Real-world vehicle emissions in four major Scottish cities

A comprehensive analysis of 2021–2023 remote sensing data

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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 uses 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

Emissions from on-road transport are one of the main sources of air pollution in Scottish urban areas. To evaluate real-world emissions from on-road transport, between 2021 and 2023, Transport Scotland deployed remote sensing technology to conduct emissions testing campaigns in four major cities: Edinburgh, Glasgow, Aberdeen, and Dundee. The third and final remote sensing campaign took place from June to July 2023 and added around 560,000 measurements to the samples collected in 2021 and 2022. The resulting database contains over 1.4 million emissions measurements of nitrogen oxides (NO_x), particulate matter (PM), carbon monoxide (CO), and hydrocarbons (HC) from Scottish vehicles of various types, including light- and heavy-duty vehicles.

Emissions data from vehicles operating in real-world conditions allow for a more accurate assessment of the on-road fleet and its emissions and can be used to develop evidence-based policies to reduce emissions from the transportation sector. This study, by The Real Urban Emissions (TRUE) Initiative, evaluates the real-world NO_x and PM emission performance of in-use vehicles in Scottish urban areas and suggests measures that could address pollution from high-emitting vehicle groups. While previous TRUE studies have assessed real-world emissions from Scottish vehicles in a particular year, this study extends the analysis to evaluate emissions trends measured over three testing campaigns.

This analysis supports the following conclusions and policy considerations:

Excess NO_x emissions remain a problem for older Scottish vehicles, particularly taxis and private hires, and there are no policy measures in place to address elevated NO_x emissions from these vehicles. Our analysis shows that Scottish passenger cars have higher real-world NO_x emissions than the average of all European data within the TRUE Initiative dataset. In particular, diesel vehicles in Scotland registered before 2020 showed around 30% higher emissions than counterparts elsewhere in the region. Real-world NO_x emissions from diesel taxis and private hires that drive longer distances are up to 84% higher than those from private cars in Scotland due to the deterioration of emission control systems. Updating the UK's annual vehicle testing to include NO_x alongside other pollutants in diesel and petrol vehicles could effectively flag and address high-emitting vehicles with deteriorated emission control systems.

Policy measures to accelerate fleet renewal could address excess NO_x emissions in high-mileage vehicle groups prone to emission control system deterioration or malfunction. Our case study examining changes in emissions from the same fleet over time demonstrates that naturally occurring fleet renewal results in a 7% reduction in average NO_x emissions from passenger cars annually, assuming no additional policy measures. The reduction in emissions is significantly less for taxis and private hires, which are more prone to emission degradation. Accelerating fleet renewal through such policies as scrappage, feebate, and rebate programs can be effective for generating more substantial emission reductions. At the same time, exempting battery electric vehicles from age and mileage limits on taxis and private hires and providing easier and more affordable charging options can help encourage the adoption of zero-emission vehicles.

Remote sensing can be used to identify trucks with unusually high emissions for further testing for defective or manipulated emission control systems. Using the methodology developed in a previous TRUE study and updated data from Scotland, we identified 26 g/kg as a NO_x emission threshold for flagging high-emitting Euro VI and Euro VI-D vehicles. This threshold minimizes the likelihood of falsely identifying normally behaving trucks as high-emitters and is optimal for roadside inspection settings. In longer-term remote sensing monitoring settings, vehicles that exhibit emissions that repeatedly exceed the threshold can be flagged for inspection and repair.

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INTRODUCTION

Air pollution from transportation is one of the biggest and most persistent health risks in urban areas in Scotland.[1] Long-term exposure to nitrogen dioxide (NO_2) and particulate matter (PM), primarily emitted by vehicles powered by fossil fuels, poses cardiovascular, respiratory, and cancer mortality hazards to the Scottish population.[2] As part of efforts to reduce the environmental and health impacts of the transport sector, between 2021 and 2023, Transport Scotland commissioned the Air Remote Sensing Project, in partnership with the ICCT, Hager Environmental & Atmospheric Technologies (HEAT), and Environmental Resources Management (ERM), to gather and measure real-world emissions data from the Scottish fleet.

This study, by The Real Urban Emissions (TRUE) Initiative, summarizes the results of remote sensing campaigns in four major cities in Scotland: Edinburgh (the capital), Glasgow, Aberdeen, and Dundee. It is the third and final study in a TRUE Initiative series on Scotland; the first assessed vehicle emissions collected in Edinburgh and Glasgow in 2021, while the second examined emissions in all four cities in 2022.[3] In this report, we update the analysis done in previous studies with additional emissions data from remote sensing testing in 2023 and provide a more comprehensive evaluation of real-world emissions from passenger cars and trucks based on the full dataset of 1.4 million emissions measurements collected from 2021 to 2023. Specifically, we use emissions data from the 2023 remote sensing testing to provide updates to the following analyses:

- Real-world performance of diesel Euro 6d-TEMP and Euro 6d vehicle families prevalent on the Scottish roads; and
- Determination of NO_x thresholds using repeat vehicle measurements for the identification of trucks with likely defective or tampered emission control systems.

Additionally, we analyse all emissions data from the remote sensing campaigns conducted in 2021, 2022, and 2023 with the following objectives:

- To define emission factors of Scottish passenger cars, including taxis and private hires, and heavy-duty trucks;
- To examine variations in the real-world performance of passenger cars and trucks across the cities of Edinburgh, Glasgow, Aberdeen, and Dundee; and
- To evaluate changes in vehicle emissions measured at the same sites over time.

2023 SAMPLE OVERVIEW

Emissions Detection and Reporting (EDAR) systems, a remote sensing technology developed by HEAT, were deployed from June 29 to July 31, 2023, in Edinburgh, Glasgow, Aberdeen, and Dundee and collected 558,956 measurements from 260,657 unique vehicles.[4] Table 1 and Figure 1 show the location, road slope, and number of raw measurements from the selected site in each city. Some sites where previous testing took place were reselected for the 2023 testing campaign: Glasgow Road in Edinburgh (a testing site in October–November 2021), Wellington Road in Aberdeen (a testing site in April–May 2022), and A90 in Dundee (a testing site in September–October 2022).

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

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

3 Kaylin Lee, Yoann Bernard, and Jonathan Cooper, *Assessment of Real-World Vehicle Emissions in Scotland in 2021: Emissions Testing Campaigns in Edinburgh and Glasgow* (TRUE Initiative, June 13, 2023), https://www.trueinitiative.org/publications/reports/assessment-of-real-world-vehicle-emissions-in-scotland-in-2021; Kaylin Lee, Yoann Bernard, and Richard Riley, *Assessment of Real-World Vehicle Emissions from Four Scottish Cities in 2022* (TRUE Initiative, March 20, 2024), https://www.trueinitiative.org/publications/reports/assessment-of-real-world-vehicle-emissions-from-four-scottish-cities-in-2022.

4 A more detailed description of how EDAR systems measure vehicle emissions can be found in Lee, Bernard, and Cooper, *Assessment of Real-World Vehicle Emissions in Scotland in 2021.*

Table 1. Testing sites for the 2023 measurement campaign and number of measurements collected

Site	Road (location)	Slope	Raw measurements
Edinburgh	Glasgow Road, A8 (western skirt of city)	1.6%	231,682
Glasgow	M74 (highway)	1.6%	55,080
Aberdeen	Wellington Road (near harbour)	3.0%	139,344
Dundee	A90, Forfar Road (highway)	4.0%	132,850

Figure 1. Location, slope, and number of raw measurements collected for each site.

The driving conditions of all measured vehicles at the time of measurement are summarised in Figure 2. The main parameters of driving behaviour and ambient conditions that influence emissions were normally distributed, with median values of 18.1 °C (for ambient temperature), 45.6 km/h (speed), 0.17 km/h/s (acceleration), and 7 kW/t (vehicle specific power [VSP], a proxy of instantaneous engine power demanded during vehicle operation). The 2023 testing took place during the summer, resulting in a higher mean ambient temperature than in the previous campaigns, conducted in winter (2021) and spring and fall (2022), which may have contributed to lower levels of emissions. Meanwhile, the median acceleration and VSP values were between those from the vehicles measured in 2021 (which were higher) and 2022 (lower). By taking measurements at various sites and different times of the year across the three campaigns, we captured a range of driving conditions representative of those of the typical Scottish vehicle.

As shown in Figure 3, the predominant vehicle class was passenger cars, making up 75% of all vehicle measurements. The remaining sample consisted of light commercial vehicles, trucks, and buses. The overall fleet composition closely resembled those observed during the 2021 and 2022 campaigns. Of the passenger cars measured, 56% were powered by petrol, 36% by diesel, 7% by hybrid engines, and 2% by electricity. A small portion (1.4%) of passenger car measurements were of taxis and private hires, which were predominantly powered by diesel (79%). Heavier duty vehicles, such as light commercial vehicles, trucks, and buses, were mainly powered by diesel (99%). Of all vehicles measured, 6% were missing from the Scottish Driver and Vehicle Licensing Agency database, likely because they were registered elsewhere.

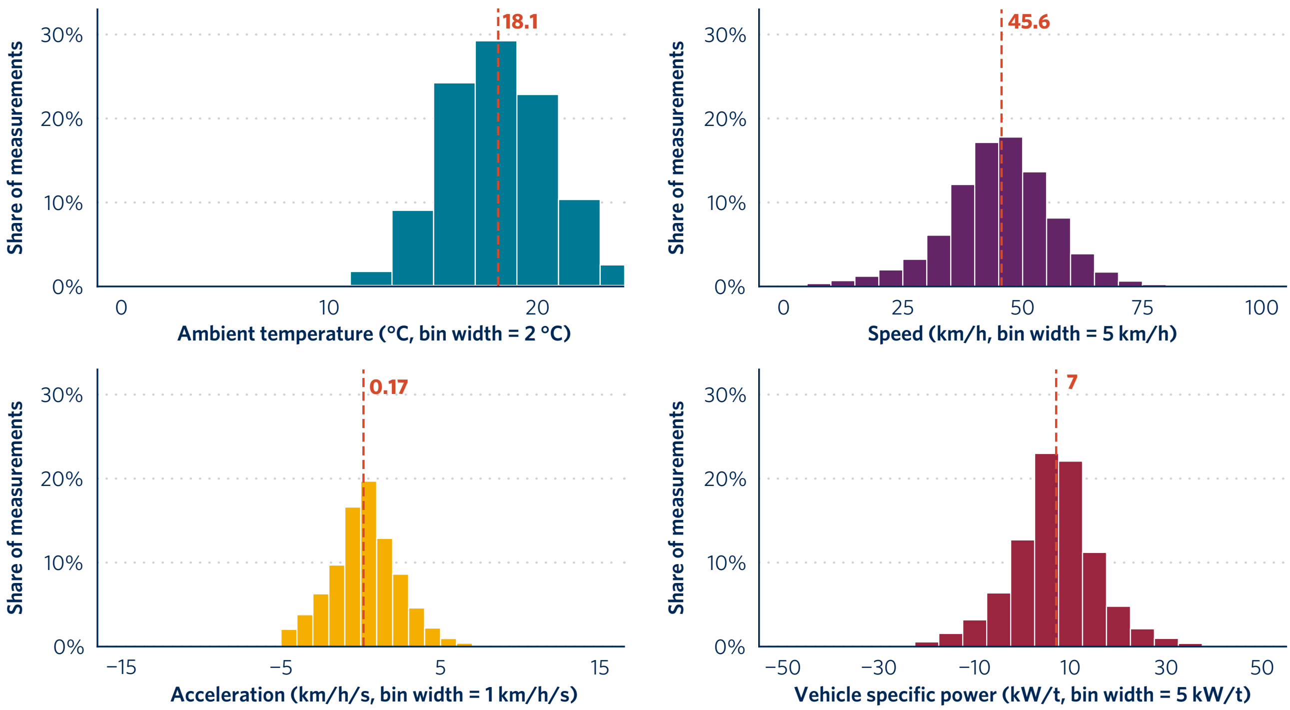

Figure 2. Distribution of driving and ambient conditions of sampled vehicles. Red dotted lines represent median values.

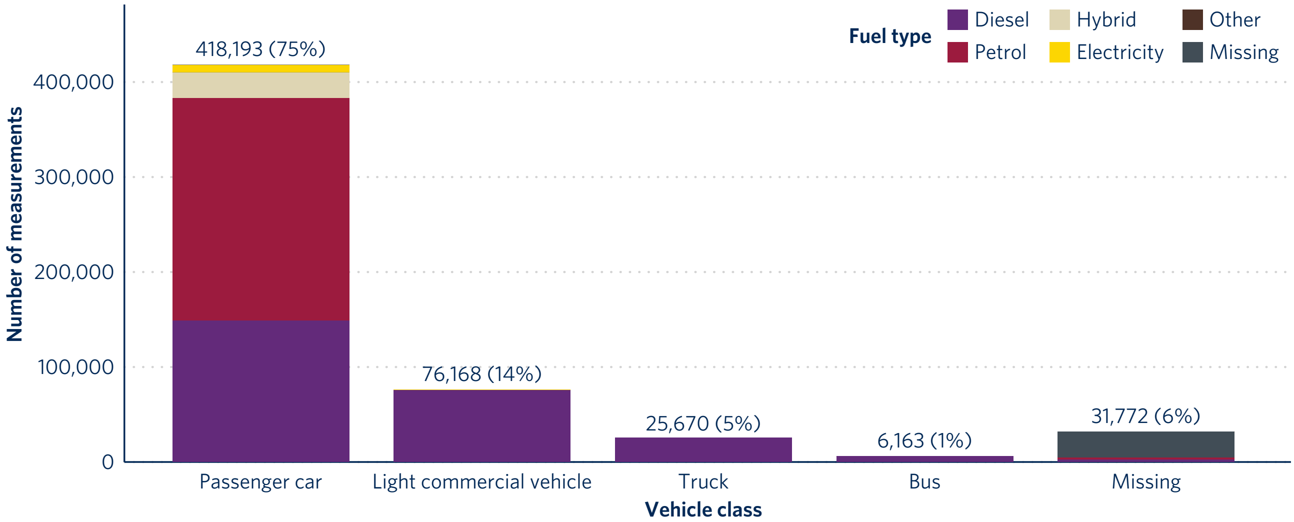

Figure 3. Fleet composition of all sites measured in 2023. Only vehicle classes that account for over 1% of all measurements are presented.

REAL-WORLD VEHICLE EMISSION FACTORS

We next define real-world emission factors of vehicles in Scottish urban areas using all data collected during the three remote sensing campaigns carried out between 2021 and 2023. For this analysis, a total of 1,061,918 passenger car measurements—including 28,578 taxi and private hire passes—and 51,117 truck measurements were used to define nitrogen oxide (NO_x) and PM emission factors. Where possible, we compare the emission factors of Scottish vehicles with those found in previous TRUE remote sensing campaigns in eight European cities: Flanders, Antwerp, and Brussels (Belgium); Paris (France); Milan (Italy); Krakow and Warsaw (Poland); and Prague (the Czech Republic).

PASSENGER CARS

We present the real-world emission factors of diesel and petrol private passenger cars, not including taxis and private hires, by registration year, in milligram of pollutant per kilometre travelled (mg/km), consistent with EU regulatory emission limits. Figure 4 compares the distance-specific NO_x emission factors of passenger cars in Scotland with those of passenger cars in other European cities in the TRUE dataset.

Scottish diesel vehicles registered before 2020 showed real-world NO_x emissions around 30% higher than those from other European cities. The lower temperatures at which Scottish cars were measured partially explain the gaps: Light-duty diesel vehicle NO_x emissions are strongly associated with ambient temperature, with low temperatures resulting in higher emissions.[5] Additionally, the Scottish remote sensing campaigns were conducted between 2021 and 2023, whereas the TRUE data were gathered between 2018 and 2022, meaning Scottish cars with earlier registration years are likely to have accumulated more mileage, leading to the deterioration of emission control systems and higher emissions. Scottish vehicles registered before 2020, which are likely certified to Euro 3 through Euro 6a–c standards, had real-world NO_x emissions 2–6 times the regulatory emission limits, as shown in Figure 5. This gap is less significant for cars registered after 2020, as newer cars are less prone to emission degradation. Similarly, Scottish petrol cars registered between 2000 and 2008 had real-world NO_x emissions around 20% higher than their counterparts from the TRUE dataset, but those registered after 2008 had emissions 20% lower, indicating possible emissions degradation of old vehicles.

5 Stuart K. Grange et al., "Strong Temperature Dependence for Light-Duty Diesel Vehicle NO_x Emissions," *Environmental Science & Technology* 53, no. 11 (2019): 6587–96, https://doi.org/10.1021/acs.est.9b01024.

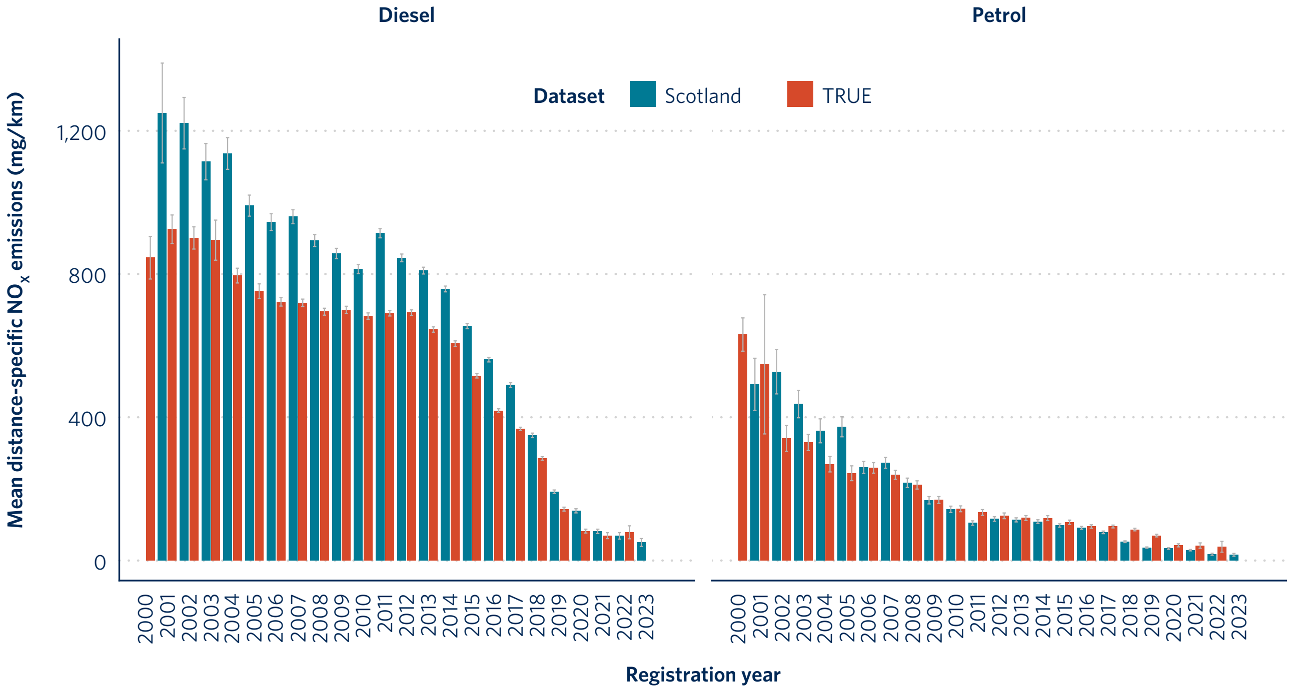

Figure 4. Mean distance-specific NO_x emissions from diesel and petrol passenger cars by registration year for Scotland and all TRUE remote sensing data. Whiskers represent the 95% confidence interval of the mean. Only measurements of 100 or more are presented.

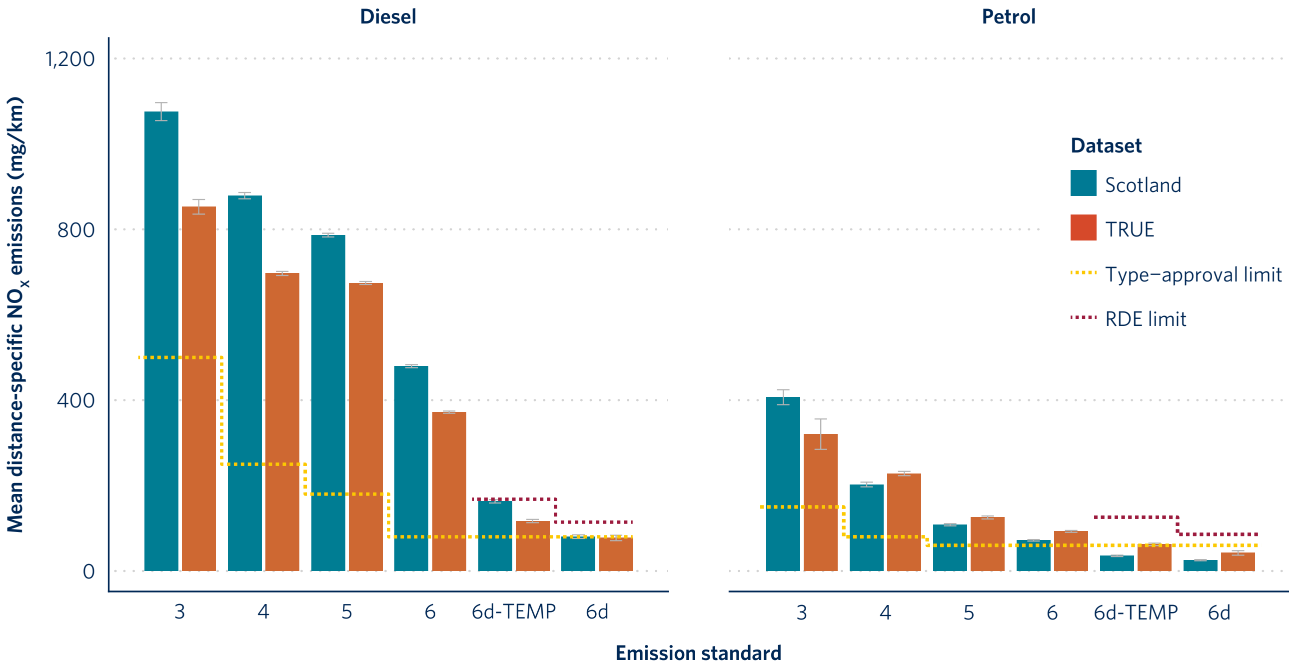

Figure 5. Mean distance-specific NO_x emissions (mg/km) from passenger cars by emission standard. Euro 6d-TEMP and Euro 6d are distinguished from Euro 6 a-c (labelled as Euro 6 in the figure), as on-road limits were introduced with these standards. Whiskers represent the 95% confidence interval of the mean. Yellow and red dotted lines represent type-approval and on-road (Real Driving Emissions, RDE) emission limits, respectively. Only emission standards with over 100 measurements are presented.

Despite the difference in absolute emission levels with the TRUE European dataset, real-world NO_x emissions of both diesel and petrol Scottish passenger cars show a downward trend over time, consistent with trends observed across the TRUE dataset. For instance, although notably higher than those of petrol counterparts, the real-world NO_x emissions of diesel cars have declined considerably over the years, with the most recent models certified to Euro 6d showing nearly 95% lower emissions than the oldest standard shown, Euro 3. A large reduction of almost 50% between cars registered in 2018 and 2019 can be attributed to the introduction of on-road Real Driving Emissions (RDE) testing with the Euro 6d-TEMP standard. As shown in Figure 5, Scottish diesel cars certified to Euro 6d-TEMP and above also showed real-world emissions below on-road regulatory limits. Real-world NO_x emissions from petrol cars have also tapered off over the years, reaching 16 mg/km in 2023. NO_x emissions from all Euro 6d-TEMP and Euro 6d petrol cars were significantly below their respective on-road limits, which are 25% lower than diesel limits.

PM emission factors of diesel and petrol private passenger cars are presented in Figure 6. Due to differences in the methods used to measure PM between the Scottish remote sensing campaign and other TRUE studies, PM emissions in Scotland were not directly comparable with the TRUE dataset.[6] Figure 6 shows that PM emissions largely stem from older diesel vehicles. Diesel cars registered before 2010 were emitting around 3–7 times higher PM emissions than their petrol counterparts. PM emissions from diesel cars show a rapid decrease over time, notably between 2010 and 2014, due to the introduction of diesel particulate filters (DPFs) required from the Euro 5 standard. As shown in Figure 7, diesel Euro 5 cars had PM emissions over 75% lower than Euro 4 cars. Thereafter, PM emissions from diesel cars stabilize at around 15 mg/km, a level similar to those of their petrol counterparts. Petrol cars show little variation in PM emissions over time.

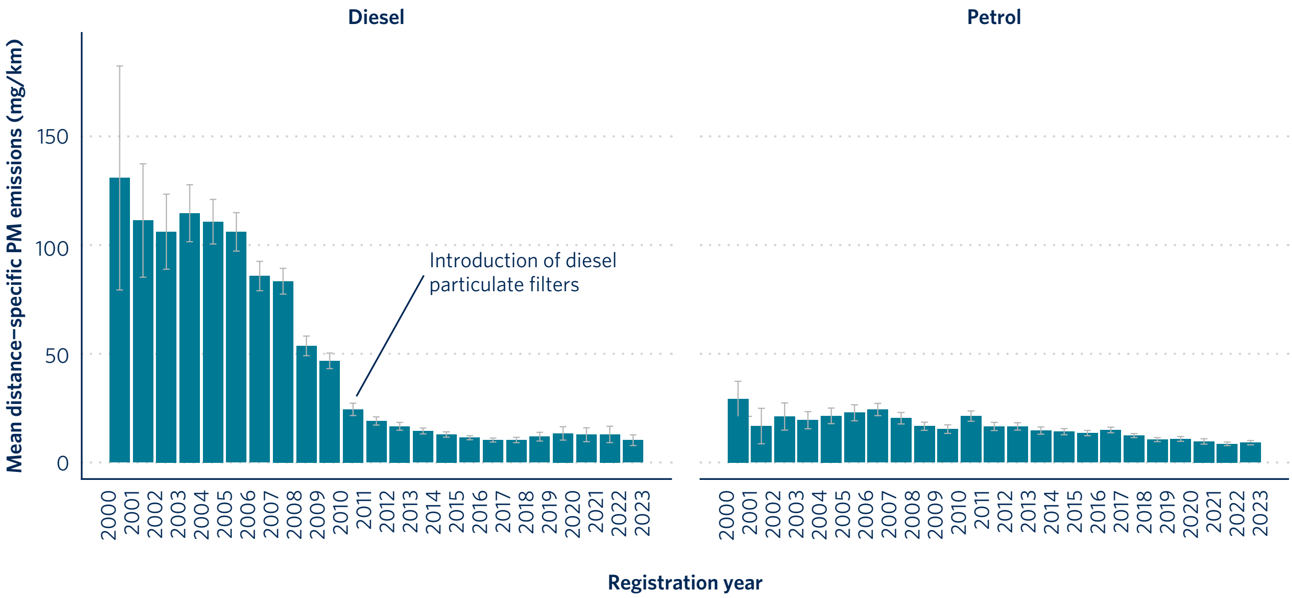

Figure 6. Mean distance-specific PM emissions (mg/km) from diesel and petrol passenger cars by registration year for Scotland. Whiskers represent the 95% confidence interval of the mean. Only measurements of 100 or more are presented.

6 Specifically, these differences relate to the incompatibility of methodologies used to measure PM emissions deployed by different remote sensing instruments and updates to the PM measurement method of the EDAR instruments applied in the Scotland campaigns.

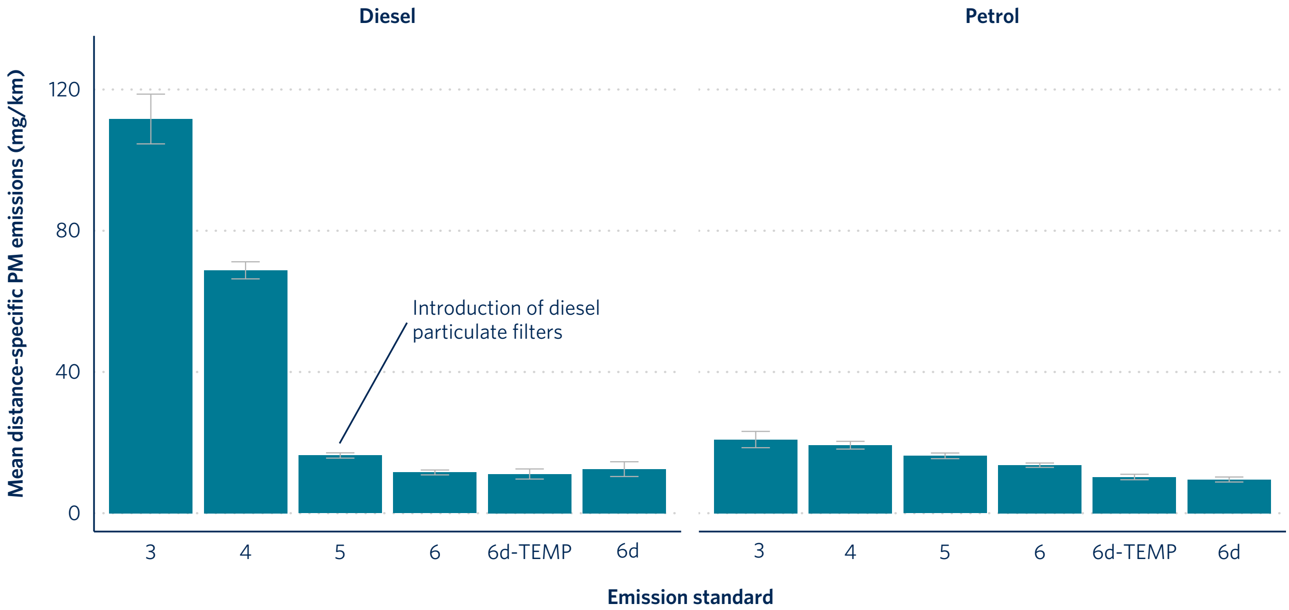

Figure 7. Mean distance-specific PM emissions (mg/km) from passenger cars by emission standard for Scotland. Euro 6 represents Euro 6 a-c. Whiskers represent the 95% confidence interval of the mean. Only emission standards with over 100 measurements are presented.

Passenger car NO_x emission factors are further broken down by city in Figure 8. Diesel cars of registration years up to 2019 measured in Dundee and Glasgow showed emissions notably higher than those measured in Aberdeen and Edinburgh. This is likely because a large share of the Dundee and Glasgow measurements were taken in conditions conducive to elevated emissions: the Dundee testing site in 2022 and 2023 and the Glasgow testing site in 2023 were on motorways characterized by higher speeds, which require high power demand (VSP) and are associated with high NO_x emissions,[7] while the Glasgow testing sites in 2021 and 2022 were located in the city centre and marked by low-speed, stop-and-start traffic, which can lead to decreased efficiency of the emission control system and increased NO_x emissions. The sites in Aberdeen and Edinburgh, however, represented more optimal conditions for controlling NO_x emissions. Petrol cars depicted a similar trend, with the Dundee and Glasgow cars showing higher NO_x emissions across almost all registration years. However, the magnitude of the variations for petrol vehicles was 62% smaller than that for diesel vehicles (standard deviation). City-level PM emission factors are not presented due to uncertainties introduced by an insufficient sample size.

The emission variations across different cities highlight operating conditions as important factors influencing vehicle emissions and imply potential benefits of controlling them to reduce emissions. There is a growing body of evidence showing that NO_x emissions from light-duty vehicles are highest in areas that require frequent stop-and-start, such as motorway entrances and exits, traffic signals, and intersections.[8] Complementary to phasing out the most polluting vehicles, policy measures to minimize these high emission-inducing conditions, like traffic control and speed limits, could address some excess emissions. Moreover, by identifying these urban emission hotspots and designating car-free zones, cities could take steps to reduce the exposure of populations that are particularly vulnerable to air pollution and alleviate public health risks.

7 Martin Weiss et al., *Analyzing On-Road Emissions of Light-Duty Vehicles with Portable Emission Measurement Systems (PEMS)* (Joint Research Centre Technical Report JRC62639, 2011), https://publications.jrc.ec.europa.eu/repository/handle/JRC62639.

8 Ahmad Khalfan, Gordon Andrews, and Hu Li, Real World Driving: Emissions in Highly Congested Traffic (SAE Technical Paper 2017-01-2388, 2017), http://papers.sae.org/2017-01-2388/; Ran Xia et al., "A Study on the Relationship Between Vehicle Operating Conditions and NO_x Emission Characteristics," *E3S Web of Conferences* 522 (2024): 01008, https://doi.org/10.1051/e3sconf/202452201008; G. M. Hasan Shahariar et al., "On-Road CO^2 and NO_x Emissions of a Diesel Vehicle in Urban Traffic," *Transportation Research Part D: Transport and Environment* 107 (June 2022): 103326, https://doi.org/10.1016/j.trd.2022.103326.

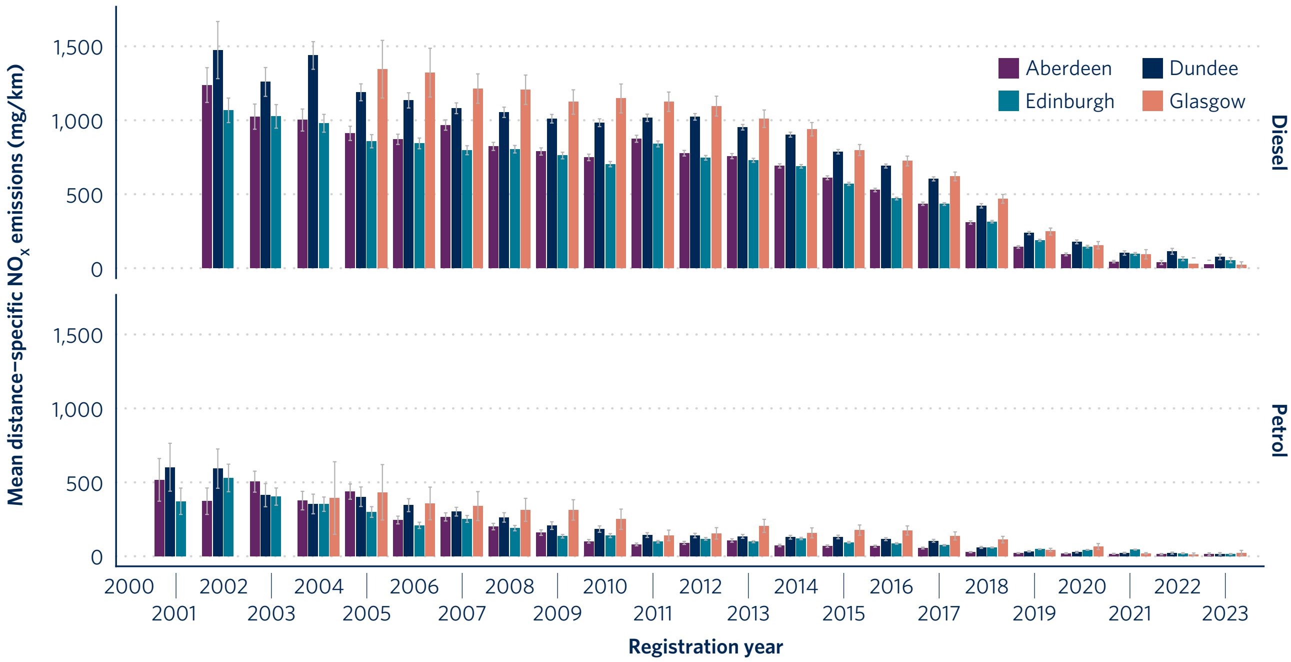

Figure 8. Mean distance-specific NO_x emissions from diesel and petrol passenger cars by registration year for the four Scottish cities. Whiskers represent the 95% confidence interval of the mean. Only registration years with over 100 measurements are presented.

TAXIS AND PRIVATE HIRES

Emission factors of taxis and private hires are presented separately from other passenger cars as these vehicles tend to have higher real-world emissions due to their high mileage, which leads to emission deterioration. Figure 9 shows the NO_x and PM emissions of taxis and private hires powered by diesel, which constituted nearly 85% of the measurements from the 2021–2023 sample, and compares them with emissions from private passenger cars.[9] Real-world NO_x emissions of taxis and private hires were consistently higher than those of other passenger cars, but variations were observed within the fleet. Taxis of registration years 2009–2016 showed NO_x emissions 84% higher, on average, than other passenger cars of the same registration years. These are likely taxis certified to Euro 6 showing significant emission degradation with mileage. Taxis registered between 2013 and 2016 also exhibited real-world NO_x emissions 56% higher than private hires of the same registration years. The gap between NO_x emissions of taxis and private hires decreased visibly from 2017, when RDE testing was introduced. The impact of the additional on-road emission limits is reflected in the notable NO_x emission performance improvement of taxi makes that comprise a large portion of the taxi fleet, such as Ford, Mercedes, and Peugeot, during this period (see Figure A1). There were only about 200 measurements of retrofit taxis available in the sample and therefore the NO_x emission performance of these taxis showed a large variance (see Figure A2).

9 Taxis and private hires from the remaining sample were hybrids (10%) and petrol-powered (3%).

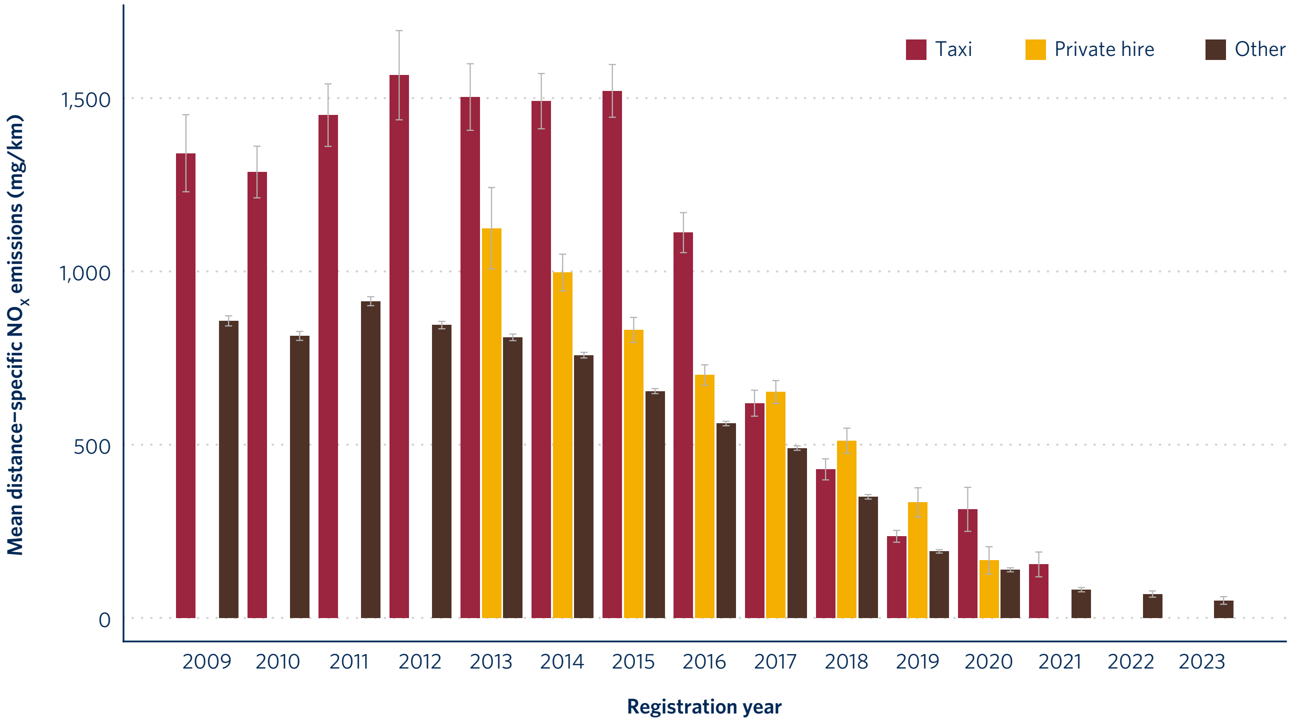

Figure 9. Mean distance-specific NO_x emissions from diesel taxis, private hires, and other passenger cars by registration year. Whiskers represent the 95% confidence interval of the mean. Only registration years with over 100 measurements are presented.

PM emissions from taxis, private hires, and other cars are presented in Figure 10. Despite large confidence intervals, highly elevated PM emissions from taxis stand out. Larger emission gaps between taxis and other cars from earlier registration years may indicate the deterioration of the emission control system with mileage. PM emissions from taxis were also notably higher than those from private hires, and this gap was more significant than for NO_x; mean PM emissions above 50 mg/km from taxis registered between 2013 and 2015 may indicate removed or malfunctioning DPFs. Taxi makes that showed substantial decreases in NO_x emissions from 2015 to 2018, like Ford, Mercedes, and Peugeot, showed little change in real-world PM emissions (see Figure A1).

The composition of taxis and private hires is largely shaped by policy measures targeting the fleet. Fewer private hires registered before 2013 were observed due to stricter policies limiting the use of old private hire vehicles. For example, in Dundee, all new private hires must be electric and emission testing is required for those over 8 years old, and in Glasgow private hires are subject to a 7-year age limit from which taxis are exempted. Strengthening taxi regulations so that the same age limits are applied to taxis and private hires would remove some of the highest-emitting vehicles from the road.

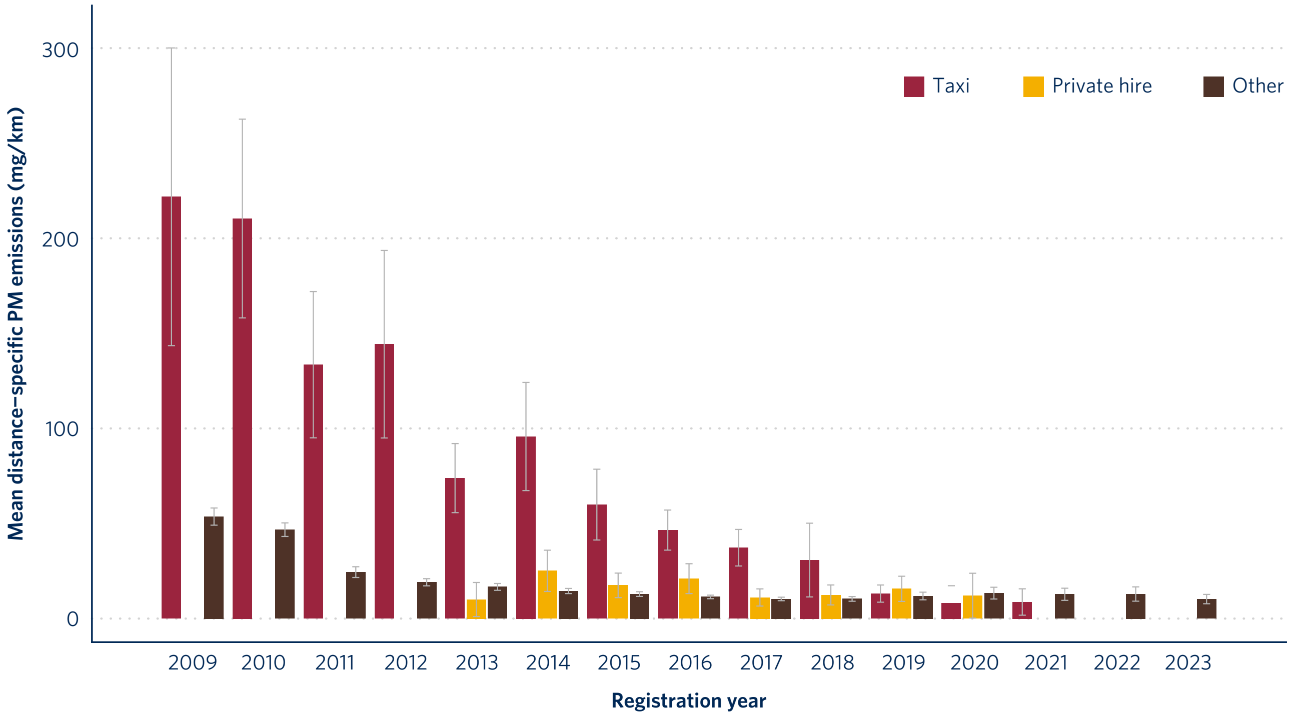

Figure 10. Mean distance-specific PM emissions from diesel taxis, private hires, and other passenger cars by registration year. Whiskers represent the 95% confidence interval of the mean. Only registration years with over 100 measurements are presented.

TRUCKS

For trucks, we convert emission results to gram of pollutant per kilowatt-hour (g/kWh), consistent with regulatory limits for heavy-duty vehicles, using the methodology developed by Bakhshmand et al. (2022) to define emission factors.[10] Unlike passenger cars, trucks were not observed consistently across all sites; nearly 90% of truck measurements were from three sites in Edinburgh, Aberdeen, and Dundee. More specifically, 38% were measured on Wellington Road in Aberdeen in 2021 and 2023, 34% on A90 in Dundee in 2022 and 2023, and 18% on Glasgow Road in Edinburgh in 2021 and 2023. Because the 2021 and 2023 Glasgow testing sites were located in the city centre, only a small number of trucks from Glasgow were in the sample. Trucks sampled in Aberdeen and Dundee were considerably bigger than those in other cities, with a median weight 1.7 and 2.4 times more, respectively, than those in Edinburgh and Glasgow; theses trucks were likely measured exiting the nearby harbours. We only present emission factors of trucks powered by diesel, the fuel type used by 99.9% of all trucks in our sample.

As shown in Figure 11, truck NO_X emissions fell markedly beginning with vehicles registered in 2014, largely owing to the implementation of in-service conformity (ISC) requirements, a measure introduced with the Euro VI standard to ensure on-road emission compliance by testing in-use vehicles.[11] Emissions were the highest for trucks registered between 2010 and 2013, the majority of which are certified to Euro V. As shown in Figure 12, mean NO_X emissions of Euro V trucks were 3.5 times the regulatory limit. These were vehicles operating beyond the durability requirement periods in which manufacturers must ensure engines comply with emission limits and, therefore, may have been showing natural degradation of emission control systems.[12] The increased emissions shown by Euro V trucks compared with trucks of preceding standards may also indicate a higher tampering rate of Euro V trucks due to the wider use of Euro V trucks in Scotland. The gradual decrease in NO_X emissions of trucks since registration year 2014 suggests that the tightening of ISC requirements with successive emission standards, such as through the

10 Sina Kazemi Bakhshmand et al., *Remote Sensing of Heavy-Duty Vehicle Emissions in Europe* (International Council on Clean Transportation, August 29, 2022), https://theicct.org/publication/remote-sensing-of-heavy-duty-vehicle-emissions-in-europe/.

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

12 The emission durability period for N2 and N3 Euro V heavy-duty vehicles that are less than or equal to 16 tons is 200,000 km or 6 years, while that of N3 Euro V heavy-duty vehicles that are greater than 16 tons is 500,000 km or 7 years. Most of the trucks in the sample belonged to the N3 vehicle category.

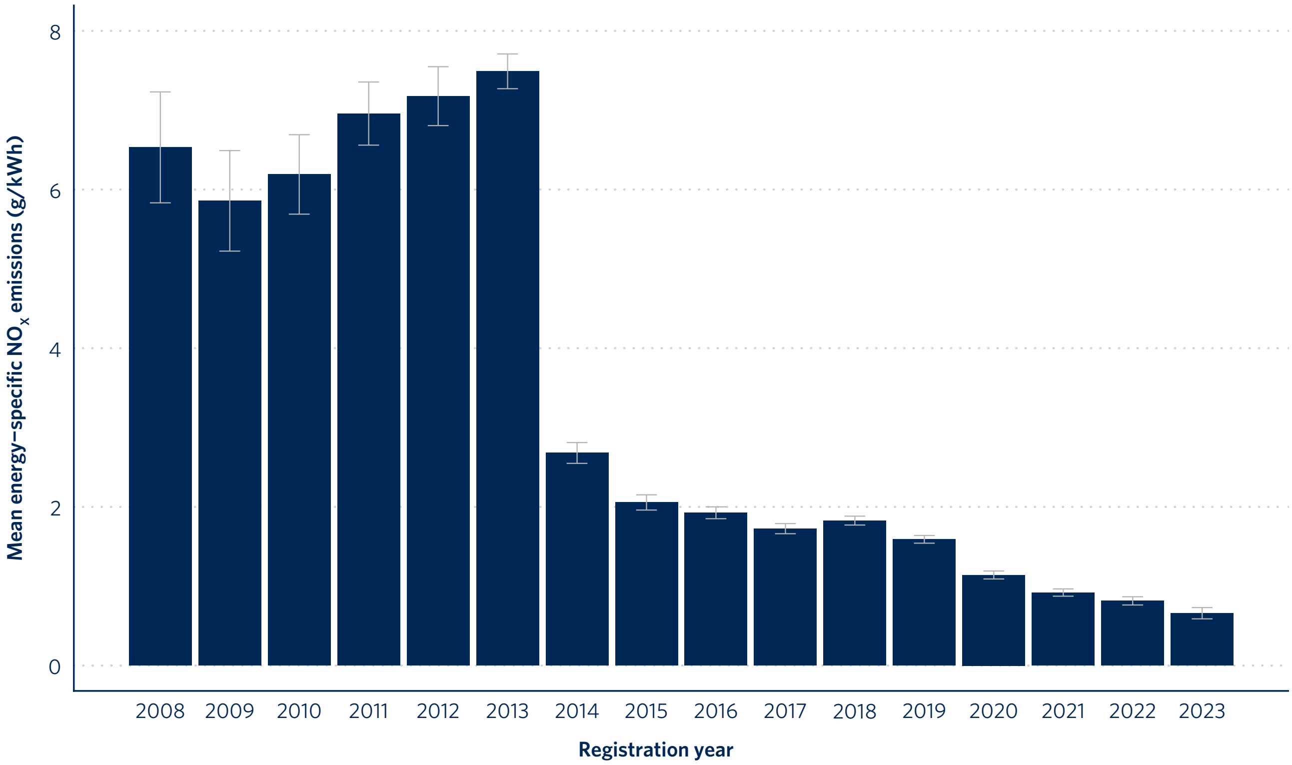

Figure 11. Mean energy-specific NO_x emissions from trucks by registration year. Whiskers represent the 95% confidence interval of the mean. Only registration years with over 100 measurements are presented.

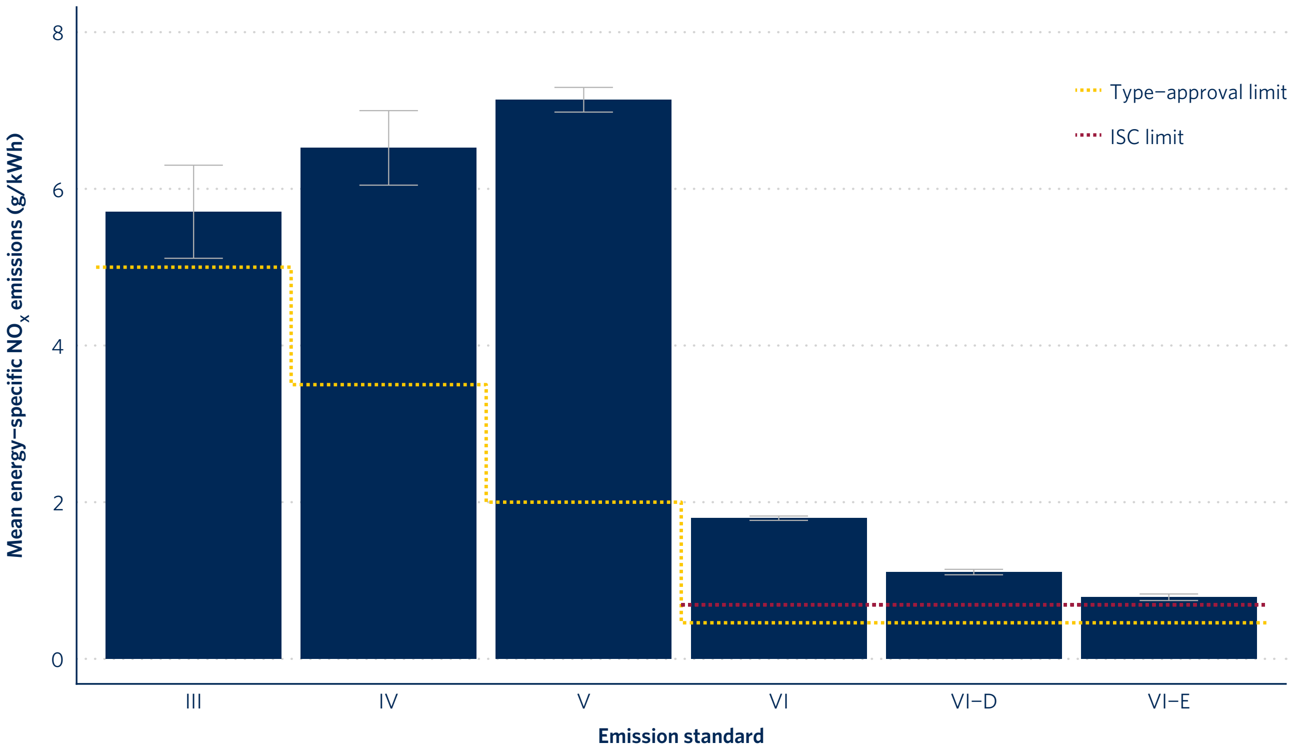

Figure 12. Mean energy-specific NO_x emissions from trucks by emission standard. Euro VI includes trucks certified to Euro VI A-C. Whiskers represent the 95% confidence interval of the mean. Yellow dotted line and red dotted line represent type-approval and in-service conformity limits, respectively. Only registration years with over 100 measurements are presented.

inclusion of cold starts in Euro VI-E, have helped achieved a consistent reduction in NO_x emissions.

Figure 13 examines truck emissions at the city level in comparison with truck data from two remote sensing studies in Belgium: one conducted in the port of Antwerp in 2021 and the other in multiple Flemish cities (including Aalst, Antwerp, Bruges, and Ghent) in 2019.[13] In general, Scottish trucks had far higher real-world NO_x emissions than the Belgian truck fleet. The Belgian testing campaigns were conducted during warmer weather, with median ambient temperatures of around 28 °C (Antwerp) and 20 °C (Flanders), which could have led to lower emissions. Although the trucks in the Scottish sample were generally larger than those in Belgium, no consistent trend was observed by weight.

As shown in Figure 13, trucks measured in Aberdeen showed significantly higher NO_x emissions than those in other cities across all registration years. Mean real-world NO_x emissions from the Aberdeen trucks were up to 2.4 times higher than those from the trucks measured in Antwerp, a comparable site where the measured trucks were likely operating with cold engines as they were exiting the harbour. In Dundee, 96% of trucks measured were on a motorway (A90), where lower emissions were anticipated due to high speeds and less likelihood of cold engines. However, these trucks had real-world emissions over 2 times those from Flanders trucks, over 99% of which were measured on motorways with similar driving conditions across all registration years.

The bigger emission gaps between Belgian and Scottish trucks from 2010 to 2013 may further support the hypothesis that emission deterioration and tampering may be more prevalent in Euro V trucks in Scotland than in Belgium. Based on a Flemish anti-tampering campaign in 2019, it was estimated that 9.5% of Euro V trucks in Flanders had been tampered with or were operating with defective SCRs.[14] The emission gap between different Scottish cities decreases with trucks with more recent registration years, but persistent high emissions observed for Aberdeen trucks registered after 2022 suggest that conditions covered in the latest ISC testing requirements

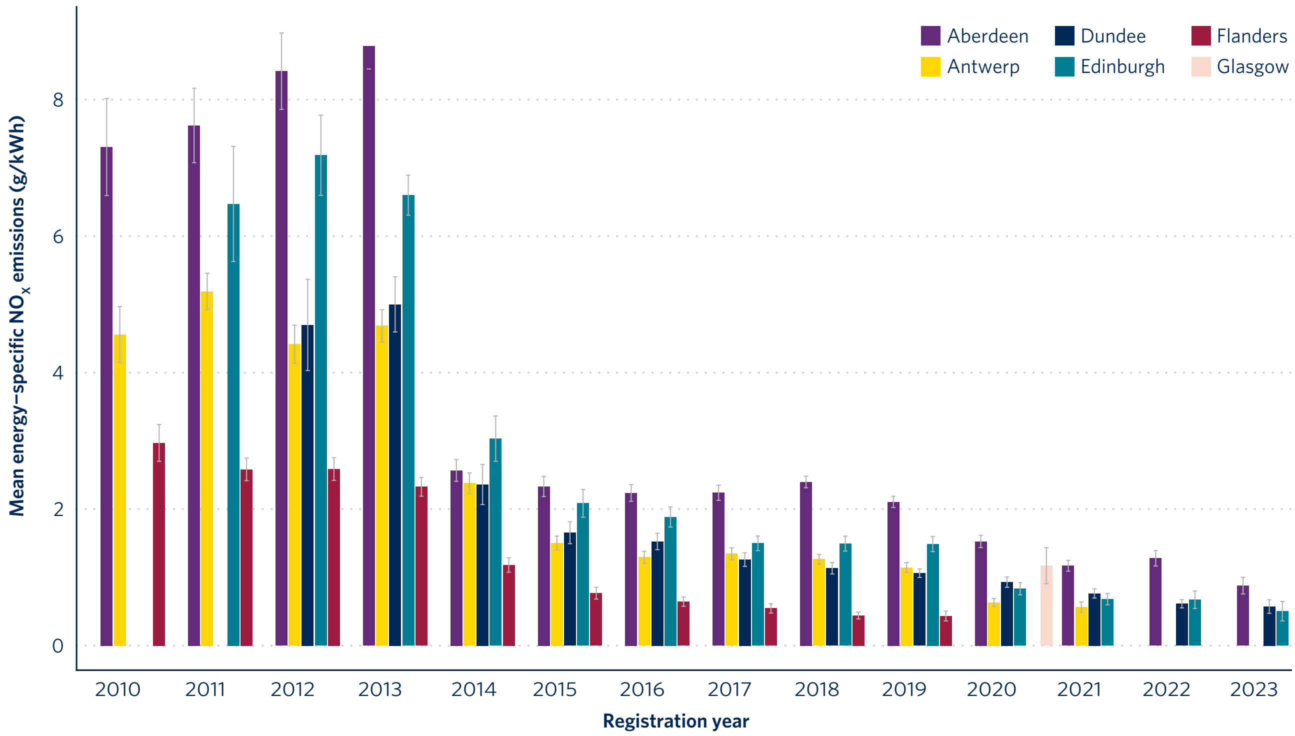

Figure 13. Mean energy-specific NO_x emissions from trucks by registration year for the four Scottish cities and two Belgian testing campaigns, in Antwerp (2021) and Flanders (2019). Whiskers represent the 95% confidence interval of the mean. Only registration years with over 100 measurements are presented.

13 The data from the Antwerp (2021) and Flanders (2019) testing campaigns comprise the largest remote sensing dataset of heavy-duty vehicles available in Europe. These data sets were accessed with the permission from the Port of Antwerp-Bruges (www.portofantwerpbruges.com) and Flanders Environment Agency (www.vmm.be).

14 Nils Hooftman, Norbert E. Ligterink, and Akshay Bhoraskar, *Analysis of the 2019 Flemish Remote Sensing Campaign* (TNO, 2020), https://repository.tno.nl/SingleDoc?find=UID%207e96bc14-46e3-4e5a-8f06-e436c85160f7.

do not fully capture real-world operating conditions and still have room for improvement.

UPDATE: EMISSIONS PERFORMANCE OF NEWER DIESEL VEHICLES

In this section, we update the analysis of NO_x emission performance of vehicle families certified to the Euro 6d-TEMP and Euro 6d standards with the additional measurements collected in 2023 and present the results using all measurements collected between 2021 and 2023.[15] Figure 14 presents the mean NO_x emissions of all diesel Euro 6d-TEMP passenger cars measured in 2021, 2022, and 2023 broken down by vehicle family. The addition of the 2023 data allowed us to evaluate vehicle families of which we did not previously have sufficient measurements, such as the FCA 1600cc, Daimler 2920cc, PSA 1600cc, PSA 1500cc, Renault-Nissan 1740cc, and Hyundai Motor Company (HMC) 2200cc.

The updated results show that certain vehicle families display NO_x emissions consistently higher than RDE limits in real-world operating conditions. The NO_x emissions of the Jaguar Land Rover (JLR) 3000cc, Volvo 1960cc, Ford 1500cc, Ford 2000cc, and HMC 1600cc engines have exceeded RDE limits over multiple years and across different testing conditions, suggesting excess emissions from these engines may be widespread. Meanwhile, the PSA 1500cc, Renault-Nissan 1740cc, and HMC 2200cc newly emerged in the 2023 data with emissions multiple

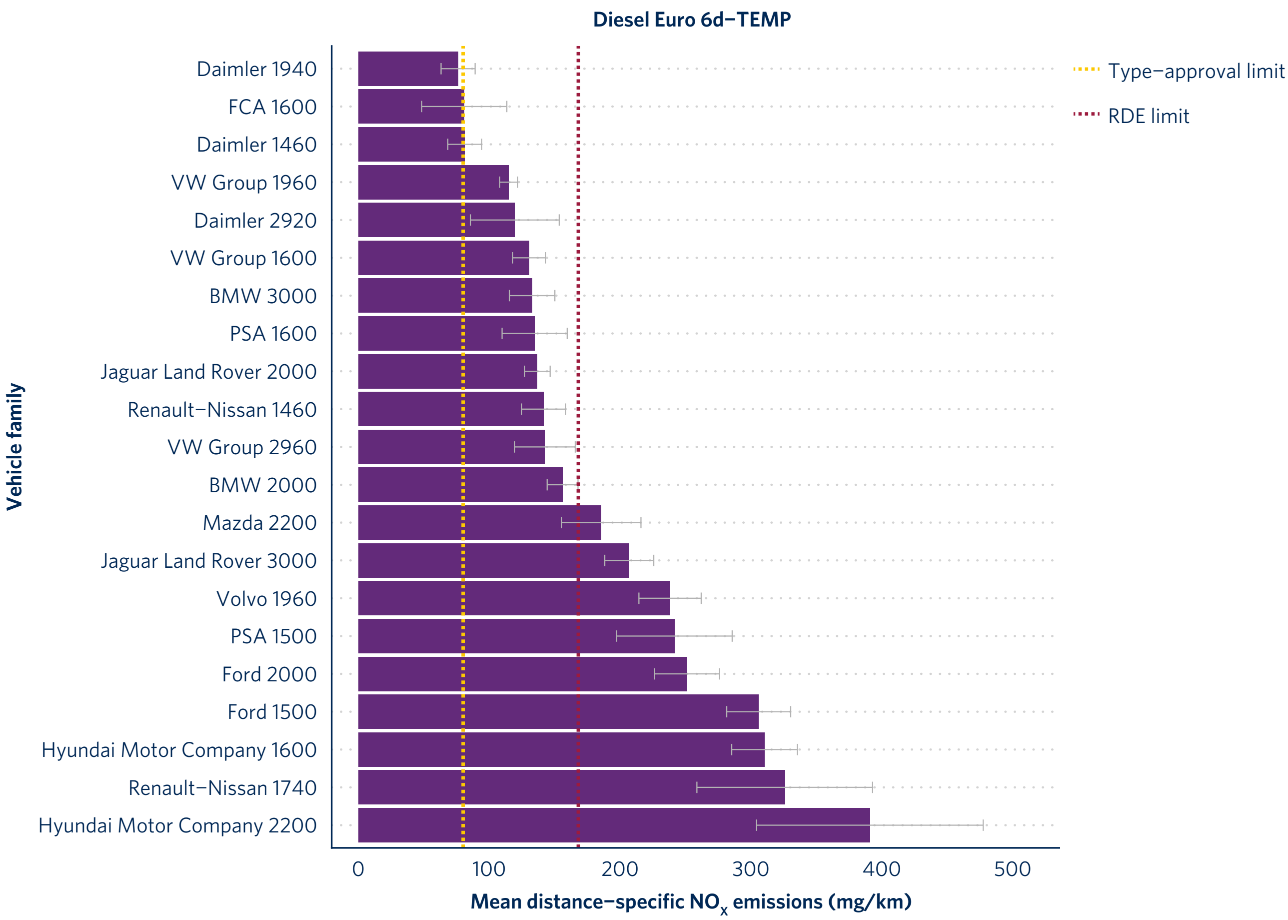

Figure 14. Mean distance-specific NO_x emissions from diesel passenger cars certified to Euro 6d-TEMP by vehicle family. Whiskers represent 95% confidence intervals of the mean. Yellow and red dotted lines represent type-approval and on-road (RDE) emission limits, respectively. Only measurements of 100 or more are presented.

times above type-approval limits. In particular, the Renault-Nissan 1740cc and HMC 2200cc had mean NO_x emissions

15 For the results of the previous campaigns, see Lee et al. *Assessment of Real-World Vehicle Emissions in Scotland in 2021*, and Lee et al., *Assessment of Real-World Vehicle Emissions from Four Scottish Cities in 2022*.

over 2 times higher than the RDE limit, suggesting the possible non-compliance of these vehicle families with RDE regulations.

The mean NO_x emissions of Euro 6d vehicle families are shown in Figure 15. The 2023 data allowed for the examination of the Volkswagen (VW) Group 2960cc, Daimler 2920cc, and BMW 1500cc vehicle families, which did not have sufficient measurements from previous campaigns. Euro 6d vehicle families exhibited around 50% lower mean NO_x emissions than Euro 6d-TEMP vehicle families, largely owing to the tightening of the RDE regulations, which lowered the on-road emission limit from 168 mg/km to 114 mg/km. Although most of the vehicle families measured in Scotland showed mean NO_x emissions below the lowered RDE limit, the Ford 2000cc and JRL 2000cc had emissions above the limit. Indeed, the JLR 2000cc emerged as one of the highest-emitting engines across all three campaigns, a trend Scottish authorities may consider investigating further.

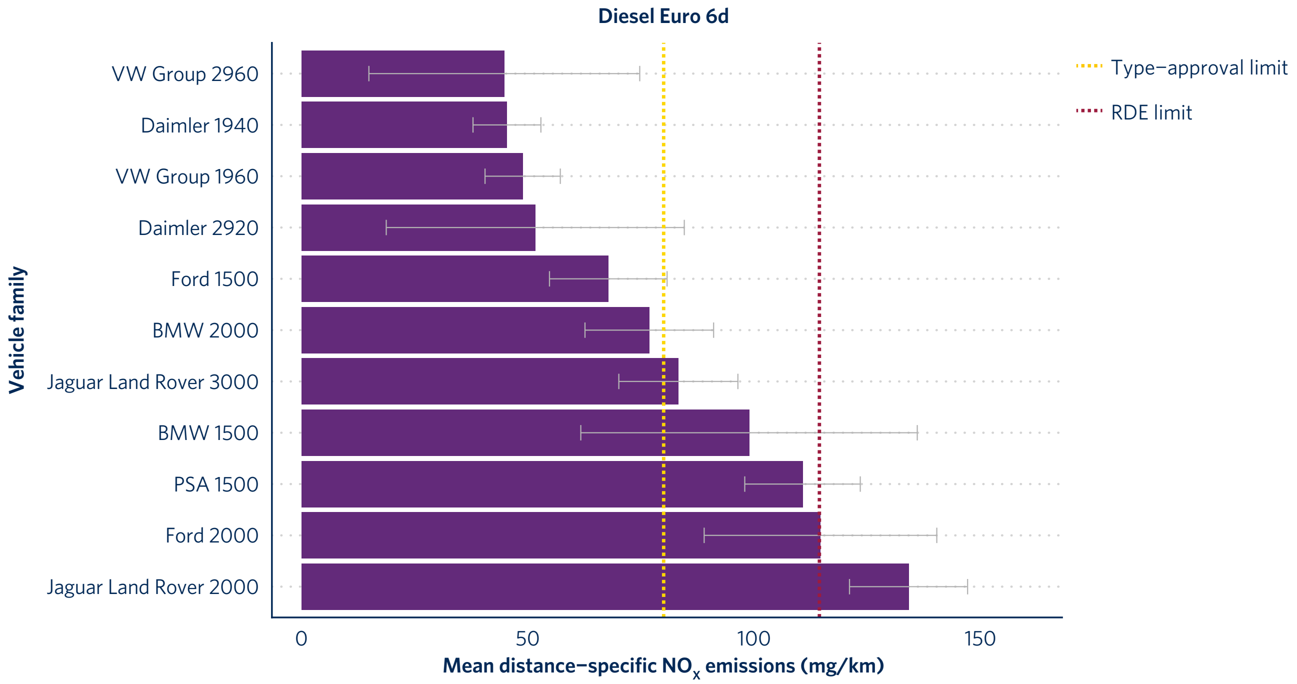

Figure 15. Mean distance-specific NO_x emissions from diesel passenger cars certified to Euro 6d by vehicle family. Whiskers represent 95% confidence intervals of the mean. Yellow and red dotted lines represent type-approval and on-road (RDE) emission limits, respectively. Only measurements of 100 or more are presented.

UPDATE: HIGH-EMITTER THRESHOLDS FOR TRUCK ENFORCEMENT USING REPEATED MEASUREMENTS

In this section, we apply the same methodology used to determine thresholds for the enforcement of high-emitting trucks in the March 2024 TRUE study of real-world emissions of Scottish vehicles in 2022 to the aggregate sample of trucks measured in 2021, 2022, and 2023.[16] In line with the March 2024 study, we selected a subset of Euro VI and Euro VI-D trucks that showed a relatively similar distribution of NO_x emissions with small variations across cities. Euro V trucks were excluded from this study as they showed inconsistent NO_x emission performance in urban settings, posing a challenge for defining their normal and abnormal emission behaviours. Table 2 presents the sample of valid NO_x emission measurements and unique trucks these emissions were measured from after filtering for trucks with VSPs between 3 kWh/t and 12 kWh/t that were measured five or more times.

Table 2. Number of valid emission measurements and unique Euro VI and Euro VI-D trucks measured five or more times

Emission standard	Number of measurements	Number of unique vehicles
VI	10,788	1,076
VI-D	4,419	383
Total	15,207	1,459

As in the March 2024 study, we assumed a high-emitter cutoff point of 3.68 g/kWh, 8 times the type-approval emissions limit. This is to account for the fact that normally behaving vehicles can also show high levels of emissions in certain instances, such as cold starts, very high acceleration, or very low speed. We found 111 trucks with five or more emission measurements to have mean NO_x emissions exceeding this cutoff point, accounting for 7.6% of the sample, around 1% lower than the high-emitter share found in the 2021–2022 sample (8.5%).

We assume the remaining 1,348 trucks in the sample are normally behaving trucks. Figure 16 shows the breakdown of high emitters by emission standard, with Euro VI trucks accounting for a predominant share.

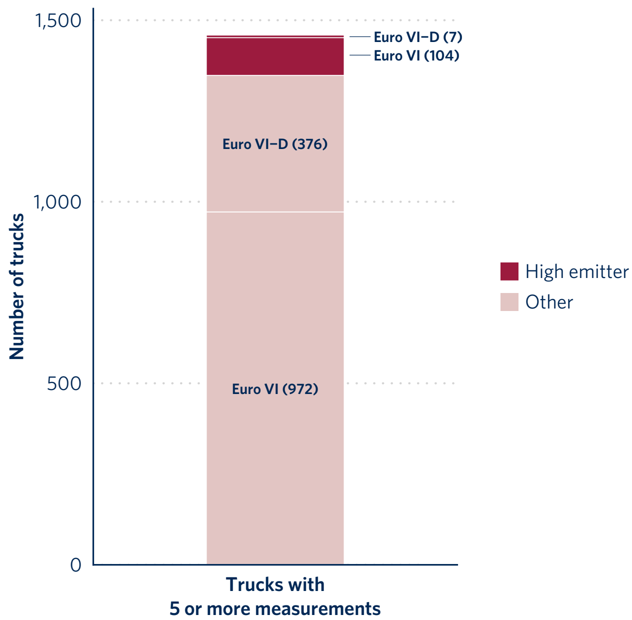

Figure 16. Number of vehicles tagged as high emitters by emission standard

Emission measurements from these 1,348 vehicles were subsequently used to define the emissions distribution of normally behaving Scottish Euro VI trucks, which is the basis for calculating the high-emitter detection threshold as defined by Hooftman, Ligterink, and Bhoraskar.[17] Figure 17 shows the NO_x emission distributions of high emitters and normally behaving trucks against that of all measured trucks with five or more measurements. Using the NO_x distribution of normally behaving vehicles defined by our sample in the formula developed by Hooftman, Ligterink, and Bhoraskar, we derive a NO_x emission threshold of 26 g/kg for Euro VI and Euro VI-D trucks, which roughly corresponds to 5.7 g/kWh.[18]

16 For a detailed explanation of this methodology, see Lee et al., *Assessment of Real-World Vehicle Emissions from Four Scottish Cities in 2022.*

17 Hooftman, Ligterink, and Bhoraskar define a threshold for flagging high-emitter candidates as two standard deviations above the median from the NO_x emission distribution of clean vehicles.

18 As vehicular NO_x emissions do not follow a normal distribution, we first performed a Yeo-Johnson transformation to derive a meaningful standard deviation. For this, we applied an estimated parameter (lambda, λ) of 0.63 to the distribution of NO_x emissions of normally behaving trucks. The resulting median and standard deviation of the transformed distribution were 3.13 and 3.94, respectively. The resulting threshold (two standard deviations from the median) of 11.0 is reversed back to the value of 26.1 g/kg.

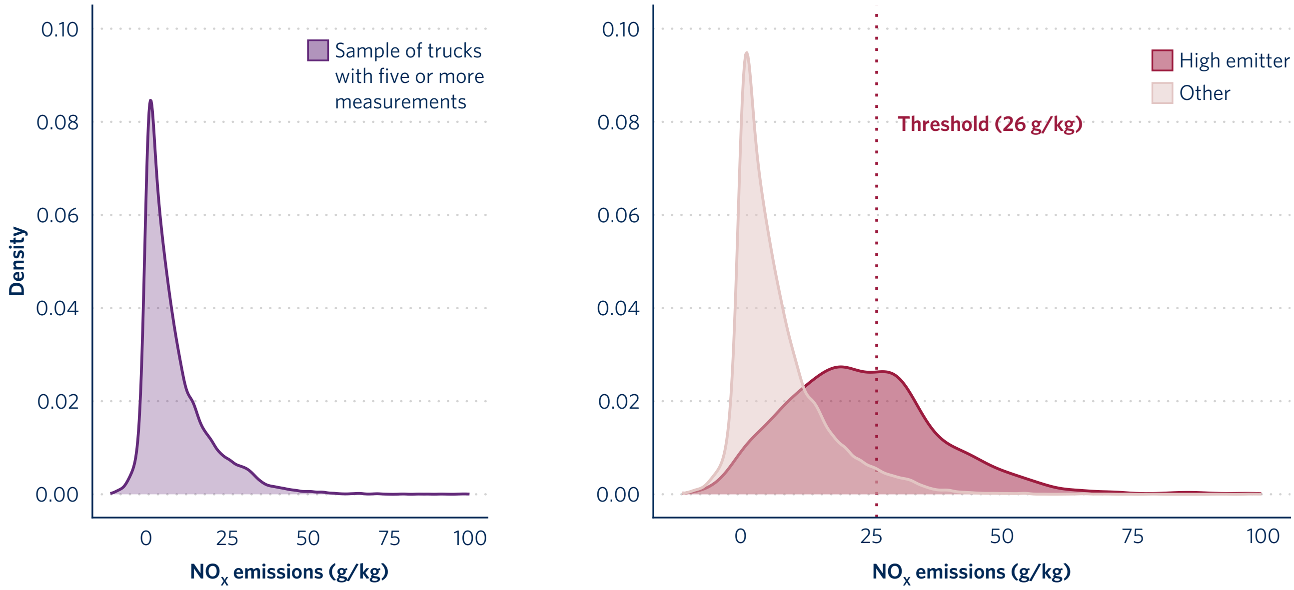

Figure 17. Distribution of fuel-specific NO_x emissions (g/kg) of trucks with five or more emission measurements (left) and NO_x distributions of high emitters and others identified from the sample with the newly identified measurement threshold of 26 g/kg (right). Areas below lines cover 100% of respective measurements from the sample.

As in the March 2024 TRUE study covering only measurements from 2021–2022, NO_x emissions from normally behaving vehicles are skewed to the right, with around 3% of the emission measurements exceeding the identified threshold of 26 g/kg. This means that there would be a 3% false positive rate, or chance of falsely identifying normally behaving trucks as high emitters, if this threshold were to be applied in real-world enforcement settings. The threshold and the false positive rate derived from this 2021–2023 dataset are in line with those from the previous TRUE study, which suggests that a threshold of between 24 g/kg (used in the March 2024 study) and 26 g/kg (used in this study) would likely result in a low false positive rate in Scottish urban areas.

Although only 36% of the high emitters have instantaneous emission measurements exceeding the threshold, the likelihood of detecting high emitters increases substantially with multiple measurements. The chance of at least one emissions measurement exceeding the threshold becomes 90% with five measurements. This highlights that long-term monitoring of emissions with remote sensing technology could be effective for flagging trucks for inspection or emissions testing.

CASE STUDY: CHANGE IN FLEET EMISSIONS OVER TIME

For the 2023 emissions testing, we selected sites in Edinburgh, Aberdeen, and Dundee where prior emissions testing took place with the intention of assessing changes in fleet emissions over time. Information on the sites and testing campaigns are summarized in Table 3. Vehicle classes commonly found at each site were similar across different testing dates. For all three sites, passenger cars were the predominant vehicle class, followed by light commercial vehicles and trucks. We focus on the emission evolution of passenger cars and trucks in this section.

The vehicle samples exhibited some variations in operating conditions between the two campaigns. The median ambient temperature during the 2023 testing campaign was around 18 °C, 5–7 °C higher than those measured during the previous campaigns. Vehicles were driving at similar speeds across the campaigns at each site, but VSPs varied due to the differences in road slope, acceleration, and individual driving behaviour: The 2023 sample from Edinburgh had a median VSP 70% lower than that of the 2021 sample, for instance, while the 2023 sample from Aberdeen had a median VSP around 70% higher than that of the 2022 sample. The Dundee samples showed comparable VSPs with a difference in median of around 24%. Despite these variations, we consider the comparison of fleets and emissions measured at the same sites to be insightful as it can show the emissions impact of natural fleet turnover and emissions degradation.

PASSENGER CARS

In all three cities, mean NO_x emissions of all private passenger cars, excluding taxis and private hires, decreased from 2021 and 2022 to 2023 largely due to natural fleet turnover, a trend of newer and cleaner vehicles replacing older and more polluting vehicles. Figure 18 compares mean NO_x emissions from passenger cars measured at different times in each city. The reduction in emissions is most notable in Edinburgh, where a 16% decrease was recorded between the first campaign, in 2021, and the second campaign, held 21 months later. This large decrease could be partly attributed to the lower VSPs and higher ambient temperatures under which these vehicles were operating, which are typically associated with lower emissions.[19] However, it is also due to a significant increase in the share of new vehicles registered from 2021 and likely certified to Euro 6d with improved emission performance; these vehicles made up 13% of all fleet passes in 2023, up from 5% in 2021.

In Aberdeen, mean emissions showed a slight decrease of 3.5% between the two campaigns, conducted 13 months apart, despite the share of new vehicles (registered 2021 and after) doubling. This is likely because the vehicles measured in 2023 were operating at higher VSPs, which leads to higher NO_x emissions. The Dundee fleet, meanwhile, showed a 7% decrease in emissions between campaigns, with new vehicles (2021 and after) making up 13% of the fleet in 2023, compared with 5% less than a year prior. The overall level of NO_x emissions in Dundee was higher than in the two other cities, likely because the vehicles, measured on a highway, were driving at higher VSPs.

The mean NO_x emissions of private passenger cars across Scottish cities have decreased at an annual average rate of 7% without any policy measures to accelerate fleet renewal. As discussed in the policy considerations below, scrappage programs and other incentives to encourage the replacement of old and polluting vehicles wither newer, cleaner alternatives like electric vehicles could further accelerate fleet renewal, leading to faster and more significant reductions in emissions.

Table 3. Sites reselected for emissions testing in 2023, dates of the first and second campaigns, and time between testing dates

City	Location	First testing campaign	Second testing campaign	Time between campaigns
Edinburgh	Glasgow Road	October–November 2021	June–July 2023	21 months
Aberdeen	Wellington Road	April–May 2022	June–July 2023	13 months
Dundee	A90	September–October 2022	June–July 2023	9 months

19 Hui Mei et al., "Characterization of Exhaust CO, HC and NO_x Emissions from Light-Duty Vehicles under Real Driving Conditions," *Atmosphere* 12, no. 9 (September 2021): 1125, https://doi.org/10.3390/atmos12091125.

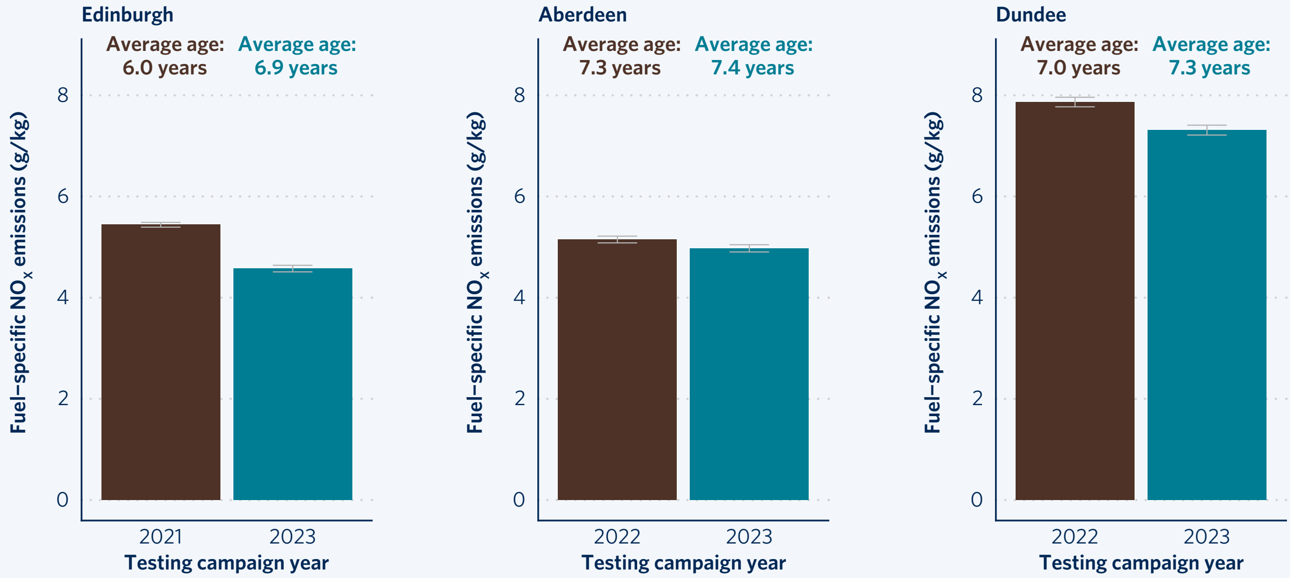

Figure 18. Comparison of total mean NO_x emissions (g/kg) of passenger cars measured at two campaigns. Number above bars indicates mean age of each fleet. Whiskers represent 95% confidence interval to the mean.

We evaluated the potential emission degradation of vehicles by comparing NO_x emissions of vehicles observed at different campaigns on a more granular level. The differences in emissions among vehicles with the same registration years across cities and campaigns varied widely, likely due to the varying conditions under which the vehicles operated. The degradation of NO_x emission performance, however, was more prominent when vehicles were distinguished by emission standards. Both Euro 3 and Euro 4 petrol and diesel vehicles observed in later campaigns consistently showed higher emissions, highlighting the importance of retiring vehicles certified to these standards (see Figure A3). The results also demonstrated that diesel engines, which have so far shown little evidence of emission degradation, are also prone to elevated NO_x emissions with prolonged usage.

TAXIS AND PRIVATE HIRES

Taxis and private hires that have accrued higher mileage than private passenger cars exhibited a more pronounced effect of emission degradation. Figure 19 shows the mean NO_x emissions of all diesel taxis and private hires alongside breakdowns by registration year in Edinburgh and Dundee, the two cities for which taxi and private hire data were available. NO_x emissions from taxis and private hires of most of the available registration years increased from 2021 and 2022 to 2023, including in Edinburgh, where lower VSPs and higher ambient temperatures were observed in 2023. The increase in emissions is more prominent in taxis and private hires registered between 2013 and 2017, likely certified to Euro 6 or below, highlighting potential emission deterioration with mileage accumulation.

The negative impact of emission degradation offsets the positive impact of fleet renewal on NO_x emissions of taxis and private hires. In Edinburgh, taxis and private hires showed only a 1% decrease in mean emissions from 2021 to 2023, a minor change compared with private passenger cars (16%), while in Dundee, their mean emissions increased by 8% between the two campaigns. The larger increase in mean ages of taxis and private hires between the two campaign years compared with private passenger cars also indicates that fleet renewal of taxis and private hires occurred more slowly (e.g., due to the COVID pandemic in 2020). These findings indicate that mileage is also an important factor for emission degradation and suggest that restrictions based on mileage as well as age could be more effective in curbing emissions from high-usage fleets like taxis and private hires. Due to limited access to taxi and private hire fleets' mileage data, however, we were not able to determine the mileage at which emission control systems begin to deteriorate significantly.

TRUCKS

Changes in NO_x emissions over time varied by city for trucks. As shown in Figure 20, the overall NO_x emissions of trucks decreased by 34% over 21 months in Edinburgh and 14% over 9 months in Dundee. The significant decrease in

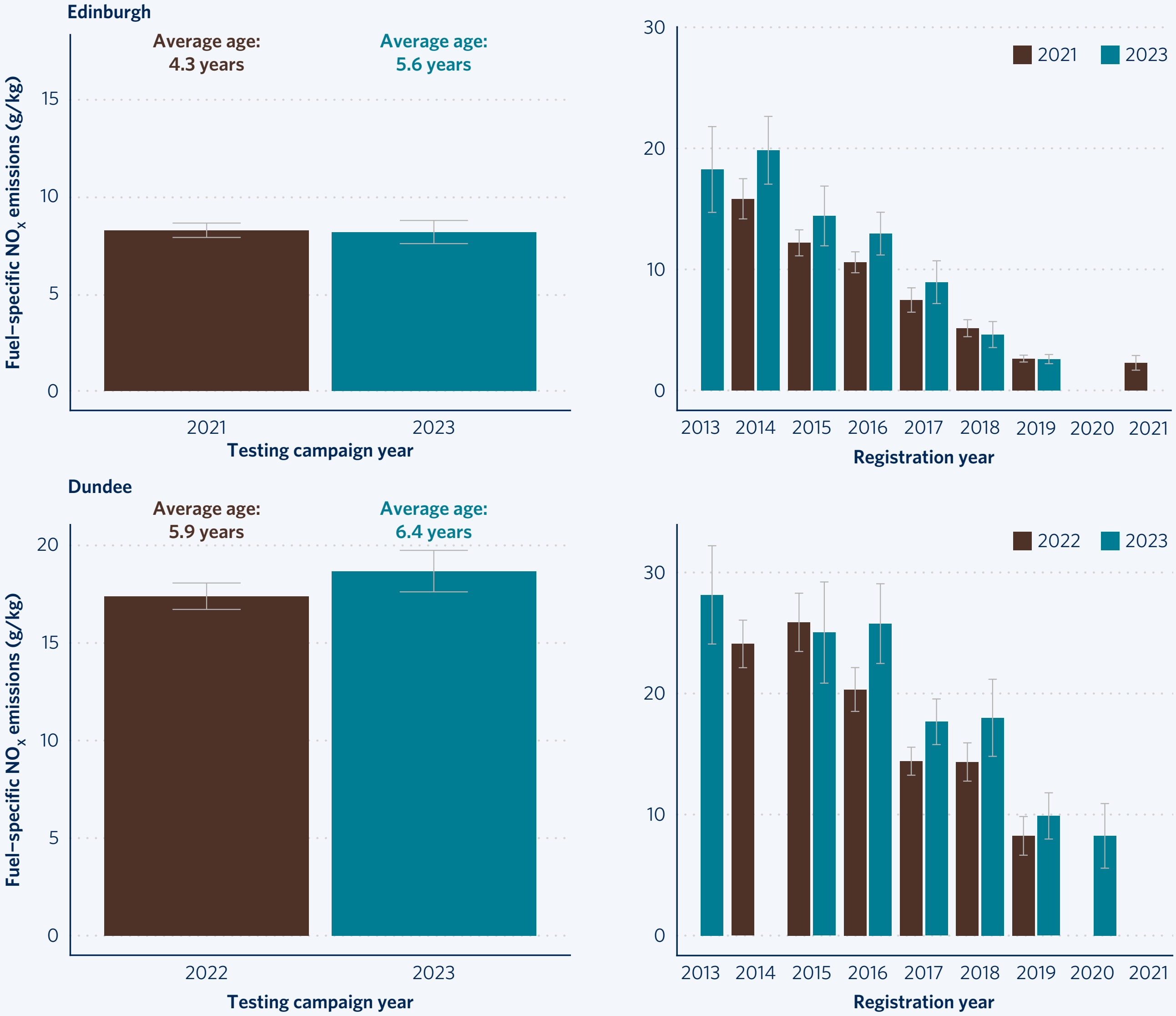

Figure 19. Comparison of total mean NO_x emissions (g/kg) of diesel taxis and private hires by testing campaign year (left) and registration year (right). Fleet average ages are shown for different campaign years above bars. Whiskers represent 95% confidence interval to the mean. Only registration years with over 50 measurements are presented.

the Edinburgh truck emissions can partly be attributed to the emergence of trucks certified to Euro VI-E, the newest standard required for all new trucks from 2022, which shows real-world emissions around 20% lower than Euro VI-D.[20] The number of VI-E trucks in Edinburgh increased from 15 to nearly 700 in two years, accounting for around 22% of the measured truck fleet in 2023. In Dundee, the share of Euro VI-E trucks in the fleet jumped fourfold from 2022 to 2023, which likely lowered the mean age of trucks measured in the city. Meanwhile, despite a rate of fleet renewal similar to that of the Dundee fleet and no change in mean age, the Aberdeen trucks exhibited a 20% increase in total emissions between the two campaigns. This trend may be linked to the presence of a larger share of trucks with cold engines during the 2023 campaign, reflected in a median exhaust temperature (29.9 °C) of the 2023 sample that was over 40% lower than that of the 2022 sample (50.8 °C). Trucks measured in Aberdeen were more prone to have cold starts due to the Aberdeen testing site's proximity to the port exit.

A detailed look at mean NO_x emissions by emission standard further indicates that Euro V trucks are particularly prone to emission increases over time. In Edinburgh, although warmer temperatures and fleet

20 Lee, Bernard, and Riley, *Assessment of Real-World Vehicle Emissions from Four Scottish Cities in 2022.*

renewal led to lower emissions in 2023 across other emission standards, Euro V trucks did not exhibit this trend. Similarly, in Dundee, Euro V trucks showed an emission increase while the newer standards showed decreases between the two campaigns. Meanwhile, in Aberdeen, the increase in emissions observed for Euro V was notably more significant than increases seen for other standards.

Under emission durability requirements, vehicle manufacturers are currently required to ensure that engines comply with emission limits for 500,000 km or 7 years for Euro V trucks. Trucks operating beyond this timeframe likely show signs of emission control system deterioration. Older trucks, like those certified to Euro V, are also more likely to have defective or tampered emission control systems, as studies conducted in Europe have shown.[21] Euro V trucks measured multiple times across different campaigns generally showed an increase in emissions over time, but more data are needed to prove significance ($R^2 < 0.5$). For trucks certified to Euro VI and above, emission degradation was not evident.

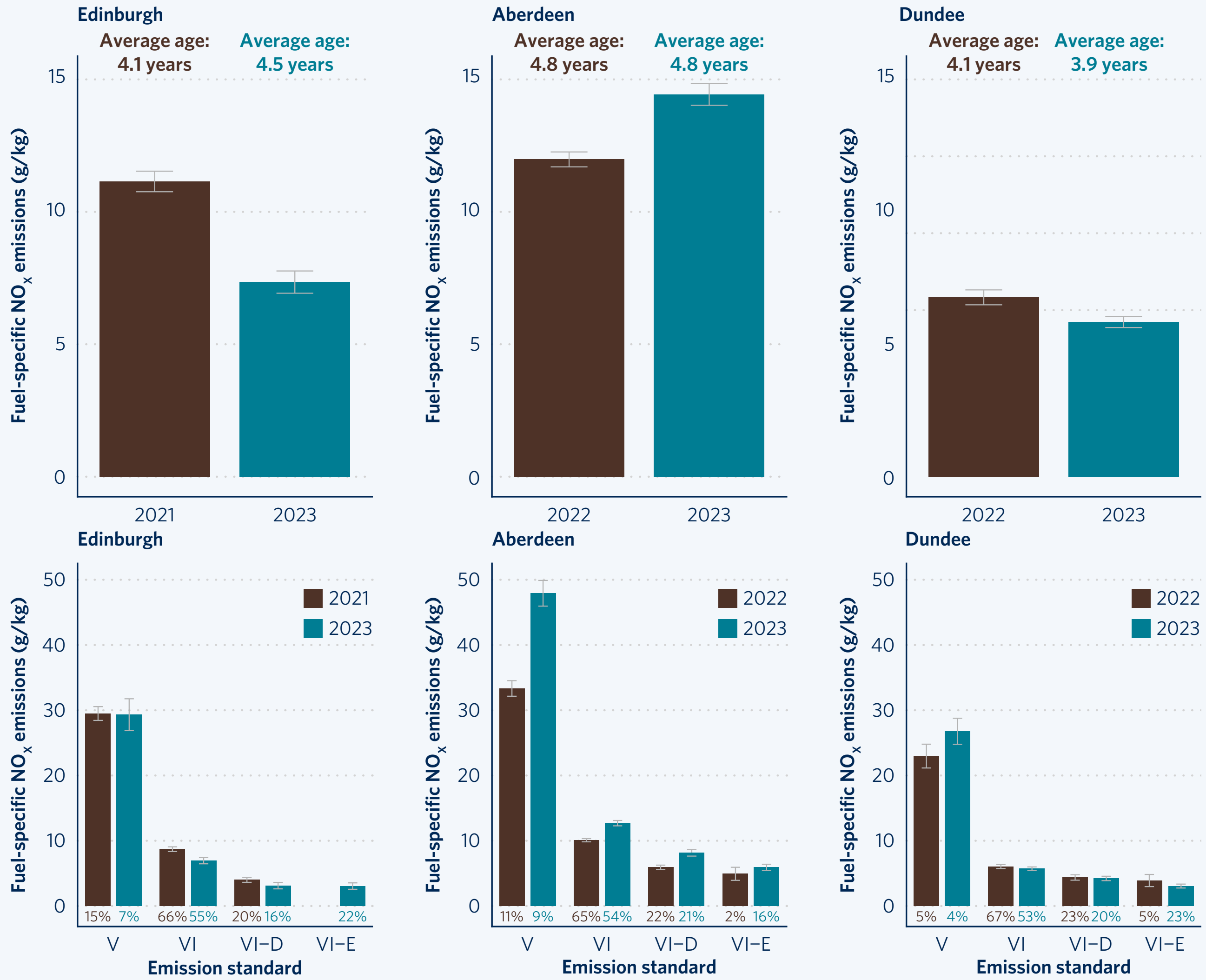

Figure 20. Comparison of mean NO_x emissions (g/kg) of diesel trucks by testing campaign year (top) and emission standard (bottom). Fleet average ages are shown for different campaign years above bars (top) and percentage below bar indicates the share of each standard in the fleet (bottom). Whiskers represent a 95% confidence interval to the mean.

21 Hooftman, Ligterink, and Bhoraskar, *Analysis of the 2019 Flemish Remote Sensing Campaign;* D. Pöhler and T. Engel, *Bestimmung von LKW NO_x Emissionen (Real Driving Emissions) Auf Tiroler Autobahnen Und Potenziellen Abgasmanipulationen* (Heidelberg University Institute of Environmental Physics, November 5, 2018), https://www.tirol.gv.at/fileadmin/themen/verkehr/verkehrsrecht/downloads/2019/2018-11-05_LKW-Emissionsmessungen-Tirol_Abschlussbericht_v1.0_Anonymisiert.pdf.

true THE REAL URBAN EMISSIONS INITIATIVE

POLICY RECOMMENDATIONS

This study provides insight into the real-world NO_x and PM emissions from vehicles in Scottish urban areas measured using remote sensing technology between 2021 and 2023. Based on our analysis of over 1.4 million emission measurements of passenger cars, taxis and private hires, and trucks, we highlight notable trends—such as elevated NO_x levels of Scottish vehicles relative to vehicles in other countries in the European TRUE data—and identify NO_x thresholds which could be used to detect high-emitting trucks with likely defective or tampered emission control systems.

Based on our findings, we offer the following policy considerations for the Scottish government to address pollutant emissions from on-road transport. A combination of national, regional, and local policies could ensure that emission benefits are maximized by targeting the most polluting vehicles. Additionally, supplementary policy measures could be implemented at the city level for a long-term, just transition to zero-emission vehicles.

NATIONAL VEHICLE INSPECTION PROGRAM UPDATES

Ministry of Transport (MOT) testing in the United Kingdom currently checks for correct operation of vehicles by testing exhaust emissions of carbon monoxide (CO), hydrocarbons (HC), and the air-to-fuel ratio in petrol vehicles, with opacity measures also used to assess soot emissions in diesel vehicle exhausts.[22] Exceeding the limits for these tests results in the car failing the MOT test, which prevents it from being used on public roads until the issue is fixed and the test is passed. None of these tests are designed to measure NO_x emissions or ensure that NO_x control technologies do not deteriorate over time. Testing of taxi and private hire vehicles in this study has shown that when a vehicle reaches very high mileage, emission control technologies can deteriorate, and NO_x emissions rise sharply. Working with the UK Government, Scottish authorities could consider updating MOT testing to include NO_x testing and lowering the emission limits allowed for other pollutants to help remove high polluters from the fleet without the need for more expensive on-road testing.

22 UK Government, "Emissions Testing," accessed July 11, 2024, https://www.gov.uk/emissions-testing.

ADDRESSING EMISSIONS FROM TAXIS AND PRIVATE HIRE VEHICLES

Taxis and private hire vehicles produce a disproportionately high share of emissions because they are driven more than most other cars, resulting in more emissions per day and a higher chance of emission control technology deterioration. In Scottish cities, taxis and private hires are also predominantly powered by diesel, producing more NO_x and PM emissions than taxis and private hires powered by petrol. We found that diesel taxis not subject to on-road (RDE) testing, or registered before 2017, had NO_x emissions nearly double those from other private cars (Figure 9). These taxis also exhibited highly elevated PM emissions, indicating removed or malfunctioning diesel particulate filters (Figure 10). These results point to the importance of reducing emissions from the taxi and private hire fleet, which can be more easily regulated with local policy measures compared with private cars.

To this end, in the short term, cities could consider enforcing a milage limit or a stricter age limit on taxi and private hire vehicles, from which battery electric vehicles (BEVs) could be exempt.[23] As demonstrated in the increased emissions shown by taxis and private hires in Edinburgh and Dundee over time, taxis and private hires are more prone to degradation of the emission control system the longer they remain in the fleet (Figure 19). Such measures could help remove the highest emitting vehicles from the taxi and private higher fleets.

In the longer term, transitioning the taxi and private hire fleet to BEVs would remove a large share of emissions from transport in the urban areas studied. This could be done by working with taxis and private-hire drivers to support them in this transition. For example, city governments could work with drivers and industry bodies to aggregate BEV demand and identify a leasing company willing to offer financially competitive rates to a large number of drivers. Policymakers could also provide additional non-financial benefits to BEV drivers, as in Amsterdam, where only BEVs can use the taxi rank at the central city station.[24] Improving charging access for drivers by creating rapid charging

23 Currently, in Edinburgh, there is a 10-year age limit for both taxis and private hires. In Dundee, all new private hires must be electric vehicles from an approved list; for private hires of over 8 years of age, three emission tests per year are required. In Glasgow, a 7-year age limit applies only to private hires.

24 Friðrik Már Baldursson, Ewa Lazarczyk Carlson, and Nils-Henrik von der Fehr, *Electric Vehicles Rollout in Europe: Towards an Improved Regulatory Regime* (Centre on Regulation in Europe, 2019), https://cerre.eu/wp-content/uploads/2020/05/cerre_2019_electricvehicles_energyregulation.pdf.

hubs and making street charging available could further incentivise the transition to BEVs.

RESTRICTING THE USE OF EURO V TRUCKS AND IDENTIFYING EURO VI HIGH-EMITTERS FOR REPAIR

Trucks are a major source of emissions, particularly in Scottish cities where Scotland's major harbours are located. Trucks in Scottish cities exhibited higher NO_x emissions than those in Belgium, and emissions from trucks measured near a harbour were significantly higher due to cold engines, posing health dangers to the adjacent population. In particular, NO_x emissions from Euro V trucks (registered between 2010 and 2013) showed that tampering and emission deterioration of these vehicles may be more prevalent in Scotland than Belgium (Figure 13). Euro V trucks measured in all four Scottish cities also showed a notable increase in NO_x emissions over time, reinforcing the likelihood of emission degradation or tampering (Figure 20).

Trucks' emissions performance largely improved from 2014 with the introduction of the Euro VI standard requiring in-service conformity testing (Figure 13). The Scottish low-emission zone, which is in force in all four cities, stipulates that trucks and buses must be certified to Euro IV petrol or Euro VI diesel standards. Our results suggest that only confirming a vehicle's emission standard may not be enough for the LEZ to be a success and that other enforcement measures to check real-world emissions are needed to remove the most polluting trucks from the fleet.

Enforcement thresholds for trucks certified to Euro VI and above could be utilized in road-side inspection to further identify a small portion of high-emitters with excess NO_x emissions. This analysis shows that remote sensing could be complementary to an enforcement campaign and help to identify potentially faulty vehicles or vehicles with defeat devices fitted for roadside inspection. Unlike broader roadside checks where all or a large share of vehicles need to be pulled over, this approach would only require pulling over a very small number of vehicles with a high chance of being a high emitting vehicle, significantly reducing disruption and required manpower. Alternatively, the process could be automated by connecting remote sensing information to the vehicle registration database and requiring drivers to obtain additional inspections of trucks with high emissions.

ACCELERATING FLEET RENEWAL

As set out in the case study, emissions will fall over time due to the natural replacement of the fleet with newer, lower polluting vehicles (Figure 18). For example, mean NO_x emissions of private cars across Scottish cities decreased at an annual average rate of 7% without any policy in place to encourage fleet replacement. This process could be accelerated through a scrappage scheme, such as the one offered in London to residents affected by the creation of the city's Ultra Low Emission Zone that gives them £2,000 for scrapping a non-compliant car, or a scheme in Italy which offers a €2,000 subsidy towards the purchase of a low-emission car if an old vehicle is scrapped at the same time.[25] To be cost-effective, a scrappage scheme could target vehicles that account for a disproportionate share of emissions and scale the support to focus on households with lower incomes. For example, a scheme in France takes into account the type of vehicle being scrapped (petrol or diesel), the emissions of the car being purchased or leased, and the taxable income of the individual to assess the level of support provided.[26]

Renewal of the fleet can also be driven by accelerating the purchase of new, cleaner cars. One option to achieve this is a feebate at car purchase, which places a fee on the purchase of high polluting vehicles and a rebate on the purchase of battery electric vehicles. Such a program could be crafted to be revenue neutral to governments and provide targeted support for households with lower incomes to ensure it is cost effective.

Single policies are often not as effective as combinations of policies to help encourage emissions reductions in several ways. Scottish policymakers could therefore consider a mix of these and other measures to drive down emissions as quickly as possible in Scottish urban areas.

25 Transport for London, "Scrappage Scheme," accessed July 11, 2024, https://tfl.gov.uk/modes/driving/ultra-low-emission-zone/scrappage-schemes?cid=scrappage-scheme; International Energy Agency, "Ecobonus: Subsidy for Low Emission Vehicles," updated March 18, 2022, https://www.iea.org/policies/6789-ecobonus-subsidy-for-low-emission-vehicles.

26 French Government, "Prime à la Conversion pour une Voiture [Conversion Subsidy for a Car]," updated February 14, 2024, https://www.service-public.fr/particuliers/vosdroits/F36848#:~:text=Le%20montant%20de%20la%20prime,est%20sup%C3%A9rieur%20%C3%A0%2030%20km.

APPENDIX

Figure A1 shows the evolution of mean distance-specific NO_x emissions (top) and PM emissions (bottom) of the most common taxi makes, which made up over 10% of the Scottish taxi sample: Ford, London Taxi Company, Mercedes, and Peugeot. There is a notable decrease in mean NO_x emissions of Ford, Mercedes, and Peugeot taxis from 2015 to 2019, but mean PM emissions show little improvement.

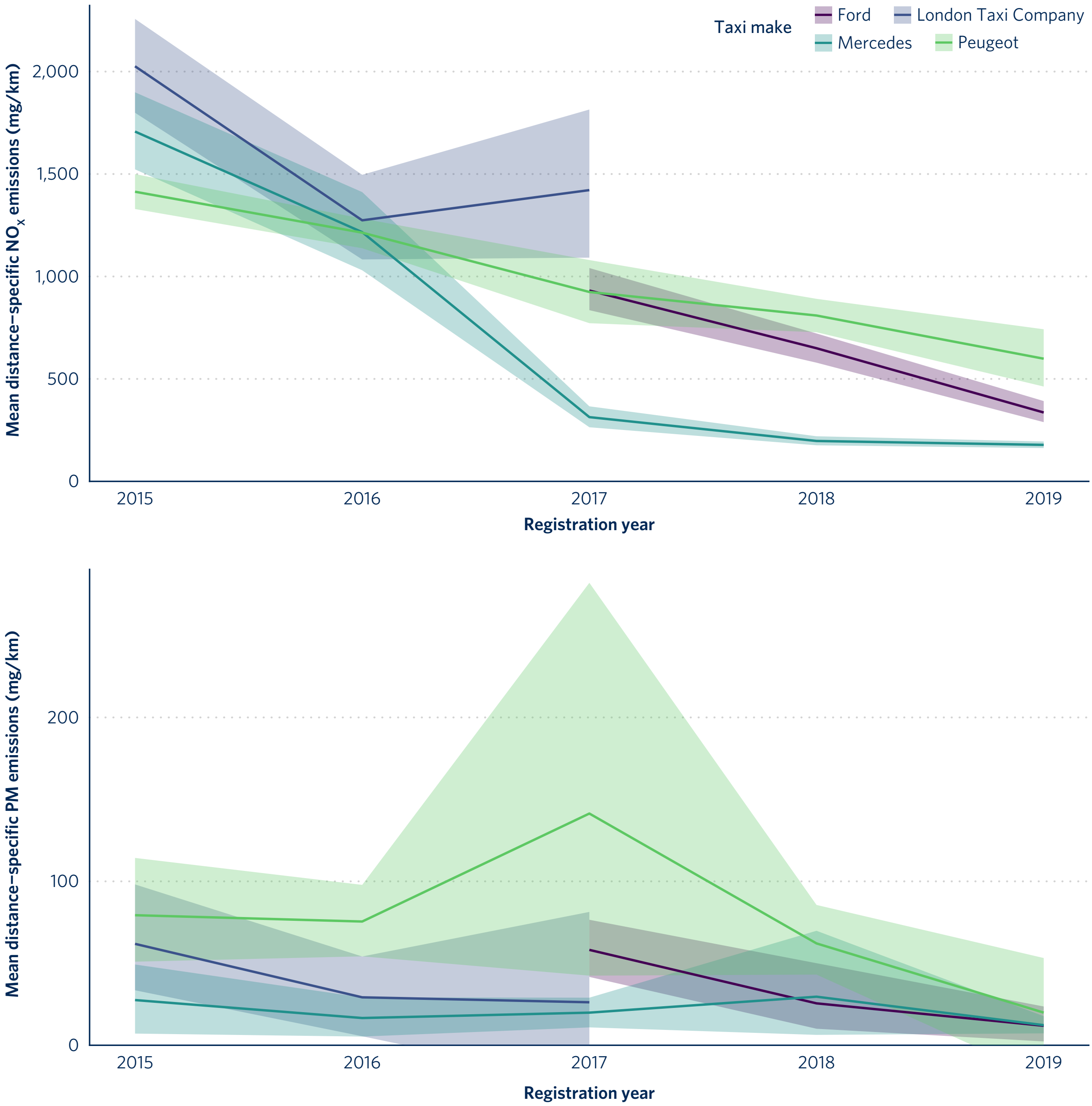

Figure A1. Mean distance-specific NO_x emissions (mg/km) (top) and PM emissions (mg/km) (bottom) from taxi makes that accounted for over 10% of taxi measurements by registration year. Line indicates the mean and shaded area indicates 95% confidence interval to the mean. Only registration years with over 30 measurements are presented.

Figure A2 compares the mean fuel-specific NO_x emissions of taxis, taxis retrofitted with selective catalytic reduction systems, and private hires by emission standard. Regardless of the emission standards to which they were originally type-approved, retrofitted taxis showed comparable mean fuel-specific NO_x emissions, at a level that was more than 50% lower than those of other Euro 5 taxis and private hires but higher than those of Euro 6d-TEMP taxis. However, the large confidence intervals indicate that the emission performance may not be consistent.

Figure A3 shows the mean fuel-specific NO_x emissions from passenger cars by emission standard broken down by campaign year. A consistent trend of emissions increase from the earlier year to the later year is seen for Euro 3 and Euro 4 vehicles across different cities.

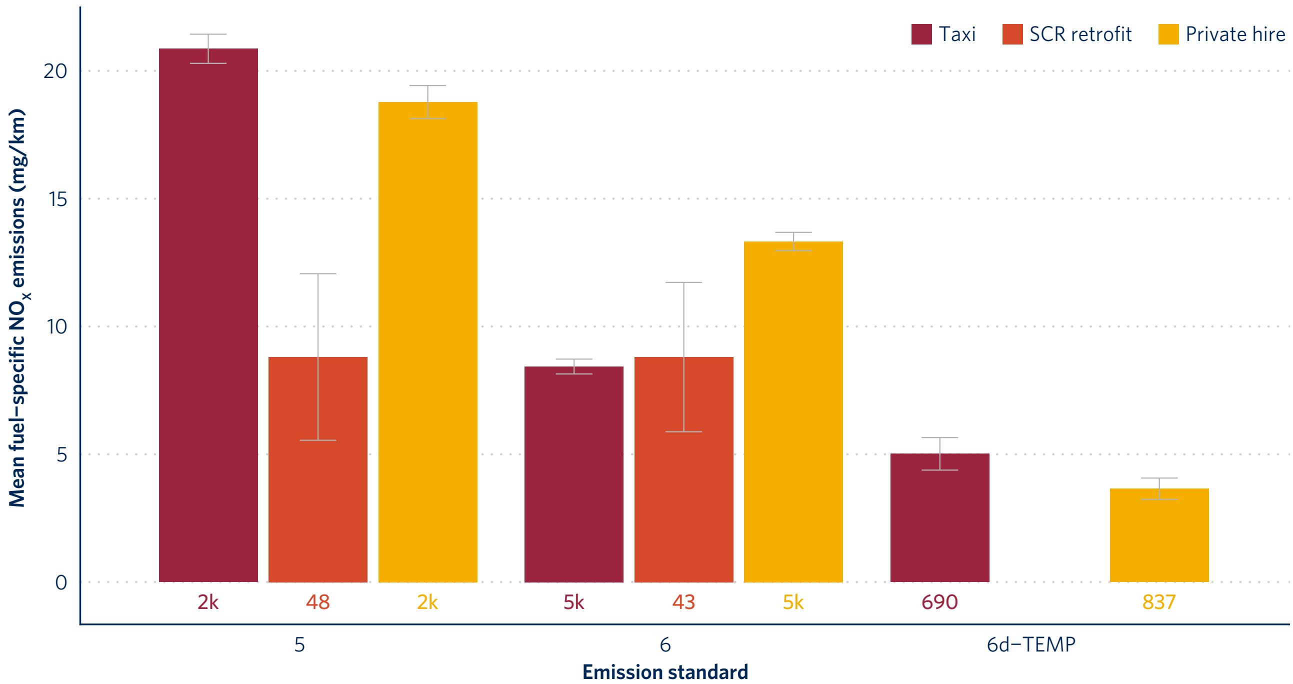

Figure A2. Mean fuel-specific NO_x emissions from taxis, retrofit taxis, and private hires of the Euro 5, Euro 6, and Euro 6d-TEMP standards. Whiskers represent the 95% confidence interval of the mean. Only emission standards with over 30 measurements are presented.

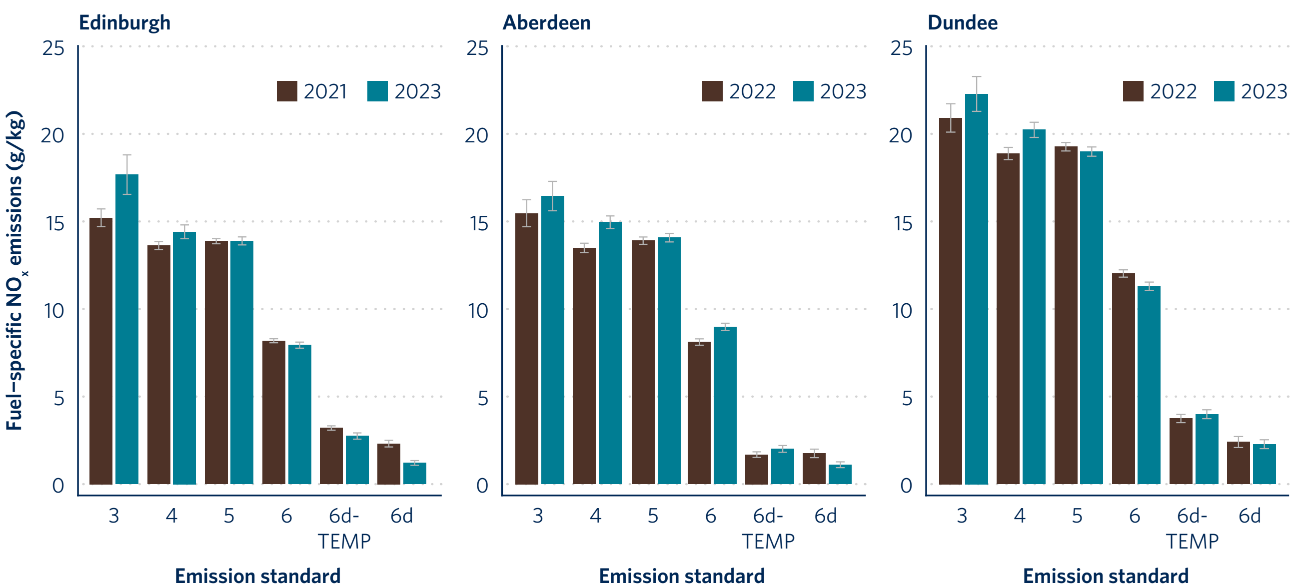

Figure A3. Mean fuel-specific NO_x emissions from passenger cars by emission standard measured at two campaigns. Whiskers represent 95% confidence intervals to the mean.

THE REAL URBAN EMISSIONS INITIATIVE

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