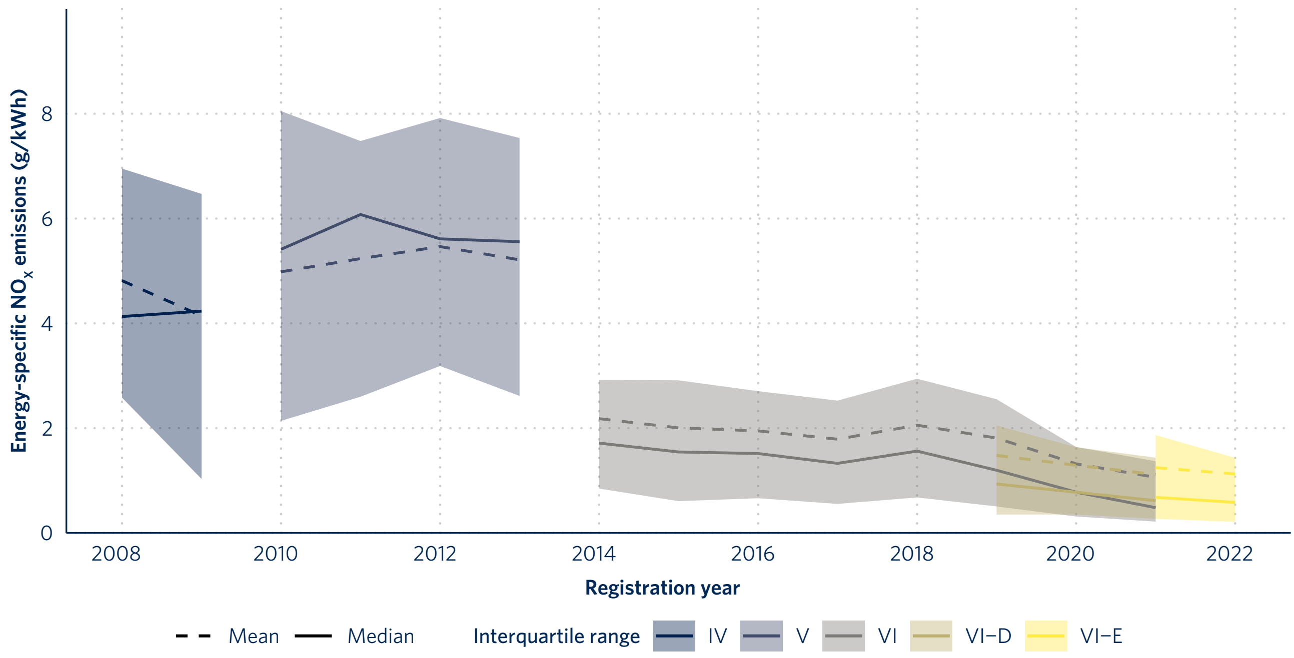

Figure 21. Evolution of mean and median energy-specific NOx emissions (g/kWh) for all truck measurements collected during the 2022 emission testing in Scotland. Shaded area represents the interquartile range (25th to 75th percentile range). Only registration year with 50 or more measurements are shown.

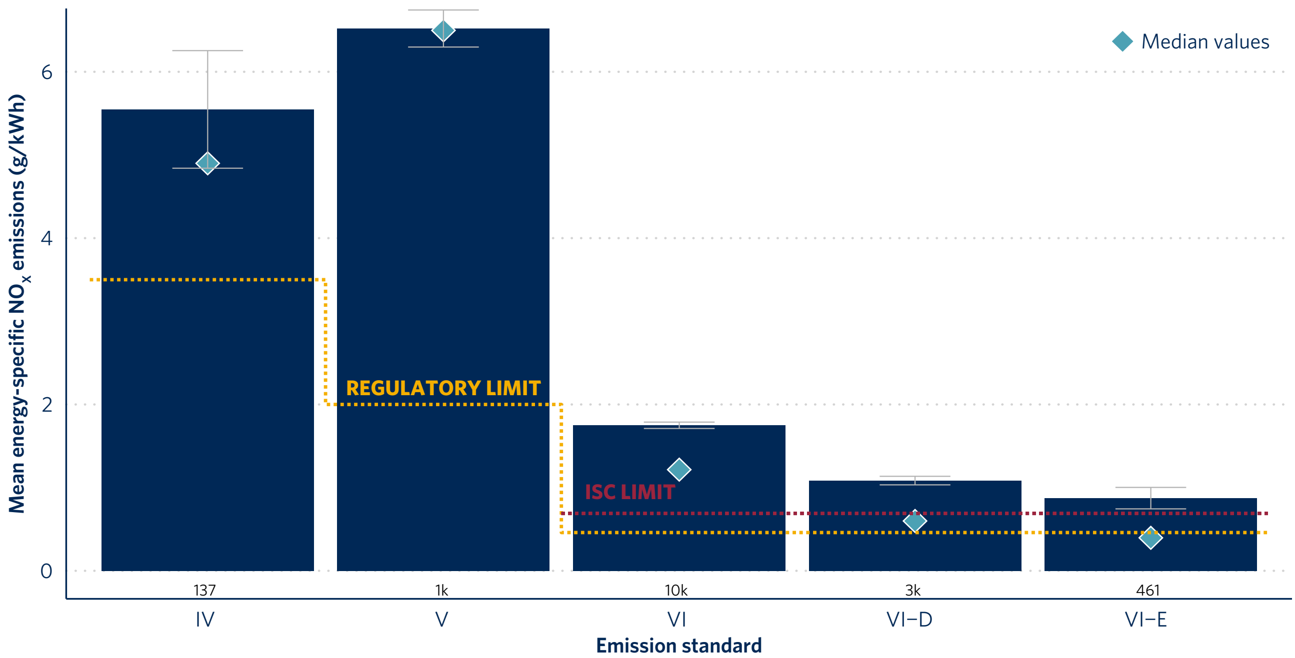

Figure 22. Mean and median energy-specific NO_x emissions (g/kWh) of trucks measured during the 2022 emission testing in Scotland by emission standard. Whiskers represent 95% confidence interval of the mean and diamond shape indicates the median NO_x emissions (g/kWh). Only measurements of over 100 are presented.

emissions may vary, ranging from a regulatory loophole in early Euro VI standards which did not cover low load conditions to cold engines and tampered or malfunctioning emission control systems. The following section discusses a way to derive possible thresholds that could be used for detecting tampered or malfunctioning trucks with excess NOx emissions to help enable the removal of the small fraction of very highly-emitting trucks from the fleet.

HIGH-EMITTER THRESHOLDS FOR TRUCK ENFORCEMENT USING REPEATED MEASUREMENTS

This section builds on the experimental approach to identifying high-NO_x-emitting trucks applied in the previous TRUE report on the 2021 Scottish remote sensing results.[29] The 2021 report highlighted the importance of testing vehicles such that they are measured under a range of conditions representative of the real world while avoiding testing conditions that may cause higher-than-normal emissions. Studying vehicle emissions in varying driving conditions while excluding known occasions in which vehicles require more power and create more emissions (e.g., cold starts, very high acceleration, or very low speed) can help to characterize the emission variance of a normally behaving vehicle and, by extension, an abnormally behaving vehicle. In more practical terms, such as during stop-and-inspect roadside enforcement, this consideration can lower the chance of false positives—vehicles that are flagged as high-emitters but are in fact normally behaving.

To go beyond the attempt to identify individual high-emitting trucks from the 2021 report, we further refine the method to identify individual high-emitters using emission measurements from vehicles measured repeatedly and to define a threshold for identifying high-emitting trucks in future roadside enforcement.

SAMPLE SELECTION

For this analysis, we examined all valid emission measurements from trucks collected during the 2021 and 2022 emission testing campaigns. Since the sample contained emissions data from trucks of various sizes measured in a range of driving conditions, we first assessed the correlation between the main parameters of driving conditions and NO_x emissions to filter out emissions measurements with the possible influence of extreme VSP, ambient temperature, and cold start.

VSP showed no significant correlation with NO_x emissions ($p = 0.9$). For better comparability with regulatory limits, however, we only utilized measurements with VSP values between 3 kW/t and 12 kW/t, a range used in laboratory testing.[30] Ambient temperature, meanwhile, showed a significant correlation with NO_x emissions ($p < 0.001$). However, as the ambient temperature range (2–25 °C) was well within the range of Scotland's usual temperatures, all data points were included.[31] Mean NO_x emissions of trucks measured in ambient temperatures lower than 5 °C were similar to those in other ambient temperature bins, so the impact of cold engines in low temperatures was ruled out. NO_x emissions from different vehicle categories of trucks, namely N2 and N3, defined by gross vehicle weight, showed the same emissions trends, in line with the results from a previous study, which found that there is little influence of weight on NO_x emissions from Euro VI heavy-duty vehicles.[32] The variance of NO_x emissions by different categories for Euro VI-D trucks was also minor.

We further examined the distribution of fuel-specific NO_x emissions by emission standard to determine the applicability of a high-emitter threshold. Figure 23 shows the cumulative distribution of fuel-specific NO_x emissions, from the lowest to the highest by campaign. It demonstrates that there is a large variance in NO_x emission performance of Euro V trucks across campaigns, suggesting that there may not be a one-size-fits-all threshold for Euro V trucks. Similarly, findings from the 2021 study using one threshold suggested that it is difficult to distinguish whether Euro V trucks flagged as high-emitters were normally behaving vehicles experiencing high emission events or had tampered or defective emission control system.[33]

Euro VI and VI-D trucks, however, show a smaller variance in NO_x emissions across sites and campaigns, making them more suitable subjects for the high-emitter threshold analysis. This also means that there is a larger difference in emissions between normally behaving and defective or tampered vehicles. A previous study showed that tampered or defective Euro VI trucks tend to emit as much as 15 times more than regular Euro VI trucks.[34] Past analysis of Euro VI-D trucks is more limited, as they were introduced to the market more recently.

29 "Assessment of Real-World Vehicle Emissions in Scotland in 2021: Emissions Testing Campaigns in Edinburgh and Glasgow."

30 Minghao Qiu and Jens Borken-Kleefeld, 'Using Snapshot Measurements to Identify High-Emitting Vehicles', *Environmental Research Letters* 17, no. 4 (March 2022): 044045, https://doi.org/10.1088/1748-9326/ac5c9e.

31 "Met Office: A Review of the UK's Climate in 2022," *Carbon Brief*, 11 January 2023, https://www.carbonbrief.org/met-office-a-review-of-the-uks-climate-in-2022/.

32 Sangchul Ko et al., 'NOx Emissions from Euro 5 and Euro 6 Heavy-Duty Diesel Vehicles under Real Driving Conditions', *Energies* 13, no. 1 (January 2020): 218, https://doi.org/10.3390/en13010218.

33 "Assessment of Real-World Vehicle Emissions in Scotland in 2021: Emissions Testing Campaigns in Edinburgh and Glasgow."

34 "Analysis of the 2019 Flemish Remote Sensing Campaign."

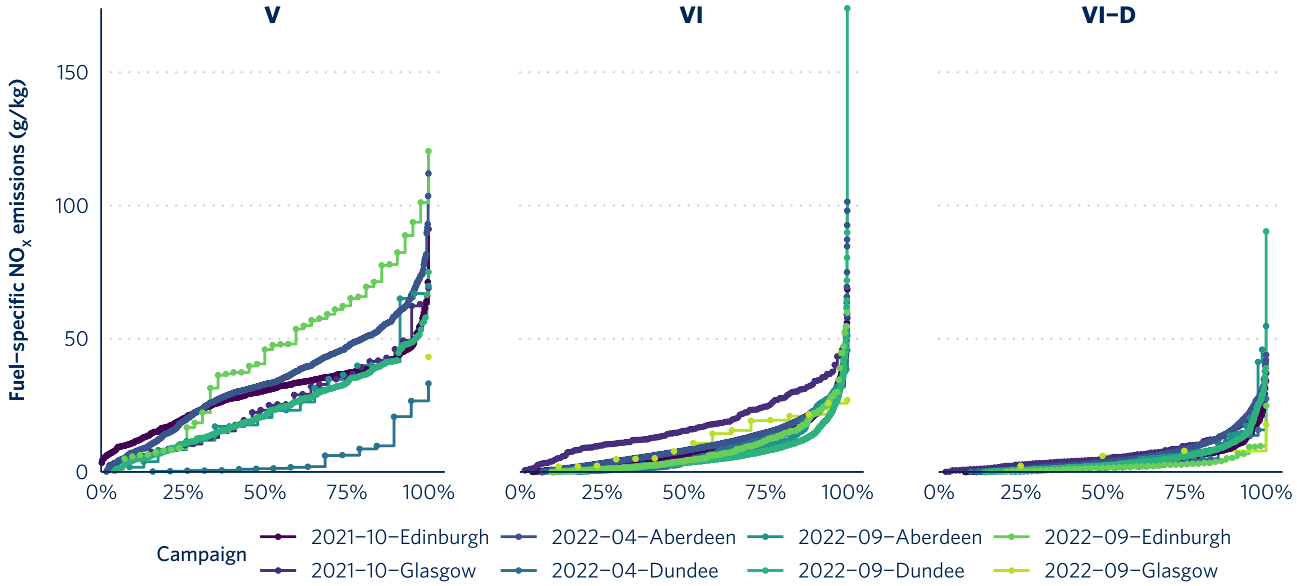

Figure 23. Fuel-specific NO_x emissions as a function of the cumulative share of the Scottish truck measurements by emission standard. Campaigns include the two remote sensing deployments in all four cities in October 2021, April 2022, and September 2022.

Therefore, this study focused on Euro VI and Euro VI-D trucks. The resulting sample consisted of 10,963 valid NO_x emission measurements from 4,715 Euro VI trucks and 3,639 valid measurements from 1,388 Euro VI-D trucks.

IDENTIFICATION OF HIGH EMITTERS USING REPEAT MEASUREMENTS

To find a threshold that could be used in real-world enforcement settings, high-emitting vehicles from the sample must first be identified. Here, we define high-emitting vehicles as those with suspected tampered or malfunctioning emission control systems. In the absence of accompanying roadside inspection to verify if the vehicle's emission control system is tampered with or malfunctioning, however, it is difficult to confidently identify high emitters. Factoring in the possibility of a few high-emission events from a normally behaving vehicle, we focus on a sample of vehicles whose NO_x emissions were measured five times or more, which included nearly 500 Euro VI and 200 Euro VI-D trucks (see Table 4).

Table 4. Number of valid emission measurements and unique Euro VI and Euro VI-D trucks that were measured five or more times in the sample.

Emission standard	Number of valid NOx emission measurements	Number of unique trucks
VI	4,683	497
VI-D	1,797	187

Multiple measurements collected from the same vehicles on different occasions, such as data collected at different testing sites or under various driving conditions, can depict emission behaviors of the measured vehicles better than single measurements. Repeated high-emission measurements from the same vehicle can indicate a malfunctioning or tampered emission control system.

To minimize false positives (normally behaving vehicles measured during high emission events), we set a conservative cut-point for tagging high-emitters of 3.68g/kWh, 8 times the type-approval emission limit of 0.46 g/kWh. For comparison with the cut-point, fuel-specific NO_x emission values (g/kg) given by the EDAR systems were converted to energy-specific NO_x emissions (g/kWh).[35] The type-approval limit was the same for Euro VI and Euro VI-D, and despite the tightened on-board diagnostics threshold limits to further reduce real-world emissions throughout different stages of Euro VI, the NO_x emission trends of Euro VI and Euro VI-D trucks were similar (see Figure 24). In particular, the emission peaks from measurements of Euro VI and Euro VI-D trucks measured five times or more were centered around nearly identical NO_x emission values, suggesting similar emissions performance for vehicles with properly functioning emission control systems across the two standards. This further suggests that with a sufficiently high cut-point, both Euro VI and Euro VI-D high-emitters

35 Bakhshmand, Mulholland, Tietge, Felipe Rodríguez, "Remote Sensing of Heavy-Duty Vehicle Emissions in Europe."

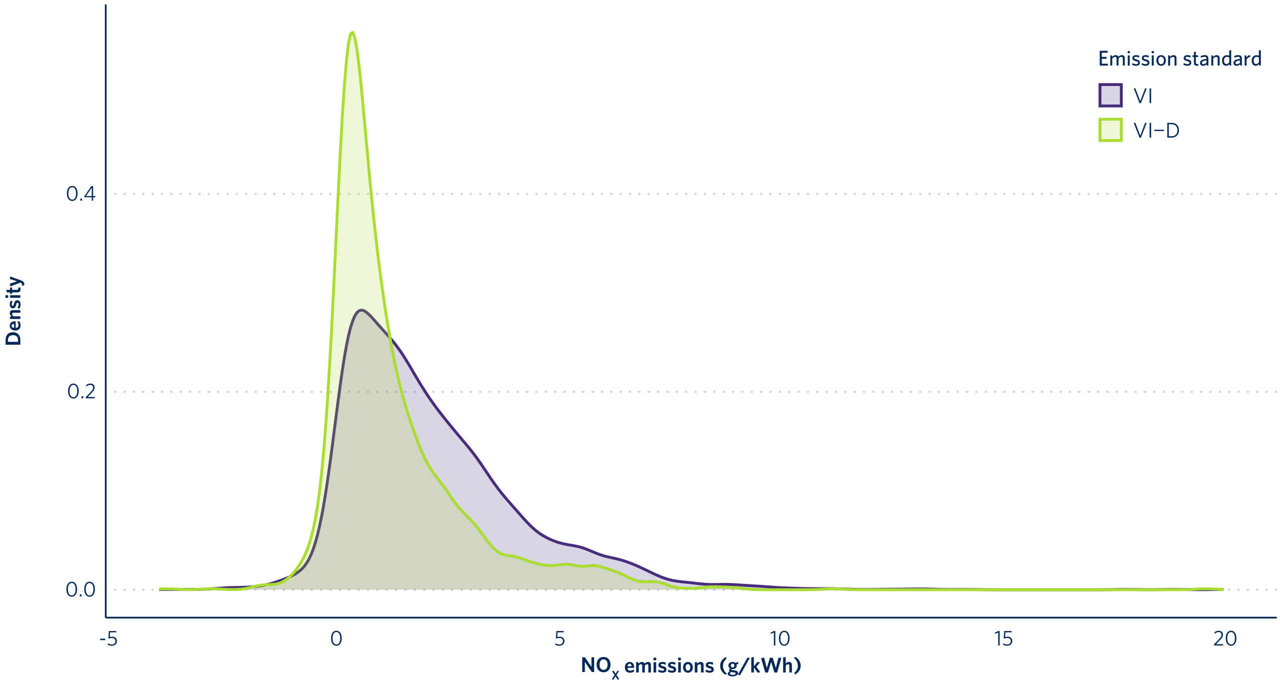

Figure 24. Distribution of energy-specific NO_x emissions by emission standard for the measured Euro VI and Euro VI-D trucks in Scotland. Areas below lines cover 100% of respective emission standard measurements from the vehicles measured five times or more.

could be detected. Euro VI and VI-D trucks were thus grouped together for this analysis.

A total of 58 trucks, consisting of 51 Euro VI and 7 Euro VI-D vehicles, were tagged as high-emitters, with mean NO_x emissions above the cut-point of 3.68 g/kWh, making up 8.5% of the sample. This rate is in line with the results from an enforcement campaign conducted by the Driver and Vehicle Standards Agency of the UK Department for Transport in 2017, which reported that 8.2% of lorries were fitted with tampering devices.[36] Figure 25 summarizes the number of tagged high-emitters and others in our sample.

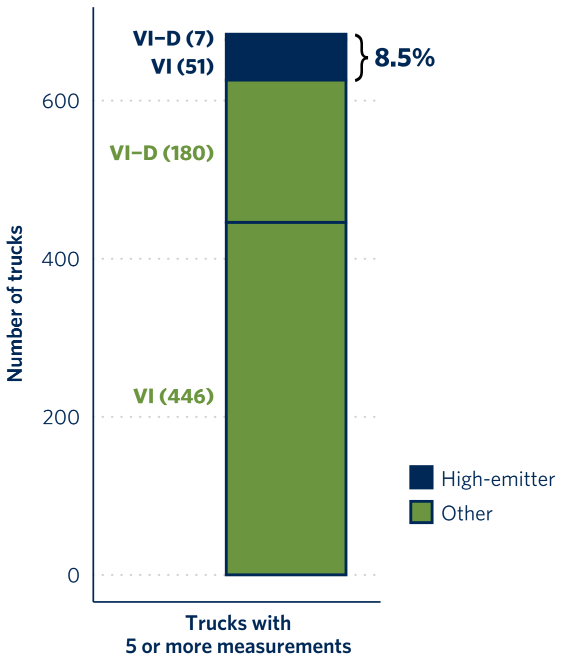

Figure 25. Number of vehicles tagged as high-emitters by emission standard.

36 Caleb Braun, Huzeifa Badshah, Vahid Hosseini, Lingzhi Jin, Josh Miller, and Felipe Rodríguez, "Heavy-Duty Emissions Control Tampering in Canada," (Washington, DC: ICCT, 2022), https://theicct.org/publication/hdv-emissions-tampering-can-mar22/.
The rate of trucks that are tampered with varies by country. In Belgium, the rate was at 9.5% for Euro V and 4.8% for Euro VI heavy goods vehicles (Source: "Analysis of the 2019 Flemish remote sensing campaign").

DEFINING A HIGH-EMITTER THRESHOLD FOR INDIVIDUAL MEASUREMENTS

A threshold for flagging high-emitter candidates for investigation is defined in an analysis of a Flemish remote sensing campaign by Hooftman et al. as two standard deviations above the median from the NO_x emission distribution of clean vehicles.[37] Theoretically, this would correspond to the emission level that marks the top 2.5% sampled emissions from trucks that are normally behaving in terms of emissions, assuming a normal distribution.

As vehicle emissions do not follow a normal distribution, an additional step was taken to transform the sampled NO_x emissions from tagged clean vehicles into a more meaningful standard deviation. Using the estimated parameter (lambda, λ) of 0.438, a Yeo-Johnson transformation was performed on the NO_x emission data from tagged clean vehicles. The median and the standard deviation of the transformed distribution were found to be 0.90 and 0.94, respectively. Using the equation below, a standardized threshold of 2.78 was calculated and then reversed to get the actual value of 5.2 g/kWh. This is translated to approximately 24 g/kg. This threshold was significantly higher than the values used in previous roadside enforcement programs.[38] However, it is in line with the level of NO_x emissions of 5-6 g/kWh exhibited by vehicles with SCR emulators, a tampering device that imitates proper functioning of the selective catalytic reduction system while the system is inactive.[39]

High-emitter detection limit:

$$X_{Threshold} = \mu + 2\sigma$$

μ = *median of clean vehicle emission distribution*

σ = standard of deviation, or spread, of clean vehicle emission *distribution*

Figure 26 compares the identified threshold of 5.2 g/kWh against the distribution of NO_x emissions from the sampled vehicles that are tagged as high-emitters and others. As the emission distribution is skewed to the right for cleaner vehicles, the threshold marks the top 3.8% of

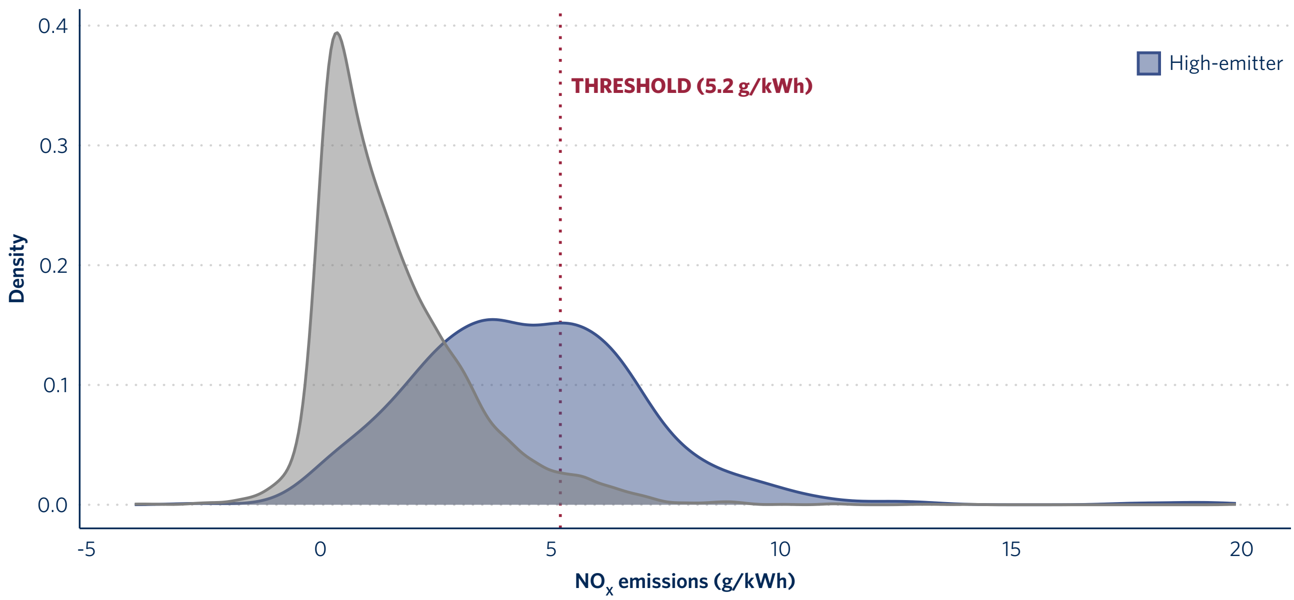

Figure 26. Distribution of NOx emissions from vehicles tagged as high-emitters and others and the newly identified measurement threshold 5.2 g/kWh. Areas below lines cover 100% of respective emission standard measurements from the vehicles measured five times or more.

37 "Analysis of the 2019 Flemish Remote Sensing Campaign."

38 Ole Hertel, Christian Rud Ingvardsen, Thomas Ellermann, and Jacob Klenø Nøjgaard, "Control of SCR-Systems Using Roadside Remote Sensing," (Danish Centre for Environment and Energy, 2020). https://dce2.au.dk/pub/SR387.pdf.
"Analysis of the 2019 Flemish Remote Sensing Campaign."

39 Barouch Giechaskiel, Fabrizio Forloni, Massimo Carriero, Gianmarco Baldini, Paolo Castellano, Robin Vermeulen, Dimitrios Kontses, Pavlos Fragkiadoulakis, Zissis Samaras, and Georgios Fontaras, "Effect of Tampering on On-Road and Off-Road Diesel Vehicle Emissions," *Sustainability* 14, no. 10 (January 2022): 6065, https://doi.org/10.3390/su14106065.

the emissions measurements, meaning that the threshold would result in a false positive rate of 3.8% when applied to single instantaneous measurements.

All high emitters from the sample had at least one measurement that was above the threshold. The threshold of 5.2 g/kWh, however, corresponds to the 62nd percentile from the distribution of NO_x emissions from the high-emitter sample, suggesting that the threshold would result in a false negative rate of 62% for single measurements. In other words, the threshold would be able to capture 38% of the high-emitter with one instantaneous measurement if high-emitters behave according to the given distribution.

IMPLICATIONS FOR REAL-WORLD ENFORCEMENT

High-emitter detection thresholds have important implications for real-world enforcement of vehicles with tampered or defective emission control systems. Remote sensing systems have previously been used to flag vehicles with unexpectedly high emissions but with contested thresholds.[40] Here, we suggest a conservative threshold for flagging high emitters which maximizes the likelihood of captured vehicles having tampered or malfunctioning emission control systems based on the NO_x emission behavior seen for Euro VI Scottish trucks.

The threshold, when applied to the entire data set of valid instantaneous NO_x measurements from all Euro VI and Euro VI-D trucks measured at least once, would flag around 6% of all measurements, out of which 5.1% are Euro VI and 0.7% are Euro VI-D trucks. During roadside inspection campaigns with remote sensing systems, the fuel-specific emission threshold of 24 g/kg could be used to flag highly emitting trucks for investigation. While this threshold would fail to capture around 62% of measurements from high-emitters, it would be able to ensure a low number of clean vehicles were identified as high-emitters.

The rate of high-emitter detection with the identified threshold, however, can be significantly improved with multiple measurements. The analysis results show that the chance of detecting a high emitter increases to 91% with at least five emissions measurements from the vehicle, as there is a high chance that one of the measurements would be above the threshold. With such a high rate of successful detection, determining whether a vehicle is a high-emitter or not based on multiple measurements can prevent false detections and thus avoid making unwarranted requests for inspection or emissions testing.

Deployment of remote sensing instruments capable of accessing vehicle information from the registry database in real-time, like the EDAR system, over a long period of time could effectively flag possible high-emitter candidates for inspection. An application of on-road remote sensing for inspection has been in use in Hong Kong to control excess CO and HC emissions from petrol and LPG vehicles, with conservative cut-points used to achieve zero false negatives with single measurements.[41] An enforcement program utilizing multiple on-road remote sensing measurements and the proposed threshold could be an option for Scotland to pioneer automatic surveillance of excess emissions from diesel trucks.

POLICY RECOMMENDATIONS

Vehicle emission data collected from Aberdeen, Dundee, Edinburgh, and Glasgow in 2022 provided insight into the real-world NO_x and PM emissions of passenger car, bus, and truck fleets. Overall, the results highlight that certain vehicle groups contribute disproportionately to air pollution, presenting opportunities for more effective policy action. By identifying and effectively targeting disproportionately high-emitting vehicle groups, Scottish cities can achieve outsized air quality benefits.

Taxis and private hires were responsible for a high share of pollutant emissions. Their emissions are more elevated compared to private cars due to high mileages that contribute to the deterioration of emission control systems. Among private cars, diesel vehicles—more specifically, pre-Euro 6d-TEMP vehicles, which are not subject to on-road emission testing—were the highest-emitting portion. Among trucks, malfunctioning of emission control systems,

40 "Analysis of the 2019 Flemish Remote Sensing Campaign"; Yuhan Huang, Bruce Organ, John L. Zhou, Nic C. Surawski, Yat-shing Yam, and Edward F.C. Chan, "Characterisation of Diesel Vehicle Emissions and Determination of Remote Sensing Cutpoints for Diesel High-Emitters," Environmental Pollution 252 (September 2019): 31–38, https://doi.org/10.1016/j.envpol.2019.04.130; Thomas Ellermann, Ole Hertel, Morten Winther, Jesper Risager Nielsen, and Christian Rud Ingvardsen, "Measurements of Cheating with SCR Catalysts on Heavy Duty Vehicles," (Danish Environmental Protection Agency, June 2018), https://www2.mst.dk/Udgiv/publications/2018/06/978-87-93710-42-9.pdf.

41 Yuhan Huang, Casey K. C. Lee, Yat-Shing Yam, Wai-Chuen Mok, John L. Zhou, Yuan Zhuang, Nic C. Surawski , Bruce Organ, and Edward F. C. Chan, "Rapid Detection of High-Emitting Vehicles by on-Road Remote Sensing Technology Improves Urban Air Quality," *Science Advances*, February 2022, https://doi.org/10.1126/sciadv.abl7575.

whether it be from tampering or poor maintenance, leads to abnormally high real-world emissions.

Below we summarize recommendations on enhancing existing and new policy tools that could be leveraged to effectively curb emissions from high-emitting vehicle groups.

ENHANCING LOW EMISSION ZONE POLICIES

Scotland has introduced a low emission zone in Glasgow, with three others slated for implementation in Edinburgh, Aberdeen, and Dundee by mid-2024. These zones cover the city center and charge non-compliant vehicles a fine, which increases with subsequent breaches of the LEZ rules. Scottish policy on low emission zones currently states that cars must be certified to Euro 4 petrol or Euro 6 diesel and buses and trucks must be Euro IV petrol or Euro VI diesel or higher. The results of our analysis show that vehicles that meet these standards are, on average, much cleaner than older vehicles c ertified to earlier emission standards.

However, it is also worth noting that in several cases the range of emissions produced from these vehicles can be large, either because emission control technology has deteriorated or because the technology is not designed to function properly under the wide range of driving conditions seen in the real world. This can be seen in the NO_x emission trend of passenger cars registered between 2000 and 2022 (Figure 8), in which mean NO_x emissions are well above the median, suggesting a positively skewed distribution where a group of high emitters are driving up average emissions. The difference between the mean and median drops over time and levels off after Euro 6d-TEMP diesel cars. This suggests that strengthening the LEZ restrictions for diesel cars certified to pre-Euro 6d-TEMP standards would significantly cut the number of high-emitting vehicles operating within city centers, thus helping to improve local air quality. However, given the risk that even these more advanced emission standard vehicles will deteriorate over time, it may also be necessary to introduce an age or maximum mileage limit alongside the current standards to ensure emission benefits do not slip in the future.

Euro VI appears to be a reasonable minimum for buses and trucks entering a low emission zone, as both mean and median emissions appear consistently low after this point. However, as with cars, there is a risk of increased emissions as emission control equipment deteriorates, suggesting Scottish policymakers should consider adopting an age or mileage cap alongside the Euro standard.

INCENTIVIZING CLEANER TAXI AND PRIVATE HIRE VEHICLES

Taxis and private hire vehicles could be a key focus area for policy because they drive significant distances within cities, their high mileage leads to emission control system deterioration, and they are much more closely regulated, providing an opportunity for policymakers to control emissions in a way they often cannot for general passenger cars.

Policymakers could consider implementing policies that transition these vehicles to battery electric to reduce their contribution to air pollution from the on-road fleet. To support drivers in such a transition, cities could provide information to operators and fleet owners on the cost benefits of running a BEV and support drivers to aggregate their demand for BEV to access better leasing deals. To address charging needs of BEV taxis, cities could partner with charge point operators to ensure on street charging is available near drivers' homes and possibly provide land to support rapid charging hubs within city centers with amenities for drivers to use during breaks.

Toward this long-term goal, policymakers could also take intermediate steps to prevent drivers from choosing known high-emitting models by creating an approved list of makes and models of vehicles for the driver to choose from. This could be improved by only allowing drivers to choose full petrol hybrid models, petrol plug-in hybrid models, or battery electric models. Full petrol hybrid models such as the Toyota Prius have been around long enough to be a cheap option on the second-hand market. That these vehicles are very efficient in city driving conditions compared to diesel engines, and that petrol is currently several pence per liter cheaper than diesel, mean this switch would not only improve emissions in the city but would also be better financially for drivers.

IDENTIFYING HIGH-EMITTING TRUCKS FOR REPAIR

This work builds on a previous TRUE study in Scotland to develop an effective approach to using remote sensing to identify high-emitting trucks. The analysis shows that remote sensing could be complementary to an enforcement campaign and help to identify potentially faulty vehicles or vehicles fitted with defeat devices for roadside inspection. Unlike broader roadside checks, where all or a large share of vehicles need to be inspected, this approach would enable the interdiction of a very small number of vehicles with a high chance of being a high-emitting vehicle, significantly reducing disruption and required manpower. Alternatively, an enforcement program that utilizes automated remote sensing technology linked to the vehicle registration database could be considered to flag possible high-emitter candidates for inspection.

THE REAL URBAN EMISSIONS INITIATIVE

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