Assessment of real-world vehicle emissions in Scotland in 2021

Emissions testing campaigns in Edinburgh and Glasgow

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ACKNOWLEDGMENTS

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

Transport Scotland commissioned Hager Environmental & Atmospheric Technologies (HEAT), the International Council on Clean Transportation (ICCT), and Element Energy to conduct a remote sensing study to assess real-world vehicle emissions in four main cities in Scotland. These cities—Aberdeen, Dundee, Edinburgh, and Glasgow—plan to begin enforcement of the proposed low emission zones in 2023 and 2024. The first of three emission testing campaigns, scheduled for 2021 to 2023, took place in the fall of 2021 in Edinburgh and Glasgow. The campaign collected over 225,000 measurements from 95,000 unique vehicles using contact-less remote sensing technology.

This report examines the real-world tailpipe emissions of vehicles in Edinburgh and Glasgow and provides an assessment of various transportation policies that have been proposed or planned to address air quality issues in urban areas. Particular attention is given to the environmental performance of passenger cars, including taxis and private hire vehicles, that constitute the largest portion of vehicle activity in these cities. Emissions from taxis and private hires are particularly important as these vehicles are driven significantly more than private passenger cars, making them more prone to deterioration of the emission control system, while accounting for a minor fraction of the fleet. We further investigate emission levels on a more granular level, e.g., by Euro standard and manufacturer, to identify high-emitting vehicle groups. The identification of high-emitting vehicle groups can inform more effective targets of vehicle restriction policy, such as a low emission zone.

In addition to producing data to inform policy, remote sensing technology can assist in the enforcement of high-emitting heavy-duty vehicles in real-time and help to identify individual high-emitters. In this report, we explore an evolving method of identifying high-emitting trucks by using data from multiple measurements of the same truck from two different remote sensing campaigns. One instantaneous measurement of emissions from a passing vehicle does not give a good indication whether the vehicle is high emitting but, with a larger number of emission measurements, a more robust conclusion can be drawn.

The main findings of the Scottish remote sensing study and related policy recommendations to accelerate air quality improvement are summarized below.

KEY FINDINGS

- Passenger car was the most predominant vehicle type found in the remote sensing measurement sample. In Edinburgh and Glasgow, Euro 6 vehicles, generally registered between 2015 and 2019, accounted for over 30% of all measurements, followed by Euro 5 (registered between 2011 and 2014) and Euro 6d-TEMP (registered between 2019 and 2020). In Glasgow, passenger cars were found to use mostly diesel fuel, while petrol vehicles were more common in Edinburgh.
- The nitrogen oxides (NO_x) emission performance of measured diesel vehicles did not improve significantly until the introduction of Euro 6d-TEMP standards. Euro 6d-TEMP vehicles were found to emit, on average, 198mg/km, or 40% the level of the preceding Euro 6 standard (498 mg/km). This improvement is likely due to the Real Driving Emissions (RDE) limits introduced with the Euro 6d-TEMP and 6d standards. The petrol vehicles measured were found to have achieved a steady reduction in real-world NO_x emissions. Euro 3 vehicles emitted 374mg/km while Euro 6d vehicles emitted 70 mg/km, on average.
- While diesel vehicles emit higher levels of NO_x, petrol vehicles are largely responsible for carbon monoxide (CO) and hydrocarbons (HC) emissions. Petrol vehicles were found to have mean CO emissions up to ten times and mean HC emissions around three times those of their diesel counterparts. However, newer petrol vehicles certified to Euro 6d-TEMP and 6d were found to have significantly lower CO emissions, emitting on average below 4g per kg fuel burnt.
- Vehicles measured in Glasgow showed higher mean NO_x and CO emissions than those measured in Edinburgh. This may be attributable not only to the steeper slope of the Glasgow measurement site but also to frequent cold starts and slower speeds characteristic of typical urban driving conditions, which contribute to elevated levels of pollutant emissions.
- Despite improvements compared to vehicles certified to previous standards, post-RDE Euro 6 vehicle families showed varied emissions performance. Only 5 of 15 Euro 6d-TEMP vehicle families, defined by the combination of manufacturer and engine size, and 3 of 7 Euro 6d vehicle families had mean real-world NO_x emissions below their respective on-road limits of 168 mg/km and 114 mg/km.

- Although capturing only a snapshot of vehicle emissions, remote sensing can reveal trends of emission deterioration. When emissions were investigated as a function of the registration year of measured vehicles, there were positive correlations between the NO_x emissions from diesel passenger cars certified to Euro 4–6 and how long they have been registered, or in use. Similar trend was found for CO emissions from petrol passenger cars certified to Euro 4–6. The results allude to the possible degradation of emission control systems of diesel vehicles that were previously not widely studied.
- The remote sensing measurements show that taxis and private hires certified to Euro 4–6, or registered between 2006 and 2019, emit NO_x emissions 41%–68% more on average than other private cars. Taxis were shown to emit significantly higher levels of NO_x than private hire vehicles, with London Taxi Company as the highest emitting taxi brand that still circulate the Scottish cities.
- Large commercial trucks used for long-haul operations are prone to having poor emissions performance in cities because their emission control system may not be optimized for urban driving conditions. The Scottish measurements showed that NO_x emissions from Euro V and Euro VI trucks driven in urban conditions characterized by low speed and cold engines were almost double those from Euro V and Euro VI trucks driven in motorway conditions.
- Buses in Scottish cities showed highly elevated levels of real-world NO_x emissions compared to other buses measured on motorways, mainly due to cold engines and low speeds. Buses certified to the newest standard, Euro VI-D, however, achieved an 80% reduction in NO_x emissions compared to the preceding standard. Limiting the use of older Euro V and VI buses, which made up over 80% of buses measured in the campaign, can be effective at improving air quality.

RECOMMENDATIONS

- Low emission zones (LEZ) will be enforced from the summer of 2023 in Glasgow and from the summer of 2024 in Edinburgh. Based on the fleet composition and real-world emissions data obtained from remote sensing measurements, we find that the LEZ restrictions on diesel cars and vans certified to below Euro 6 and petrol cars and vans below Euro 4 would have disproportionate NO_x emissions benefits. The LEZ will restrict the use of 21% of cars responsible for 52% of the total passenger car NO_x emissions in Edinburgh and 24% of cars responsible for 48% the total passenger car NO_x emissions in Glasgow.
- The two cities can reap greater emissions benefits by expanding the restrictions to diesel vehicles not subject to on-road emissions testing, namely those certified to Euro 6 (not including Euro 6d-TEMP and Euro 6d). These vehicles account for 23% and 29% of the total NO_x emissions from all passenger cars in Edinburgh and Glasgow, while making up 15% and 23% of the total passenger car activities in respective cities.
- Additional measures to limit the use of old taxis and private hires in the cities, such as an age or mileage limit, are recommended to address disproportionate emissions from this group of high-usage vehicles. Particularly, these measures should target taxis, which are currently exempted from the LEZ restrictions until 2024 in Glasgow but emit on average more NO_x emissions than private hire vehicles.
- Despite the significant volume of NO_x emissions from all types of vehicles illustrated by the Scottish remote sensing measurements, there is currently no capability within the Scottish Ministry of Transport (MOT) to screen for NO_x emissions. However, opportunities may lie at the annual MOT certification, either via adding enhanced emissions monitoring as a routine part of testing or following the identification of high emitters using remote sensing.

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INTRODUCTION

Clean air is essential to human health and well-being. Although Scotland's air quality is relatively cleaner than its neighbouring countries due to regulations that have curbed emissions from industry, heating, and transport, it is estimated that air pollution still contributes to 1,700 premature deaths annually in the country.[1] Air pollution remains a particular concern in highly urbanized areas. In these so-called urban air pollution hot spots, transportation is the biggest source of air pollution. On-road transportation emits air pollutants, such as particulate matter (PM), nitrogen oxides (NO_x), carbon monoxide (CO), hydrocarbons (HC), ammonia (NH3), to which the short- and long-term exposure can pose great health risks, such as increased rates of respiratory and cardiovascular illnesses.

Particulate matter concentrations in urban areas, such as Aberdeen, Dundee, Edinburgh, and Glasgow, were found to be substantially higher compared to rural areas in Scotland.[2] To address the elevated levels of air pollution and its resulting health consequences, Scotland adopted the *Cleaner Air for Scotland strategy* that delineates measures to curb emissions from different sources and sets timelines for their implementation.[3] Alongside its plans to encourage a modal shift from cars to public transit and reduce overall on-road traffic, the strategy also supports local authorities in developing, implementing, and enforcing low emission zones in four major cities: Aberdeen, Dundee, Edinburgh, and Glasgow. The Scottish low emission zones aim to improve the cities' air quality by limiting the access of the most polluting vehicles to the city centres.

In line with these efforts, Transport Scotland has formed a consortium with Hager Environmental & Atmospheric Technologies (HEAT), the International Council on Clean Transportation (ICCT), and Element Energy to collect real-world emissions data from on-road vehicles using a cutting-edge remote sensing technology and develop air quality monitors in the proposed low emission zones. As part of the Air Remote Sensing Project, Emissions Detection and Reporting (EDAR) systems were deployed near the proposed low emission zones in Aberdeen, Dundee, Edinburgh, and Glasgow in 2021, 2022, and a future trial will collect more data in 2023. The EDARs measure real-time vehicle emissions of air pollutants, including nitrogen oxides (NO and NO_2), carbon monoxides (CO), and hydrocarbons (HC). Real-world emissions data collection at this scale is the biggest of its kind in Europe.

This report summarizes the main findings from the analysis of the Scottish measurements from the first deployment which took place in October 2021 in Edinburgh and Glasgow. The report first provides an overview of remote emissions sensing technology and the 2021 emissions testing in Edinburgh and Glasgow. The second section presents how the fleet activity has evolved over time in Scotland based on the remote sensing measurements taken in 2017, and in two previous campaigns led by HEAT in 2017 and 2019–2020. Emission measurements of NO_X and CO from these three testing campaigns are compared for passenger cars to provide insight into various emissions characteristics of vehicles in Scotland. The paper further investigates the passenger car fleet on a more granular level, focusing on city-specific emissions trends, the emissions performance of new diesel passenger cars, the possible effect of ageing on emissions, and the emissions impact of low emission zones in two cities. Other vehicle classes, such as light-commercial vehicle, truck, and bus, are also assessed. More notably, this paper explores the potential use of remote sensing measurements for identifying individual high-emitting trucks and defining high-emitter thresholds for real-world enforcement. The paper concludes with policy recommendations derived from the findings.

1 Air Quality in Scotland, "About Air Quality," (2021), https://www.scottishairquality.scot/air-quality.

2 'Public Health Scotland, "Air Pollution & Health Briefing Note: Mortality Associated with Exposure to Fine Particulate Matter (PM2.5 Attributable Mortality) in Scotland," (June 2018), https://www.hps.scot.nhs.uk/web-resources-container/air-pollution-and-health-briefing-note-mortality-associated-with-exposure-to-fine-particulate-matter-pm25-attributable-mortality-in-scotland/.

3 Scottish Government, "Cleaner Air for Scotland 2: Delivery Plan," (22 July, 2021), https://www.gov.scot/publications/cleaner-air-scotland-2-delivery-plan/.

REMOTE SENSING TECHNOLOGY OVERVIEW

Remote sensing technology was deployed to measure real-world emissions from in-use vehicles in Scotland. Set up at the side of or above a roadway, open-path remote sensing systems use a light beam to measure pollutant concentration ratios from the exhaust plumes of passing vehicles. The emission measurements are subsequently paired with vehicle specification data and other parameters measured with the accompanying device, such as speed, acceleration, and ambient temperature, to provide information about the emissions performance of measured vehicles. Thanks to its unobtrusiveness and ability to capture a large quantity of passing vehicles with relatively small efforts, remote sensing has been applied for various compliance and enforcement purposes, such as inspection for emission limit exceedances and identification of high-emitting vehicle groups. Remote sensing measurements are also used to develop emissions factors for emissions inventories, and the assessment of real-world emissions from vehicles helps support and inform certain policy decisions.[4]

The EDAR systems, a commercial open-path remote sensing instrument developed by HEAT, were deployed in Scotland for emissions testing in 2021. Figure 1 illustrates how the EDAR unit measures exhaust emissions of passing vehicles. The EDAR systems capture the air pollutant concentrations of NO, NO_2, CO, and HC in exhaust plumes, which are expressed in terms of CO_2. The instrument also records speed and acceleration of each passing vehicle which, once combined with the road slope, allows the calculation of vehicle specific power (VSP), a proxy of the power demand on the engine during driving.

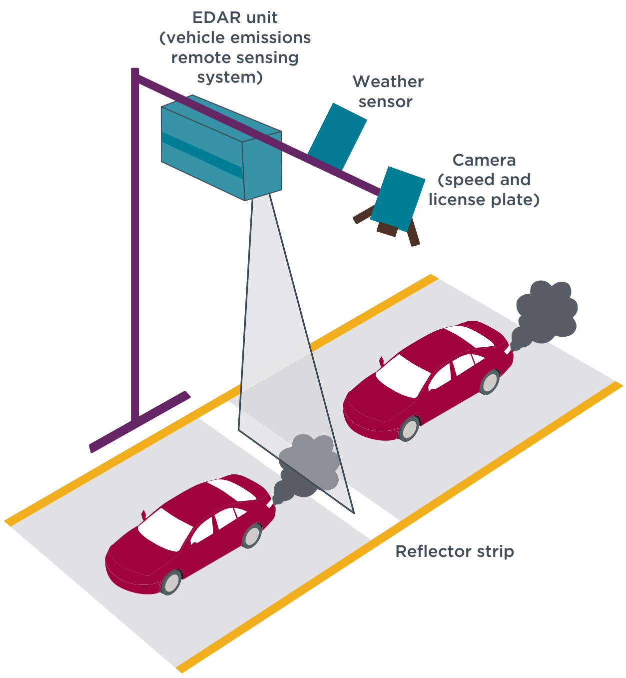
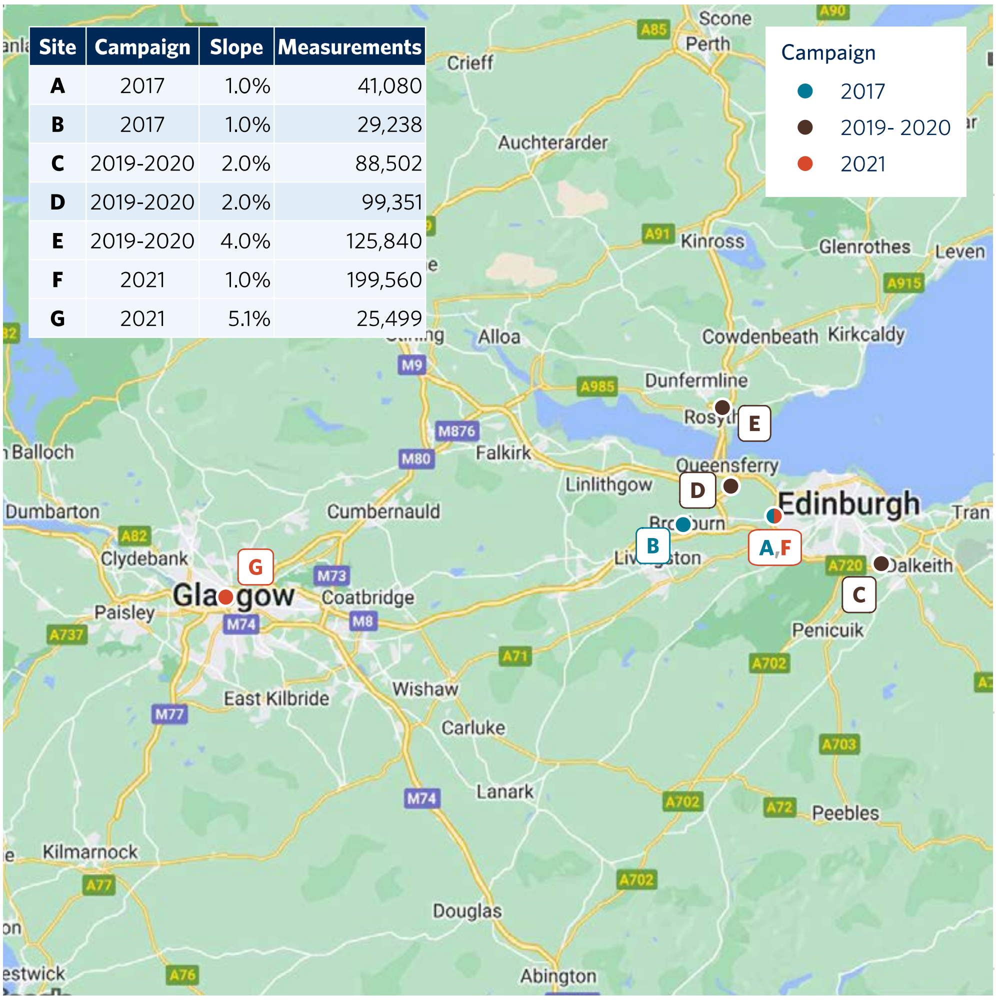


Figure 1. Illustration of how the EDAR unit measures exhaust emissions from on-road vehicles (left), and an EDAR system measuring emissions from a bus in Glasgow (right).

4 Yoann Bernard, John German, and Rachel Muncrief, "Worldwide Use of Remote Sensing to Measure Motor Vehicle Emissions," (Washington, DC: ICCT, 2019) https://theicct.org/publication/worldwide-use-of-remote-sensing-to-measure-motor-vehicle-emissions/.

REMOTE EMISSIONS SENSING TESTING OVERVIEW

A total of over 225,000 measurements were collected from 95,000 unique vehicles in Edinburgh and Glasgow in 2021. The measurement campaigns, which took place between October 20 and November 18, collected 199,560 measurements from 84,201 unique vehicles from Glasgow Road in Edinburgh and 25,499 measurements from 10,926 unique vehicles at the junction of West Campbell Street and St. Vincent Street in Glasgow. Glasgow Road, located at the western skirt of Edinburgh and is mixed-used (commercial and residential), is a four-lane road with a daily traffic flow of around 40,000 vehicles.[5] St. Vincent Street is located in the Glasgow city centre and has an estimated daily road traffic of around 6,000 vehicles.[6] Both sites are located within the proposed Scottish low emission zones that will be enforced from June 2023 in Glasgow and from June 2024 in Edinburgh. The higher number of measurements than the number of unique vehicles indicates that some vehicles were measured more than once. HEAT previously collected emissions measurements from Edinburgh in 2017 and 2019–2020, which are assessed in addition to the 2021 measurements in this paper. The testing locations, the numbers of measurements collected, and the slopes of the testing sites for all three testing campaigns is shown in Figure 2.



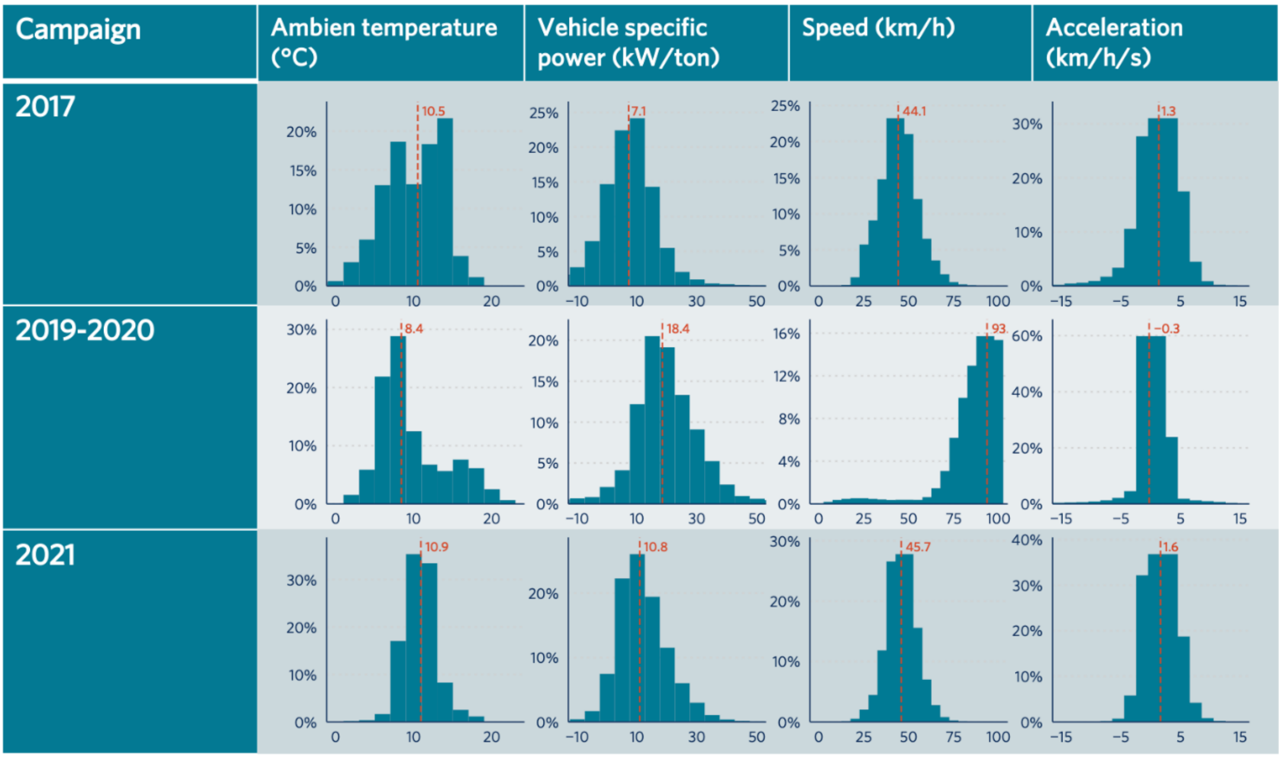
Site	Campaign	Slope	Measurements
A	2017	1.0%	41,080
B	2017	1.0%	29,238
C	2019-2020	2.0%	88,502
D	2019-2020	2.0%	99,351
E	2019-2020	4.0%	125,840
F	2021	1.0%	199,560
G	2021	5.1%	25,499

Figure 2. The location of measurement sites, the slope in each location, and the number of measurements taken during the remote sensing measurement campaigns.

5 UK Department for Transport, "Road Traffic Statistics," https://roadtraffic.dft.gov.uk/.

6 UK Department for Transport, "Road Traffic Statistics."

Table 1. Distributions of ambient temperature, vehicle specific power (VSP), speed, and acceleration of measured vehicles in the Scottish remote sensing testing campaigns.



Driving and testing conditions are closely associated with emissions. Understanding the distribution of these parameters is particularly important when comparing emissions from vehicles tested in different locations. The distributions of testing condition parameters, such as ambient temperature, VSP, speed, and acceleration, are summarized in Table 1 for each campaign. All three testing campaigns showed similar ambient temperatures, with respective mean temperatures of 10.5°C in 2017, 8.4°C in 2019–2020, and 10.9°C in 2021. However, the 2019–2020 campaign is characterized by significantly higher VSP and speed, and lower acceleration, typical of conditions found on a motorway. The vehicles measured from the 2017 and 2021 testing campaigns showed highly comparable distributions and mean values of speed and acceleration, which allowed a reasonable comparison of their emissions.

FLEET COMPOSITION

VEHICLE CLASSES

The vehicle classes of the measured vehicles were identified using the vehicle specification data available in the Scottish Driver and Vehicle Licensing Agency database. The distribution of vehicle measurement samples is shown in Figure 3. All vehicle measurements, including those with invalid emissions measurements, were used to describe the vehicle activity for more accurate representation. The most common vehicle class was passenger car, which made up the highest share in all testing campaigns, followed by light commercial vehicle and truck. There were higher shares of light commercial vehicles and trucks measured in 2019–2020 due to the testing site being on a motorway, which tends to have higher traffic of heavy-duty vehicles. The vehicle classes of over 10% of vehicles in the 2019–2020 and 2021 campaigns were not identifiable, likely because they are foreign vehicles and information is not available in the Scottish registry database.

The distribution of fuel types varied by vehicle class. More than half of the measured passenger cars were petrol-powered. The remaining vehicles were mainly diesel-powered, with some vehicles powered by alternative fuels like liquefied petroleum gas (LPG) and compressed natural gas (CNG). Electric passenger cars were identified in the more recent testing campaigns in 2019–2020 and 2021. For larger vehicle classes, diesel was the predominant fuel type.

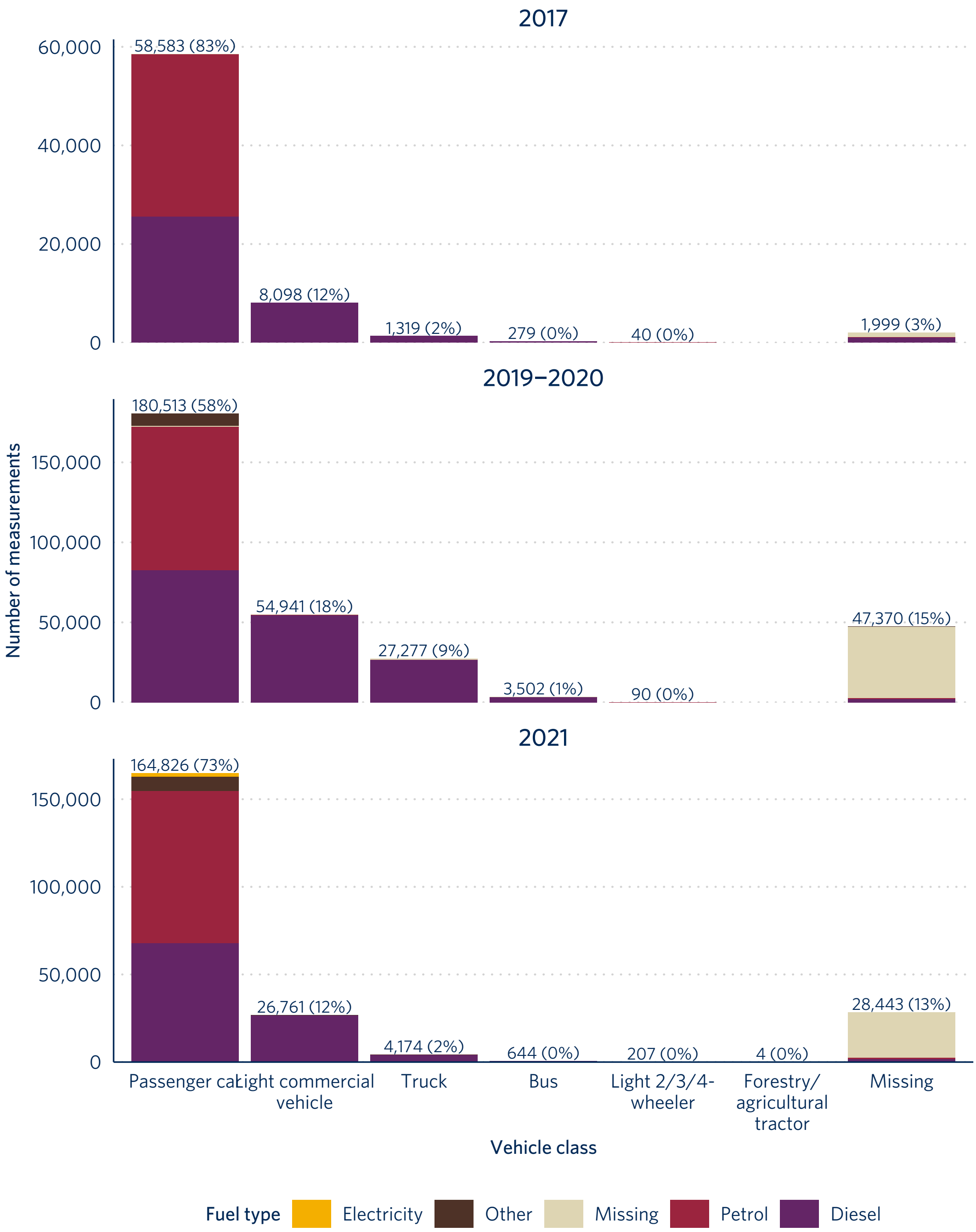


Figure 3. Distribution of measurements from the 2017, 2019–2020, and 2021 testing campaigns by vehicle class and fuel type.

PASSENGER CAR COMPOSITION

As passenger car was the most common vehicle class found in all testing campaigns, the following section further focuses on the composition of the measured passenger cars. The distribution of fuel types and Euro standards of passenger car measurements is shown in Figure 4. More detailed information on fuel type was available in the 2019–2020 and 2021 data and, therefore, cars powered by LPG, CNG, and electricity are shown for these years. For the measurements in 2019–2020 and 2021 with missing Euro standard information, the Euro standard was estimated based on registration date. The composition of passenger cars from the 2021 measurements in Figure 4 also include taxis and private hires.

The comparison of passenger car sample distribution across the three campaigns gives an indication of how

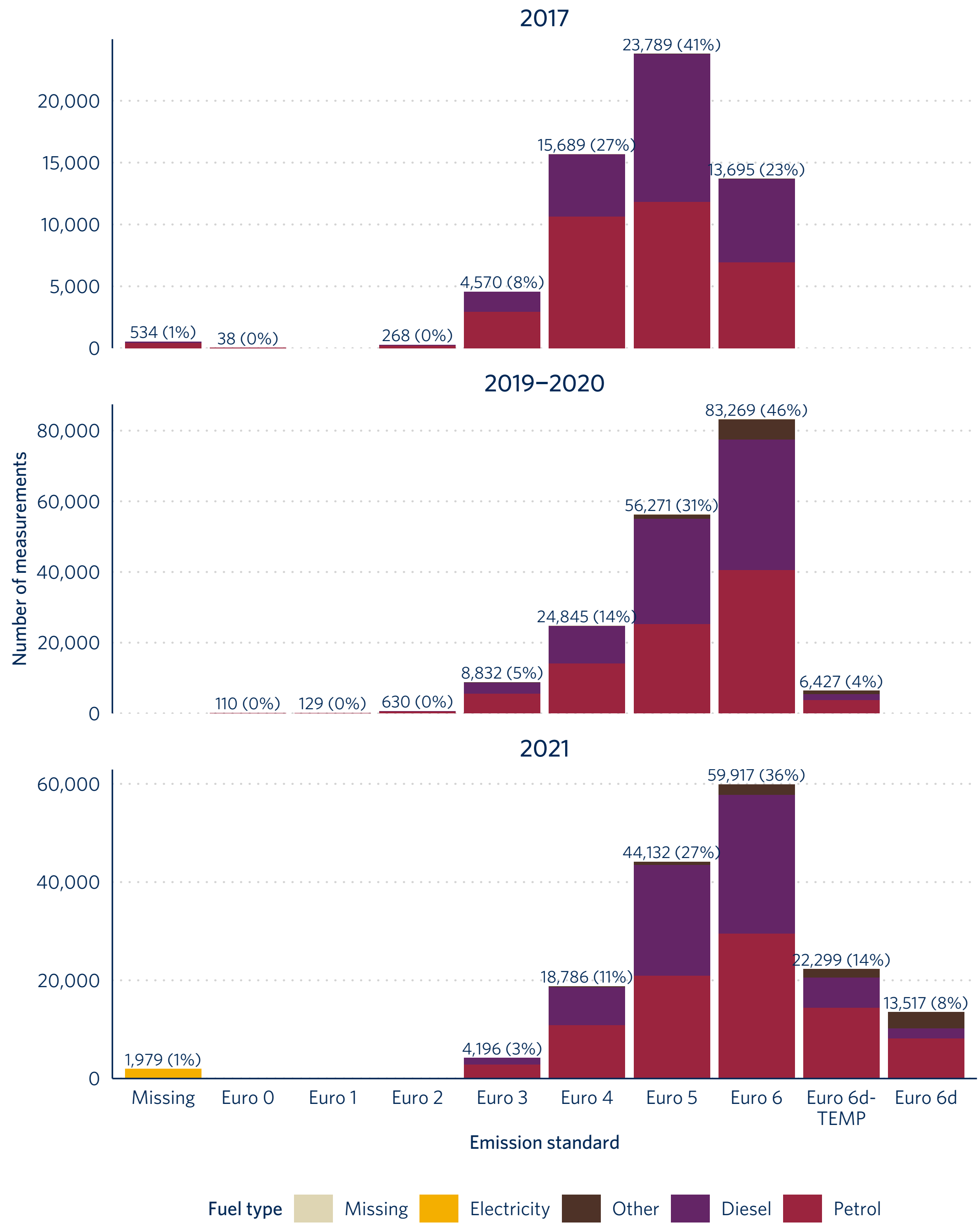


Figure 4. Distribution of passenger cars from the 2017, 2019–2020, and 2021 testing campaigns by fuel type and Euro standard.

the Scottish passenger car fleet has evolved. Vehicles certified to older Euro standards, such as Euro 2 and 3, were gradually phased out over time and replaced by vehicles of newer standards, as evident in the 2019–2020 and 2021 data. In 2017, Euro 5 was the most predominant standard in the data, followed by Euro 4, but this shifted to Euro 6 and Euro 5, as older passenger cars retired. More notably, there is a clear upward trend of the Euro 6d-TEMP vehicle share, the standard that was introduced from late 2019, and an emergence of vehicles certified to Euro 6d, which was mandatory for new passenger cars from early 2021. Vehicles with newer standards like Euro 6d-TEMP and above were primarily petrol-powered, highlighting the diminishing demand for diesel vehicles in recent years.

PASSENGER CAR EMISSIONS COMPARISON ACROSS CAMPAIGNS

This section explores the trends of main pollutant emissions that were measured during the testing campaigns: NO_X, CO, and HC. All measurements collected in 2017 and 2019–2020 had valid emissions measurements and, therefore, the numbers of measurements remain unchanged for the emissions analysis. Approximately 87% of the 2021 sample had valid emissions measurements. To remove unusually high or low values of emissions and ensure the comparability of the samples, emissions measurements with only positive VSP were included.

Remote sensing technology typically reports pollutant emissions in terms of amount of pollutant per kilogram of fuel burnt (g/kg). However, to allow the comparison between the measured emission levels and regulatory limits, the fuel-specific values were converted to distance-specific values, or grams of pollutant per kilometre travelled (g/km), using available type-approval CO_2 emissions information from passenger cars.[7] As not all passenger cars had CO_2 information, the number of valid distance-specific NO_X measurements was lower.

FUEL-SPECIFIC NO_X EMISSIONS

The mean fuel-specific NO_X emissions by Euro standard for all three testing campaigns appear to be in good agreement, showing similar downward trends with newer standards (Figure 5). When comparing standard by standard, diesel vehicles showed significantly higher NO_X levels than their petrol vehicle counterparts. Particularly, diesel vehicles certified to below Euro 6d-TEMP had mean NO_X emissions four to five times those of the petrol cars certified to the same standards. However, the emissions difference between the fuel types diminishes with the introduction of Euro 6d-TEMP and 6d, which mandated on-road emissions testing in addition to laboratory testing during type approval.

Diesel vehicles do not show a large improvement in NO_X emissions performance until Euro 6d-TEMP, when additional Real-Driving Emissions (RDE) testing became

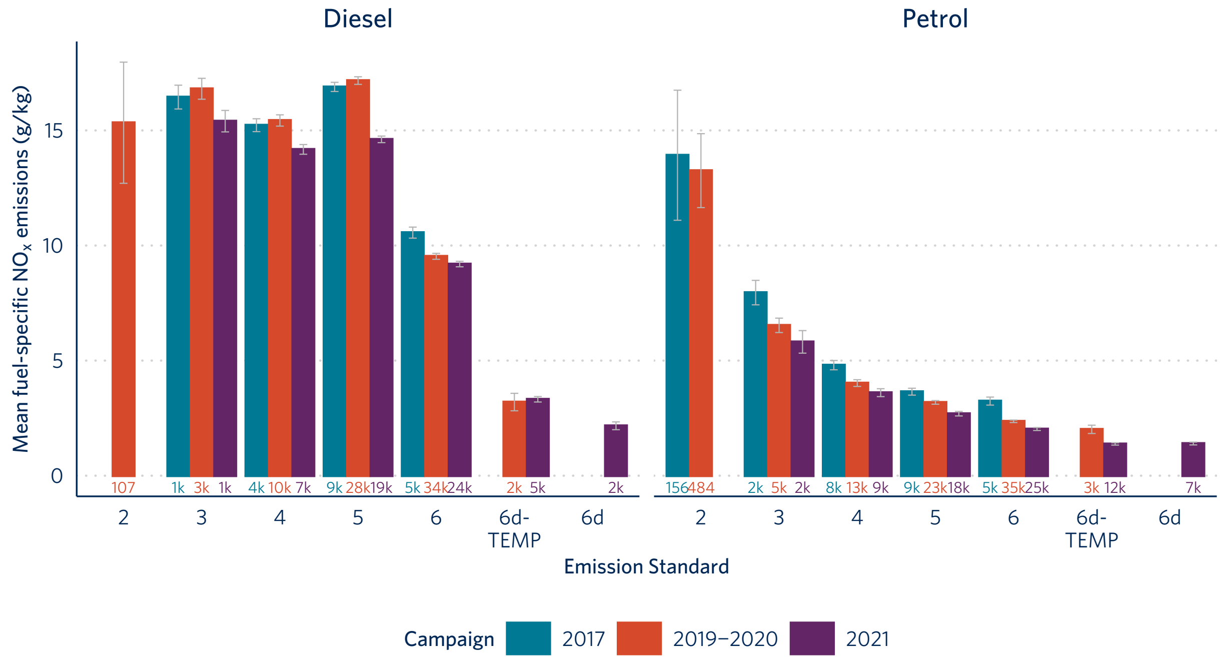


Figure 5. *Mean* fuel-specific NO_X emissions from passenger cars measured in Scotland in 2017, 2019–2020, and 2021. The number of measurements is presented below each bar and only measurements of over 100 are presented. Whiskers represent the 95% confidence interval of the mean.

7 Yoann Bernard, Jan Dornoff, and David Carslaw, "Can accurate distance-specific emissions of nitrogen oxide emissions from cars be determined using remote sensing without measuring exhaust flowrate?," *Science of the Total Environment* 860 (April 2022): 151500, https://doi.org/10.1016/j.scitotenv.2021.151500

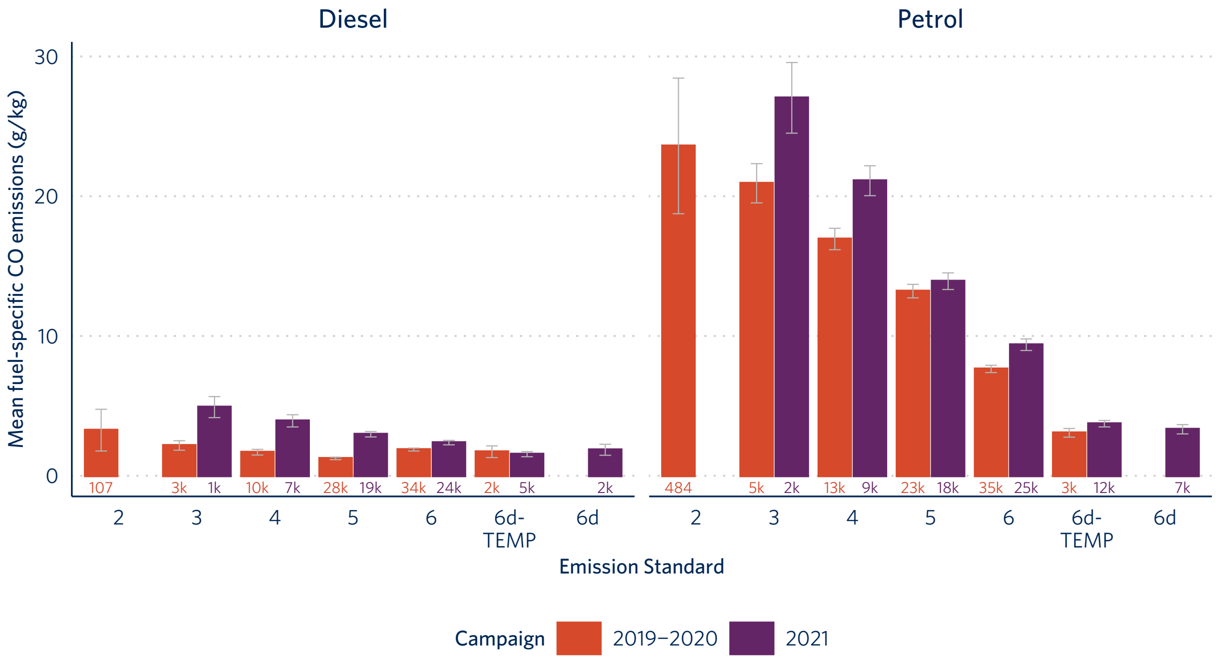


Figure 6. Mean fuel-specific CO emissions from passenger cars measured in Scotland in 2019–2020 and 2021. The number of measurements is presented below each bar and only measurements of over 100 are presented. Whiskers represent the 95% confidence interval of the mean. CO emissions measurements were not available for vehicles measured during the 2017 campaign.

obligatory. Diesel vehicles certified to the standards subject to RDE testing, Euro 6d-TEMP and 6d, show NO_X levels of around 30% of the Euro 6 level. A small increase of around 10% in the mean NO_X emissions from diesel Euro 4 to Euro 5 demonstrates a possible influence of diesel particulate filters (DPFs), which were introduced for Euro 5 to reduce tailpipe PM emissions. but may have motivated manufacturers to maintain elevated real-world NOx emissions to limit excessive soot emissions. This is because the excess soot emissions more quickly load the filter and require more frequent regeneration. Petrol vehicles show a steady and gradual improvement in NO_X performance over time, with the newest standards still emitting NO_X at levels half of their diesel counterpart.

FUEL-SPECIFIC CO EMISSIONS

Diesel vehicles emit lower levels of CO emissions than petrol vehicles, owing to excess oxygen available in the diesel engines. The results from the 2019–2020 and 2021 measurements show that the mean CO emissions from petrol vehicles were up to ten times those from their diesel counterparts (Figure 6). However, petrol vehicles show a steady improvement in CO performance with newer standards. From Euro 4 to Euro 6, every subsequent standard achieved a reduction of around 30% and CO emissions from Euro 6d-TEMP and Euro 6d vehicles showed real-world mean CO emissions at below 4 g/kg.

Vehicles measured in 2021 showed higher mean CO emissions than those measured in 2019–2020 across all available standards. This trend can be attributable to the higher average speed and VSP in the 2019–2020 data or may further indicate possible deterioration of emissions control systems.

FUEL-SPECIFIC HC EMISSIONS

Similar to CO emissions, petrol vehicles are largely responsible for HC emissions due to the incomplete combustion characteristic of spark ignition engines used for these vehicles. In the 2019–2020 sample, petrol vehicles showed real-world HC emissions around three times those from diesel counterparts across standards (Figure 7). In 2021, however, the gap between vehicles of the two fuel types appeared to be smaller, mainly due to the more elevated HC emissions seen in diesel vehicles. Higher HC emissions from diesel vehicles in 2021 than those in 2019–2020 are likely due to cold engines, commonly found in urban driving conditions.

The HC emission performance of diesel vehicles in 2021 do not show great improvement with newer standards, especially in urban settings. The newest standard, Euro 6d,

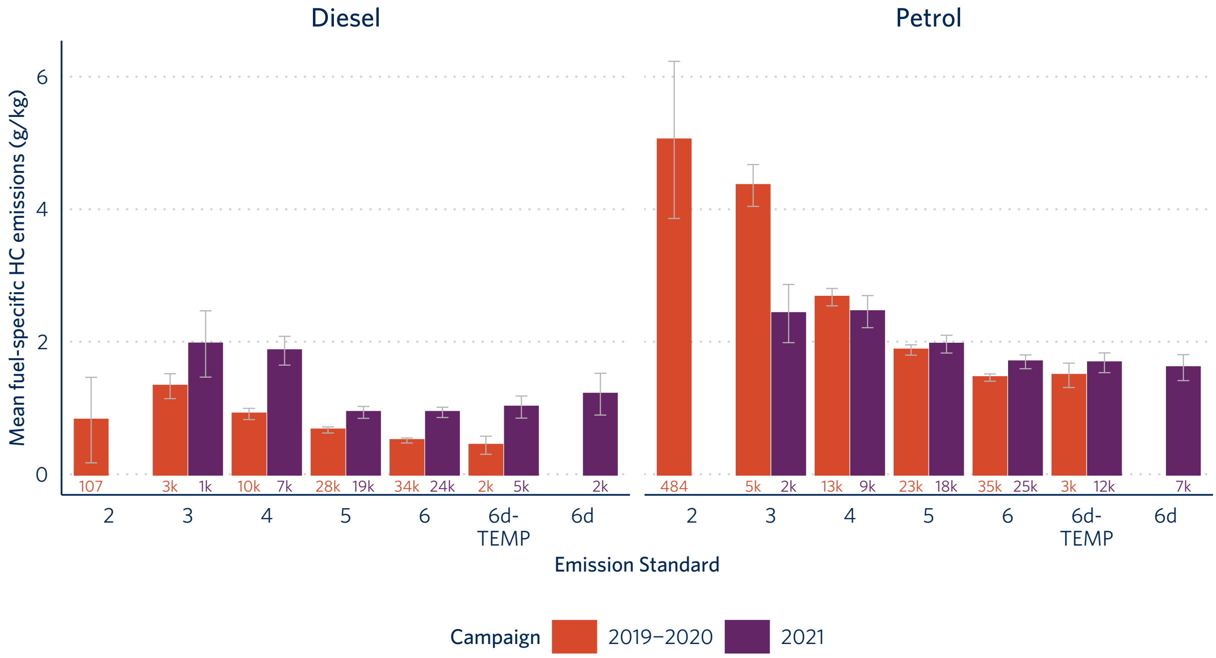


Figure 7. Mean fuel-specific HC emissions from passenger cars measured in Scotland in 2019-2020 and 2021. The number of measurements is presented below each bar and only measurements of over 100 are presented. Whiskers represent the 95% confidence interval of the mean. HC emissions measurements were not available for vehicles measured during the 2017 campaign.

showed both higher mean HC emissions and its variance than the preceding Euro 6d-TEMP standard. Similar levels of median HC emissions from Euro 6d-TEMP and Euro 6d diesel vehicles further confirmed the finding that little improvement has been made to the HC performance of recent diesel vehicles.

DISTANCE-SPECIFIC NO_X EMISSIONS

In order to assess the real-world performance of vehicles on road, mean NO_x emissions expressed in grams per kilometre travelled are compared with emission limits which vehicles are subject to meet in the laboratory or during on-road testing for the Euro 6d-TEMP standard or above. Due to the lack of CO_2 emissions information, distance-specific NO_x emissions for the 2017 measurements were not calculated. The mean distance-specific NO_x emissions followed the same trend as the fuel-specific NO_x emissions (Figure 8). Real-world distance-specific NO_x emissions from vehicles of all fuel types and Euro standards were above the type-approval emissions limits. The exceedances are especially noteworthy for diesel vehicles certified to Euro 3–6, whose real-world emissions were several times their respective limits. Despite a significant improvement in emissions performance, vehicles certified to post-RDE Euro standards measured in the Scottish fleet showed higher emissions than the on-road limits, which introduced the conformity factors of 2.1 and 1.43 for Euro 6d-TEMP and 6d, respectively. Petrol vehicles had real-world distance-specific NO_x emissions generally significantly lower than their diesel counterparts. However, the distance-specific NO_x levels of all emission standards exceeded respective type-approval laboratory limits.

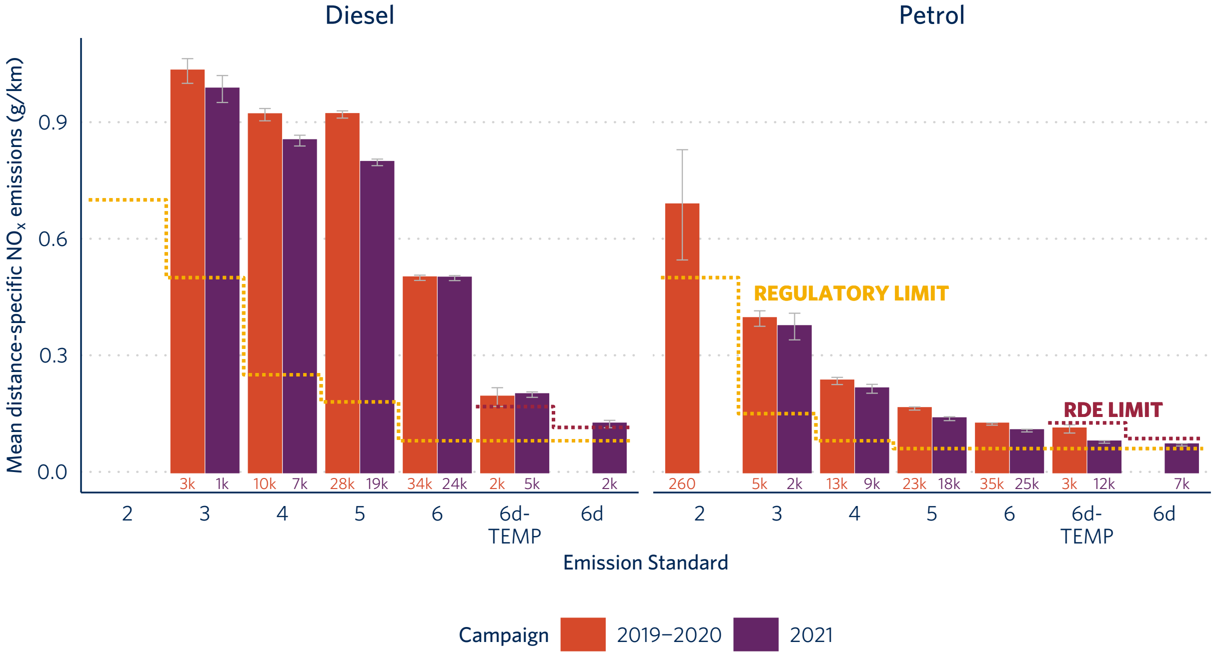


Figure 8. *Mean* distance-specific NO_x emissions from passenger cars measured in Scotland in 2019–2020 and 2021. The number of measurements is presented below each bar and only measurements of over 100 are presented. Whiskers represent the 95% confidence interval of the mean. Distance-specific NO_x emissions were not calculated for the 2017 measurements. Type-approval limits are indicated in dotted yellow line and RDE limits in red dotted line.

DETAILED ASSESSMENT OF THE 2021 MEASUREMENTS

EMISSIONS TREND BY REGISTRATION YEAR FOR ALL VEHICLE CLASSES

Vehicles of different classes and powered by different fuels inevitably emit different levels of pollutant emissions due to differences in mass or weight, technology, and fuel efficiency. To give an overview of how emission trends vary by vehicle classes, however, this section presents fuel-specific NO_x emissions for all vehicle classes powered by diesel. Petrol vehicles were not included in this analysis as they were mostly found only in one vehicle class, passenger car. It is important to note that the use of the fuel-specific metric does not take into account the differences in fuel consumption across different vehicle classes and may not provide an accurate comparison between different vehicle classes. Therefore, the following analysis focuses on the NO_x emissions trend for each vehicle type, rather than a cross-comparison of different vehicle types.

The fuel-specific NO_x emissions trend by year of registration for each vehicle class is shown in Figure 9.

Light-duty vehicles, including passenger cars, light commercial vehicles, taxis, and private hire vehicles, generally showed a downward trend with no huge variance over time. Only the taxi fleet showed a slight upward trend in the early 2000s because taxis registered during this time consisted mostly of London Taxi Company taxis which showed lower fuel-specific NO_x emissions than distance-specific NO_x emissions.

Heavier duty vehicles, such as trucks and buses, show a bigger variance in fuel-specific NO_x emissions by registration year. Heavy-duty vehicles have a shorter lifespan than light-duty vehicles and, therefore, had insufficient data points for registration dates before 2015; this likely explains the high fluctuation before 2014 for both bus and truck. The variance in recent years, such as the peak emissions in 2018 for buses, may be attributable to the improvement in fuel efficiency these vehicles underwent during this time.

Figure 10 shows the trend of the mean and median NO_x emissions, as well as their interquartile range. For all diesel vehicle classes, there is little discrepancy between the mean and median NO_x emissions over time, which likely indicates that all vehicles showed similar levels of emissions with no or few high- or low-emitting vehicles that influenced the mean emissions. The interquartile range (25th to 75th percentile range) of each vehicle class narrows for vehicles registered in recent years, giving an indication of possible emission control system deterioration in older vehicles, as well as consistent emissions performance of newer vehicles. The evidence of possible deterioration of emission control systems from passenger cars in Scotland is further discussed in the *Age and Emissions of Passenger cars* section.

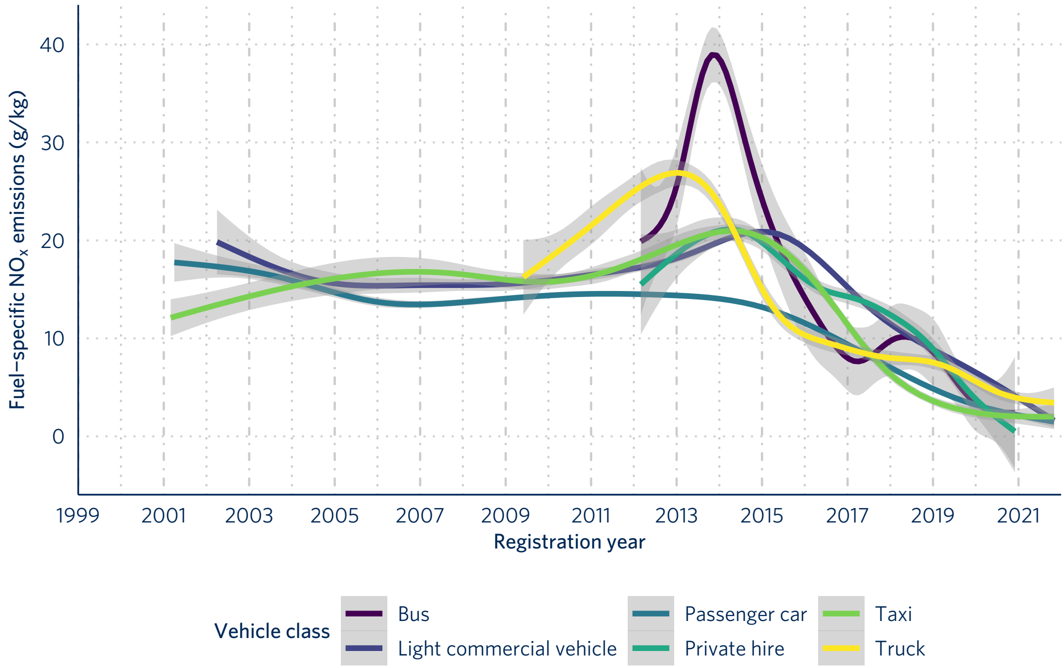


Figure 9. Regression of registration year and fuel-specific NOx emissions for vehicle classes of all diesel vehicles using the GAM method. Shaded area of each fitted line represents 95% confidence interval on the fitted values.

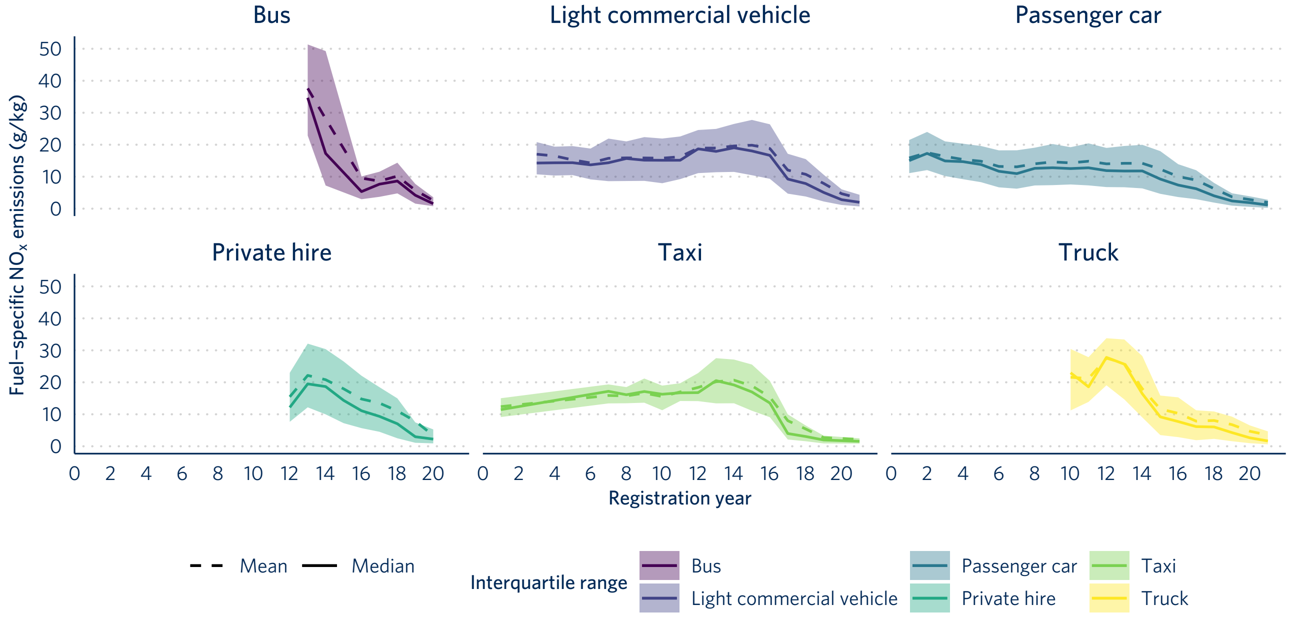


Figure 10. Mean and median fuel-specific NOx emissions (g/kg) by registration year for all diesel vehicle classes. Shaded area represents the interquartile range (25th to 75th percentile range).

EMISSIONS FROM PRIVATE PASSENGER CARS

A total of 155,000 passenger car measurements were collected from the remote sensing testing in 2021. The following analysis only covers private passenger cars; emissions from taxis and private hires are investigated in a separate section. The remote sensing testing collected a total of 144,343 measurements from 67,460 unique private passenger cars in Edinburgh and 10,738 measurements from 7,332 unique cars in Glasgow. The two cities conducted the measurements under similar testing conditions (Table 2), which allowed for valid comparison between the two fleets. The main difference was speed; the passenger car fleet measured in Glasgow had a mean speed slightly lower than that measured in Edinburgh, representing the urban driving conditions.

The compositions of private passenger cars measured in the two cities, which included both valid and invalid emissions measurements, were also comparable, as shown in Figure 11. In both cities, Euro 6 was the predominant standard, accounting for over 30% of the private passenger car fleet, followed by Euro 5 and Euro 6d-TEMP. Although small, a similar share of electric vehicles was seen in the two cities. There was also a growing share of hybrid vehicles with newer standards. The share of diesel vehicles, however, was higher in Glasgow than in Edinburgh, making up 51% and 37% of the total measurements, respectively. A minor share of other fuel types, such as CNG and diesel-electric hybrids, was also found in the sample. The mean age of these vehicles was slightly older in Edinburgh (5.8 years) than in Glasgow (5.4).

MEAN FUEL-SPECIFIC NO_X EMISSIONS BY SITE

The mean NO_X emissions measured in Glasgow were consistently higher than those in Edinburgh for early Euro standards (Euro 3–6). Figure 12 demonstrates that vehicles perform consistently worse in Glasgow, likely due to the location where measurements were collected, that is in

Table 2. Testing conditions of measurements taken in Edinburgh and Glasgow in 2021.

	Ambient temperature (°C)	VSP (kW/t)	Speed (km/h)	Acceleration (km/h/s)
Edinburgh	10.9	12.4	46.6	1.7
Glasgow	11.3	12.0	38.1	1.2

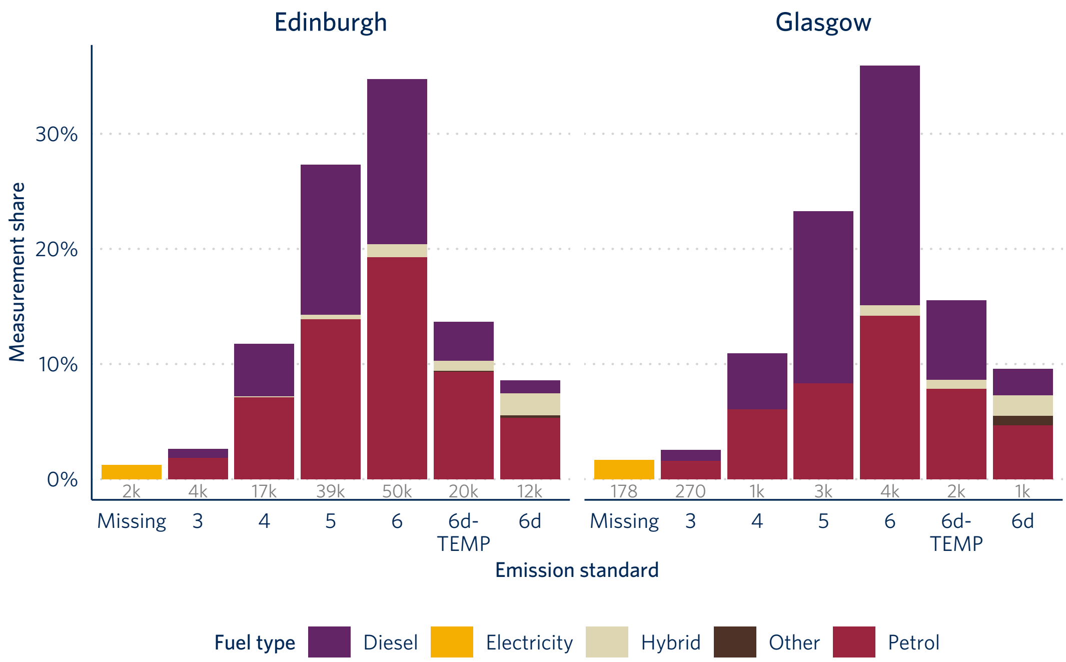


Figure 11. Fleet composition of private passenger cars measured in Edinburgh and Glasgow in 2021. The number of measurements is presented below each bar and only measurements of over 100 are presented.

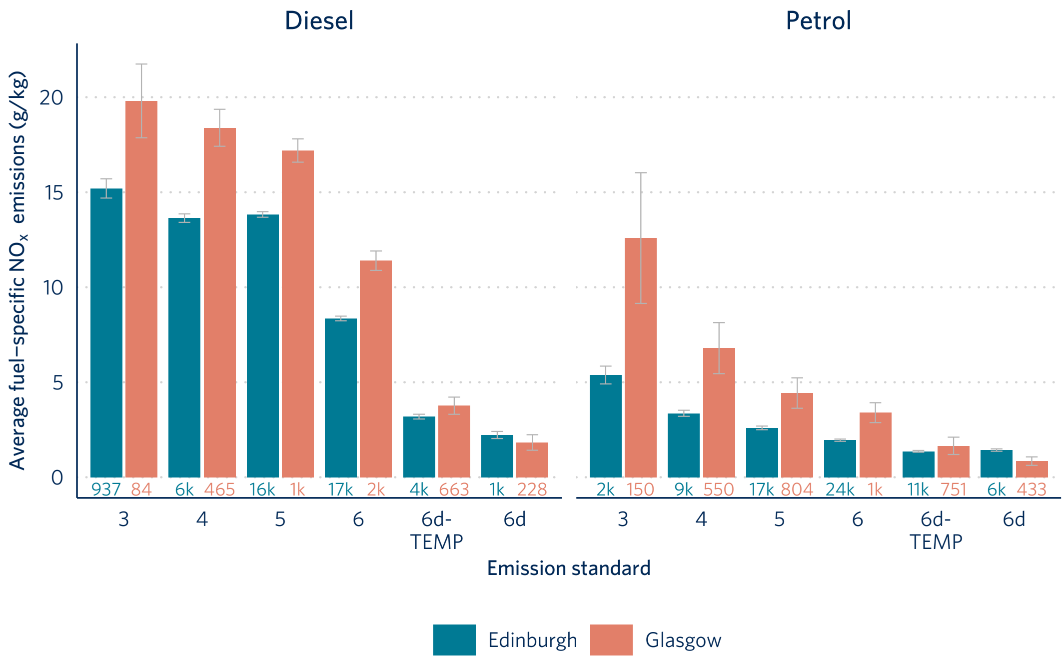


Figure 12. *Mean* fuel-specific NO_x emissions from private passenger cars measured in Edinburgh and Glasgow in 2021. The number of measurements is presented below each bar and only measurements of over 50 are presented. Whiskers represent 95% confidence interval of the mean.

urban driving conditions characterized by slower speed and a higher prevalence of cold engines. The emissions gap diminished from Euro 6d-TEMP, a standard that introduced an additional on-road test for type approval, highlighting that emissions from vehicles certified to newer standards are less influenced by low speed and cold start.

FUEL-SPECIFIC CO EMISSIONS BY SITE

Petrol vehicles measured in Glasgow also showed significantly higher mean CO emissions than those measured in Edinburgh, as shown in Figure 13. Mean CO emissions from the Glasgow petrol vehicles certified to even newer standards, such as Euro 6d-TEMP and 6d,

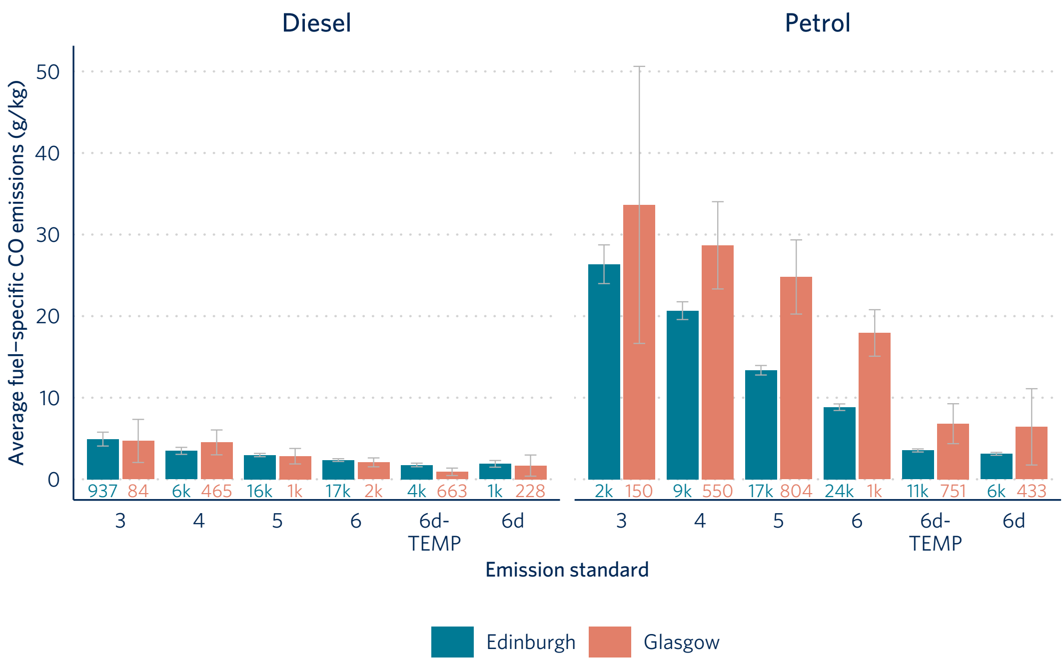


Figure 13. *Mean* fuel-specific CO emissions from private passenger cars measured in Edinburgh and Glasgow in 2021. The number of measurements is presented below each bar and only measurements of over 50 are presented. Whiskers represent 95% confidence interval of the mean.

were double those from the Edinburgh petrol vehicles. The difference may stem from the fact that vehicles in Glasgow city centre are more likely to have cold engines due to insufficient time and distance driven to warm up engines. Diesel passenger cars, however, show little difference between the two sites, possibly indicating that diesel engines' CO emission performance is not considerably influenced by such conditions.

FUEL-SPECIFIC HC EMISSIONS BY SITE

Mean HC emissions from passenger cars measured in Edinburgh and Glasgow did not show large differences by Euro standard. Site-specific HC emissions echoed the earlier findings that petrol vehicles emit more HC emissions than diesel vehicles. HC emissions did not appear to be reduced with newer Euro standards for both fuel types. As shown in Figure 14, however, the emission performance of different Euro standards was difficult to assess due to the large variance seen in the measurements of all vehicles.

DISTANCE-SPECIFIC NO_x EMISSION BY SITE

Distance-specific NO_x emissions by site were compared with regulatory limits, as shown in Figure 15. In addition to the previous assessment of the distance-specific NO_x emissions (Figure 8), the mean NO_x emissions by site demonstrate that both diesel and petrol vehicles certified to Euro 6d-TEMP and 6d in Edinburgh have real-world NO_x emission levels that meet (diesel) or are well below (petrol) the RDE limits.

The median NO_x emissions trend by registration year shows that the NO_x emissions performance gap between the Edinburgh and Glasgow diesel vehicles has decreased over time (Figure 16). Diesel vehicles in both cities achieved the same levels of median NO_x emissions with little variance around 2019, the year when all passenger cars were required to go through RDE testing. However, the performance of the newly registered diesel vehicles warrants further investigation, as it may not reflect any influence of ageing or deterioration.

The gap between the NO_x performance between petrol vehicles in Edinburgh and Glasgow, however, persists over time although the overall emissions levels have gradually gone down. This may indicate that the emissions performance of petrol vehicles is more susceptible to urban driving conditions.

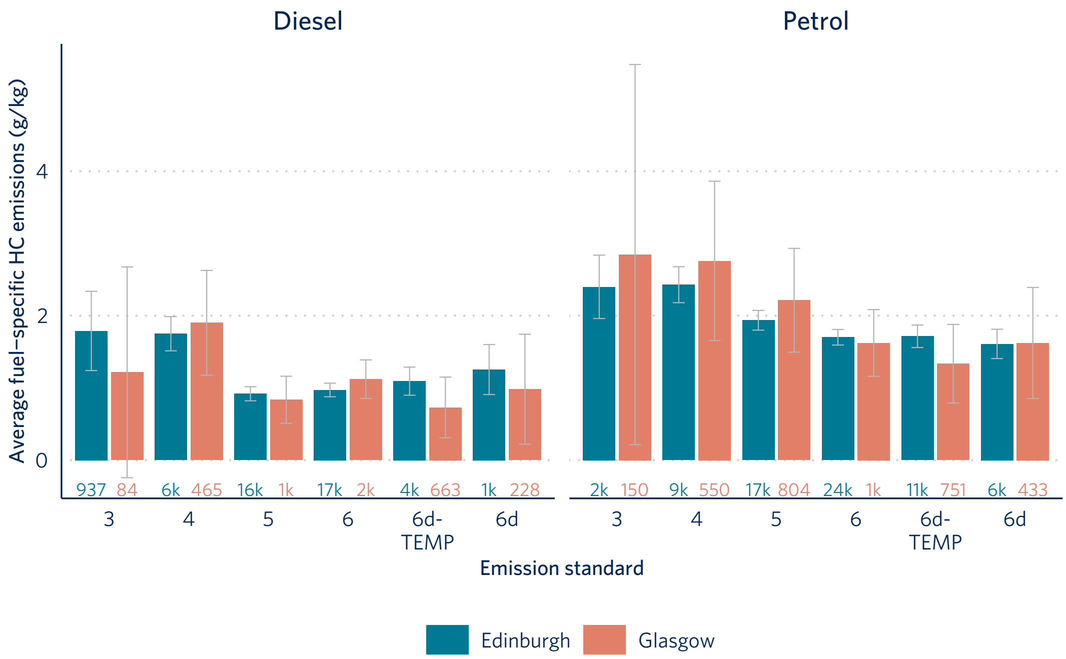


Figure 14. Mean fuel-specific HC emissions from private passenger cars measured in Edinburgh and Glasgow in 2021. The number of measurements is presented below each bar and only measurements of over 50 are presented. Whiskers represent 95% confidence interval of the mean.

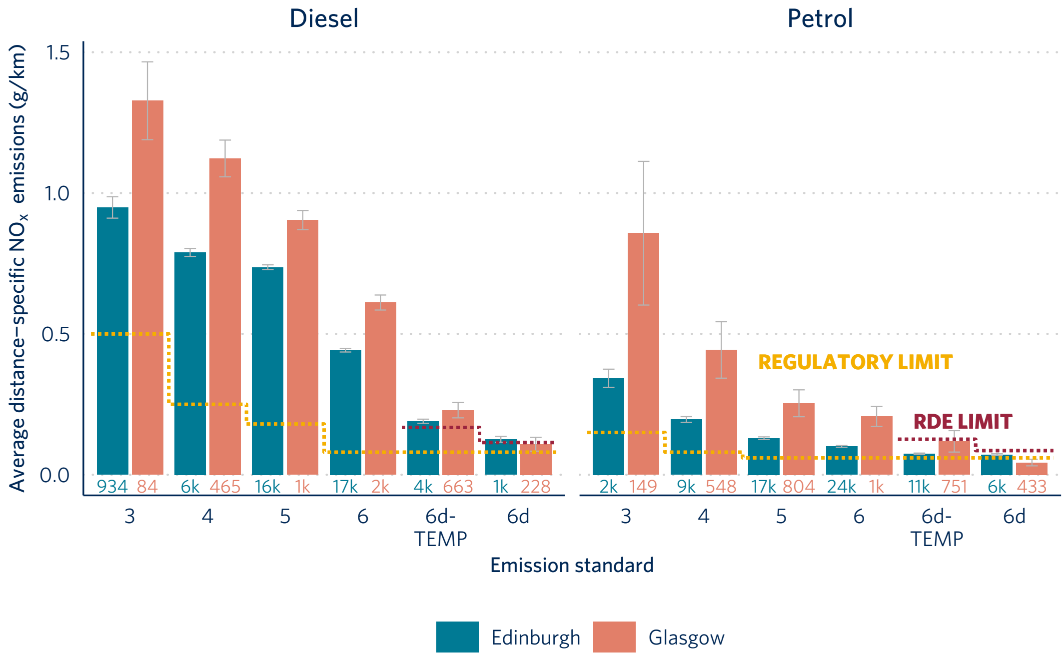


Figure 15. Mean distance-specific NO_x emissions from private passenger cars measured in Edinburgh and Glasgow in 2021. The number of measurements is presented below each bar and only measurements of over 50 are presented. Whiskers represent 95% confidence interval of the mean. Type-approval limits are indicated by the dotted yellow line and RDE limits by the red dotted line.

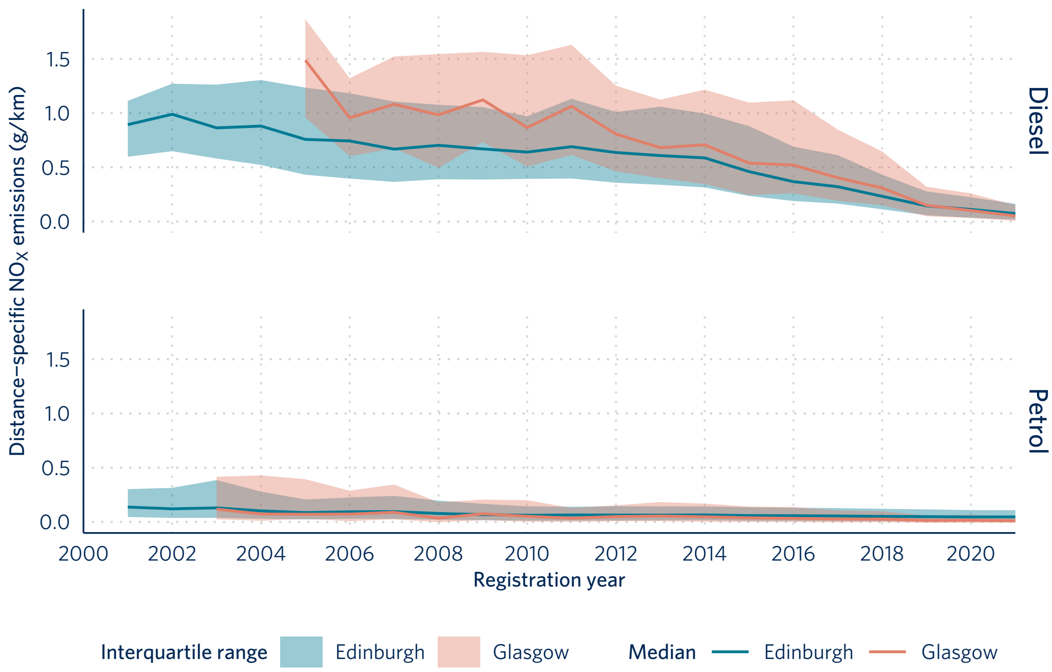


Figure 16. Evolution of median distance-specific NOx emissions of vehicles measured in Edinburgh and Glasgow in 2021 by registration year. Top panel shows diesel-powered vehicles and bottom panel shows petrol-powered vehicles. Only registration years with over 30 measurements are presented.

EMISSIONS PERFORMANCE OF EURO 6D-TEMP AND 6D DIESEL VEHICLES

This section assesses the emission performance of diesel vehicles certified to Euro 6d-TEMP and 6d standards, which were introduced in 2019 and include additional measures to limit on-road tailpipe emissions. The 2021 testing campaign collected sufficient measurements of these vehicles, which enabled the further breakdown to vehicle families, defined by manufacturer and engine size.

The assessment of the emissions performance by vehicle family demonstrated that some vehicle families emit significantly more NO_x than others. As shown in Figure 17, the highest emitting vehicle family, Hyundai Motor Company 1600cc engine, emit more than three times the NO_x emissions from the lowest emitting vehicle family, Daimler's 1460cc engines. While the real-world NO_x emissions of Daimler engines were well below the on-road limits, more than half of the vehicle families found in the Scottish sample showed real-world NO_x emissions above this limit. The highest emitting manufacturers were Hyundai Motor Company, Ford, and Volvo.

Less measurements were available for the assessment of emissions performance of diesel Euro 6d by vehicle family, as the Euro 6d standard became a requirement for all new vehicles only in 2021. A total of 7 vehicle families with over 50 measurements are assessed in Figure 18. Owing to the small sample size, the confidence intervals of the mean NO_x emissions were wide. However, PSA and Jaguar Land Rover vehicles showed mean NO_x emissions significantly exceeding the on-road limit, highlighting a weakness in the RDE regulations, which do not comprehensively cover the range of typical lengths of urban trips.

A breakdown into different vehicle makes identified Vauxhall 1499cc as the highest-emitting engine, which is part of the PSA: 1500 vehicle family. This same engine is also used in Ford's Euro 6d-TEMP vehicles, which was one of the top highest-emitting family (Figure 17). However, a more robust investigation into the emission performance of different engines requires a bigger sample that can be attained by incorporating successive testing campaign measurements.

AGE AND EMISSIONS OF PASSENGER CARS

Although remote emissions sensing measurements represent a snapshot of emissions from the measured vehicles at the time of testing, linking the vehicle information with emissions can provide insight into some emissions trends, such as the effect of ageing on emissions

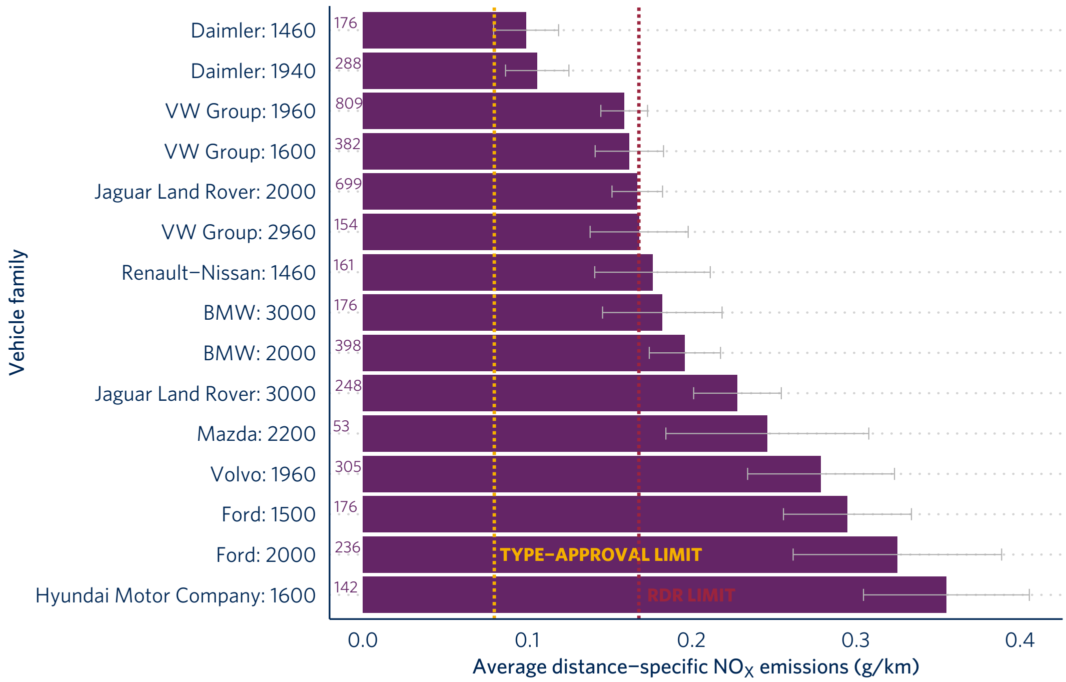


Figure 17. *Mean* distance-specific NOx emissions from Euro 6d-TEMP diesel vehicles by vehicle family. The number of measurements is presented below each bar and only measurements of over 50 are presented. Whiskers represent 95% confidence interval of the mean. Type-approval limits are indicated in dotted yellow line and RDE limits in red dotted line.

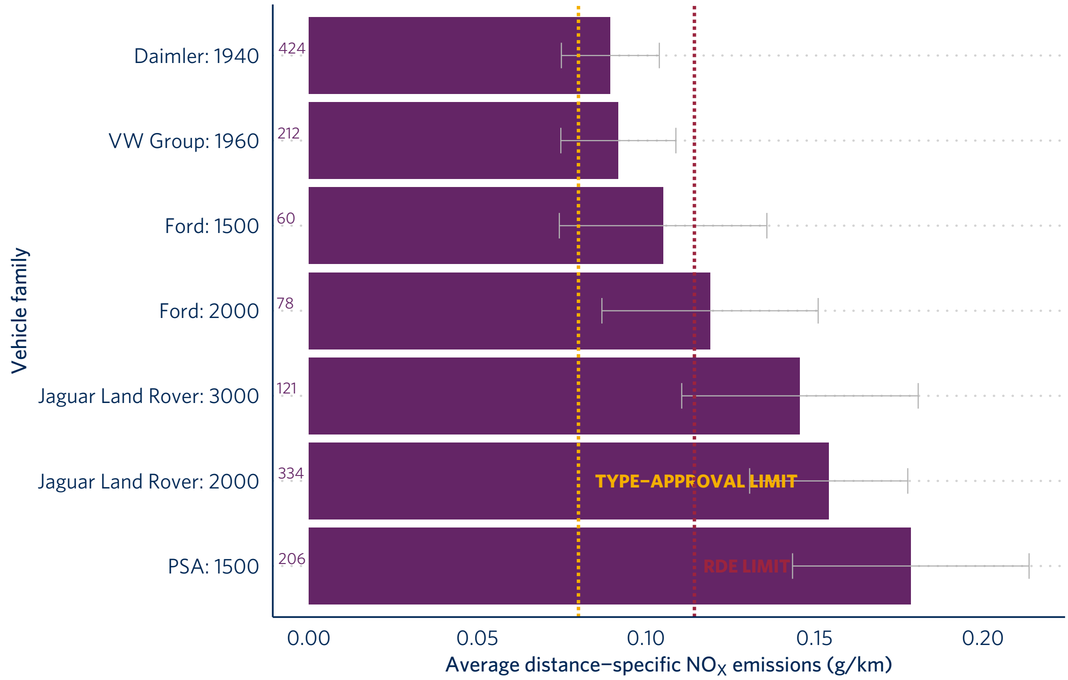


Figure 18. *Mean* distance-specific NOx emissions from Euro 6d diesel vehicles by vehicle family. The number of measurements is presented below each bar and only measurements of over 50 are presented. Whiskers represent 95% confidence interval of the mean. Type-approval limits are indicated in dotted yellow line and RDE limits in red dotted line.

performance. There is long-standing evidence that as a vehicle is driven, its emission performance declines due to malfunctions or deterioration of emissions control systems.[8] In this section, the effect of ageing on the emissions performance of private passenger cars was investigated using linear regression. Although regression only depicts the correlation between the two variables, years of registration and levels of emissions, the results highlight that remote sensing data can help identify possible emissions degradation in vehicles.

To assess the possible emission deterioration of passenger vehicles over time, real-world emissions of NO_x and CO are shown as a function of registration years of passenger cars which are directly linked to the vehicle ages in Figure 17. To account for the effect of legislative updates e.g., for newer Euro standards, the results are shown by Euro standard. The results for petrol vehicles corroborate the findings from previous studies which provided evidence of increased NO_x and CO emissions of petrol vehicles with higher age and mileage.[9] This is particularly evident in the NO_x and CO emission performance of older vehicles certified to Euro 3–5.

The results additionally showed that there may be a positive correlation between ages and NO_x emission performance of diesel vehicles, especially for those that are at least 6 years old, or certified to below Euro 6. As shown in Figure 19, the degradation of distance-specific NO_x emissions with usage was prominent for diesel Euro 3–5 vehicles. Small discrepancies seen in the results for fuel-specific and distance-specific NO_x emissions, such as for diesel Euro 4, is a likely indication of the improvement in fuel efficiency this vehicle group underwent.

8 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; Jack Davison, Rebecca Roseb, Naomi Farrena, Rebecca Wagner, Shona Wilde, Jasmine Wareham, and David Carslaw, "Gasoline and Diesel Passenger Car Emissions Deterioration Using On-Road Emission Measurements and Measured Mileage," *Atmospheric Environment: X* 14 (1 March 2022): 100162, https://doi.org/10.1016/j.aeaoa.2022.100162; Qingyu Zhang, Juwang Fan, Weidong Yang, Bixin Chen, Lijuan Zhang, Jiaoyu Liu, Jingling Wang, Chunyao Zhou, and Xuan Chen, "The Effects of Deterioration and Technological Levels on Pollutant Emission Factors for Gasoline Light-Duty Trucks," *Journal of the Air & Waste Management Association* 67, no. 7 (19 May 2017): 814–23, https://doi.org/10.1080/10962247.2017.1301275.

9 Jens Borken-Kleefeld and Yuche Chen, "New Emission Deterioration Rates for Gasoline Cars – Results from Long-Term Measurements," *Atmospheric Environment* 101 (January 2015): 58–64, https://doi.org/10.1016/j.atmosenv.2014.11.013; Yoann Bernard, Tim Dallmann, Uwe Tietge, Huzeifa Badshah, and John German "TRUE U.S. Database Case Study: Emissions Deterioration of U.S. Gasoline Light-Duty Vehicles and Trucks" (Washington, DC: TRUE Initiative, 2020), https:// theicct.org/publications/true-us-database-emissions-deteriorationoct2020; Tao Zhan, Chris Ruehl, Gary Bishop, Seyedehsan Hosseini, John Collins, Seungju Yoon, and Jorn Herner, "An Analysis of Real-World Exhaust Emission Control Deterioration in the California Light-Duty Gasoline Vehicle Fleet," *Atmospheric Environment* 220 (January 2020): 117107, https://doi. org/10.1016/j.atmosenv.2019.117107.

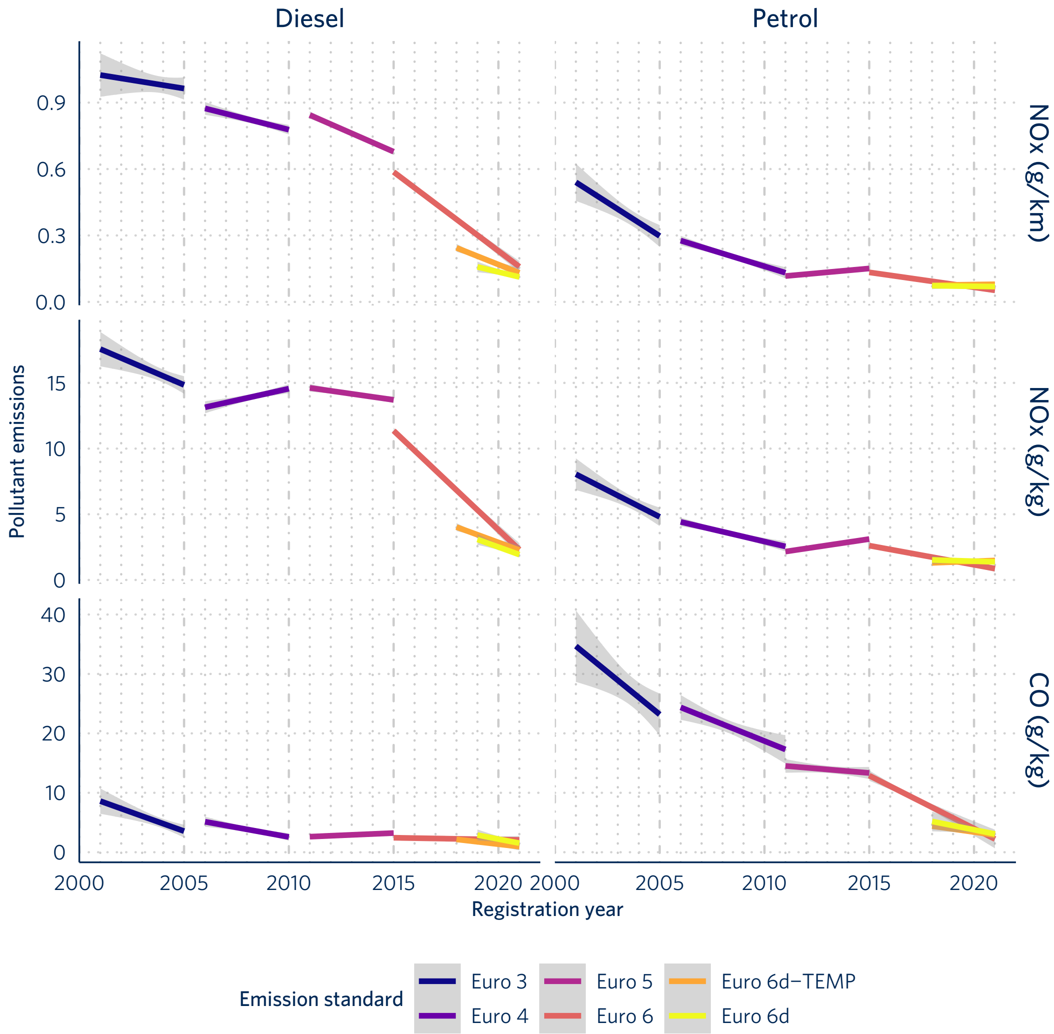


Figure 19. Effect of age on distance-specific NO_x, fuel-specific NO_x, and fuel-specific CO emissions from private passenger cars measured in Scotland in 2021 using linear regression. Only registration years with measurements of over 100 are presented.

Despite the notable downward trend of distance-specific NO_X emissions from Euro 6 diesel vehicles shown, the improvement in emissions performance of these vehicles more likely resulted from multiple legislative updates of the Euro 6 standard, e.g., from 6a to 6b to 6c, and manufacturers' deliberate efforts to clean up diesel vehicles in the aftermath of the "Dieselgate" scandal. The samples of vehicles certified to Euro 6d-TEMP and Euro 6d show emission levels significantly lower than those of the preceding standards. However, no concrete conclusions about the influence of ageing on emissions could be drawn, as their registration dates span only across 3 years. With more measurements of vehicles certified to Euro 6d, the evidence of emission deterioration of newer vehicles could be further established.

POTENTIAL IMPACT OF THE SCOTTISH LOW EMISSION ZONES ON PASSENGER CAR EMISSIONS

In 2019, Scotland introduced a legislative framework for implementing low emission zones (LEZs), starting in Aberdeen, Dundee, Edinburgh, and Glasgow, the four cities from which remote emissions sensing measurements are planned to be collected from over three years. Scotland has defined the minimum requirements to enter one of these zones based on the Euro classification standards:[10]

- Euro 4 for petrol cars and vans (generally vehicles registered from 2006)

10 Low Emission Zones Scotland, "How Low Emission Zones Work," https://www.lowemissionzones.scot/about/how-lezs-work.

- Euro 6 for diesel cars and vans (generally vehicles registered from September 2015)
- Euro VI for buses, coaches, and HGVs (generally vehicles registered from January 2013)

These restrictions will apply 24 hours a day, 7 days a week, with some exemptions applied to vehicles driven by disabled persons, emergency vehicles, and those carrying a Blue Badge holder.[11] The LEZ rules will be enforced using Automatic Number Plate Recognition (ANPR) cameras and non-compliant vehicles will be charged with penalties.

Implementation schedules of the proposed restrictions, however, vary by city. The LEZ will enter into force in 2023 in Glasgow and one year later, in 2024, in Edinburgh. Taking the remote sensing measurements collected in 2021 as a proxy of the Scottish fleet activity, this section assesses the potential impact of the proposed LEZ restrictions on drivers and NO_x emissions in Edinburgh and Glasgow. Figure 20 shows that, in 2021, 21% of the passenger cars measured in Edinburgh and 24% of those in Glasgow do not meet the minimum requirements listed above. The share of activity affected by the LEZs when they enter into force, however, is expected to be lower as some of these older vehicles will retire and newer, cleaner vehicles may replace them in 2023 and 2024. These vehicles' activity accounted for around half of the total NO_x emissions from passenger cars in each city. The high share of NO_x emissions these vehicles were responsible for in 2021 demonstrates the potentially large benefits the first step of the LEZs would generate.

Scotland could further benefit from restricting Euro 6 diesel vehicles that are not subject to real-driving emissions (RDE) testing and therefore emit higher levels of NO_x emissions in urban driving conditions. NO_x emissions from diesel vehicles certified to Euro 6 are double the emissions from the subsequent standard, Euro 6d-TEMP, and their emissions are higher by 40% in urban driving conditions, as shown by the Glasgow measurements. While making up 15% and 23% of the total passenger car activities, these vehicles account for 23% and 29% of the total NO_x emissions from all passenger cars in Edinburgh and Glasgow, respectively. Expanding the LEZ restrictions to vehicle groups disproportionately contributing to emissions can accelerate a reduction in pollutant emissions and improvement in urban air quality. Additionally, while RDE vehicles (Euro 6d-TEMP and Euro 6d) have lower real-world emissions than Euro 6, they are not an exception to

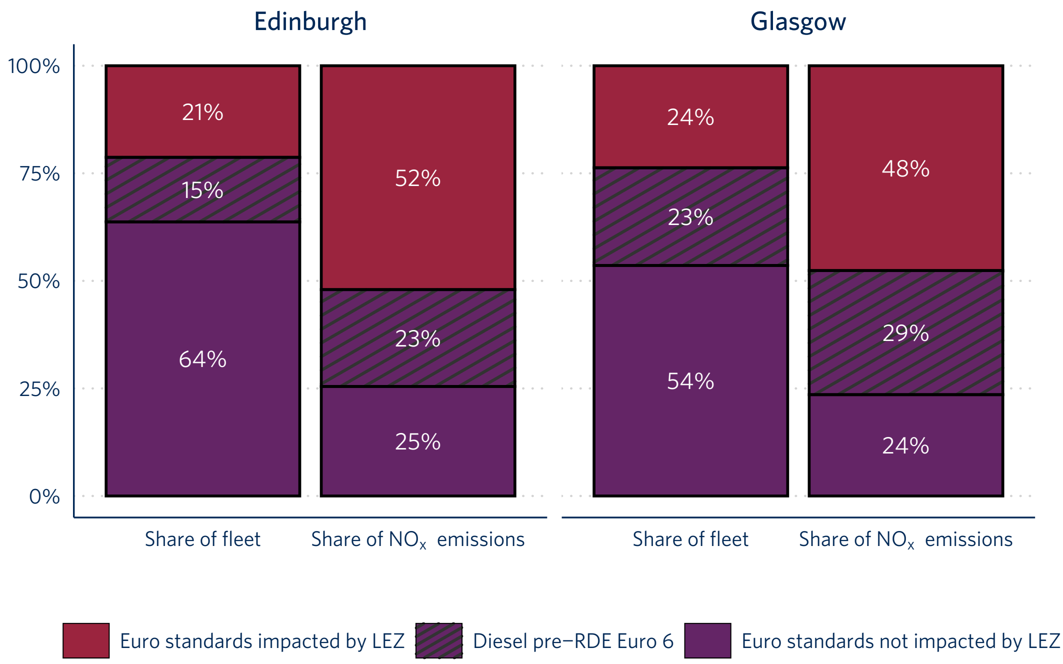


Figure 20. Share of passenger car fleet impacted by the proposed LEZ restrictions and share of NO_x emissions for which these vehicles are responsible based on the 2021 remote sensing measurements from Edinburgh and Glasgow.

11 Low Emission Zones Scotland, "Blue Badge Holder Exemption," https://www.lowemissionzones.scot/blue-badge-exemption.

the possibility of emission control system deterioration and therefore monitoring of vehicle emissions would be critical to the success of the LEZ policy.

EMISSIONS FROM TAXIS AND PRIVATE HIRES

This section focuses on the emissions from taxis and private hire cars (PHCs) in Scotland, as these vehicles play an important role in urban areas. These vehicles comprise a high-usage and -mileage fleet and can be an opportunity for local policy. Vehicles with high mileage have further implications of increased emissions. As 99% of the measured taxis and private hires were passenger cars, this analysis takes only those whose vehicle class is passenger cars for emissions comparison.

Taxis and PHCs made up 3% of all unique passenger cars measured in 2021, while accounting for 6% of all passenger car activity. The vehicle activity share was much higher in Glasgow (38%) than in Edinburgh (2%), likely because the Glasgow testing sites were in the city centre where taxis and PHCs are frequently hired. The majority of taxis and PHCs were diesel-powered (88%) and the remaining 10% were either petrol hybrid or petrol vehicles.

When compared with other private passenger cars, taxis and PHCs had a mean age of around a year younger at 4.6 years. As shown in Figure 21, most of the taxis and PHCs were registered between 2014 and 2020 and only a small share of them were registered before 2014. High-usage vehicles like taxis and PHCs tend to retire earlier than passenger cars for private use due to engine deterioration with the accumulation of mileage.

Taxis identified from the sample had a bigger mean mass and, therefore, higher CO_2 emissions compared to PHCs or other private passenger, which rendered the comparison of fuel-specific emissions obsolete. Therefore, to account for the difference in fuel consumption, the analysis focused on distance-specific emissions. The results showed that distance-specific NO_x emissions from diesel taxis and PHCs were significantly higher than their private passenger car counterparts, as shown in Figure 22. The biggest difference was spotted for vehicles registered between 2007 and 2013, when the mean distance-specific NO_x emissions from taxis and PHCs were 1.5–2 times those from other passenger cars. NOx emissions from these vehicles decreased from 2013 onward, achieving around the same mean distance-specific NO_x emissions in 2019 and later. The linear increase shown between 2001 and 2007 is due to the sparse data points for vehicles registered during this time. The large emission gap between the two fleets may indicate a clear influence of usage, demonstrated by taxis and PHCs' higher accumulated mileages, on NO_x emissions performance in taxis and PHCs aged between 8 and 14

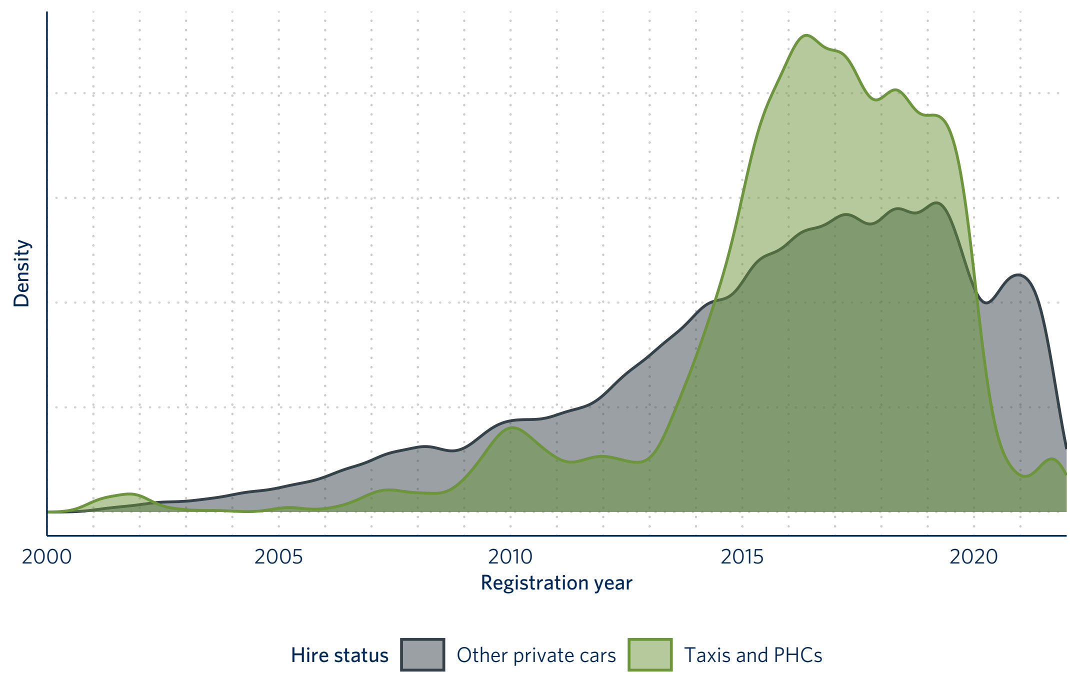


Figure 21. Distribution of registration years of taxis and PHCs and other private passenger cars measured in 2021. Each shaded area covers 100% of vehicles measured.

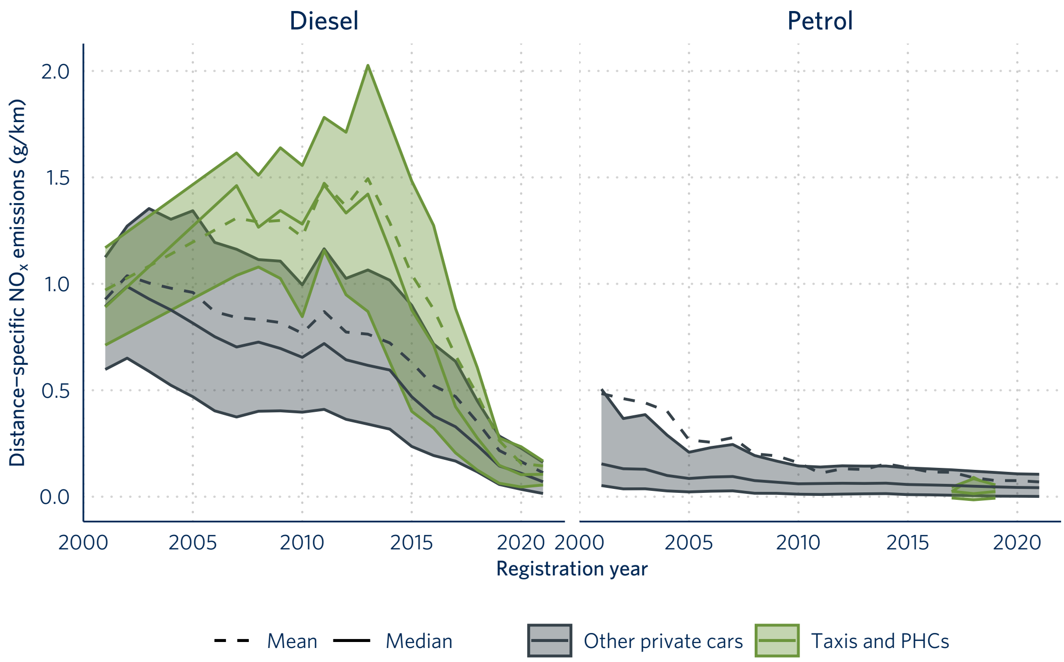


Figure 22. Mean and median distance-specific NOx emissions from taxis and PHCs and other passenger cars by registration year. Dotted line indicates mean values and solid line indicates median values. Shaded area shows the interquartile range (25th and 75th percentile). Only registration years with over 30 measurements are presented.

years. The diminishing emission gap in newer cars may be attributable to the introduction of on-road testing, which curbed emissions in urban driving conditions. However, more longitudinal data on these new standards are necessary to conclude that these standards are less likely to demonstrate emissions deterioration over time.

The results for petrol vehicles show clearly that taxis and PHCs are mostly diesel vehicles; taxis and PHCs powered by petrol were limited to those registered between 2017 and 2019. Due to insufficient data, it was not possible to determine the emissions deterioration from petrol taxis and PHCs. However, this may highlight that petrol vehicles are typically not preferred for the purpose of taxis or PHCs, as their lifespan is considered lower than diesel vehicles. The large discrepancy between the median and mean distance-specific NO_x emissions from other petrol private cars suggests the presence of some high-emitting petrol vehicles pulling up the mean emissions. This may further indicate the possible presence of tampered or defective vehicles.

Figure 23 echoes the findings from NO_x emissions difference between taxis and PHCs and other passenger cars for different Euro standards. Additionally, for Euro 4 to 6 diesel taxis and PHCs that show the largest discrepancies with private car emissions, the mean distance-specific NO_x emissions were five to eight times the regulatory limits. It is important to note that the comparison is between real-world emissions and drive cycle limits to which vehicles in narrower testing conditions are subject. Diesel taxis and PHCs certified to Euro 6d-TEMP had mean NO_x emissions of 230 mg/km, a level around 60% lower than the mean NO_x emissions from the preceding standard but were still emitting NO_x emissions at levels almost three times the regulatory limit.

This trend continues when broken down by different measurement sites. As shown in Figure 24, all diesel passenger cars show visibly more elevated levels of real-world NO_x emissions, most likely owing to driving characteristics often found in urban settings, like low speeds and cold starts. The Glasgow testing site also had a steeper slope which contributes to the higher emissions from vehicles.

At the time of the 2021 testing, some cities in Scotland had already put in place some minimum requirements to restrict old, high-emitting taxis and PHCs, in the form of minimum requirements. In Edinburgh, the minimum standard for both taxis and PHCs was Euro 5, which explains the small number of Euro 4 taxis and PHCs collected in Edinburgh. In Glasgow, an age limit of 7 years was applied only to PHCs, which

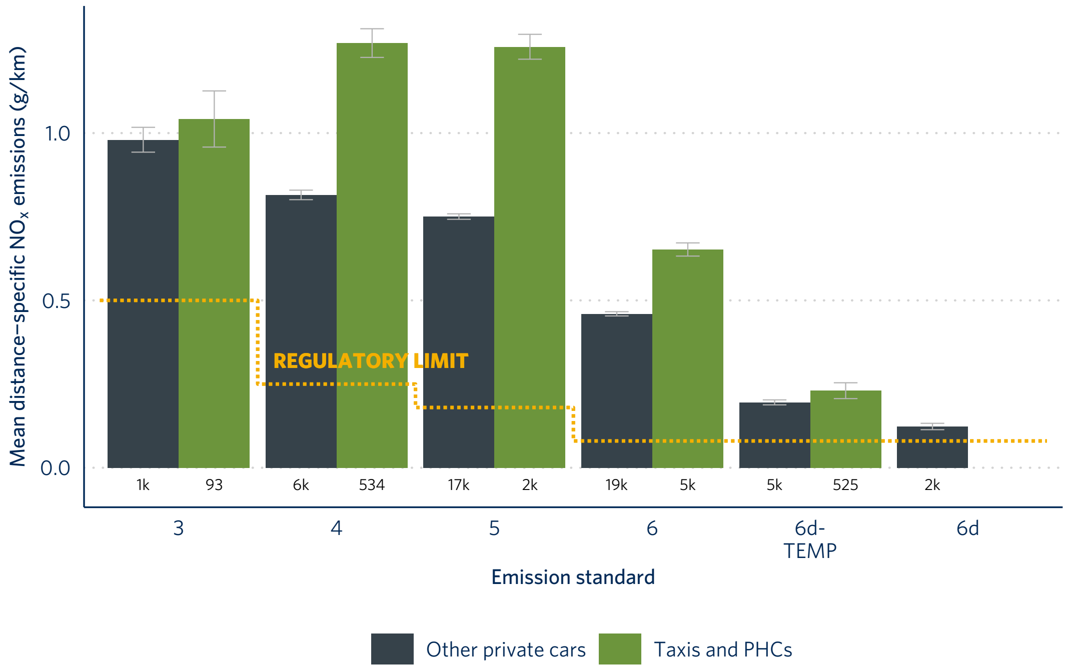


Figure 23. Mean distance-specific NO_x emissions from taxis and PHCs and other private cars powered by diesel. The number of measurements is presented below each bar and only measurements of over 50 are presented. Whiskers represent 95% confidence interval to the mean. Type-approval limits are indicated by the dotted yellow line.

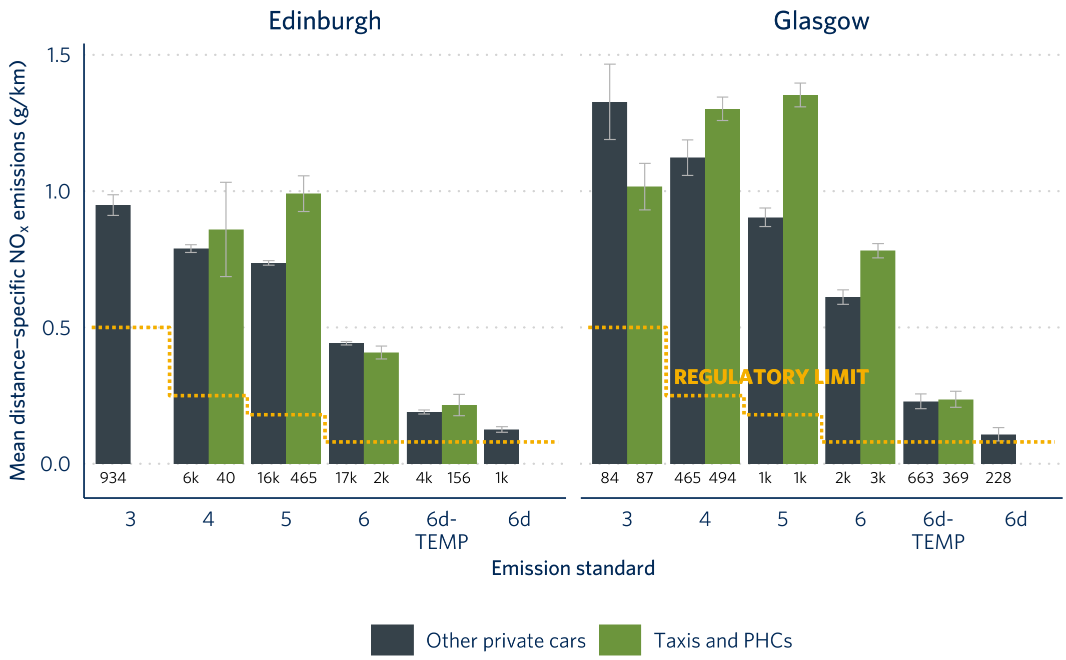


Figure 24. Mean distance-specific NO_X emissions from taxis and PHCs and other private cars powered by diesel in Edinburgh and Glasgow. The number of measurements is presented below each bar and only measurements of over 30 are presented. Whiskers represent 95% confidence interval to the mean. Type-approval limits are indicated by the dotted yellow line.

created a loophole that allowed the use of old taxis that are certified to below Euro 4.[12]

On a more granular level, the emissions performance between taxis and PHCs was also examined. Figure 25 illustrates both the distribution of Euro standards within these fleets and their NO_X emissions performance. More recent Euro standards, from Euro 5 and above, were found in PHCs, while taxis span across Euro 3 to 6d-TEMP. More notably, Euro 5 taxis showed real-world distance-specific NO_X emissions 1.7 times those from Euro 5 PHCs, while the emissions from PHCs were higher than taxis for Euro 6. The emissions gap between taxis and PHCs decreased with the 6d-TEMP standard.

Emissions performances of the primary makes of Scottish taxis and PHCs are compared in Figure 26. The results are reiterated in Figure 25, highlighting large exceedances of type-approval emissions limits of all measured taxis and PHCs. Within the Euro 5 taxis and PHC fleet, all three taxi makes had the highest mean distance-specific NO_X emissions compared to the PHC makes. In particular, London Taxi Company (hereafter LTC), which made up around 40% of the measured Euro 5 taxis, showed real-world NO_X levels over 30% more than the highest-emitting PHC make, Vauxhall, and more than double those from the least-emitting make, Škoda. LTC taxis certified to Euro 5 were, however, subject to a different emission limit from other taxis, as they could be classified as a commercial vehicle (category N1 class 3) at 280 mg/km, rather than 180 mg/km.[13] The vehicles still showed real-world NO_X emissions almost seven times its limit.

LTC was also the highest-emitting taxi make among the Euro 6 taxis and PHCs, as shown in Figure 27. The LTC taxis, despite a limited number of measurements, showed levels of distance-specific NO_X emissions over five times those from the least-emitting taxi make, Mercedes, and eight times those from the least-emitting PHC make, Audi.

LTC does not only produce diesel taxis. Besides plug-in hybrid vehicles produced before 2019, LEVC (formerly LTC) has started introducing plug-in hybrid taxis that are zero-emission capable range extended electric vehicles

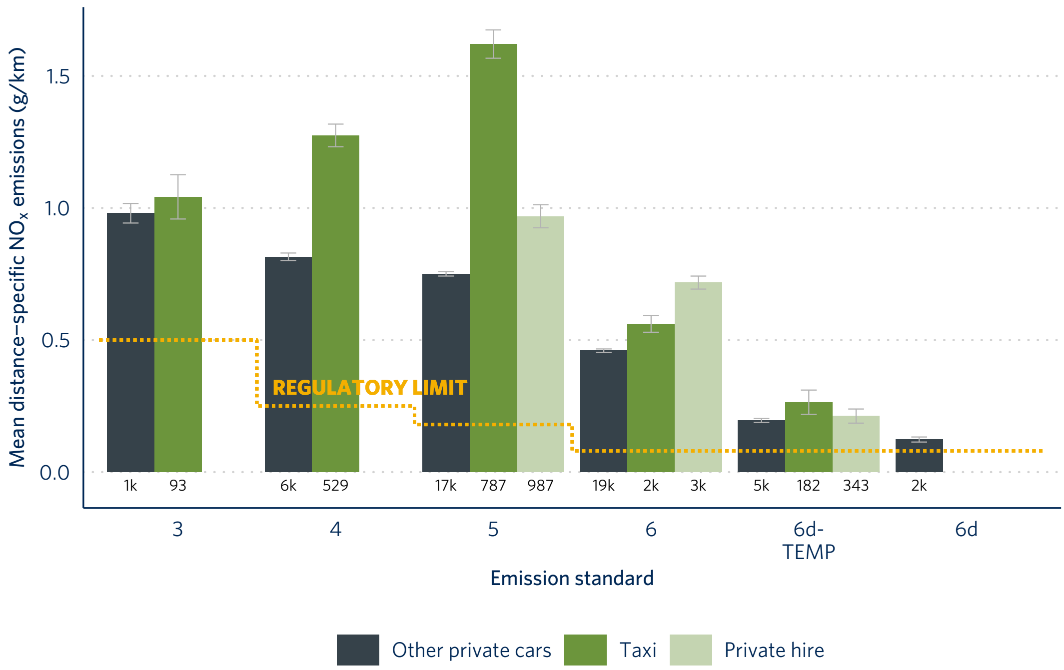


Figure 25. Mean distance-specific NO_X emissions from taxis, PHCs, and other private cars powered by diesel in Scotland. The number of measurements is presented below each bar and only measurements of over 30 are presented. Whiskers represent 95% confidence interval to the mean. Type-approval limits are indicated by the dotted yellow line.

12 Seven years at the point of annual test, meaning private hires of up to eight years old could be in use. The age limit for PHCs was removed by Glasgow City Council in 2021.

13 Tim Dallmann, Yoann Bernard, Uwe Tietge, and Rachel Muncrief, "Remote sensing of motor vehicle emissions in London," (Washington, D.C.: TRUE Initiative, December, 2018), https://www.trueinitiative.org/data/publications/remote-sensing-of-motor-vehicle-emissions-in-london

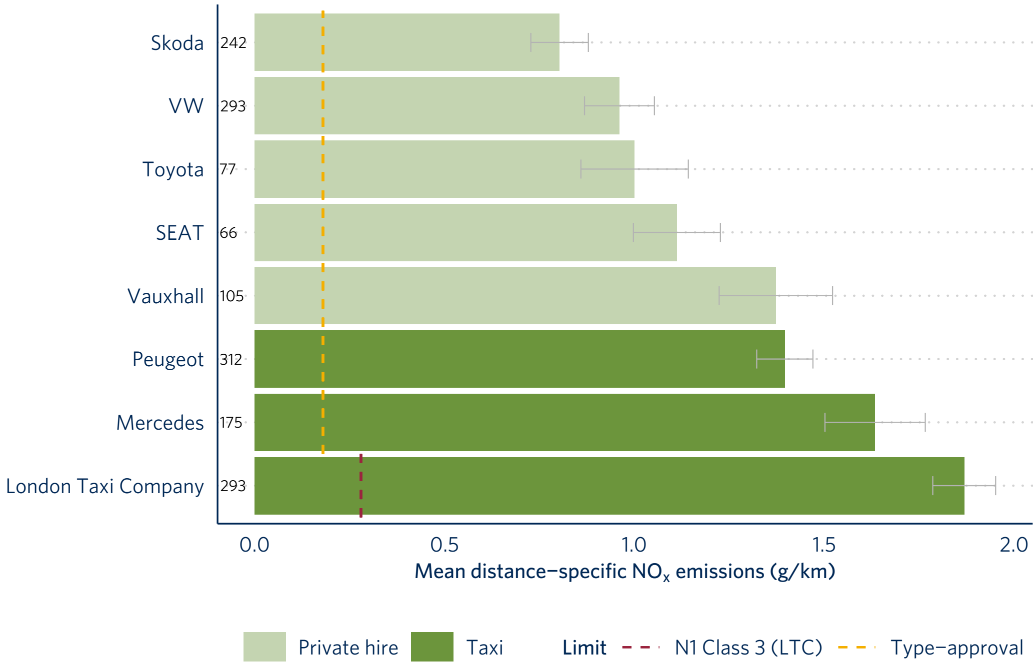


Figure 26. Mean distance-specific NOx emissions from Euro 5 diesel taxis and PHCs by vehicle family. The number of measurements is presented below each bar and only measurements of over 50 are presented. Whiskers represent 95% confidence interval of the mean. Type-approval limits are indicated in dotted yellow line and commercial vehicle (N1 Class 3) limit, applied to London Taxi Company, is indicated by the dotted red line.

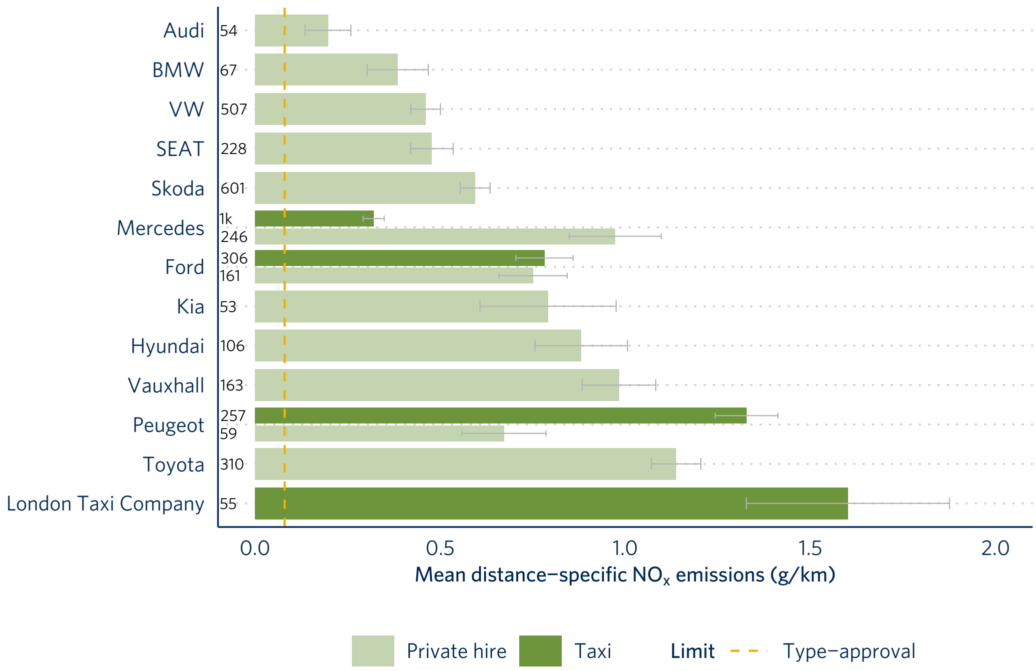


Figure 27. Mean distance-specific NOx emissions from Euro 6 diesel taxis and PHCs by vehicle family. The number of measurements is presented below each bar and only measurements of over 50 are presented. Whiskers represent 95% confidence interval of the mean. Type-approval limits are indicated by the dotted yellow line.

that use a battery covering up to around 125 km and a petrol engine range extender in 2019. Almost 100% of the measured plug-in hybrid taxis and PHCs measured were LEVC plug-in hybrid taxis, or more specifically 91 Euro 6 plug-in hybrid vehicles and 182 Euro 6d-TEMP range extended electric vehicles, which enabled an additional assessment of their zero-emission capability. Our measurements showed that these new taxis have drastically reduced their fuel-specific NO_x emissions, emitting NO_x at levels 7%–12% of the previous diesel models (Euro 6 LTC taxis).

A valid pollutant emissions measurement indicates a sufficient size of CO_2 plume, which in turn suggests that internal combustion engines are burning fuel passing by the instrument. As shown in Figure 28, the measurement validity rate of LTC plug-in hybrid taxis was significantly lower than conventional engine (ICE) taxis, suggesting they were emitting zero emissions, or being electrically powered by the battery. However, pollutant emissions from around 20% of Euro 6 and 30% of Euro 6d-TEMP plug-in hybrid taxis were detected, hinting that their battery was empty for at least 20% of the activity and the petrol engine range extender was being utilized, resulting in emissions.

In the Scottish taxi fleet, there was a small sample of Euro 5 taxis retrofitted to use liquefied petroleum gas (LPG). Despite a small sample, the results showed that LPG retrofit halved the NO_x emissions from Euro 5 diesel taxis and PHCs and perform slightly better than diesel Euro 6 taxis and PHCs. However, the conclusion was based only on 55 measurements and additional measurements would help determine the performance of the LPG retrofit taxis.

LIGHT-COMMERCIAL VEHICLES

FLEET COMPOSITION

The second most common class of vehicles found in all three testing campaigns was light commercial vehicle. The majority the light commercial vehicles (LCVs) measured were categorized as N1, small commercial vehicles of weight less than 3.5 tons. The numbers of unique vehicles and measurements captured are given in Table 3. Their measurements accounted for 12%, 18%, and 12% of measurements of all vehicle types in 2017, 2019–2020, and 2021, respectively. The higher share of LCVs identified from the 2019–2020 testing is likely because the testing campaign took place on motorways, where these vehicles carrying commercial shipments are more frequently driven. Of the LCVs measured, 99% were powered by diesel.

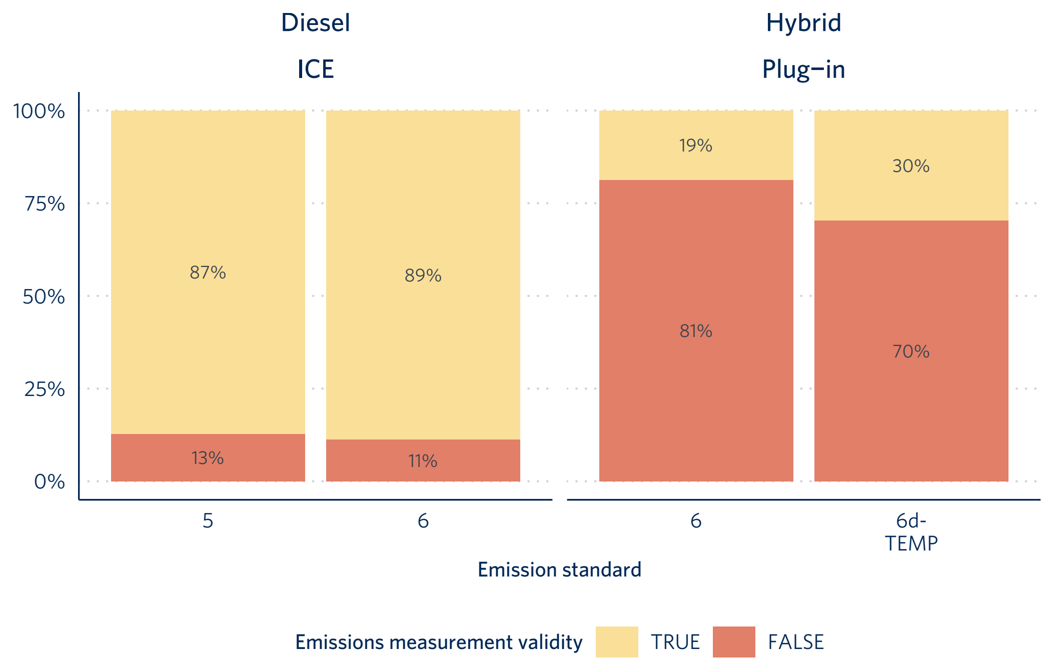


Figure 28. Measurement validity rate of each powertrain and fuel type of London Taxis Company taxis measured in Scotland in 2021. All groups of 50 or more measurements are presented.

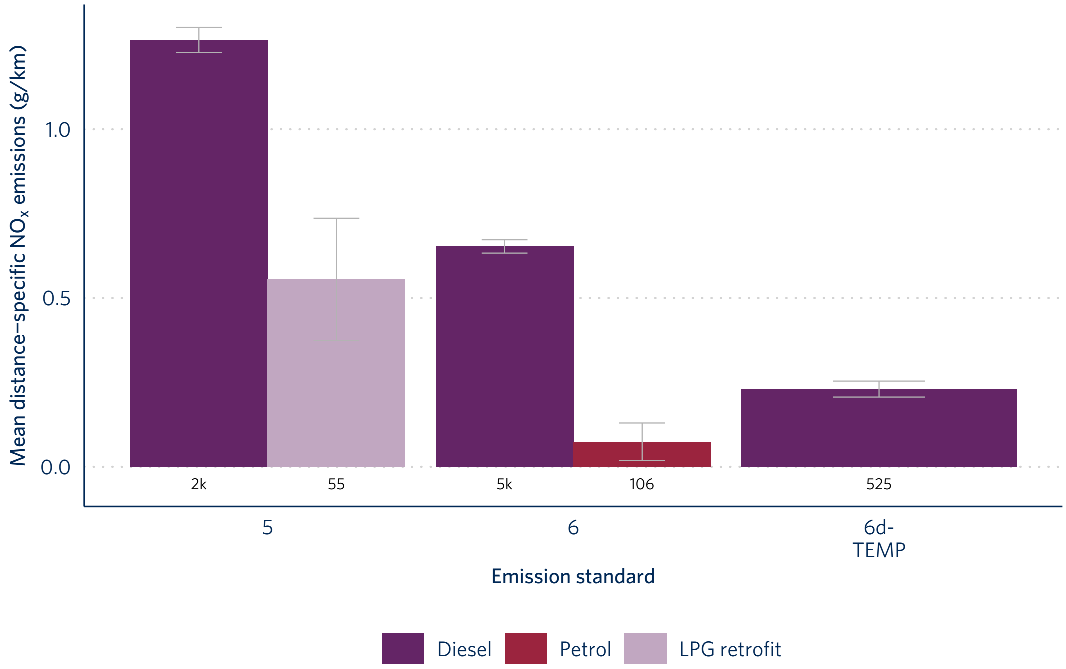


Figure 29. Mean distance-specific NOx emissions from LPG retrofit taxis and PHCs, compared with those from other fuel types. The number of measurements is presented below each bar and only measurements of over 50 are presented. Whiskers represent 95% confidence interval of the mean.

Table 3. Number of measurements and unique vehicles of light-commercial vehicles measured in each testing campaign.

Testing campaign	Number of measurements	Number of unique vehicles
2017	8,098	5,717
2019-2020	51,822	25,717
2021	31,238	11,351

Figure 30 shows the distribution of LCVs measured by their registration years and emission standards. Although the testing sites selected in 2019–2020 were not comparable with those selected in 2017 and 2021, and the registration dates from the 2017 data were not available, the distribution of LCV registration dates indicated an increase in the vehicle activity of newly registered LCVs since 2020. The bottom panel of the figure echoes this finding, demonstrating that the share of vehicles certified to newer standards increase gradually, whereas the share of older vehicles decrease steadily over time. Most of the measured LCVs were certified to Euro 5 in 2017, and most in the 2019–2020 campaign were Euro 6. In 2021, a number of LCVs certified to Euro 6d-TEMP and Euro 6d emerged in the fleet with the introduction of these standards that same year. Euro 5 vehicles, which made up over 60% of all LCV measurements in 2017, accounted for less than 30% of all LCV measurements in 2021, indicating a rapid turnover of these vehicles.

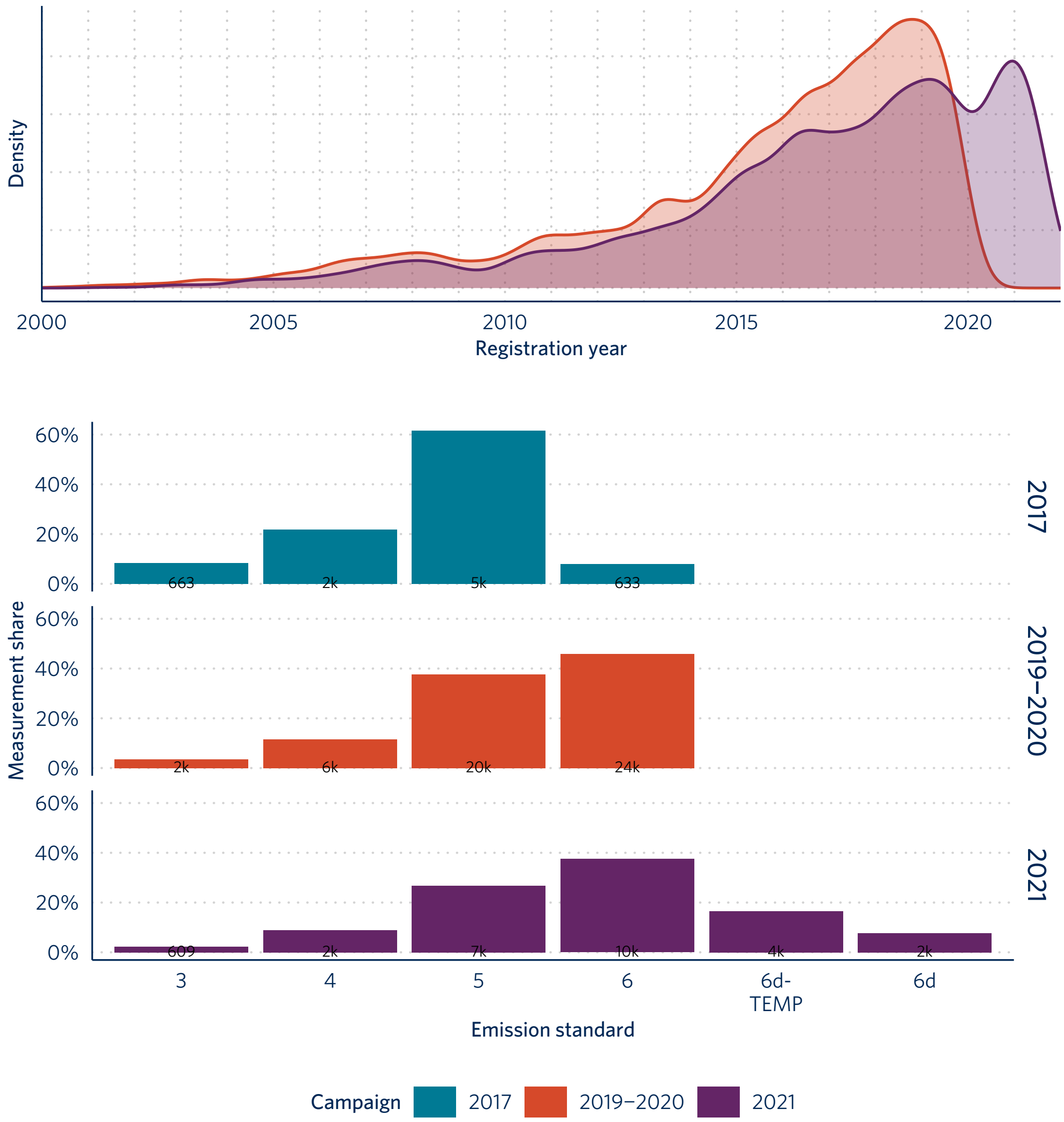


Figure 30. Top panel: Distribution of registration years of diesel light commercial vehicles measured in 2019-2020 and 2021. Each shaded area covers 100% of all measured light commercial vehicles. Registration dates were not available for the 2017 measurements. Bottom panel: Share of measurements of diesel-powered light commercial vehicles by Euro standard for each testing campaign. The number of measurements is presented below each bar and only measurements of over 100 are presented

FUEL-SPECIFIC NO_X EMISSIONS

Mean fuel-specific NO_X emissions from light commercial vehicles measured in the three campaigns are compared for each emission standard in Figure 31. The mean NO_X emission levels for each emission standard were similar across different campaigns, despite different driving conditions and the varied composition of LCVs classes that are defined by their gross vehicle weight. Compared with passenger cars, LCVs showed real-world NO_X emissions that are around 30% higher. The NO_X performance of LCVs did not improve significantly until Euro 6. The mean fuel-specific NO_X emissions from Euro 5 LCVs were at around 20 g/kg, 22%–37% higher than the mean emissions from its predecessor. As demonstrated by the 2021 data, the levels of NO_X emissions decreased substantially with the introduction of post-RDE Euro 6 standards, such as Euro 6d-TEMP and Euro 6d. Better performance of the RDE Euro 6 vehicles is not only the result of the introduction of on-road emission limits, but also may be attributable to their young age, which makes them less prone to emission degradation and maintenance issues.

Slight differences were seen between different campaigns. Euro 3–5 LCVs in the 2019—2020 sample showed the

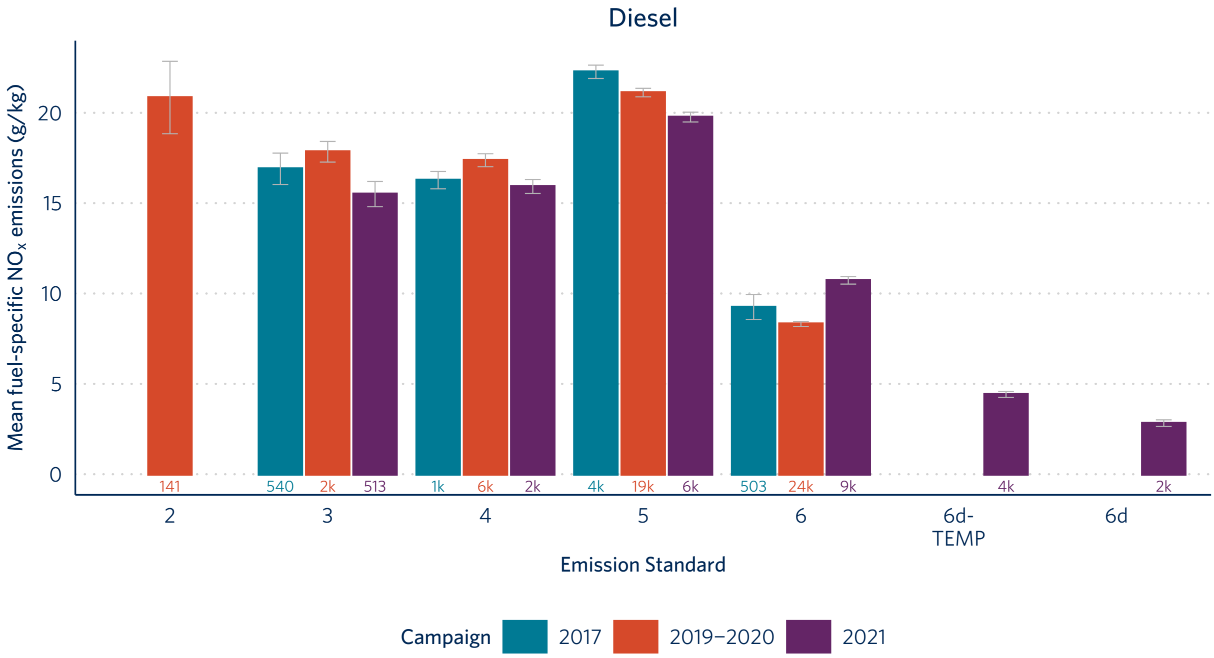


Figure 31. *Mean* fuel-specific NOx emissions from light-commercial vehicles by Euro standard measured in 2017, 2019–2020, and 2021. The number of measurements is presented below each bar and only measurements of over 100 are presented. Whiskers represent 95% confidence interval to the mean.

highest NO_X emissions, possibly associated with their high VSPs. This also demonstrated that newer LCVs within the same Euro standard, or those measured in 2021, show lower emissions, echoing the possibility of emissions deterioration.

FUEL-SPECIFIC CO EMISSIONS

The mean fuel-specific CO emissions show a large discrepancy across the two testing campaigns for which the CO emissions measurements were available. As shown in Figure 32, LCVs measured in 2021 showed mean CO emissions over double those from LCVs in 2019–2020. This not only indicates that urban driving conditions are prone to higher emissions but also highlights the importance of reducing CO emissions in urban areas where the exposure to such high levels of emissions is detrimental to health. The significantly lower levels of CO emissions from LCVs in 2019–2020 can be attributed to the testing sites on a motorway, where vehicles tend to have warm engines. The discrepancy, however, diminishes with newer vehicles, indicating a possible improvement in CO emissions performance in cold start conditions.

FUEL-SPECIFIC HC EMISSIONS

LCVs measured in 2021 showed real-world HC emissions significantly higher than those from LCVs measured in 2019—2020. Although HC emissions decreased with newer Euro standards, the mean HC emissions from RDE vehicles measured in 2021, namely Euro 6d-TEMP and Euro 6d, were still at 1 g/kg. The lower HC emissions from LCVs in 2019–2020 were attributable to the testing conditions on the motorway.

DISTANCE-SPECIFIC NO_X EMISSIONS

Distance-specific NO_X emissions from LCVs were not directly available from the remote sensing data but were obtained using the method developed by Davison et al.[14] The emission standard-specific information about the gap between CO_2 emissions in the real-world setting and those at type-approval from Zacharof et al. was then applied to calculate distance-specific NO_X emissions from the

14 Jack Davison, Yoann Bernard, Jens Borken-Kleefeld, Naomi J. Farren, Stefan Hausberger, Åke Sjödin, James E. Tate, Adam R. Vaughan, and David C. Carslaw, "Distance-Based Emission Factors from Vehicle Emission Remote Sensing Measurements," *Science of The Total Environment* 739 (15 October 2020): 139688, https://doi.org/10.1016/j.scitotenv.2020.139688.

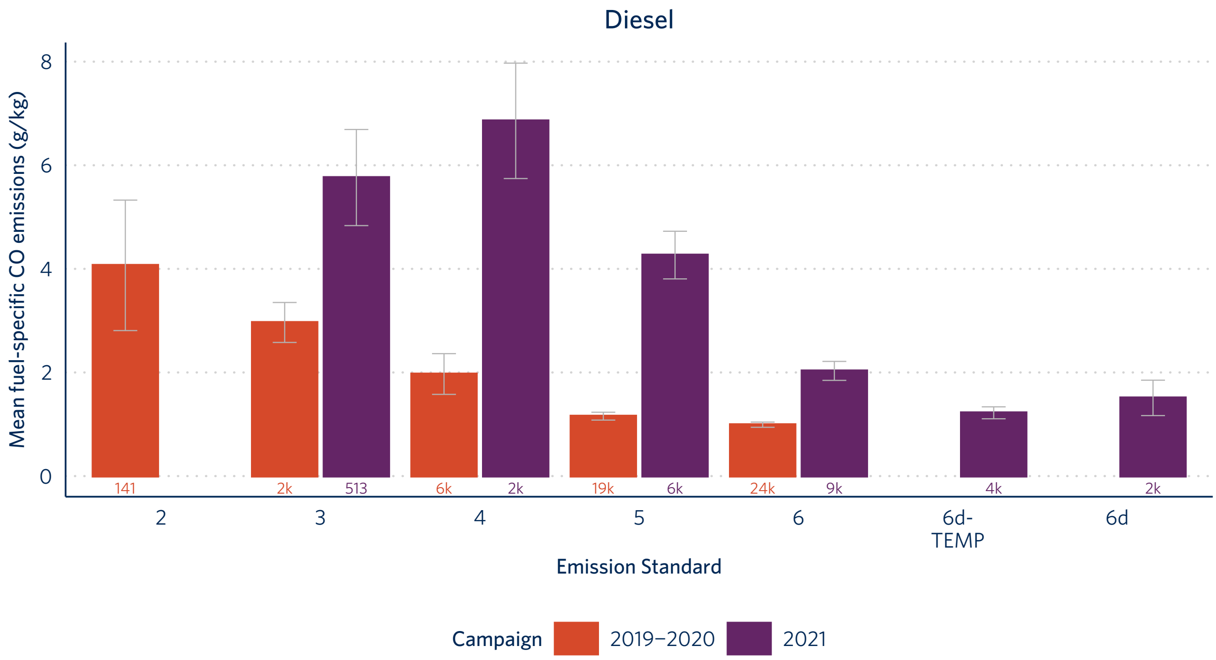


Figure 32. Mean fuel-specific CO emissions from light-commercial vehicles by Euro standard measured in 2019–2020 and 2021. CO emission measurements were not available for the 2017 measurements. The number of measurements is presented below each bar and only measurements of over 100 are presented. Whiskers represent 95% confidence interval to the mean.

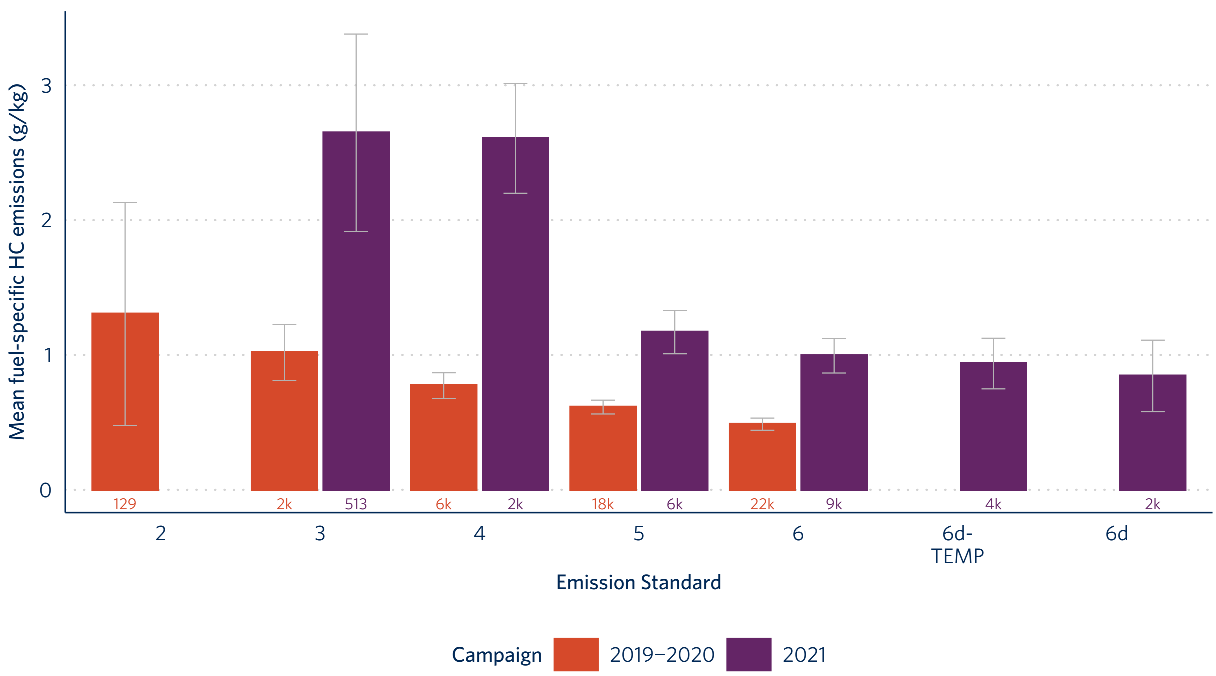


Figure 33. Mean fuel-specific HC emissions from light-commercial vehicles by Euro standard measured in 2019–2020 and 2021. HC emission measurements were not available for the 2017 measurements. The number of measurements is presented below each bar and only measurements of over 100 are presented. Whiskers represent 95% confidence interval to the mean.

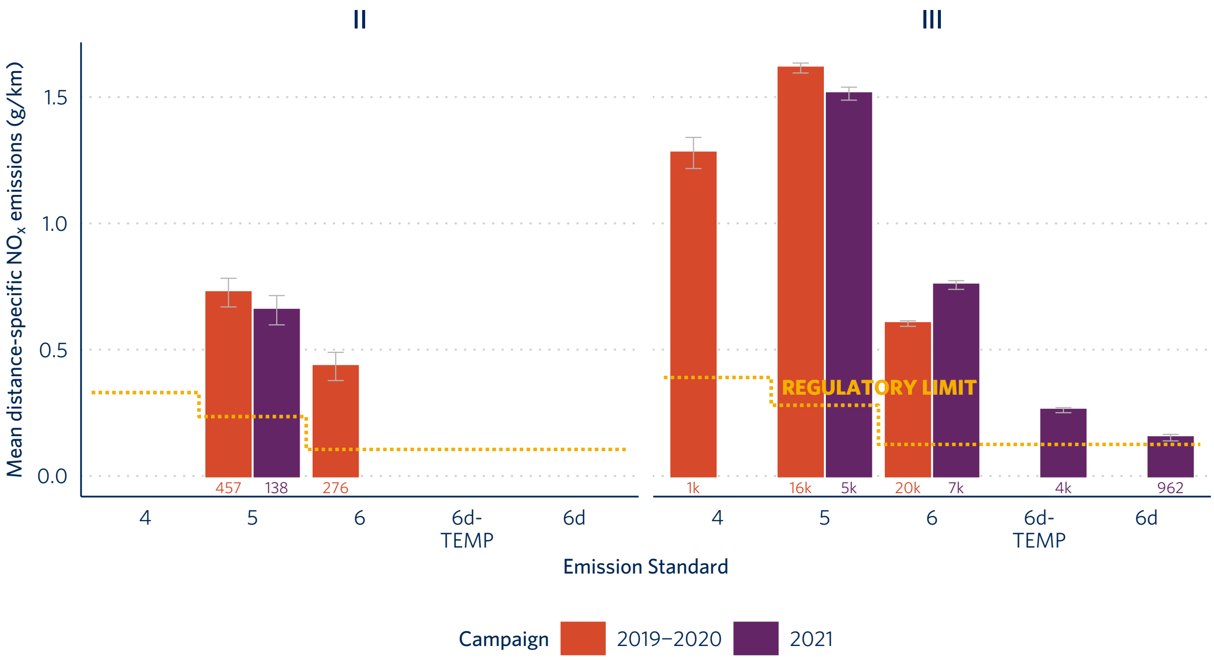


Figure 34. Mean distance-specific NO_x emissions from light-commercial vehicles by Euro standard measured in 2019–2020 and 2021.

measured LCVs.[15] Therefore, this was possible only for measurements with available type-approval CO_2 emissions.

Light commercial vehicles are further broken down into different categories and classes depending on the vehicle weight. LCV measurements from the 2017 testing campaign were excluded as they lacked the category and class information. Most of the LCV measurements from the 2019–2020 and 2021 testing campaigns had masses not exceeding 3.5 tons and were of the N1 category, and the available gross weight was used to define their classes.[16] In the process, around 20% of the LCV measurements were excluded.

The resulting mean distance-specific NO_x emissions for LCVs are presented in Figure 34. The results demonstrate that, in general, the NO_x performance of LCVs improved steadily over time with the introduction of newer standards and stricter limits. This trend is seen consistently across campaigns, despite differences in their testing conditions. Notably, the mean NO_x emissions from Class III Euro 5 LCVs were 1.5 g/km, more than double those from Class II Euro 5 (0.65 g/km). However, this gap decreases with Euro 6, of which Class III showed around 700 mg/km emissions and Class II 430 mg/km, highlighting the large reduction in NO_x emissions that Class III Euro 6 standards achieved. However, LCVs of all emission standards had real-world emissions significantly higher the type-approval limits. Particularly, the standards that were not subject to RDE testing, or those below Euro 6d-TEMP, showed NO_x levels up to 6 times the regulatory limit. The newer standards, nevertheless, appear to have achieved a significant reduction in NO_x levels, emitting on average 150 mg/km.

TRUCKS

FLEET COMPOSITION

A total of 32,770 truck measurements were collected from 12,781 unique vehicles in 2017, 2019–2020, and 2021, with some vehicles measured more than once. A summary of the measurement number and unique vehicle number for each testing campaign is summarized in Table 4. The 2019–2020 testing campaign took place on motorways, leading to a significantly higher number of truck measurements.

The distribution of Euro standards among trucks measured in each campaign is shown in Figure 35. Despite some missing Euro standards in the truck measurements in 2017, the distribution demonstrates the natural fleet turnover of trucks in Scotland. The most prevalent Euro standard in 2018 was Euro VI but the share of Euro VI jumped in 2019–2020 and successive standards, like Euro VI-D and

15 Nikiforos Zacharof, Uwe Tietge, Vicente Franco, and Peter Mock, 'Type Approval and Real-World CO2 and NOx Emissions from EU Light Commercial Vehicles', *Energy Policy* 97 (October 2016): 540–48, https://doi.org/10.1016/j.enpol.2016.08.002.

16 See https://dieselnet.com/standards/eu/ld.php for distinction by weight.

Table 4. Number of measurements and unique vehicles and some driving condition indicators from the 2017, 2019–2020, and 2021 testing campaigns in Scotland.

Testing campaign	Number of measurements	Number of unique vehicles	Mean temperature (°C)	Mean speed (km/h)	Mean acceleration (km/h/s)	Mean VSP (kW/t)
2017	1,319	986	10.2	40.1	1.12	5.5
2019–2020	27,277	9,662	10.5	79.2	0.31	16.1
2021	4,174	2,133	10.5	41.8	0.99	8.0

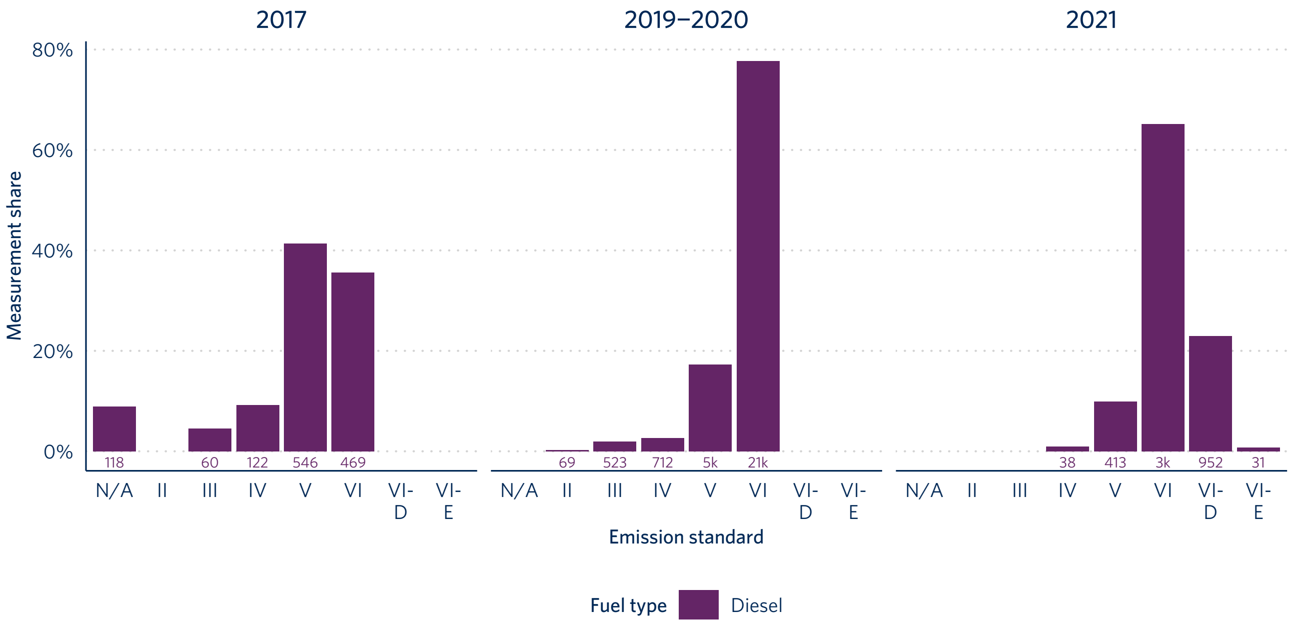


Figure 35. Share of measurements of diesel trucks by Euro standard for each testing campaign. The number of measurements is presented below each bar and only measurements of over 30 are presented.

VI-E, emerged in 2021. At the same time, older standards, such as Euro III and IV, have gradually retired over time.

The reported fuel-specific emissions (g/kg) were converted to amount of emissions per energy produced (g/kWh) for comparison with the type-approval emission limits, with the methodology using mean fuel consumption of various engine sizes.[17] As shown in Figure 36, although NO_x emissions from trucks show a downward trend over time, trucks of all Euro standards measured in Scotland showed real-world NO_x emissions above the type-approval limits. The Euro VI-D standard achieved a large reduction (almost half) in NO_x emissions from the Euro VI standard, an improvement also seen in other cities like Brussels, but it still emitted NO_x levels above the in-service conformity (ISC) limit of 460mg/kWh introduced from Euro VI to curb on-road emissions.[18]

There was also a variance in the emissions performance of trucks across different campaigns, mainly due to the different testing conditions. Within the same Euro standard, the trucks measured in 2019–2020 on motorways had NO_x emissions lower than those measured in urban settings in 2017 and 2021. NO_x emissions from the trucks certified to Euro V and VI from the 2019–2020 measurements were almost half of those measured in 2017 and 2021.

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

18 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://www.trueinitiative.org/data/publications/evaluation-of-real-world-vehicle-emissions-in-brussels.

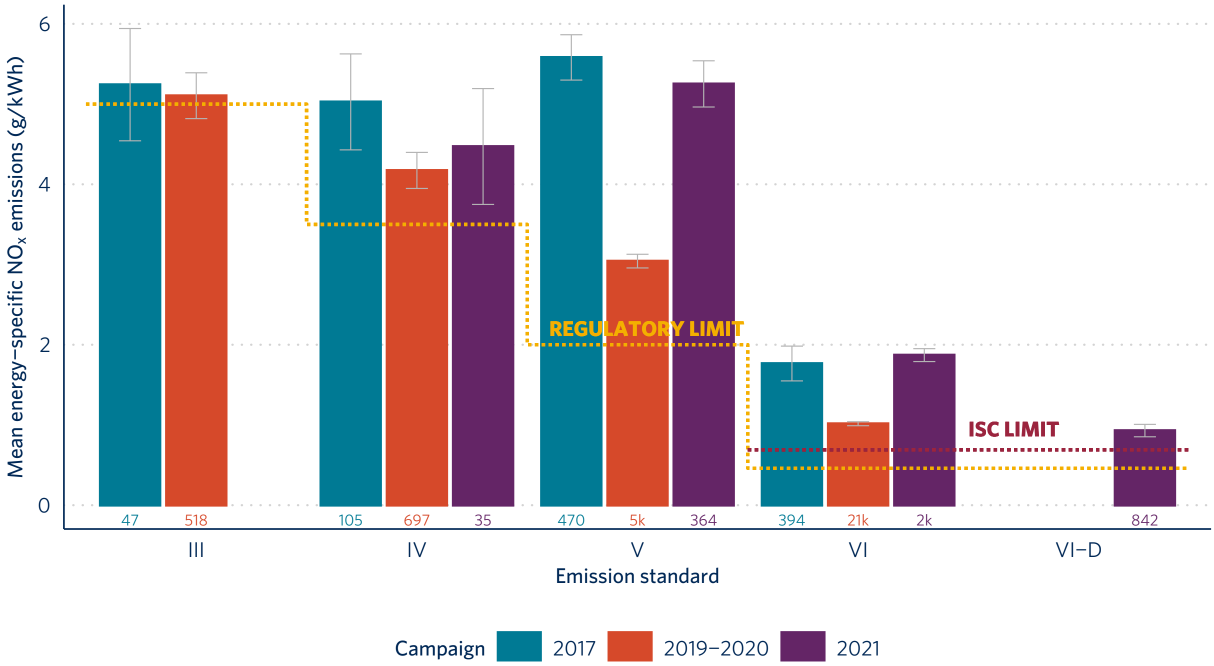


Figure 36. Energy-specific NO_x emissions from trucks measured in Scotland in 2017, 2019-2020, and 2021. The number of measurements is presented below each bar and only measurements of over 30 are presented. Whiskers represent 95% confidence interval to the mean.

INDIVIDUAL NO_X HIGH-EMITTER IDENTIFICATION

This section focuses on N3 trucks that are used for the carriage of goods and of mass exceeding 12 tons. Out of all truck measurements, over 26,000 measurements, or 80%, were N3 trucks, all measured in the 2019–2020 and 2021 testing campaigns. N2 trucks and those with no category made up around 7% each, and N1 made up 5% of the total truck measurements. Close to 90% of the N3 truck measurements were from the 2019–2020 testing campaign in Edinburgh.

In previous studies, in identifying individual high-emitting N3 trucks, fuel-specific NO_X emission thresholds of 25 g/kg for Euro V and 7 g/kg for Euro VI or above were used.[19] The application of such thresholds demonstrated that 12% of the measured Euro V trucks in 2019–2020 and 54% of those in 2021 emitted NO_X emissions above 25 g/kg. It also showed that 19% of the measured trucks certified to Euro VI or above in 2019–2020 and 41% of those in 2021 were above 7 g/kg. Although having been utilized previously, a large share of measurements above the thresholds from the Scottish measurements suggests that these thresholds are not easily transferrable for the purpose of enforcement to other cities.

The cumulative distribution of NO_X emissions from Euro V to VI-D N3 trucks (Figure 37) shows that there is no one high-emitter threshold that can be applied to any conditions. A summary of the 90th and 95th percentile NO_X emission values from each campaign is given in Table 5. The abovementioned thresholds were close to the 90th percentile emission values from the trucks measured during the 2019–2020 testing campaign, meaning using these thresholds would capture trucks with the highest 10% NO_X emissions. However, these are significantly lower than the 90th percentile emission values from the 2021 truck measurements, indicating that these thresholds are likely to not take into account the elevated NO_X emissions resulting from certain driving conditions.

Table 5. 90th and 95th percentile fuel-specific NOx emissions values for diesel N3 trucks by Euro standard and testing campaign. Euro VI and VI-D were grouped into the same category for the 2021 measurements.

Campaign	Emission standard	90th percentile	95th percentile
2019-2020	V	28.12	38.62
2019-2020	VI	11.71	17.96
2021	V	41.90	48.29
2021	VI, VI-D	17.755	23.54

19 Ole Hertel, Christian Rud Ingvardsen, Thomas Ellermann, and Jacob Klenø Nøjgaard, "Control of SCR-Systems Using Roadside Remote Sensing Results from Road Experiments 2019," (Danish Center for Energy and Environment, August 2020), https://dce2.au.dk/pub/SR387.pdf.

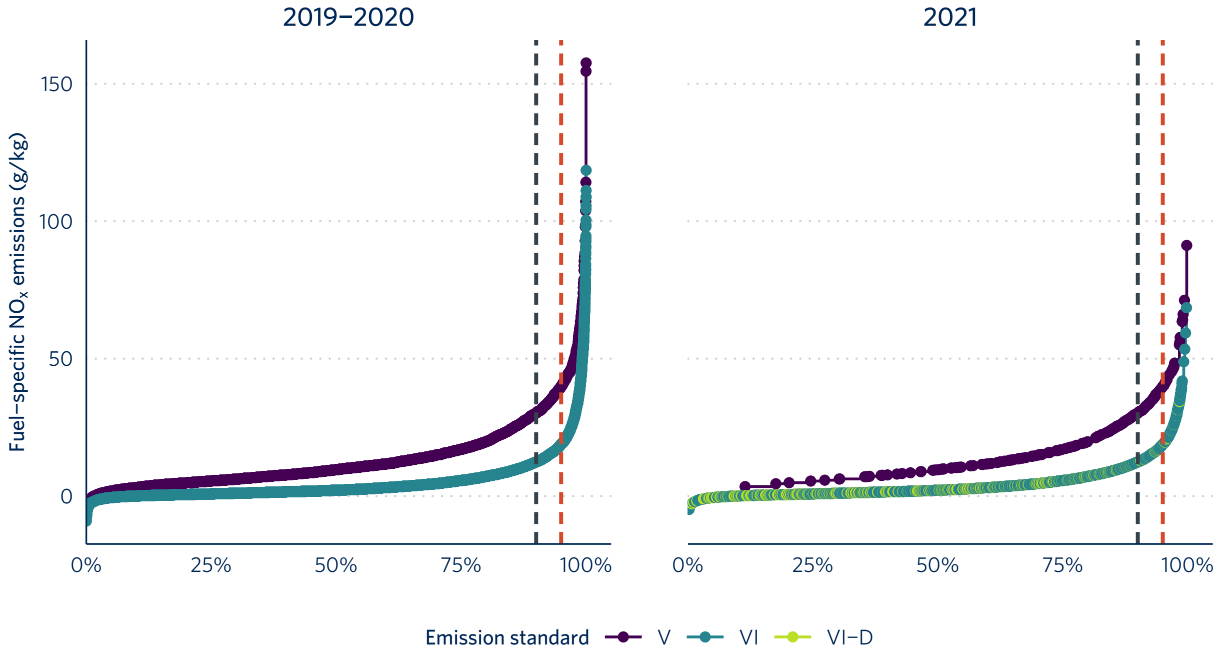


Figure 37. Fuel-specific NO_x emissions as a function of the cumulative share of the Scottish N3 truck measurements in 2019–2020 and 2021. Grey dotted line indicate 90th percentile and orange dotted line 95th percentile.

Finding adequate threshold cut-off points for the enforcement of high-emitting trucks is particularly important in stop-and-inspect situations for detecting individual vehicles which show highly elevated emissions mostly due to defects or tampering. The difference in the levels of NO_X emissions from N3 trucks measured in 2019–2021 and 2021 demonstrates that the site for enforcement should ensure the collection of emissions measurements from vehicles with similar driving conditions. As shown in Figure 38, Euro V and VI trucks in 2019–2020 show relatively even distributions of NO_X emissions, with one peak of very high emissions and the remaining reasonable levels of emissions. However, those in 2021 show generally more widespread high emissions with two visible peaks for Euro V, likely due to vehicles with cold engines commonly found in urban settings. Having many high emission measurements makes it difficult to isolate the measurements from defective or tampered vehicles from those with cold engines or low speed and, therefore, to pinpoint a threshold to identify individual high-emitting vehicles.

Since instantaneous emissions measured by the remote sensing system are influenced by various parameters of driving conditions, one emissions measurement from the vehicle does not necessarily represent the overall emissions trend of the vehicle. Acknowledging such shortcomings of remote sensing emissions measurements, a more systematic method was utilized to identify likely individual high-emitting trucks. As some vehicles passed by the EDAR systems and were measured more than once, we take a sample of only emissions measurements from the vehicles measured five times or more. Only around 19% and 4% of the 2019–2020 and 2021 measurement samples, respectively, were of vehicles measured repeatedly five or more times. The share of repeatedly measured vehicles in 2019–2020 was higher, for on motorways. For the Euro standard vehicle groups this section focuses on, Euro V, VI, and VI-D, this process shrank the sample size by on mean 50% for the 2019–2020 measurements and 80% on mean for the 2021 measurements, compared to the truck sample including all vehicles measured four times or less. The shares of measurements and unique vehicles measured five times or more in the total sample are broken down by testing campaign and Euro standard in Table 6.

We then applied thresholds of 25 g/kg for Euro V and 7 g/kg for Euro VI and VI-D to these samples, as these thresholds may not be helpful when looking at individual instantaneous emissions measurements but can provide an indication of emission control system malfunction when the thresholds were repeatedly exceeded.[20] When more emissions measurements from the vehicle were above

20 Hertel, Ingvardsen, Ellermann, and Nøjgaard, "Control of SCR-Systems Using Roadside Remote Sensing Results from Road Experiments 2019."

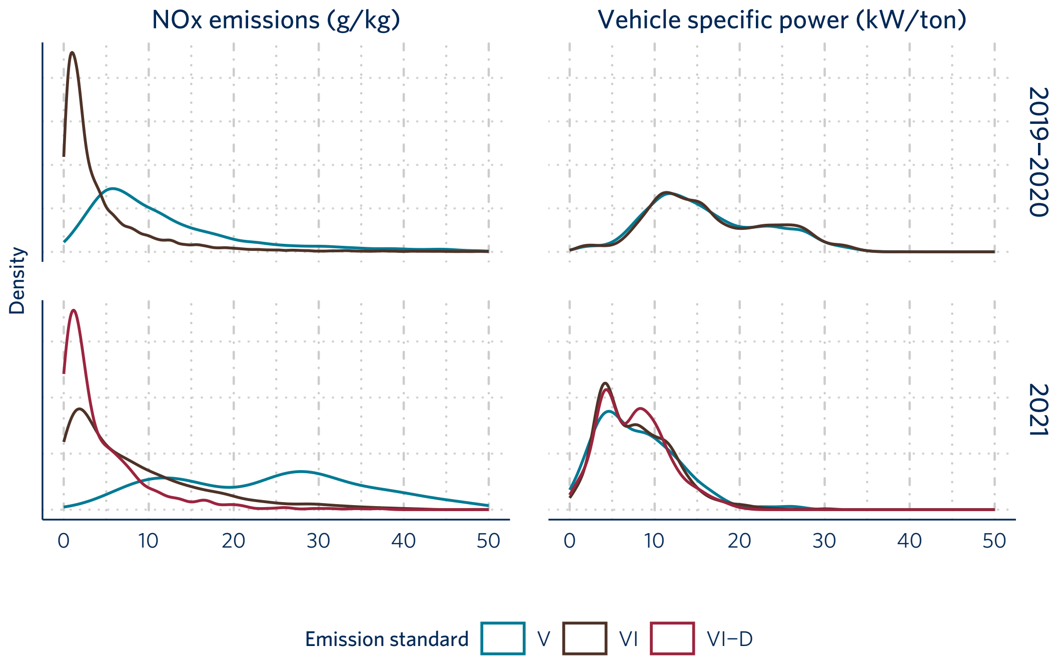


Figure 38. Distribution of fuel-specific NOx emissions (g/kg) and vehicle specific power (kW/t) by Euro standard and testing campaign. Areas below lines cover 100% of respective emission standard measurements.

Table 6. Numbers and of measurements and vehicles measured five times or more and their shares in the total sample by testing campaign and Euro standard.

Testing campaign	Euro standard	Number of measurements from vehicles measured five times or more	Share of measurements from vehicles measured five times or more in the total measurement sample	Number of unique vehicles measured five times or more	Share of unique vehicles measured five times or more in the total unique vehicle sample
2019-2020	V	3,569	49%	219	17%
2019-2020	VI	19,262	51%	1,214	19%
2021	V	201	24%	6	6%
2021	VI	1,527	18%	36	4%
2021	VI-D	492	24%	15	6%

than below the threshold, the vehicle was tagged as a high-emitter. By looking at multiple emissions measurements from one vehicle, this method was able to avoid false positives, such as vehicles that showed emission levels over the threshold once or twice due to cold starts but are not defective or tampered. The number of vehicles tagged as high-emitters and the share of tagged high-emitters in each sample is given in Table 7. The results showed that 3%–6% of Euro V and VI trucks measured in 2019–2020 and 7%–28% of Euro V to VI-D trucks in 2021 were emitting consistently high NO_x emissions. However, the samples from the 2021 measurements were significantly limited, which led to seemingly higher shares of high-emitters, and more measurements are warranted.

The distribution of NO_x emissions measurements from the tagged possible high-emitters and other vehicles is shown in Figure 39. The NO_x emissions distribution from possible high emitters is more spread out than that from other vehicles consistently across testing campaigns and Euro standards. In 2019–2020, the difference in the distribution of NO_x emissions from these two groups was more prominent than in 2021. Due to the conditions the vehicles manifested during testing, those vehicles measured in 2021 had a large variance in their emissions performance, which made it difficult to distinguish constantly high-emitting vehicles from those with occasional high emissions readings.

Table 7. Number of tagged high-emitters and their share in the smaller sample of vehicles measured 5 times or more.

Campaign	Euro standard	Total number of measurements from vehicles measured 5 times or more	Number of high emitters	Share of high emitters
2019-2020	V	219	7	3%
	VI	1214	72	6%
2021	V	6	1	17%
	VI	36	10	28%
	VI-D	15	1	7%

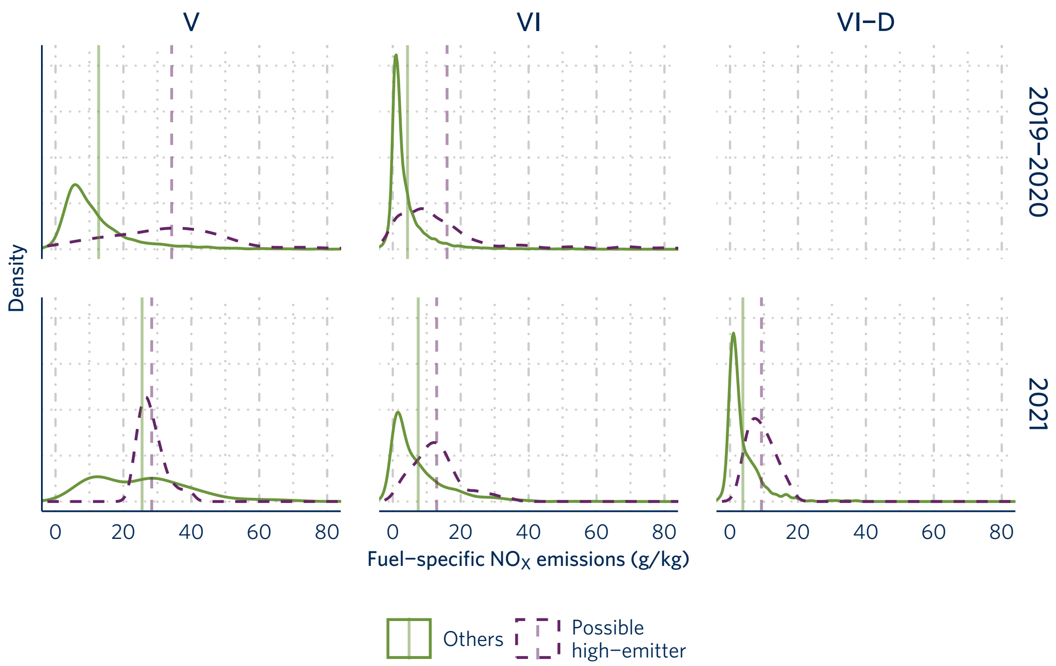


Figure 39. Distribution of NO_x emission measurements from vehicles tagged as possible high-emitters and others by testing campaign and Euro standard. Vertical lines indicate the mean fuel-specific NOx emission values (g/kg). There was only one possible Euro V and Euro VI-D/E high-emitter in the 2021 measurements. Areas below lines cover 100% of respective measurements.

The mean NO_x emissions from the possible high-emitters and others showed a greater difference in the 2019–2020 data. As shown in Table 8, the mean NO_x emissions from the tagged high-emitters were 2.7–3.7 times those from the rest of the trucks in 2019–2020, while the difference between the same groups were less than a factor of 2 for Euro V and VI measured in 2021. The comparable emission levels shown for identified high-emitting Euro V trucks and others in 2021 may additionally imply that the Euro V Euro standard regulations are not able to properly control emissions in urban settings. The one high-emitting VI-D truck was on mean emitting 2.4 times the NO_x emissions as vehicles in the rest of the sample.

Table 8. Mean NOx emissions from possible high-emitting trucks and other trucks by testing campaigns and Euro standard.

Testing campaign	Euro standard	Mean NOx emissions from high-emitters (g/kg)	Mean NOx emissions from other trucks (g/kg)
2019-2020	V	34.2	12.7
2019-2020	VI	16.0	4.3
2021	V	28.3	25.5
2021	VI	12.9	7.5
2021	VI-D	9.2	3.8

In light of an abundance of heavy-duty truck measurements collected in Scotland in 2019–2020 and 2021, this section tested previously established thresholds for the road-side enforcement of malfunctioning or tampered high-emitting trucks. Although the thresholds have been effectively used in some enforcement campaigns to identify high-emitting trucks, we find that these may not be adequate for the sites selected for the Scottish truck measurements. However, when used with repeated measurements of vehicle emissions, these thresholds could be helpful for identifying individual high-emitting trucks.

A new method using multiple emissions measurements from single vehicles was explored. In the absence of the actual inspection of the tagged high-emitting vehicles, however, we were not able to verify what share of these vehicles were in effect defective or tampered with. Moreover, this was done ex-post on the measurements already collected, providing little implications for road-side enforcement. Finding the appropriate thresholds for real-world enforcement is more complicated. Under real-world circumstances, for example, it is hard to distinguish the Euro standards of passing vehicles, unless the enforcement authority has access to a live database of Euro standards based on license plates. Therefore, using the lower threshold would lead to a fair share of false positives and be labour-intensive, but using the higher threshold would fail to capture individual high-emitting trucks certified to newer standards. It is therefore important to find a balance between avoidance of false positives and a higher success rate based on the needs of a city or capacity of the enforcement personnel. What is possible, though, is to select an enforcement or measurement site where the passing trucks are less likely to have cold engines and similar VSPs, which would limit the variance in emission performance.

BUSES

FLEET COMPOSITION

Buses accounted for only a minor fraction of the measured vehicles in all three campaigns. The total measurements of buses taken from the 2017 and 2021 campaigns combined barely reached 1,000 from around 500 individual buses. Most bus measurements were collected from the 2019–2020 testing campaign (approximately 3,500) but they made up only about 1% of the total vehicles measured. The numbers of measurements and unique buses from each campaign are summarized in Table 10.

The majority of buses measured, including both city buses and coaches, were diesel-powered, with some additional fuel information available for the 2019–2020 measurements, of which the second fuel type was identified as electricity. These diesel hybrid buses were certified to Euro V and VI. Despite the small sample size, remote sensing measurements of buses in Scotland showed the natural turnover of buses. As shown in Figure 40, buses certified to Euro IV, V, and VI accounted for similar levels of buses at around 25% in 2017. However, Euro VI buses have become predominant in the fleet, making up over half of all bus measurements in 2019–2020, and 60% in 2021. Particularly in 2021, a new standard Euro VI-D emerged and replaced old standards, like Euro III and IV. These old standards that accounted for around 40% of the bus fleet in 2017 have gradually phased out and were almost completely out of the fleet in 2021. This is largely due to Transport Scotland's support for new bus purchases and retrofitting of mid-life buses in preparation for the low emission zones.

Table 9. Numbers of measurements and unique buses measured from each testing campaign. Higher numbers of measurements indicate that some buses were measured more than once.

Testing campaign	Number of measurements	Number of unique buses
2017	279	199
2019-2020	3,502	1,122
2021	644	340

FUEL-SPECIFIC NO_x EMISSIONS

This section assesses the NO_x emission performance of only diesel buses and coaches for all three testing campaigns, as they made up the majority of measurements. Coaches retrofitted with selective catalytic reduction (SCR) systems were also identified in the 2021 measurements but were excluded from the assessment due to the low number of measurements.

The fuel-specific NO_x emissions from buses measured in 2017, 2019–2020, and 2021 showed a significant variance in performance across testing years (Figure 41). The buses measured in 2019–2020 had a mean VSP of 18, more than double that of buses from 2017 and 2021, due to high speeds characteristic of motorway traffic. High VSPs combined with a less likelihood of cold engines on motorways are attributable to the lower levels of NO_x emissions seen in the 2019–2020 measurements. The 2017 and 2021 measurements, however, showed a large discrepancy for Euro V and VI buses, despite similar driving conditions. The Euro V and VI buses measured in 2021 emitted NO_x at levels 66% and 35% higher, respectively, than their counterparts in 2017. Such increase in emissions may be associated with ageing, as Euro V and VI buses measured in 2021 would be about 3–4 years older

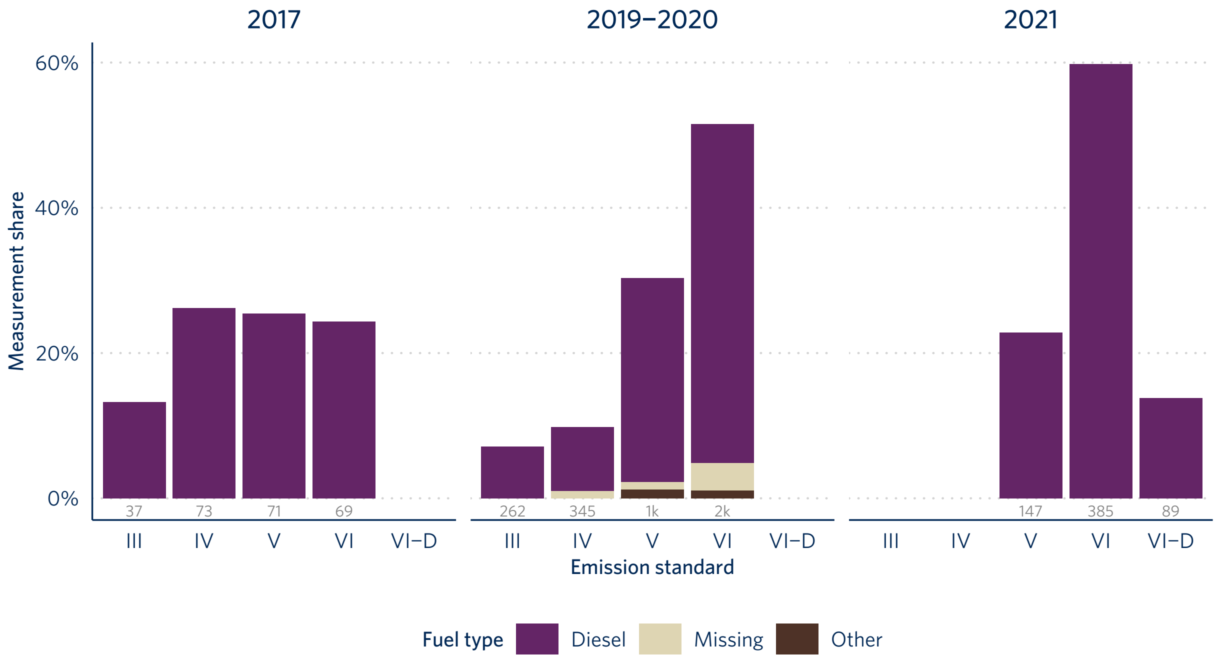


Figure 40. Distribution of fuel types and Euro standards of buses measured in 2017, 2019–2020, and 2021. Only measurements of 30 or more are presented. Measurements with the fuel type "other" are all diesel hybrid buses.

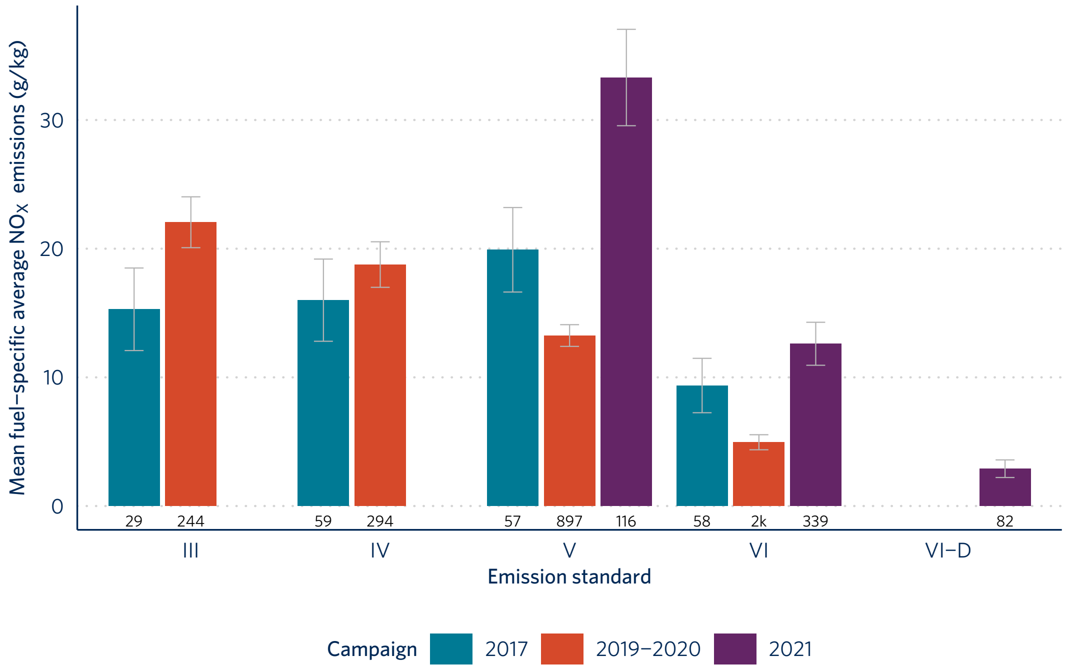


Figure 41. Fuel-specific NOx emissions from buses measured in 2017, 2019–2020, and 2021. The number of measurements is presented below each bar and only measurements of over 25 are presented. Whiskers represent 95% confidence interval to the mean.

than those measured in 2017. Further investigation of the 2021 bus measurements demonstrated that most of these buses were measured in Edinburgh and they were emitting consistently high at around 35 g/kg, which suggests a possible large influence of cold engines on high levels of emissions, given the site of the emissions data collection.

A sufficient number of Euro VI-D buses which were mandated from late 2019 was only found in the 2021 measurements. Despite the absence of Euro VI-D bus measurements from other campaigns, the average fuel-specific NO_x emissions from the Euro VI-D buses in 2021 show that this standard achieved a significant reduction in emissions of almost 80% lower than the preceding Euro VI standard.

POLICY RECOMMENDATIONS

This study has generated data on the real-world emissions produced by today's vehicle fleet, presenting an excellent opportunity to provide evidence-based recommendations for further action beyond the policies already in place. Noteworthy trends have been observed which correlate with fuel type, vehicle type, age, certified emissions standard, and accumulated mileage.

The following recommendations are made in light of the analysis presented in this report. They fall into two categories: one set of measures which represent an extension of the restrictions already proposed, and a set which would require additional investment or material change to monitoring arrangements as well as engagement with wider stakeholders. A wider discussion of the possibilities for fleet turnover is also discussed.

RESTRICTIONS ON LOW EMISSION ZONE ENTRY

As has been clearly demonstrated, NO_x emissions from diesel vehicles are significantly higher than for petrol vehicles, and this is especially true of vehicles certified to older Euro standards. For example, Euro 5 diesel vehicles produce on average between 750 and 900 mg/km compared with 150–250 mg/km for petrol equivalents. Only with the advent of Euro 6 standards which are subject to additional on-road emissions limit, such as Euro 6d-TEMP and 6d, was a significant reduction in NO_x emissions seen in diesels. Vehicles certified only to Euro 6a–c and previous standards emit significantly more NO_x.

For petrol-powered vehicles there is less of a pronounced fall in NO_x emissions as a function of Euro certification level, although a downwards trend is clearly seen with ~40% falls from Euro 3 to Euro 4, and from Euro 4 to Euro 5. NOx levels for pre-Euro 4 petrol vehicles are, however, comparable with Euro 5 diesel vehicles in Glasgow at an average of 800–900 mg/km. In addition, CO emissions are noticeably higher than in diesel vehicles in all cases, with Euro 4 vehicles in the study emitting 20–28 g CO per kg of fuel, compared to 3–4 g for diesel vehicles.

For these reasons, policymakers should consider requiring that **diesel passenger cars and light commercial vehicles be certified, as a minimum, to Euro 6d-TEMP, and petrol vehicles be certified, as a minimum, to Euro 4** in order to enter a low emissions zone.

NO_x emissions from trucks and buses show a broadly similar pattern to passenger cars and light vehicles, with the exception of the 2019–2020 data where the testing site was found to be measuring vehicles with significantly warmer engines than in the other campaigns, with measurements taken at a motorway rather than location. This led to ~50% lower measured emissions in 2019–2020. The trend in all campaigns, however, is that NOx emissions of Euro VI certified vehicles fall by 60%–70% compared with Euro V. This is justification for recommending that **trucks and buses should be certified to Euro VI or later in order to enter low emission zones.** In practice, the majority of the fleet is already certified to this emissions level, with only ~400 out of over 4000 vehicles measured during the 2021 campaign being pre-Euro VI.

FURTHER MEASURES FOR CONSIDERATION

Emissions from vehicles have been found to be lower when they are certified to later standards. Additionally, however, it is expected that a given vehicle will emit more over time as the emissions aftertreatment system deteriorates with age. Crucially, this is a function of number of miles driven more than simply age in years, as is reflected in the legislation itself, where the required mileage that must be adhered to is set at 100,000 km for Euro 4 and 160,000 km for Euro 5 and Euro 6.

Taxi and private hire vehicles are ordinarily driven for more miles per year than passenger vehicles and so higher emissions are expected from the former at a given nominal age in years. Evidence of this is seen in Figure 8, where NO_x emissions from vehicles ~5–7 years old (potentially approaching or exceeding the 160,000 km mileage for which the emissions systems are designed) are approximately 30%–50% higher than for passenger cars. Thus, a potential **mileage or age limit for private hire vehicles and taxis** as well as Euro standard level could be considered. The case for this would ideally be made stronger with additional information about vehicle mileage, and this information is recorded in annual Ministry Of Transport (MOT) road-worthiness certification testing.

The study has highlighted that a relatively small number of high-emitting vehicles generate a disproportionately high share of overall emissions. This is true for all types of vehicles. **Identifying high-emitting vehicles and mandating inspection by a garage** would be of great benefit, although currently NO_x emission capability is not routinely available at MOT centres, with opacity testing only being routinely conducted for diesel vehicles, which is capable of picking up faulty filtration equipment which would not necessarily be correlated with high NO_x emissions. The detailed practicalities of identifying high emitters are beyond the scope of this report but opportunities to take action in this way could be at the annual MOT certification, either via enhanced emissions monitoring as a routine part of testing or following the identification of high emitters using remote sensing. A combination of adequate thresholds and enforcement measures, such as stop-and-inspect with simultaneous access to vehicle specification data identified from license plates, is recommended for successful identification of defective or tampered vehicles.

Police ANPR cameras are already used to identify vehicles which for example are untaxed or uninsured and out of MOT. An analogous monitoring regime could be envisaged which is able to identify high emitting vehicles and encourages their owners, without penalty, to take their vehicles to a garage for possible servicing. This report has demonstrated the ability of the current equipment to identify individual vehicles which repeatedly produce high emissions, and it would be reasonable to require multiple instances of high emissions to be identified before action was taken. Extending the scope of traffic camera monitoring and enforcement action of any kind is again beyond the scope of this report and would necessitate wider agreement and consultation, but the opportunity for reducing emissions is clear.

THE REAL URBAN
EMISSIONS INITIATIVE

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