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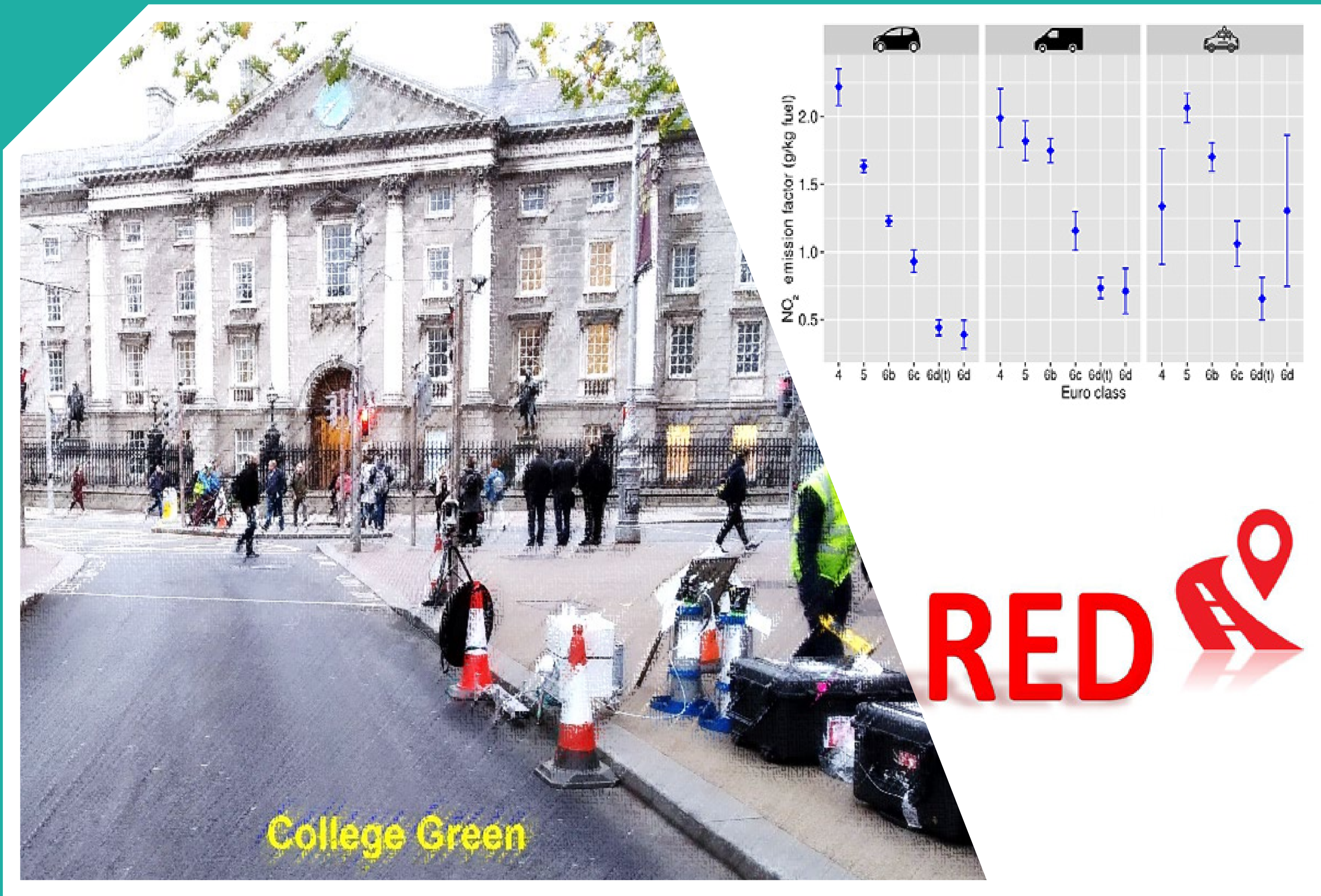
Roadside Emissions in Dublin: Measurements and Projections (REDMAP)

Authors: Srinath Mahesh, Adam Clarke, Ben Fowler, Rebecca Rose, Aonghus McNabola, William Smith, David Timoney, Jasmine Wareham, Paul Willis and Bidisha Ghosh



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Government of Ireland

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3. Office of Evidence and Assessment
4. Office of Radiation Protection and Environmental Monitoring
5. Office of Communications and Corporate Services

The EPA is assisted by advisory committees who meet regularly to discuss issues of concern and provide advice to the Board.

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Identifying pressures

In Ireland, transport accounts for about 20% of emissions, and 95.8% of these emissions are caused by on-road vehicles. Several pieces of legislation and policies have been developed to tackle this issue. However, emission reductions resulting from policies, legislation and standardisation have been lower than originally anticipated. The key challenge is the discrepancy between vehicle type approval tests and real-world emissions from vehicles powered by fossil fuels. A comprehensive understanding of real-world emissions, particularly from in-use vehicles, is lacking, as discrepancies between laboratory testing and actual on-road performance make it difficult to accurately assess the full extent of the pollution problem and devise effective mitigation strategies. Moreover, knowledge is limited about trends in the emission factors of vehicles that conform to different emission standards (Euro 4/Euro 5/Euro 6), use varying fuel types (petrol/diesel) and have high mileage. From a mitigation standpoint, the fact that there are no low-emission zones (LEZs) in Ireland indicates that few restrictions are aimed at improving ambient air quality in sensitive areas.

Informing policy

The findings of this report have significant policy relevance, as they could directly guide the design and implementation of LEZs and zero-emission zones (ZEZs) in Dublin and other Irish cities. The comprehensive dataset collected could support the introduction of restrictions on older, more polluting vehicles, as well as the development of mandatory inspection and maintenance programmes. Furthermore, the insights gained on the impact of pedestrianisation measures could inform urban planning strategies to mitigate air pollution within the city centre. This evidence-based knowledge could make a substantial contribution to improving air quality and public health in Dublin. By providing a more accurate representation of real-world vehicle emissions, this report offers policymakers the necessary data and analysis to make informed decisions and implement effective interventions. The introduction of LEZs and ZEZs could lead to a significant reduction in air pollution levels within the city. Overall, the evidence-based solutions presented in this research have the potential to make a substantial and positive impact on air quality in Dublin and in other cities in Ireland.

Developing solutions

By utilising real-world measurement techniques, such as remote sensing, it was possible to quantify emissions from an exceptionally large sample of over 130,000 vehicles, including cars, light goods vehicles, heavy goods vehicles and buses. This extensive dataset provided invaluable insights, further enhanced by the incorporation of portable emission measurement system (PEMS) data. The emission factors derived from both PEMS and remote-sensing data were then integrated into a dispersion model, offering a more accurate representation of air pollution levels in the city. Notably, the study also focused on a significant number of the latest Euro 6 vehicle models, providing crucial insights into the real-world performance of these newer, more stringent emission standards. Based on the analysis, a comprehensive set of evidence-based solutions were proposed, including the phasing out of older, more polluting vehicles (such as Euro 3 and Euro 4 models), restricting vehicle access in the city centre and implementing LEZs to effectively mitigate air pollution in the Dublin metropolitan area.

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Trinity College Dublin Ireland

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DISCLAIMER

This report is based on research carried out/data from May 2021 to January 2023. More recent data may have become available since the research was completed.

The EPA Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

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Executive Summary

A 2-year-long research project, Roadside Emissions in Dublin: Measurements and Projections, was conducted in Dublin to measure, model and project the real-world vehicular emission levels of key pollutants (including NO_x and particulate matter (PM)) from in-use vehicles in Dublin. The project involved measuring emissions from vehicles using remote sensing (RS) and portable emission measurement system (PEMS). The project partners were from the Department of Civil, Structural & Environmental Engineering at Trinity College Dublin, the School of Mechanical and Materials Engineering at University College Dublin and Ricardo Energy & Environment.

A key aspect of the project was the collection of real-world emission data for in-use vehicles in Dublin using an RS technique. Six sites across the city that met the requirements of the collection technique were selected. Emissions of NO_x (NO and NO_2), CO, hydrocarbons, NH_3 and PM were measured using an Opus RSD5000. A digital image of the vehicle licence plate and the speed and acceleration of the vehicle were also captured. The measurement campaign was split into two 8-week campaigns (one in winter and one in summer), and more than 100,000 individual vehicles were measured. Notably, the dataset included a significant number of measurements of the latest Euro 6 compliant vehicles, which are underrepresented in existing European RS studies.

The analysis of the RS dataset provided several important findings, in particular related to NO_x and PM emissions. Petrol cars were found to emit little NO_x, as required for homologation, while the emissions of NO_x by diesel cars and light goods vehicles up to and including the early Euro 6 stages were found to be far in excess of permitted levels. Furthermore, NO_x emissions from petrol cars were low across all registration years, whereas NO_x emissions from diesel cars decreased with registration year after 2015. This can probably be attributed to the introduction of more stringent emission limits for Euro 6 vehicles and more effective and representative on-road testing procedures to address the deficiencies brought to light by Dieselgate. The PM emissions, on average, were found to decrease with the introduction of Euro 5 diesel cars (around 2011). This decrease aligns with the introduction of diesel particulate filters (DPFs), introduced in late Euro 4 vehicles, which physically trap PM. Euro 5 and 6 diesel vehicles also use DPFs; as a result, emissions of PM were low for Euro 5 and 6 diesel cars and vans.

The PEMS analysis showed that the vast majority of overall emissions come from vehicles produced prior to the introduction of the Euro 6 standard. Despite making up 45% of diesel vehicles, Euro 6 diesels account for only 29% of diesel NO_x emissions. Similarly, the latest Euro 6d vehicles, despite accounting for 1.6% of all diesels, contribute only 0.01% of total diesel NO_x emissions. Therefore, the phasing out of older diesel vehicles is recommended.

A vehicular emission inventory was developed for Ireland for this project using the Computer Program to Calculate Emissions from Road Transport (COPERT) emission model. The estimated emission levels showed that the highest contribution of CO_2 was from passenger cars, because they are significantly more common than other vehicle types. Total NO_x emissions from trucks, despite the fact that trucks are much less common than cars, were 30% of total passenger cars emissions, which may be because, on average, trucks have a higher annual mileage. Thus, both number of vehicles and average annual mileage affect the emission inventory development.

Concentration models of NO_x vehicular emissions were developed for Dublin using an atmospheric dispersion modelling system. This model was used to evaluate the impacts of the introduction of a low-emission zone (LEZ) and pedestrianisation of College Green.

The highest NO_x concentrations, which ranged between $80\,\mu g/m^3$ and $120\,\mu g/m^3$, were found along the quays in the city centre. However, NO_x concentrations decreased significantly outside the canal cordon, with only the locations along the roads having relatively high concentrations. The introduction of a simulated LEZ resulted in a significant reduction in the estimated NO_x concentration levels inside the city centre.

However, owing to the high volume of traffic, the concentrations along the quays remained high.

To improve emission levels, the authors recommend phasing out older vehicles, restricting traffic volumes and limiting the emissions from buses and trucks.

1 Introduction

1.1 Background

Air pollution causes approximately seven million deaths per year worldwide, and approximately 91% of the world's population live in places where the air quality is poor (i.e. the particulate matter (PM) concentration exceeds World Health Organization guideline limits) (World Health Organization, 2016). At present, air pollution represents the greatest environmental risk to our health and environment. In Europe, approximately 364,200 premature deaths annually are attributable to fine PM (PM < 2.5 µm in aerodynamic diameter), O_3 and NO_2 exposure (EEA, 2021). The transport sector, more particularly road transport, is a major source of these key pollutants and greenhouse gases. In Ireland, transport accounts for about 20% of emissions, of which 95.8% are attributable to on-road vehicles (EPA, 2018). The impact of air pollution is higher in urban areas owing to the high density of on-road vehicles and the proximity of pollutant generators to high-density housing.

In Europe, air quality has been a priority and, through policy development, legislation, standardisation and compliance, the transport sector has successfully reduced emissions of some pollutants. However, reductions in emissions over the last two decades have been lower than originally anticipated. This is because of the increased use of road transport vehicles, especially of diesel vehicles, and the fact that the levels of "real-world emissions", particularly from diesel passenger cars and vans, generally exceed the permitted European emission (Euro) standards, which define the limits for exhaust emissions of new vehicles sold in EU Member States (EEA, 2019).

Since 1996, with the introduction of Euro legislation, the New European Driving Cycle has been used for vehicle type approval tests in the EU. Several studies (Ntziachristos and Samaras, 2014; Dey *et al.*, 2018) indicate that these laboratory tests, using the New European Driving Cycle, or similar cycles, underestimate exhaust emissions from in-use vehicles due to low acceleration pattern, constant-speed cruising and a large number of idling events and other factors. The discrepancies between type approval and real-world emissions are significant.

In addition, laboratory tests are generally conducted using new and/or well-maintained engines/vehicles, which may not be representative of the condition of a large proportion of most vehicle fleets. In reality, the vehicle condition has a significant effect on emissions (Bishop *et al.*, 1996). The type of after-treatment system used, such as diesel particulate filter (DPF) or exhaust gas recirculation, also affects emission levels, especially emissions of NO_x (Carslaw *et al.*, 2011).

The differences in emissions highlight the need to include real-world emission testing to accurately estimate the emissions from in-use vehicles (Carslaw *et al.*, 2011; Donateo and Giovinazzi, 2018). In this study, the main approaches used to measure emission rates from in-use vehicles under real-world conditions were principally the portable emission measurement system (PEMS) and vehicle emission remote sensing (RS). Typically, the PEMS is used to measure emissions under real-world driving conditions and is the basis of the European Real-Driving Emission Regulations (European Commission, 2018). PEMS has the advantage of providing detailed emissions information for individual vehicles over whole drive cycles under real-world conditions. Today, the PEMS is quite frequently used for the generation of emission factors (EFs) for models. However, it requires that individual vehicles be instrumented, which is costly and time-consuming, and it can be used to test only a small number of vehicles.

The RS technology developed by Bishop and Stedman (1996) utilises short-duration roadside measurement of individual vehicle plumes using infrared long-path photometry. RS is able to capture a large number of measurements, enabling us to detect statistically significant differences in emission estimates for different types of vehicles. RS has been successfully used to distinguish between the emission trends of petrol and diesel vehicles. In a study of light-duty vehicles in Zurich carried out between 2000 and 2012, it was found that the NO_x EFs (g/kg fuel) of diesel vehicles, in contrast to those of petrol vehicles, had increased over the period, despite the fact that emissions limits had been progressively tightened (Chen and Borken-Kleefeld, 2014). Similarly, Carslaw *et al*. (2011) and Carslaw and Rhys-Tyler (2013) used RS in London and found that only petrol vehicles showed a reduction in NO_x/CO_2 emissions over the period 1985–2012, whereas diesel vehicles, including those with after-treatment systems designed to reduce NO_x, showed little evidence of NO_x/CO_2 emission reduction.

1.2 Project Aims

The Roadside Emissions in Dublin: Measurements and Projections project aimed to measure, model and project real-world vehicular emission levels of key pollutants (including NO, NO_2, PM and NH_3) from in-use vehicles in Dublin. Emissions from real-world driving are often higher than estimated emission levels presented in the national inventory based on Euro emission standards and type approval tests; consequently, fleet renewal and the establishment of stringent emission regulations have not, as originally anticipated, led to an improvement in air quality in cities. To address this discrepancy, this project measured real-world emissions using RS and PEMS. The real-world emissions contribution of different vehicles considering their Euro standard, fuel type, make, category and vehicle modifications was utilised to improve the existing emission inventory generated using literature values. A new traffic emissions model and paired air quality model estimating pollutant concentrations was formulated based on real-world EFs. This project used a scenario-based modelling framework to estimate the potential environmental impact of real-world driving, taking into consideration future transport growth and the impact of policy changes. This project will be used to generate guidelines on measures and opportunities to reduce vehicular emissions on roads in Dublin.

1.3 Main Objectives and Targets

Our main objectives and targets during this project were:

- to carry out, based on a robust multi-location experimental design, a detailed measurement and analysis of real-world vehicle emissions across Dublin using Opus RSD5000 RS technology and establish a database of actual emissions from in-use vehicles in Dublin;
- to assess, through measured emission database analysis, the impacts of variances from expected vehicle performance and identify vehicles with higher polluting potential;
- to establish, utilising a commercially available PEMS database, evidence-based, real-world, full-cycle and speed-dependent estimates of tailpipe emission rates (real-world EFs) for passenger cars and light vans;
- to develop an integrated street-level concentration model for parts of the Dublin road network considering estimated real-world emission levels and using dispersion modelling to estimate the indicative air quality (NO_x) considering traffic emissions;
- to understand the impact of introducing a low-emission zone (LEZ) and local pedestrianisation on pollutant concentrations within the city centre.

2 Real-world Driving Emissions: Remote Sensing Measurement Campaign

2.1 What is Remote Sensing?

RS instruments measure tailpipe emissions from passing vehicles under real-world driving conditions. RS instruments use an open-path optical measurement system, which consists of ultraviolet and infrared light sources that are directed across a single-lane carriageway to a mirror and then returned to the detection system within the RS unit. The light is absorbed by pollutants as it passes through the exhaust plume and measured in relation to its absorption of CO_2 to provide pollutant emissions as ratios to CO_2 emissions.

At the same time, a camera records the number plates of passing vehicles, and a pair of light gates record the vehicle speed and acceleration. Figure 2.1 shows a typical measurement set-up. In this study, the camera was positioned to capture the rear licence plate of the vehicle. Vehicle details, such as make, model and fuel type, were later obtained (see section 2.2.1) and recorded alongside the emissions measurements for the vehicle.

RS technology has been widely used across Europe, Asia and the USA. RS offers a range of benefits, including the ability to measure thousands

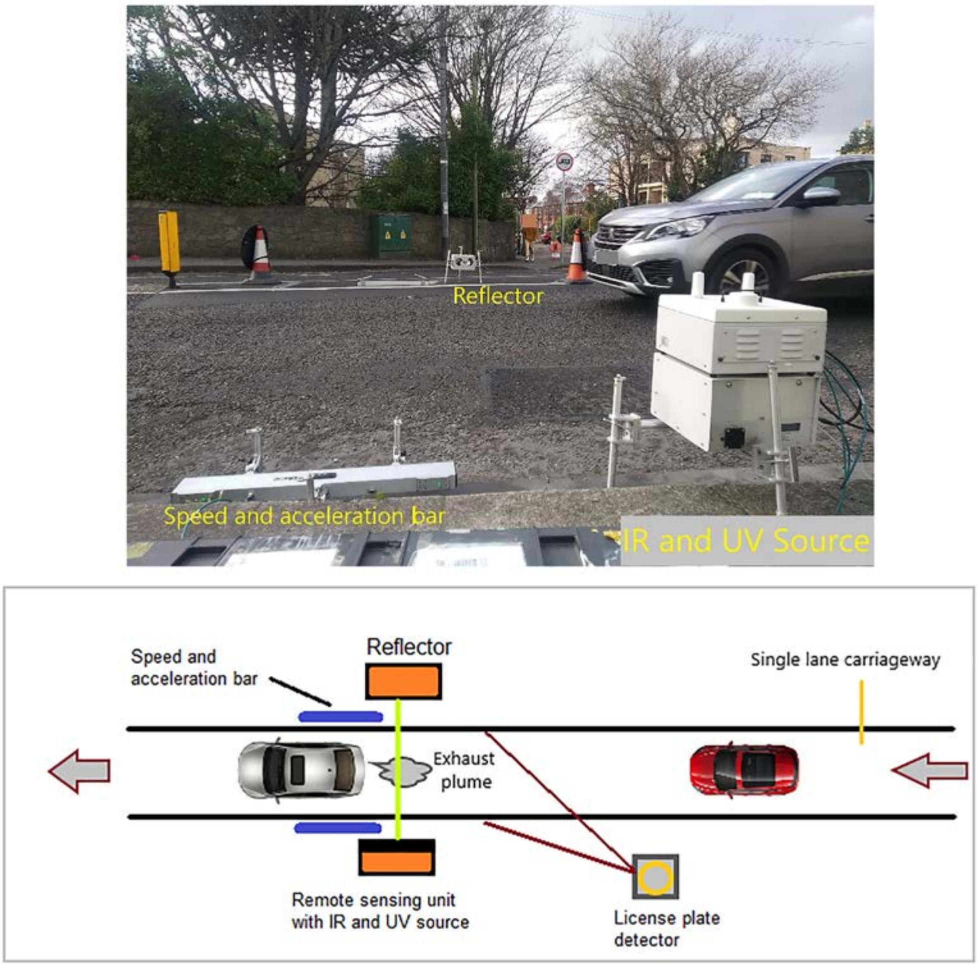


Figure 2.1. Real-world vehicle emissions testing set-up. IR, infrared; UV, ultraviolet. Reproduced from Mahesh *et al.*, 2023; licensed under CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

of vehicles in a short time frame without interfering with the vehicles being monitored. Moreover, RS measurements are local to an area and are therefore representative of the actual vehicle fleet in that area. Real-world EFs that reflect the actual driving conditions on the road can be developed. These EFs can be used in local dispersion modelling and to inform predictions of air quality.

2.2 Use of the Opus RSD5000 Instrument

Real-world emissions measurements were conducted in Dublin using the Opus RSD5000 RS instrument. This instrument is capable of measuring emissions of NO, NO_2, PM, NH_3, CO and hydrocarbons (HCs). Emissions were measured as ratios to CO_2 and the analysis routine used combustion equations to calculate fuel-specific emissions in units of grams of pollutant per kilogram of fuel (g/kg fuel). The distance-specific emissions can be roughly calculated using fuel-specific emissions by estimating the amount of fuel burnt per kilometre travelled (kg/km). The vehicle emissions presented in section 2.3 are in units of g/kg fuel.

The number plate of each vehicle was matched to a set of vehicle details obtained from the Department of Transport (Ireland), or derived from Driver and Vehicle Licensing Agency and Society of Motor Manufacturers and Traders databases in the UK, including, where available, vehicle type (i.e. car, van, bus, heavy goods vehicle (HGV)), fuel type, Euro standard, engine size, vehicle weight, date of registration and odometer reading at last MOT.

The RSD5000 was always calibrated internally prior to each data collection session, in a process that took a few minutes. During the session, the RSD5000 was audited each hour to ensure that the system was performing to specifications and did not need realignment and/or recalibration. This process involved taking measurements of gases of known concentrations using the RSD5000. As the data were collected, exhaust plume verification software reviewed each measurement in real time to ensure it was of adequate strength, that the exhaust plume decayed in a manner consistent with warm loaded-mode vehicle operations and that the prevailing background levels were stable and could be accurately determined. Each session's dataset was compiled daily and all datasets were later added to a database.

2.3 Summary of Findings

This section details the measurement locations and the fleet composition derived from the vehicle emissions measurement campaigns by location, and presents real-world emissions of NO_x and PM from the vehicle emissions RS measurements of cars, vans and buses.

2.3.1 Measurement locations

Ricardo deployed RS instrumentation in Dublin over a period of 26 days between November 2021 and February 2022. Measurements were taken at the following six locations during the winter campaign:

1. southbound on Templeogue Road, directly after the traffic light-controlled crossroads;
2. Mayor Street Lower, a single-lane road next to the tramlines;
3. College Green, on the bend of the R137 road, forking off the R138;
4. southbound on Beach Road (Strand Road), directly after the mini roundabout with St John's Road;
5. uphill on Chapelizod Hill Road, underneath the Chapelizod Bypass bridge;
6. northbound on Richmond Street, next to the cycle lane.

A further measurement campaign was conducted during May and June 2022 over a total of 30 days. During the summer campaign, measurements were made at sites 1, 3, 4 and 5 from the list above; sites 2 and 6 were found not to be suitable measurement locations. The measurement locations from both the winter and summer campaigns are indicated on the map (Figure 2.2). The photographs of the locations are shown in Figure 2.3.

Over 58,000 vehicle measurements were made over the winter campaign. The vehicles included over 30,000 cars, 5600 light goods vehicles (LGVs), 390 HGVs and 2200 buses. Over 78,000 vehicle measurements were made over the summer

Leaflet | Tiles © Esri — Source: Esri, DeLorme, NAVTEQ, USGS, Intermap, iPC, NRCAN, Esri Japan, METI, Esri China (Hong Kong), Esri (Thailand), TomTom, 2012

Figure 2.2. Locations of RS measurements in Dublin.

campaign, including over 44,000 cars, 8200 LGVs, 560 HGVs and 2300 buses.

Not every attempted measurement provided useful data, for two main reasons:

1. Not every emissions measurement could be linked to vehicle technical information. This was the case when, for example, the number plate was unreadable (e.g. if the plate was partially obscured or could not be read by the automatic number plate recognition software due to the quality of the image captured by the camera) or a readable plate could not be matched to a vehicle (e.g. vehicles with a non-Irish registration plate).
2. Not every emissions measurement was valid; for example, vehicles were sometimes too close together to enable distinct measurements to be made.

2.3.2 Fleet composition

This section presents the composition of the fleet surveyed during the Dublin vehicle emissions RS campaign. The fleet at each measurement location is presented separately and includes all passing vehicles. The fleet compositions represent the traffic at the measurement locations and do not reflect the overall fleet composition of Dublin.

The pie charts in Figure 2.4 show the proportion of cars, buses, LGVs and HGVs sampled at each of the measurement sites in Dublin during the winter campaign. Cars made up the largest component of the fleet at each of the locations. LGVs formed the second largest component at all sites except College Green, where buses constituted a larger proportion of the local fleet.

The pie charts in Figure 2.5 show the proportion of cars, buses, LGVs and HGVs sampled at each of the measurement sites in Dublin during the summer campaign. Cars made up the largest component of the fleet at each of the locations. LGVs formed the second largest component at all sites except College Green, where buses constituted a larger proportion of the local fleet. The fleet composition observed during the summer campaign was similar to that observed during the winter campaign.

Templeogue Road

Mayor Street

College Green

Beach Road

Chapelizod Hill Road

Richmond Street

Figure 2.3. Photographs/Google Earth images of measurement site locations. Images of Mayor Street and Richmond Street © Google Earth.

Vehicle emissions are strongly dependent on the fuel type used by the vehicle, so it was important to determine the proportion of vehicles that used petrol, diesel or alternative fuel types such as electricity. Figure 2.6 shows the car fleet by fuel type at all sites in Dublin, alongside the data collected from previous Opus campaigns across the UK (from 2017 to 2022). Figure 2.6 shows that diesel cars make up a larger proportion of the fleet in Dublin (50.5%) than in the UK (44.6%). Conversely, petrol cars account for a smaller proportion of the fleet in Dublin (35.2%) than in the UK (51.4%). Petrol hybrid (petrol/electric) cars are also more common in Dublin (11.1%) than in the UK (3.27%), as are cars that use other alternative fuels. For example, electric cars made up 2.72% of the fleet in Dublin, but only 0.622% of the fleet in the UK. However, the UK measurements span a range of years (from 2017 to 2022), and hence the data for the Dublin fleet probably reflect the fact that the vehicles were newer than those from which the UK measurements were taken.

2.3.3 NO_x emissions by year of registration

This section summarises the real-world emissions of NO_x from the cars and vans (LGVs) recorded during the measurement campaigns. Figure 2.7 shows the mean NO_x emissions from cars and vans by fuel type, split by year of registration, recorded at all measurement sites in Dublin. The summer and winter campaigns have been separated for comparison. The error bars show the 95% confidence interval for

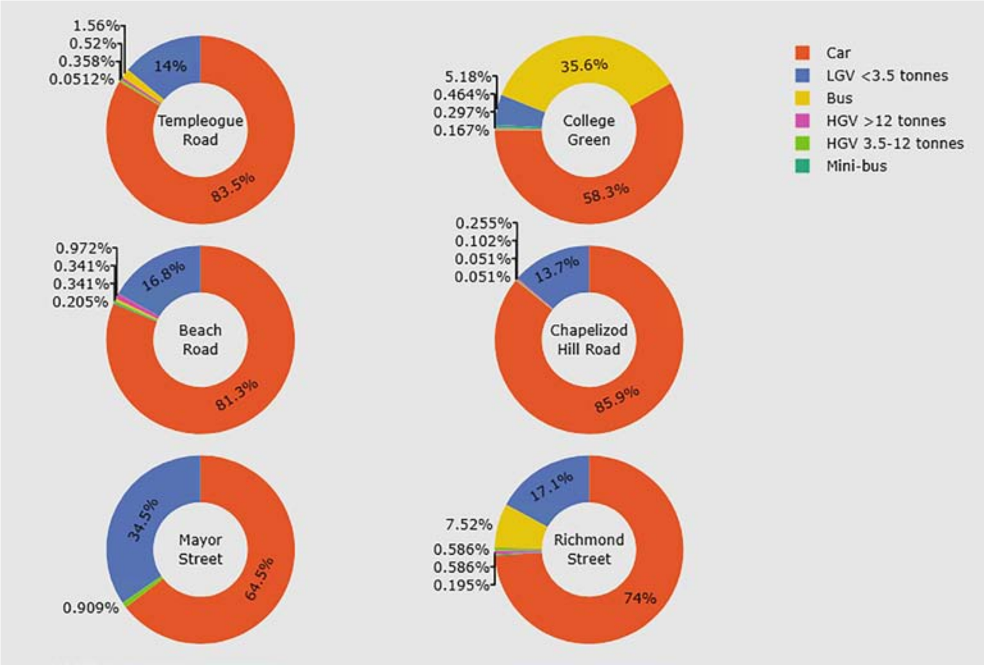


Figure 2.4. Fleet composition by measurement location and vehicle type during the winter campaign.

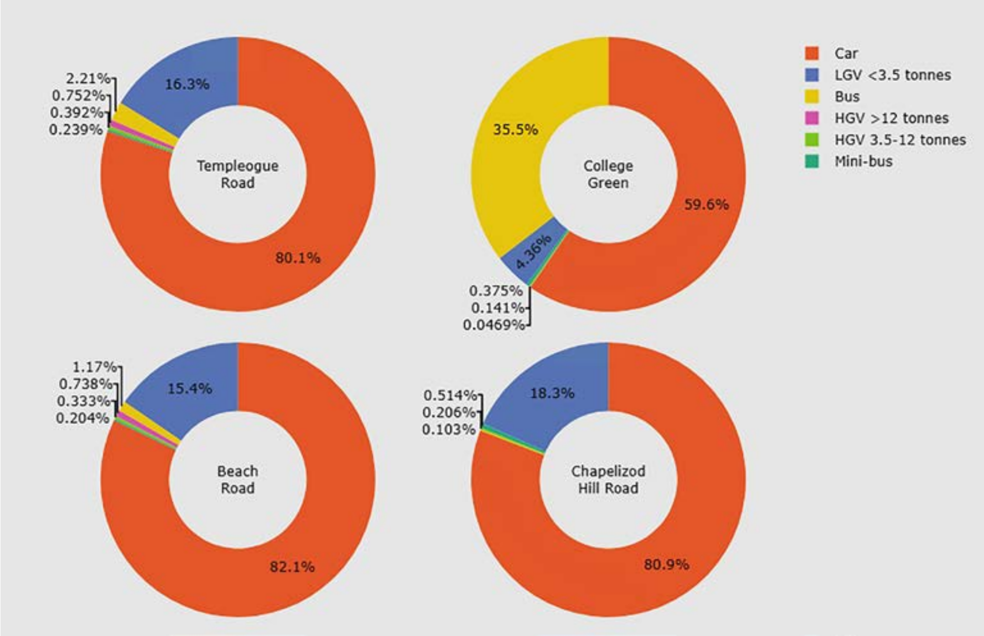


Figure 2.5. Fleet composition by measurement location and vehicle type during the summer campaign.

the mean and the number shown at the top of each bar is the number of vehicles measured. The data points for which 25 or fewer valid vehicle emissions measurements were recorded have been excluded from the plot. The grey and white background shading on each plot panel represents the approximate years during which the Euro standard annotated (e.g. E5 = Euro 5) was the most recent technology. Some key observations from Figure 2.7 are as follows:

- NO_x emissions were mostly higher from diesel cars than from petrol cars with the same vehicle registration year.
- NO_x emissions from petrol cars were low across all years of vehicle registration.

Figure 2.6. Car fleet by fuel type (Dublin compared with the UK).

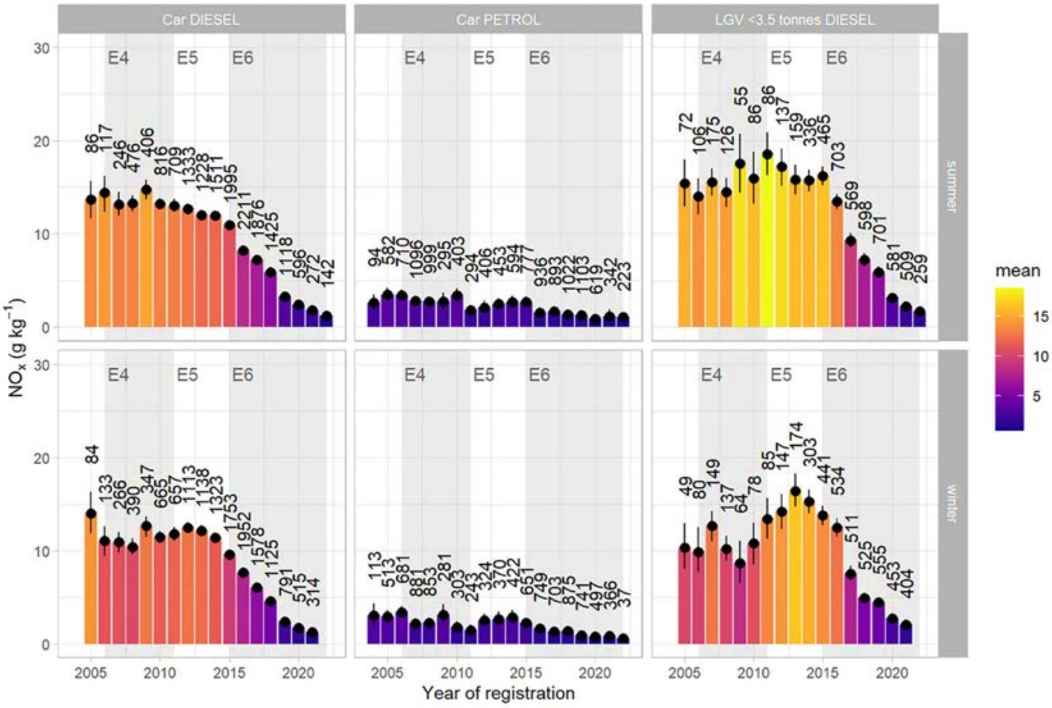


Figure 2.7. Emissions of NO_x from cars and vans by fuel type and year of registration, measured at all sites in Dublin. The uncertainty intervals shown are the 95% confidence intervals for the mean, and the number shown at the top of each bar is the number of vehicles measured.

- NO_x emissions from diesel cars decreased with registration year after 2015. This is probably a result of the instatement of more stringent emissions limits for Euro 6 vehicles.
- NO_x emissions from diesel LGVs were found to increase in vehicles registered between 2012 and 2013 during the winter campaign; however, a rapid decrease was observed from 2016 onwards (possibly because of Euro 5 vehicles being increasingly replaced by Euro 6 vehicles).

In general, the NO_x emissions during the summer campaign were similar to those during the winter campaign, with only slight increases (mainly for LGVs) for some registration years during the summer campaign. This may be because the temperatures in winter rarely dropped below 8°C. We started taking measurements after 9 am in winter because of visibility issues and to ensure that the temperature at the time of measurement was always above 5°C.

2.3.4 Particulate matter emissions by year of registration

RS provides an indicative measure of PM from vehicle exhaust that is based on a measurement of opacity. This section focuses on diesel vehicles because the ultraviolet channel (around 230 nm) used in the RS instrument has been shown to provide a measure of diesel smoke emissions (i.e. emissions dominated by black carbon). Figure 2.7 shows the mean PM emissions from diesel cars and vans split by year of registration, recorded at all measurement sites in Dublin. The summer and winter campaigns have been separated for comparison. The error bars show the 95% confidence interval in the mean and the number shown at the top of each bar is the number of vehicles measured. The data points for which 25 or fewer valid vehicle emissions measurements were recorded have been excluded from the plot. The grey and white background shading on each plot panel represents the approximate years during which the Euro standard annotated (e.g. E5 = Euro 5) was the most recent technology. Some key observations from Figure 2.8 are as follows:

- On average, there was a decrease in PM emissions around the time of the introduction of Euro 5 diesel cars and LGVs (around 2011). This decrease aligns with the introduction of DPFs, beginning with late Euro 4 vehicles, which physically trap PM.
- Euro 5 and 6 diesel vehicles also use DPFs; as a result, emissions of PM were low for Euro 5 and 6 diesel cars and LGVs.
- Emissions of PM were, on average, higher for Euro 3 and 4 diesel LGVs than for Euro 5 and 6 diesel LGVs.

In general, PM emissions during the summer campaign were similar to those during the winter campaign, with only slight increases observed for some registration years during the summer campaign. In particular, LGVs registered in 2005 and 2006 had higher emissions in the summer than in the winter, although the uncertainty intervals are greater for these measurements.

2.3.5 Summary of bus measurements

Figure 2.9 compares the mean NO_x emissions for diesel buses in Dublin, split by year of registration, and

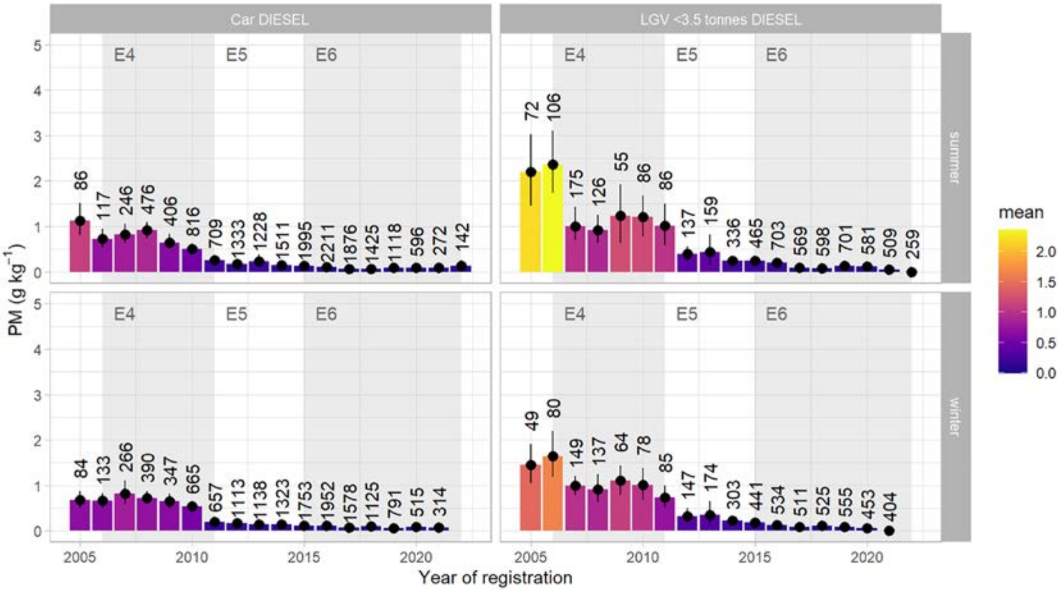


Figure 2.8. Emissions of PM from diesel cars and vans by year of registration, measured at all sites in Dublin. The uncertainty intervals shown are the 95% confidence intervals for the mean, and the number shown at the top of each bar is the number of vehicles measured.

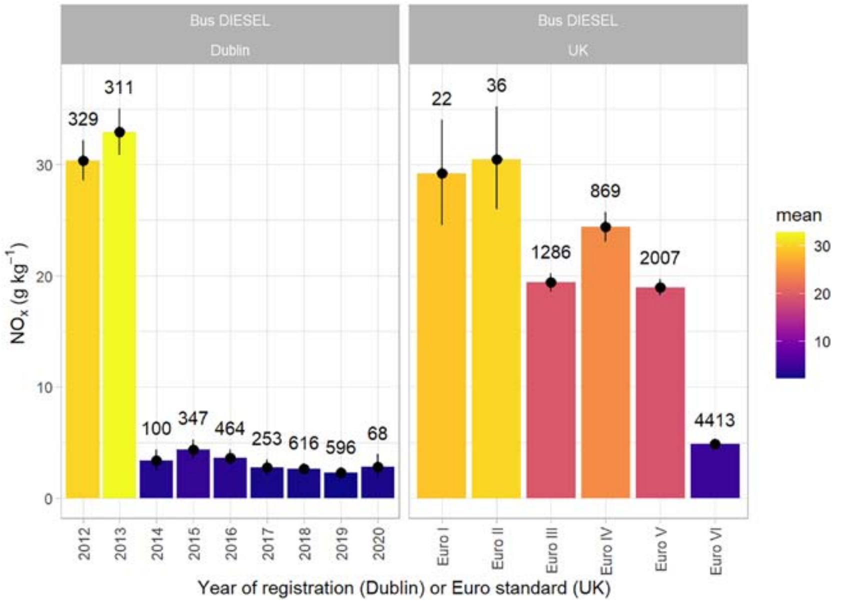


Figure 2.9. Emissions of NO_x from all measurements of buses in Dublin by year of registration, compared to buses from past Opus measurement campaigns in various UK locations. The uncertainty intervals shown are the 95% confidence intervals for the mean, and the number shown at the top of each bar is the number of vehicles measured.

mean NO_x emissions for buses in the UK, measured during previous Opus measurement campaigns and split by Euro standard. The error bars show the 95% confidence interval in the mean, and the number shown at the top of each bar is the number of vehicles measured. Data points for which fewer than 10 valid vehicle emissions measurements were recorded have been excluded from the plot. Note that the vehicle category used in this analysis includes buses and/or coaches. Some key observations from Figure 2.9 are as follows:

- NO_x emissions from buses in Dublin decreased considerably after 2013, likely owing to the introduction of Euro VI buses towards the end of 2013.
- Similarly, in the UK, NO_x emissions decreased between the time in which Euro V buses and that in which Euro VI buses were used.
- Emissions of NO_x from Euro VI buses in the UK were similar to those from buses in Dublin with a registration year of 2014 or later.
- Emissions of NO_x were high for buses in Dublin with registration years of 2012 and 2013.

3 Insights from Remote Sensing Campaign

3.1 Introduction

This chapter provides a summary of RS data and insights regarding the EFs from diesel cars and taxis. The vehicle emission RS campaign was conducted in two phases – one phase in summer and one in winter – using the Opus RSD5000 RS instrument. The winter campaign was conducted between November 2021 and February 2022, and the summer campaign was conducted between June and July 2022. The pollutants measured were CO, HCs, NO and NO_2. Over 136,000 observations across all vehicle types were made: about 58,000 in winter and 78,000 in summer. This included measurements from over 21,000 Euro 4-compliant cars, 15,000 Euro 5-compliant cars and 29,000 Euro 6-compliant cars. The analysis presented in this chapter focuses on identifying the effect of season, mileage and manufacturer on the EF values. The EFs are expressed in grams of pollutant per kilogram of fuel burnt (g/kg fuel), as commonly used in RS-based vehicle emission measurements.

3.2 Preliminary Insights on Number of Observations and Fuel Type

Table 3.1 shows the number of measurements for each fuel type, including diesel, petrol, hybrid and electricity, and their share in the total. As expected, the largest number was seen for diesel vehicles (>57,000), followed by petrol vehicles (>28,000). The dataset comprised vehicles of five different fuel types, including 57,063 (59.1%) diesel vehicles and 28,128 (29.2%) petrol vehicles. The share of hybrid and plug-in hybrid vehicles was 9.5%, and the share of electric vehicles was 2.2%.

This insight indicates that the vehicle fleet in Dublin is predominantly diesel fuelled, and that the share of hybrid/electric vehicles is small. The presence of diesel vehicles in large numbers has been recognised to have a negative impact on air quality owing to their NO_x and PM emissions.

As mentioned earlier, the RS campaign was conducted in two phases, i.e. summer and winter. This allows the comparison of the EFs between the two seasons and the determination of the effect of ambient temperature on emissions. The number of measurements was significantly larger in the summer campaign (>78,000) as was the number of cars measured (>39,000 in summer compared with >27,000 in winter) owing to (i) increases in the traffic volumes after the lifting of all COVID-19-related restrictions; (ii) increases in the number of people going to their office for work instead of working from home; and (iii) the longer daylight hours, which allowed more time for measurement over a day. Further, data from the different measurement sites show that the number of measurements made at Beach Road and Templeogue Road was significantly larger during the summer campaign than during the winter campaign.

Table 3.1. Number of measurements of each fuel type and share in the total

Fuel type	Number of measurements	Percentage of total
Diesel	57,063	59.1
Petrol	28,128	29.2
Hybrid	6911	7.2
Plug-in hybrid	2218	2.3
Electricity	2129	2.2

3.3 Insights on Mileage

The year of registration and mileage data based on the last National Car Test of the vehicle were provided by the Department of Transport. The dataset covered vehicles with a wide range of registration years (or age). Most taxis had a registration year of between 2012 and 2018; for vans, this was between 2014 and 2021; and for cars, this was between 2006 and 2021. Most of the buses had a registration year of 2012 or later.

The range of mileage was large for all vehicle types; buses had the highest median mileage and cars had the lowest. Taxis had a significantly higher median mileage (>100,000) than cars (~50,000). In terms of age, the highest median age was seen for cars and the lowest for buses. A significant number of cars were over 10 years old.

3.4 Results from the Winter Campaign

This section presents the results from the first campaign in winter, which began in November 2021 and ended in February 2022. The figures in this section present the mean EFs of CO, HCs, NO and NO_2 for different vehicle types based on their Euro class (i.e. Euro 4, Euro 5 or Euro 6). The vehicle types shown for diesel vehicles are cars, vans, taxis and buses.

From Figure 3.1, we see that the CO EF decreased with the evolution in the emission standard for all vehicle types. In the case of cars, there was a significant reduction from Euro 4 to Euro 5 vehicles (28%), but a relatively smaller reduction from Euro 5 to Euro 6b vehicles (11.36%), and a decreasing trend was seen from Euro 6b to 6d(t) vehicles. In the case of vans, the mean EF value was 10.6% lower for Euro 5 vehicles than for Euro 4 vehicles, and 16.6% lower for Euro 6b vehicles than for Euro 5 vehicles. The EF for Euro 6 buses was significantly lower (29.4%) than that for Euro 5 buses. Comparing the different vehicle types with same emission standard, vans were found to have the highest CO EF.

Figure 3.2 shows the mean HC EF (g/kg fuel) for the different vehicle types and Euro classes within each vehicle type. Clearly, the HC EF decreased with improvement in the emission standard for all vehicle types. For cars, there was a significant reduction from Euro 4 to Euro 5 vehicles (35.7%), and a relatively smaller reduction from Euro 5 to Euro 6b vehicles (21.3%). In the case of taxis, a significant reduction was observed from Euro 4 to Euro 5 vehicles (35%) and from Euro 5 to Euro 6b vehicles (22.5%). Comparing the different vehicle types with the same emission standard, among Euro 4 vehicles, the EF was highest for vans. Buses had the lowest HC EF among all the vehicle types.

The variation in the NO EFs is shown in Figure 3.3. The trends were similar for cars, vans and taxis, with Euro 6 vehicles having the lowest value and Euro 5 vehicles having the highest. In addition, among the three vehicle types, taxis had a slightly higher EF than cars and vans of the same emission standard. This could be because they have a relatively high mileage and taxi drivers adopt a more assertive driving style than car and van drivers. In the case of buses, the NO EF was significantly lower for Euro 6 vehicles (0.5 g/kg fuel) than for Euro 5 vehicles (25.6 g/kg fuel).

The variation in the NO_2 EF is shown in Figure 3.4. The trends were similar for cars and vans, with Euro 6 vehicles having the lowest value and Euro 4 vehicles having the highest. In the case of taxis, the Euro 4 taxis had a significantly lower mean EF (1.3 g/kg fuel) than Euro 5 taxis (2.1 g/kg fuel). Both

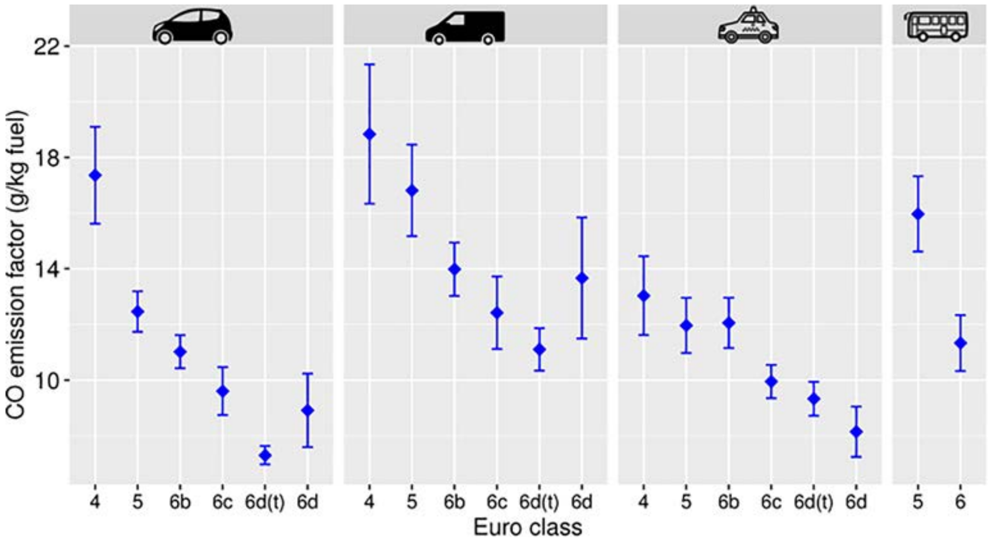


Figure 3.1. EF of CO (g/kg fuel) for different diesel vehicle types based on the Euro class. The point represents the mean and the error bars indicate one standard deviation on either side of the mean. Reproduced from Mahesh *et al.*, 2023; licensed under CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

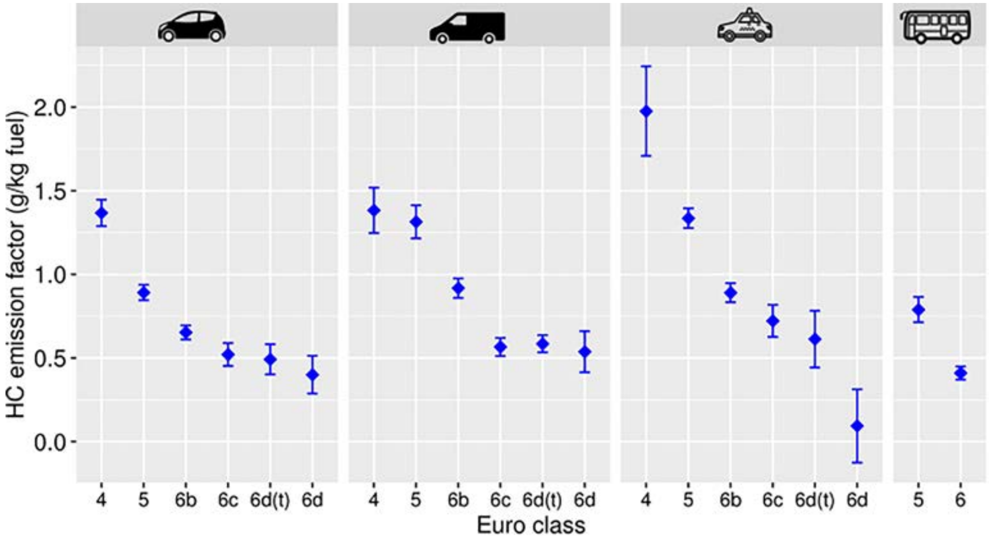


Figure 3.2. EF of HC (g/kg fuel) for different diesel vehicle types based on the Euro class. The point represents the mean and the error bars indicate one standard deviation on either side of the mean. Reproduced from Mahesh *et al.*, 2023; licensed under CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

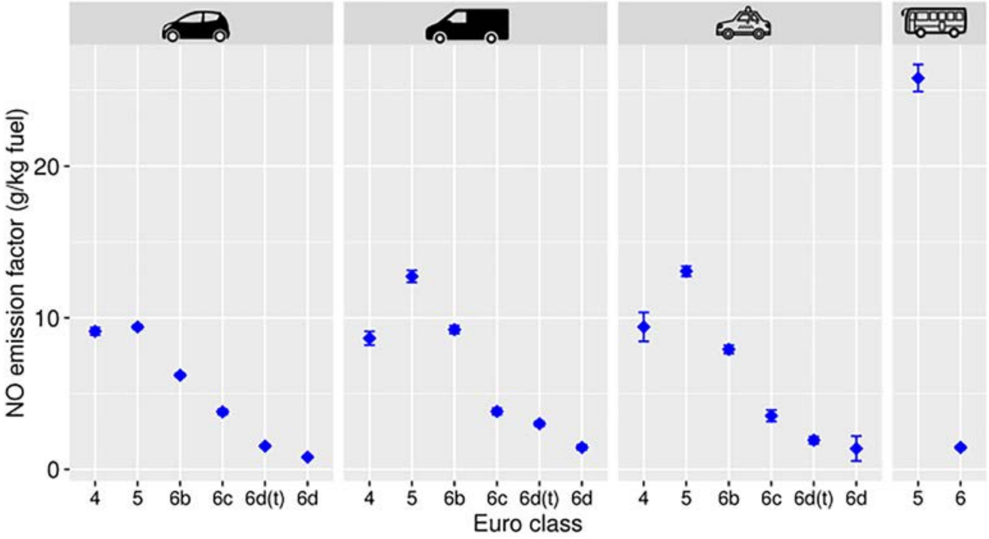


Figure 3.3. EF of NO (g/kg fuel) for different diesel vehicle types based on the Euro class. The point represents the mean and the error bars indicate one standard deviation on either side of the mean. Reproduced from Mahesh *et al.*, 2023; licensed under CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

Euro 5 and Euro 6 buses had very low NO_2 emissions (< 1 g/kg fuel).

Figure 3.5 shows the CO, HC, NO and NO_2 EFs for petrol cars of Euro 3, Euro 4, Euro 5 and Euro 6 emission standards. The CO EF was similar for Euro 3 and Euro 4 cars and significantly lower for Euro 5 (30.1% less than Euro 4 cars) and Euro 6b cars (24.6% less than Euro 5 cars). A similar trend was observed for the NO EF, with a 27.2% reduction seen for Euro 6b relative to Euro 5 vehicles. The HC EF increased from Euro 3 to Euro 4 vehicles and then decreased, with very low values for vehicles with an emission standard of Euro 6c or higher (less than 1.0 g/kg fuel). The NO_2 EFs were similar for Euro 5 and Euro 6 cars and are significantly lower than those for Euro 3 and Euro 4 cars. In general, with improving

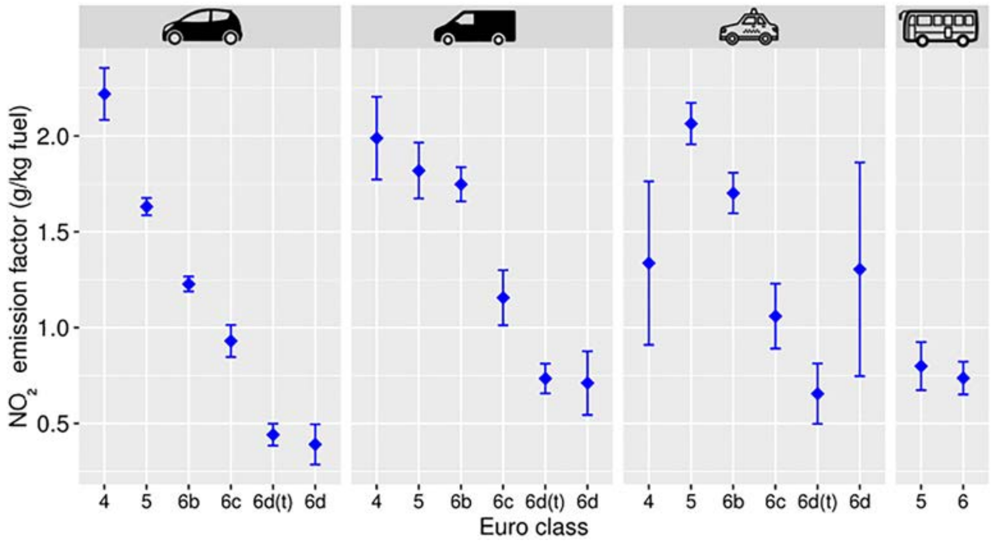


Figure 3.4. EF of NO_2 (g/kg fuel) for different diesel vehicle types based on the Euro class. The point represents the mean and the error bars indicate one standard deviation on either side of the mean. Reproduced from Mahesh *et al*., 2023; licensed under CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

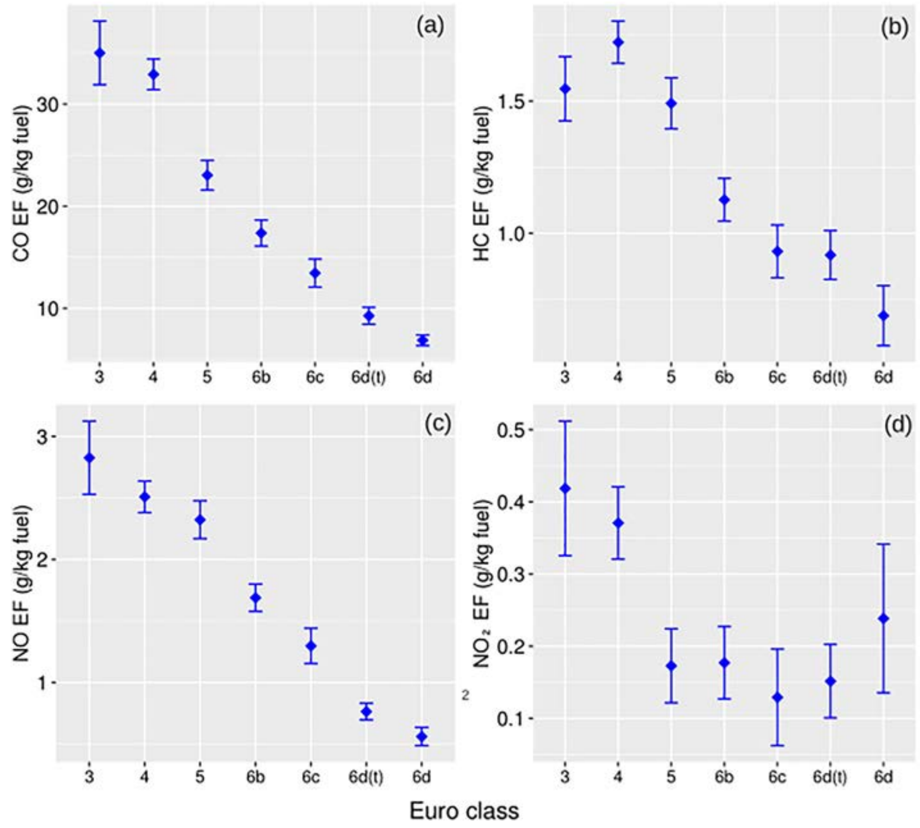


Figure 3.5. EFs (g/kg fuel) for petrol cars based on emission standards. The points represent the mean and the error bars indicate one standard deviation on either side of the mean. Reproduced from Mahesh *et al*., 2023; licensed under CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

emission standards, an overall decreasing trend in CO, NO and NO_2 EFs was observed.

3.5 Results on Effect of Mileage and Make (Diesel Cars)

This section presents the EFs based on the mileage, make and model of the diesel passenger cars. The most common makes of the diesel cars in the dataset were identified (Table 3.2). The top 10 manufacturers with more than 1000 observations, in decreasing order, were BMW, Audi, Volkswagen, Mercedes-Benz, Ford, Hyundai, Nissan, Skoda, Renault and Volvo.

The most common make and model of diesel car was the BMW 520, followed by the Volkswagen Golf, Nissan Qashqai, Ford Focus and cars in the Mercedes-Benz E series.

In total, there were 457 unique combinations of make and model in the dataset.

The effect of mileage on the EF of NO is shown in Figure 3.6. Among Euro 6 cars, EF values tended to increase with mileage, at least up to a total mileage of 100,000 km. No clear trend was observed for Euro 4 and Euro 5 cars. Similarly, among Euro 6 cars, the EF of NO_2 (Figure 3.7) increases with mileage up to 125,000 km, and then decreases at higher mileages. In the case of Euro 4 and Euro 5 cars, no clear trends were seen.

Table 3.2. Number of observations for each passenger car manufacturer

Manufacturer	Number of observations
BMW	3465
Audi	2872
Volkswagen	2815
Mercedes-Benz	2605
Ford	2154
Hyundai	1957
Nissan	1438
Skoda	1294
Renault	1220
Volvo	1079
Kia	976
Toyota	892
Land Rover	875
Peugeot	858

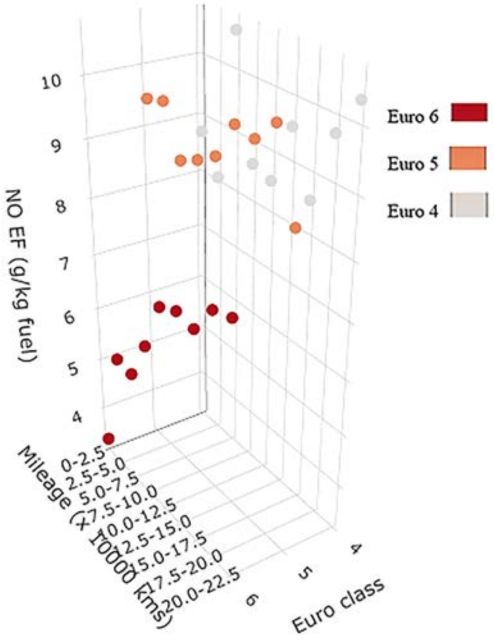


Figure 3.6. Effect of mileage on the EF of NO for diesel cars. Each point represents the mean EF value of cars in the indicated Euro class one mileage bin.

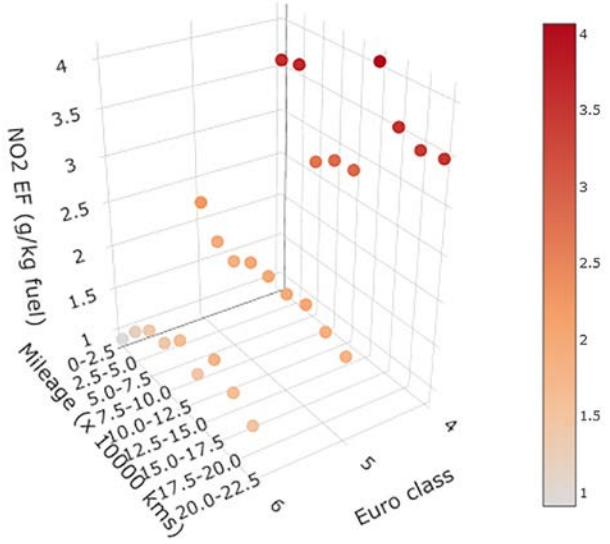


Figure 3.7. Effect of mileage on the EF of NO_2 for diesel cars. Dark-coloured points represent EF values closer to 4; light-coloured points represent EF values closer to 1.

Figures 3.8 and 3.9 present the trends in the EFs with year of registration for the 12 most common manufacturers, as observed from the dataset. The range of the year of registration was set as 2008 to 2020 so that, for each year, there were at least 30 observations.

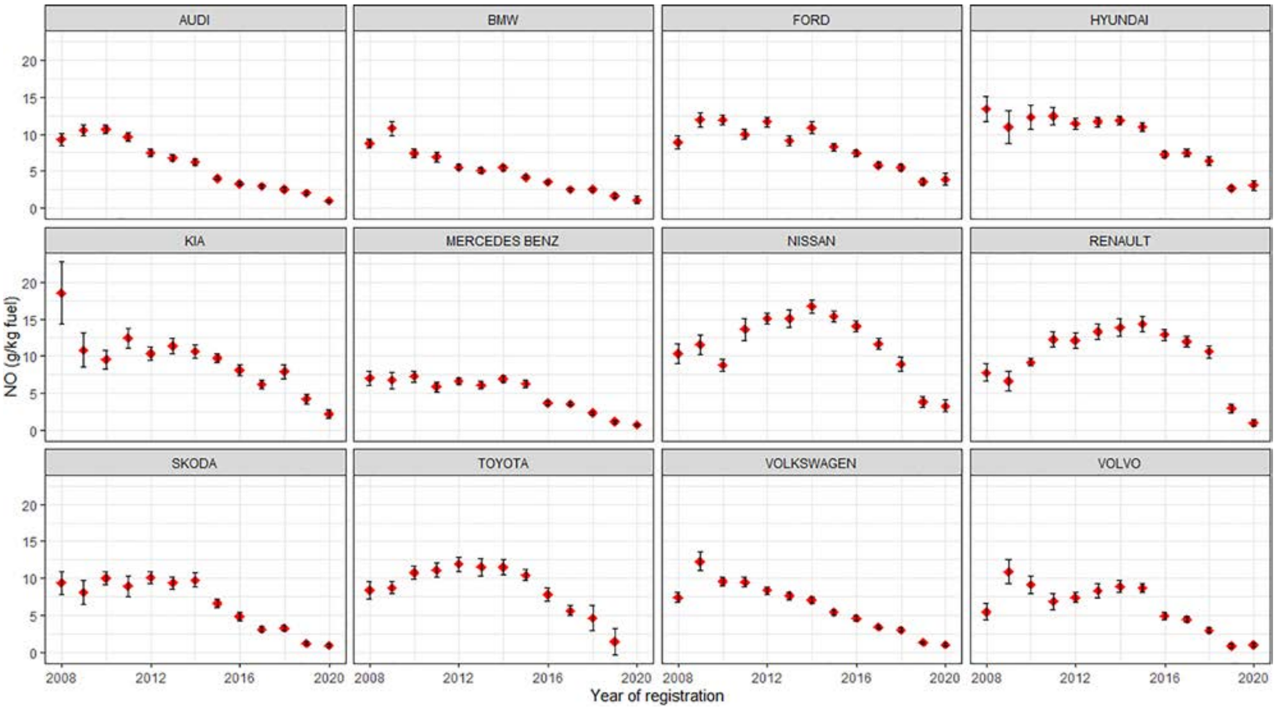


Figure 3.8. Trends in NO EF with year of registration for different car manufacturers for diesel cars.

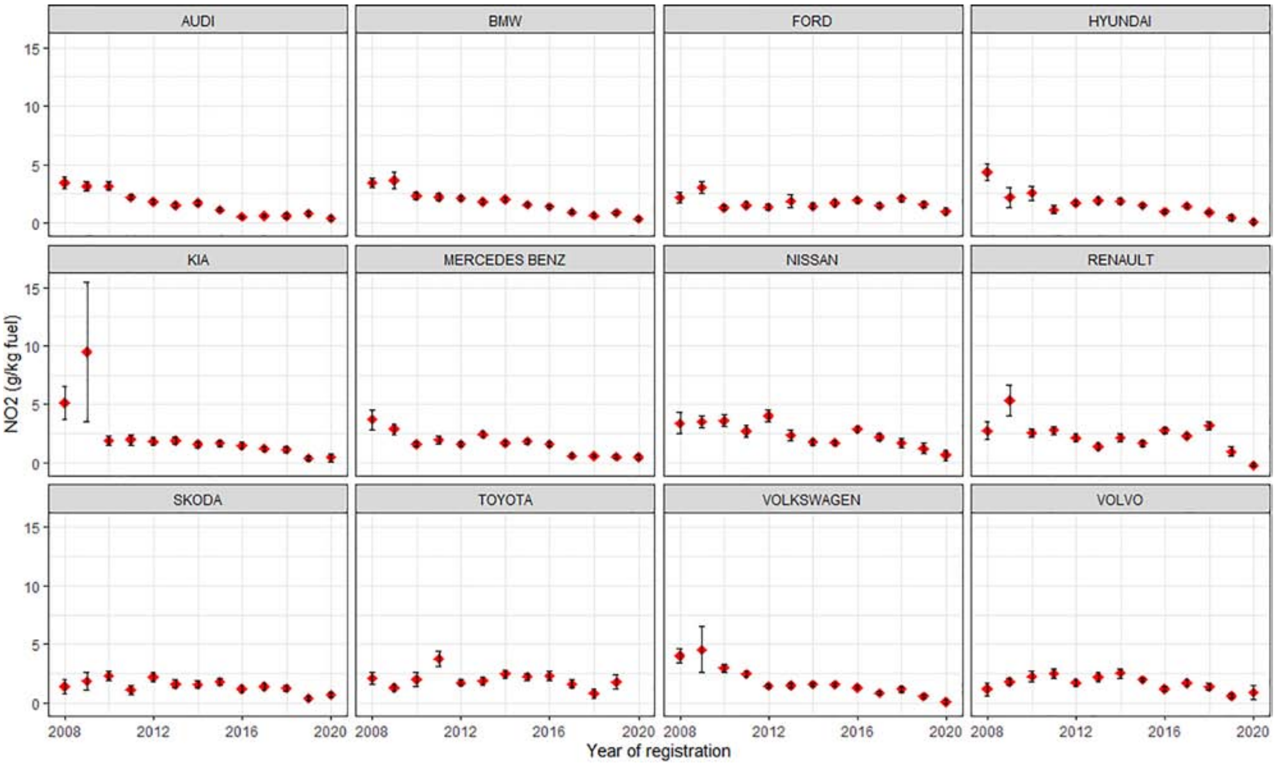


Figure 3.9. Trends in NO_2 EF with year of registration for different car manufacturers for diesel cars.

The trends in NO EF are shown in Figure 3.8. An increasing trend was observed for some manufacturers until 2012, after which a decrease was observed. Audi, BMW and Mercedes-Benz vehicles show consistently low EF values, which decreased with the year of registration. The EF values of Ford, Nissan and Hyundai vehicles were higher than those of other manufacturers' vehicles.

Figure 3.9 shows the trends in the EF of NO_2. The EF values were below 2.5 g/kg fuel for most of the vehicles, and a decreasing trend was seen for most vehicles manufactured in 2016 or later. Kia vehicles manufactured in 2008 and 2009 showed relatively high EF values.

3.6 Results for Petrol Cars

The RS dataset included more than 23,000 measurements for petrol-fuelled passenger cars. The range of the year of registration was set as 1991 to 2022, and at least 100 measurements have been taken since 2002. The year with the largest number of measurements, more than 2000, was 2018. In terms of Euro standards, 11,521 petrol cars (i.e. > 50% of all petrol cars) were Euro 6 compliant, 4426 were Euro 5 compliant, 5455 were Euro 4 compliant and 968 were Euro 3 compliant. The year of registration for petrol cars ranged from 2003 to 2022, with two distinct peaks observed in 2008 and 2018. Relatively few vehicles were registered in 2009 and 2011.

3.6.1 Effect of season

The association between year of registration of petrol cars and EF differed with season in the case of NO_2 EF but not NO EF. The trends in NO EF with year of registration for petrol cars are shown in Figure 3.10. It can be seen that the EF for NO was more variable among vehicles registered before 2015 than among those registered from 2016 onwards.

The trends in NO_2 EFs are shown in Figure 3.11. In contrast to NO EFs, mean EF values were significantly lower in winter than in the summer, and in winter were less than 0.5 g/kg fuel for most of the vehicles. The trends in both summer and winter were relatively stable for cars registered after 2015.

3.6.2 Effect of mileage

The mean mileage of petrol cars was 74,990 km and the median was 45,900 km. The 25th and 75th percentiles of the mileage were about 4650 km and 94,000 km, respectively. To analyse the effect of mileage, the average EF in each bin with a size between 10,000 km and 100,000 km was determined. Each mileage bin had at least 800 measurements. The effect of mileage on the EF of NO is shown in Figure 3.12a. An increasing trend in the EF values was seen for Euro 5 and Euro 6 cars; however, no clear trend was observed in the case of Euro 4 cars.

In the case of NO_x (Figure 3.12b), the EF for Euro 6 cars showed an increasing trend for a mileage of less than 60,000 km, and a decreasing trend was seen for vehicles with higher mileages. In the case of Euro 4 and Euro 5 cars, no clear trends were seen with an increase in mileage.

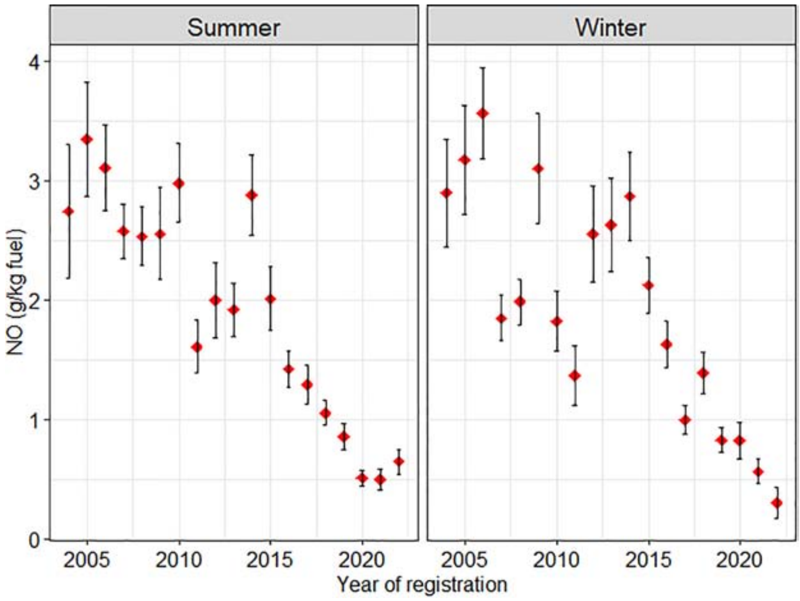


Figure 3.10. Trends in the NO EF with year of registration for summer and winter (petrol cars).

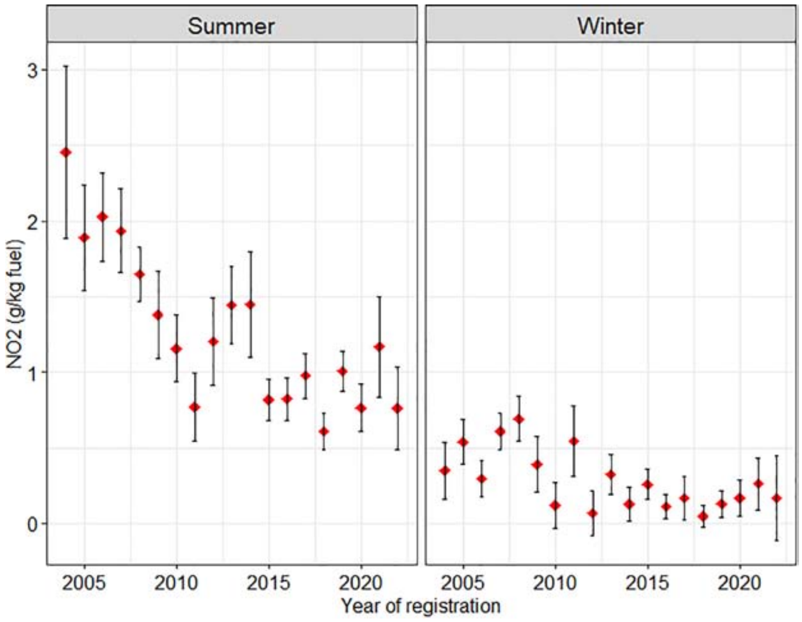


Figure 3.11. Trends in the NO_2 EF with year of registration for summer and winter (petrol cars).

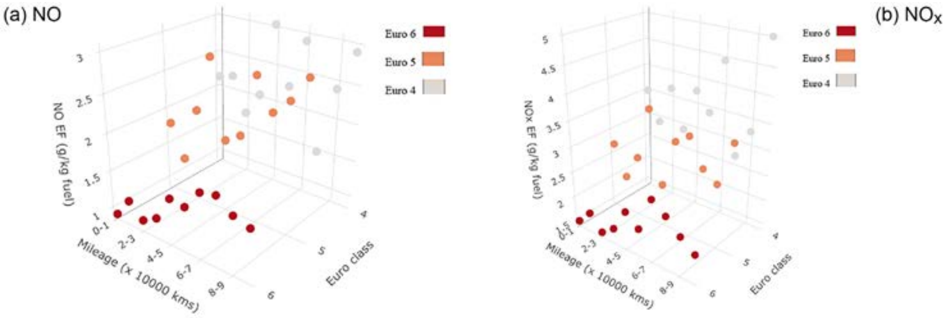


Figure 3.12. Effect of mileage on the EF of (a) NO and (b) NO_x for petrol cars.

3.6.3 Effect of manufacturer

This section presents the EFs based on the make and model of the cars. The most common makes of petrol cars in the dataset were identified. The top 10 manufacturers, each with more than 600 observations, in decreasing order, were Volkswagen, Toyota, Nissan, Ford, Hyundai, Mercedes-Benz, Skoda, Opel, Audi and Honda.

Figure 3.13 shows the trends in NO EF with year of registration for different manufacturers. Different trends were observed for different manufacturers, with a clearly decreasing trend for Ford, Toyota and Volkswagen. Higher values of mean NO EF were seen for some manufacturers for vehicles with a registration year of between 2013 and 2016. Hyundai and Toyota cars showed consistently low NO EF values.

3.7 Hybrid and Plug-in Hybrid Cars

The number of hybrid and plug-in hybrid cars in the dataset was 4287 and 1841, respectively. This section presents the EFs for these cars with respect to the year of registration.

Figure 3.14 shows the trends in the EF values for hybrid cars with year of registration. The CO EF remained low for all vehicles with a year of registration of 2009 and later. In the case of HC, a decreasing trend was seen from 2013 onwards, with the EF values approaching 1.0 g/kg fuel from 2019 to 2022. The NO EF values were also below 1.0 g/kg fuel, with a decreasing trend, for vehicles with a year of registration of 2012 or later. The NO_2 EF values were below 0.5 g/kg fuel in most of the cases, with consistently lower values observed from 2012.

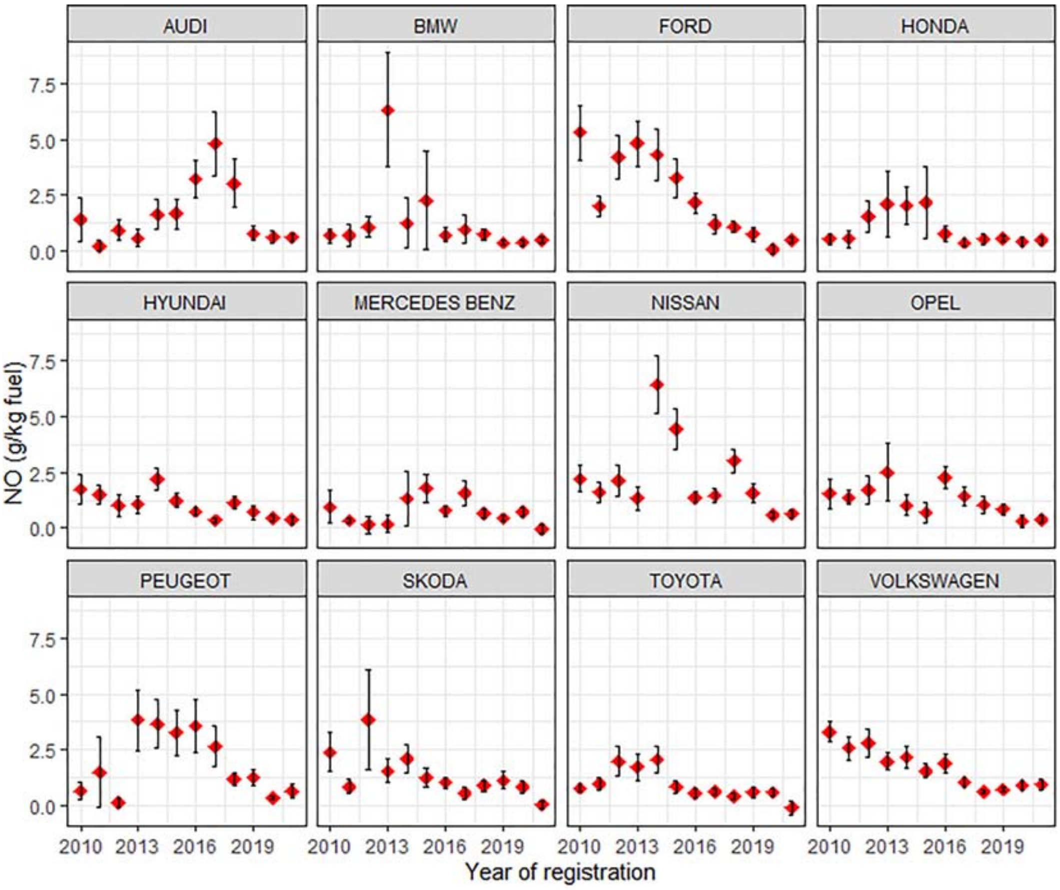


Figure 3.13. Trends in NO EF with year of registration for different manufacturers (petrol cars).

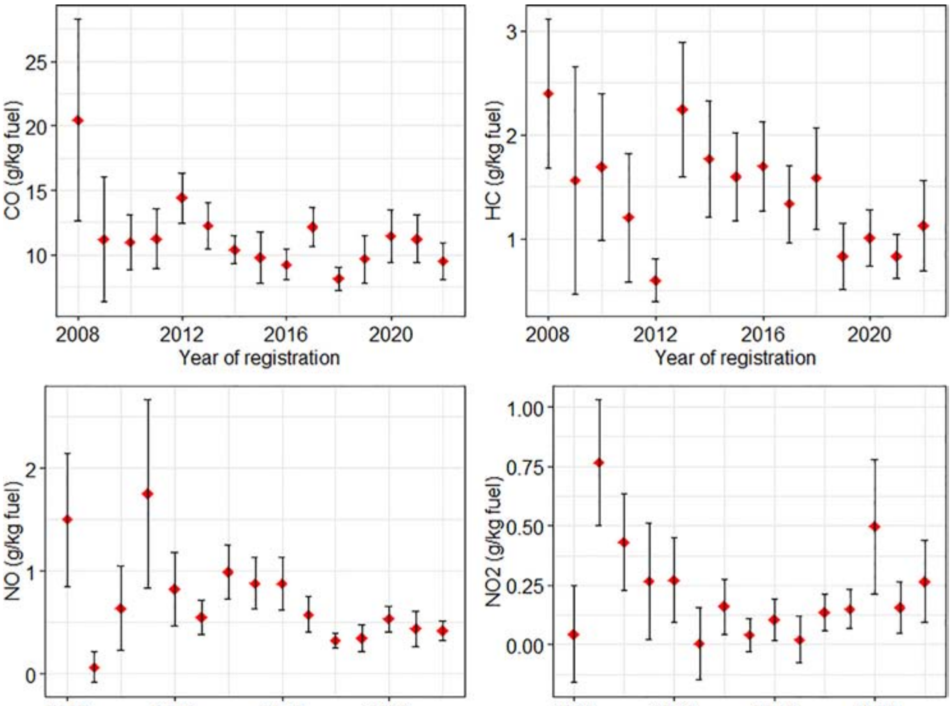


Figure 3.14. Trends in the EF with year of registration for hybrid cars.

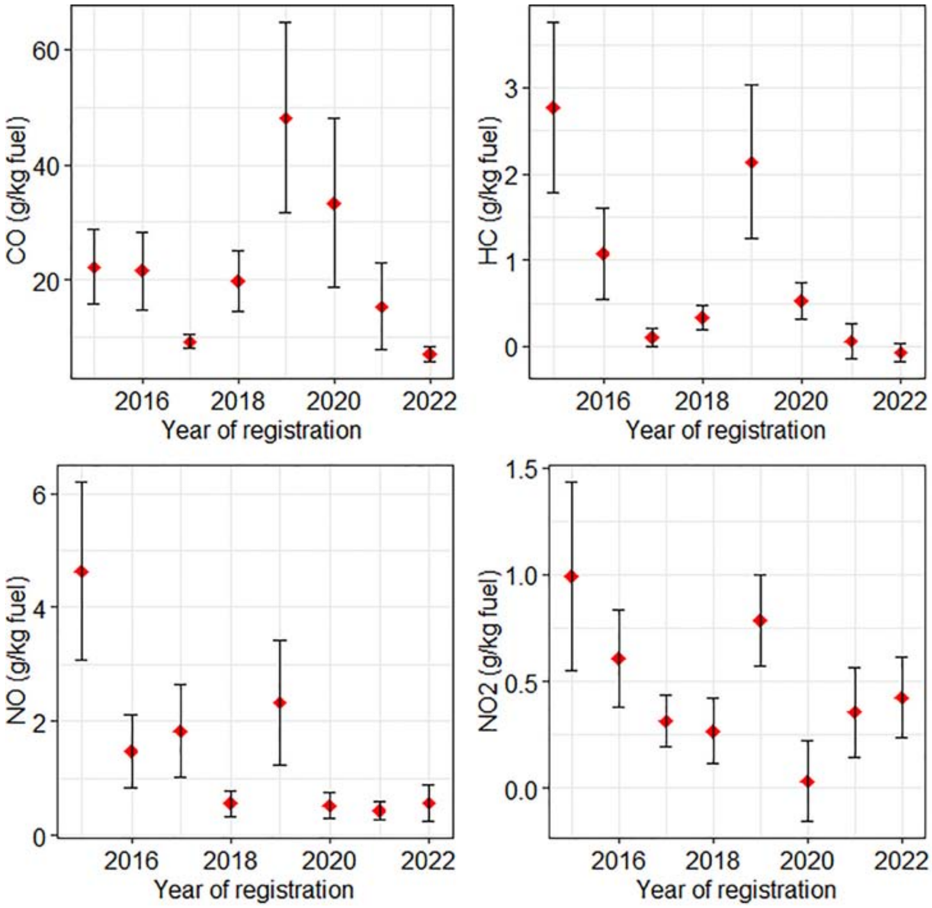


Figure 3.15. Trends in the EF with year of registration for plug-in hybrid cars.

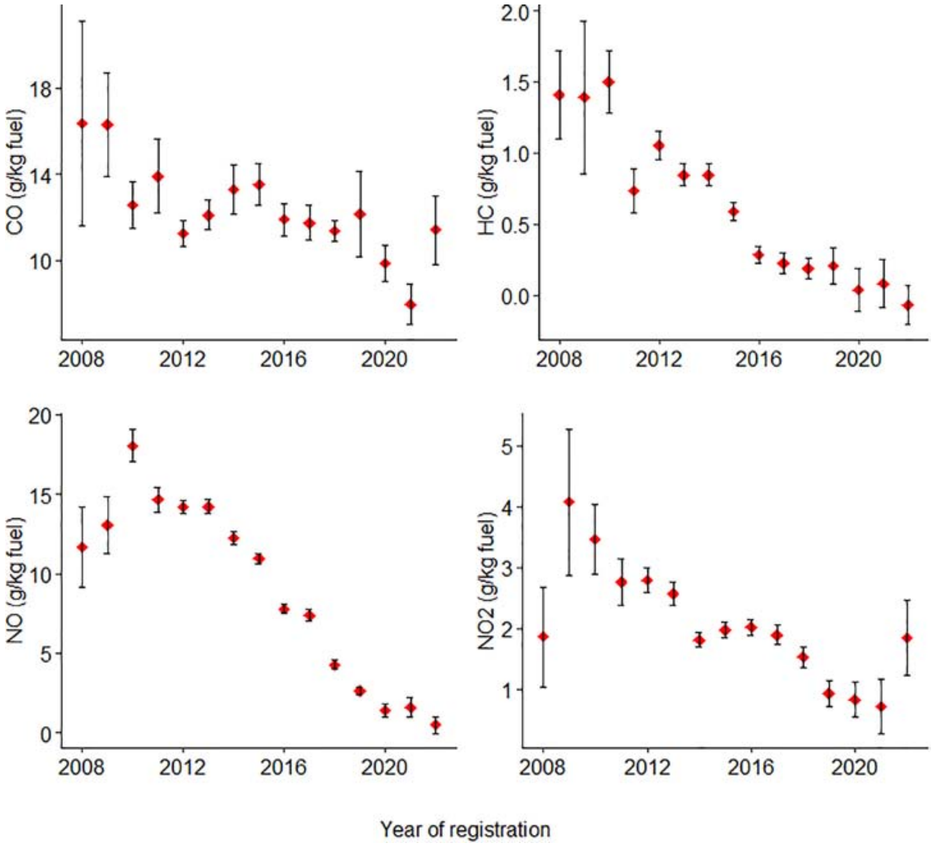


Figure 3.16. Trends in the EF of CO, HC, NO and NO_2 with year of registration (diesel taxis).

Figure 3.15 shows the trends in EF values for plug-in hybrid cars registered from 2015 to 2022. No clear trends were seen for CO and HC, whereas a decreasing trend was observed for NO. The EFs of NO_2 remained lower than 1.0 g/kg fuel in most cases, with values less than 0.5 g/kg fuel for vehicles manufactured in 2017, 2018, 2020, 2021 or 2022.

3.8 Results for Taxis

The total number of taxis was 7396. The taxi fleet is predominantly diesel, with diesel-fuelled vehicles accounting for 72% of the fleet (5330) and petrol/electric vehicles accounting for 21% (1580). Electric vehicles (141), plug-in hybrid vehicles (23), petrol-fuelled vehicles (312) and diesel/electric vehicles (10) make up the remainder of the fleet. Comparing across the different measurement locations, the largest number of taxis was observed in College Green, followed by Beach Road.

3.8.1 *Diesel taxis*

This section presents the detailed analysis of emissions from diesel taxis. The year of registration of most of the taxis was between 2010 and 2020, with the largest proportion having a 2015 year of registration.

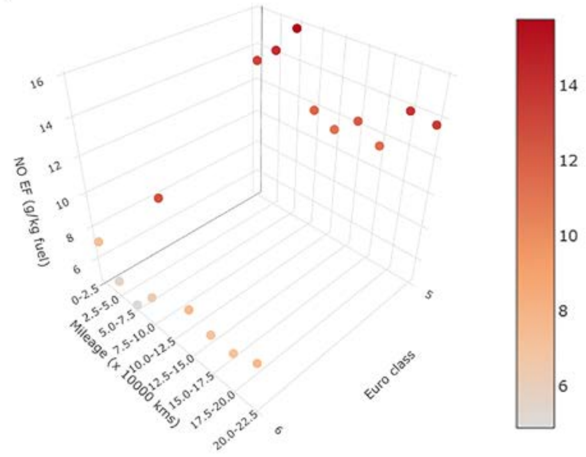
The mean taxi mileage was about 157,000 km, and the median was about 140,000 km. The 75th percentile was below 250,000 km. The distribution of the mileage data in different mileage bins was analysed. Most taxis had a mileage of between 100,000 km and 125,000 km.

Figure 3.16 shows the trends in the EF values of CO, HC, NO and NO_2 for diesel taxis with year of registration from 2008 to 2022. A decreasing trend in all pollutants was seen, with vehicles registered in 2016 or later having very low EF values.

3.8.2 *Effect of mileage*

The effect of mileage on the EFs of NO and NO_x for taxis is shown in Figure 3.17. In the case of taxis, the Euro class was limited to Euro 5 and Euro 6, since the use of taxis over 10 years old is restricted by the government. An increasing trend in the NO and NO_x EFs was observed for Euro 6 taxis. However, no clear trends were observed for Euro 5 taxis.

(a) NO



(b) NOx

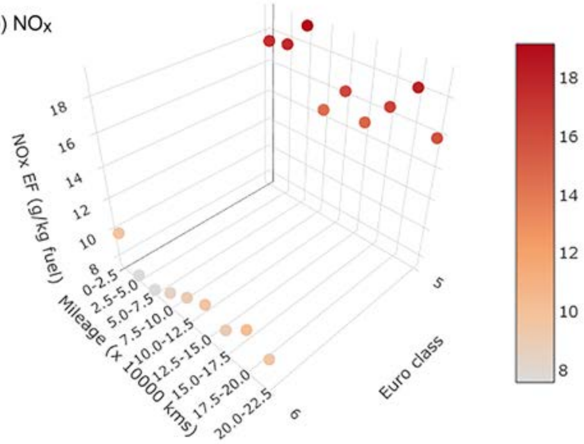


Figure 3.17. Effect of mileage on the EF of (a) NO and (b) NO_x (diesel taxis).

3.8.3 *Effect of manufacturer*

In the case of diesel taxis, the most common manufacturer was Skoda. Other manufacturers with a significant number of measurements were Toyota, Volkswagen, Peugeot, Ford and Renault. The common models in the case of Skoda were the Superb and the Octavia. In the case of Toyota, the Avensis was the most common model. In total, eight manufacturers (Ford, Volkswagen, Toyota, Skoda, Renault, Peugeot, Mercedes-Benz and Hyundai) accounted for 4739 measurements (89% of all taxi measurements).

The trends in NO EF with year of registration for different manufacturers are shown in Figure 3.18. A clearly decreasing trend is observed for Ford, Peugeot, Skoda and Volkswagen. No clear trend was observed for Hyundai, whereas for Toyota, there was a decreasing trend in the EF value from 2013 to 2016, after which an increasing trend was observed.

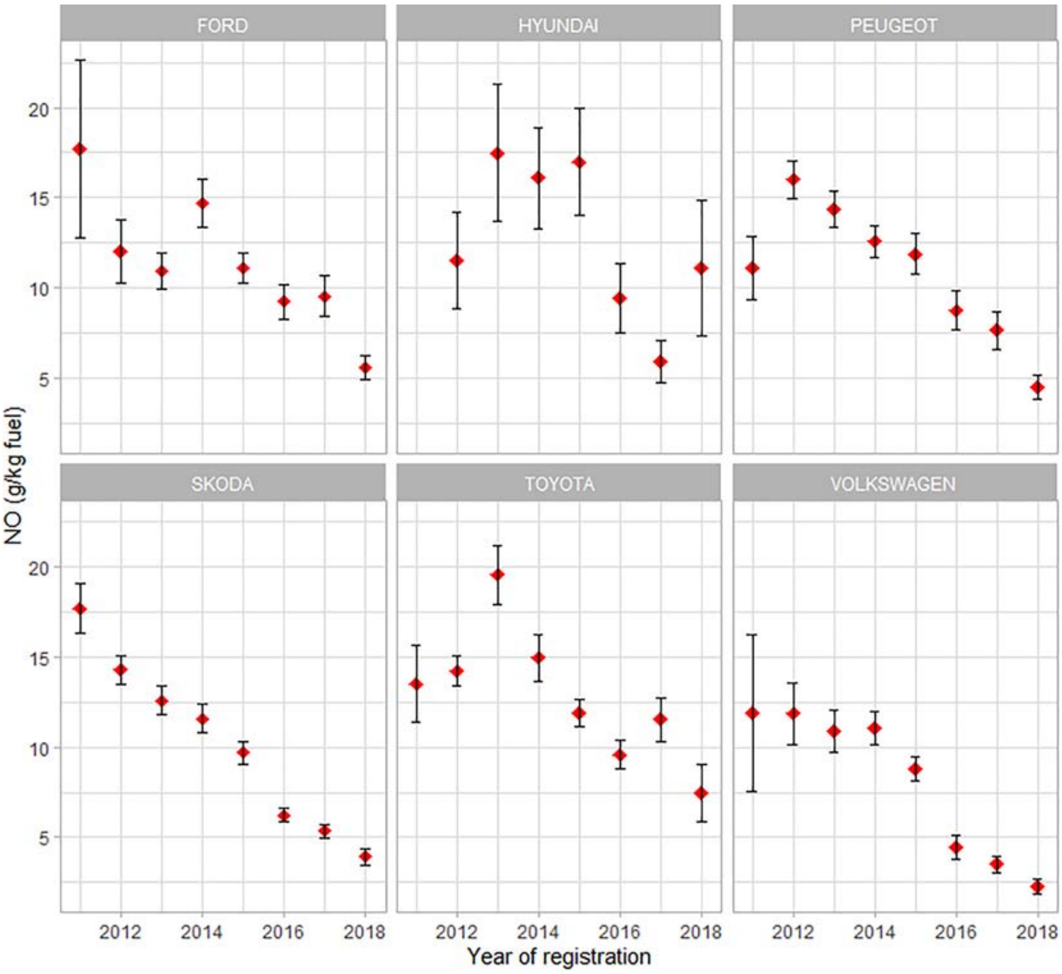


Figure 3.18. Trends in NO EF with year of registration for different manufacturers (diesel taxis).

Figure 3.19 shows the trends in NO_2 EF with year of registration for different diesel taxi manufacturers. This value remains largely constant in the case of Ford, Peugeot and Volkswagen. However, we see a clear decreasing trend for Skoda. In the case of Toyota, the EF remained constant from 2011 to 2015 and then increased continuously. In the case of Hyundai, a decreasing trend was observed from 2013.

3.9 Summary

This chapter presents detailed insights on the trends in EFs for diesel cars, petrol cars and taxis. In particular, the effect of Euro standard, season, mileage and manufacturer on the trends in EFs of CO, HC, NO and NO_2 are presented. Since the dataset is fairly comprehensive, with a significant number of Euro 6 vehicles, the EFs are expected to accurately represent the real-world conditions of the existing fleet of vehicles in Dublin. The results can be used to estimate the emissions from diesel and petrol vehicles in urban areas at a more disaggregate level considering the diversity in the vehicle fleet with respect to fuel type, manufacturer, mileage and year of registration. The trends in EFs provide evidence of improvement in the emission performance of newer vehicles. The results can be used to evaluate the expected benefits of introducing LEZs and removing diesel vehicles from the fleet.

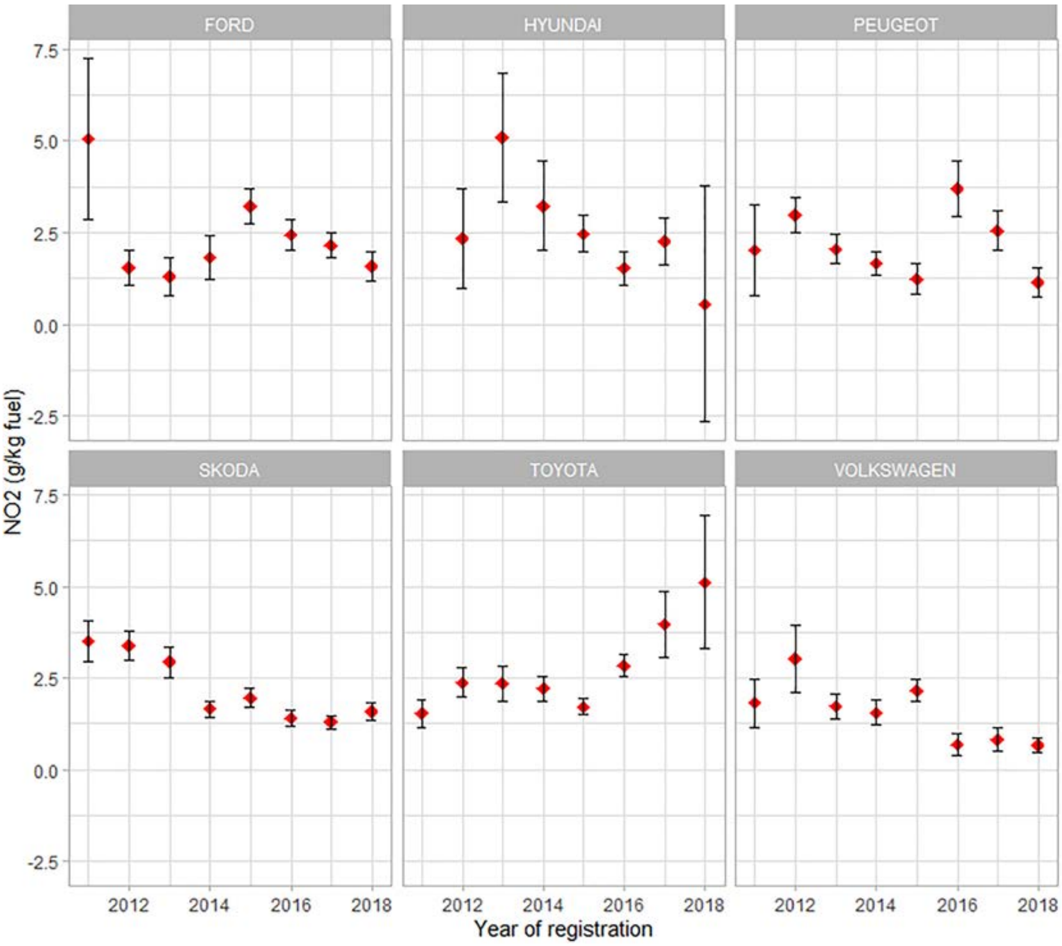


Figure 3.19. Trends in NO_2 EF with year of registration for different manufacturers (diesel taxis).

4 Insights from PEMS Data

4.1 Overview

A PEMS is an emissions-testing device that can be attached to an on-road vehicle to allow the analysis of the exhaust emissions produced during real-world driving conditions.

An on-board gas analyser within the vehicle takes a sample of the produced exhaust gas and measures the concentrations of a number of key pollutants, such as CO, NO_x and CO_2. A flowmeter instantaneously determines the volume of exhaust gas being emitted. The PEMS unit is also connected to the engine control unit of the vehicle. This allows the vehicle and engine data to be recorded in tandem with the emissions measurements. The speed and location of the vehicle are also recorded using global positioning system (GPS) data.

The unit placed on an on-road vehicle allows data to be obtained over the entirety of the drive cycle under real-world conditions. The data recorded enable the calculation of both instantaneous and average EFs. These calculated values are representative of the on-road emissions of the vehicle.

The use of a PEMS, like all forms of emissions testing, has some limitations. As only a single vehicle can be tested at any given time, the number of vehicles that can be tested in a given period is much smaller than in the case of other emissions measurement methods such as RS. In addition, the costs associated with PEMS are relatively high because both the apparatus itself and the vehicle need to be obtained.

4.1.1 Vehicle selection

A set of vehicles that was most representative of the vehicle fleet in use on Dublin roads was selected. The vehicle fleet observed during the RS campaign was analysed to identify the set of vehicles.

The next aspect to consider was where to acquire data from. It would be possible to conduct a study of a set number of vehicles on Dublin roads, but this would not be optimal because of the aforementioned cost considerations in relation to PEMS measurements. For the same cost as five individual vehicle measurements within an urban cycle on Dublin roads, it was possible to obtain commercially available data for 50 urban vehicle cycles on UK roads. The PEMS data used here were acquired from Emissions Analytics, a UK-based company specialising in the measurement of vehicle emissions.

With this in mind, a dataset was generated using the most commonly found vehicles within the initial RS campaign. Although choosing the most popular vehicles was the primary consideration, it was also important to consider the fuel type of the powertrain of the vehicle and to obtain data covering petrol, diesel and petrol hybrid vehicles. It was also necessary for the sample to represent the Euro classes most commonly seen on the roads, which are Euro 4 through to the current Euro 6d, and to select, for each Euro class, a number of different types of vehicles, including small and large/executive vehicles and some LGVs.

With all of these considerations in mind, a dataset was generated with 50 vehicles in total, covering a range of fuel types, Euro classes and vehicle types.

4.1.2 Constructing curves of emission factor versus speed

The data initially recorded by the PEMS unit were expressed in terms of the amounts of key pollutants in parts per million (ppm). This, along with the measured gas flow rate, meant that it was possible to calculate the emissions of CO, CO_2 and NO_x in g/s. These data could then be linked with the measured vehicle speed from the GPS, expressed in m/s. It was then possible to calculate the EF in g/km. This was considered the optimal way to obtain and present these data, as this is the unit in which emissions limits are specified in the Euro regulations to be followed when vehicles are manufactured.

PEMS data were available for 50 vehicles. These data were divided into 1-km subsections or segments, with EFs for CO, CO_2 and NO_x calculated for the average speed of each segment.

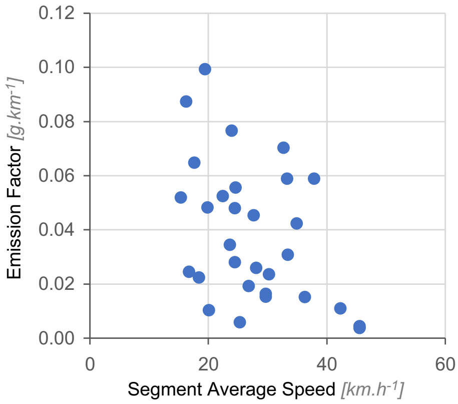


Figure 4.1. Calculated NO_x EF against segment average speed for an Opel Astra (Euro 6 petrol).

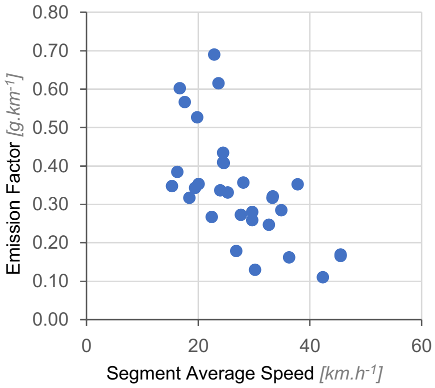


Figure 4.2. Calculated CO EF against the segment average speed for an Opel Astra (Euro 6 petrol).

This process, through which the data in Figures 4.1 and 4.2 were generated, was then repeated for each of the 50 individual vehicles to generate an EF versus speed curve for each of the vehicles.

4.2 Comparing PEMS with Remote Sensing and COPERT

4.2.1 Comparing PEMS with remote sensing measurements

The comparison between PEMS and RS is of great interest since each of these measurement technologies has its own strengths and weaknesses. Whereas PEMS relies on highly accurate, full-cycle analysis for a limited number of vehicles, the advantage of RS is that it enables instantaneous emissions data to be obtained for a large number of vehicles at any given point. Figure 4.3 shows each of the instantaneous NO_x emissions as a ratio to CO_2. Also shown are the instantaneous measurements from the RS campaign. In this example, the vehicle used in the PEMS measurement was a Euro 5 petrol Ford Fiesta found within the RS dataset. The instantaneous NO_x to CO_2 ratio and the instantaneous speeds were determined and could then be compared. The clearest point of differentiation between the RS and PEMS data is in the area below 10 km/h, which contains no RS data points because the vehicle needed to be moving and the engine under load for a valid measurement to be produced.

Overall, the ratios between RS and PEMS were broadly comparable over the 10–60 km/h speed range.

Although PEMS EFs could be calculated in g/km using measured values, this was not possible using RS. The RS EFs were obtained as g of pollutant per kg fuel. Some assumptions had to be made to convert these values into the same units as the PEMS data. This was required to estimate the instantaneous fuel consumption from each of the RS data points. The work of Davison *et al*. (2020) can be used to generate an estimate of fuel consumption at the time of the emissions measurement. This calculation relies on differentiating vehicles by both their fuel type and segment. The coefficients of each given segment and fuel type should be used in this calculation. Also used in this calculation is the mass of the vehicle being measured. The inclusion of these assumptions in the calculation means that there is a degree of uncertainty in each of the measurements, as, for example, the exact masses of the vehicles being measured are unknown. This may lead to separate vehicles under different operating conditions being assigned the same mass value as there is no means of determining the vehicle mass from RS measurements.

4.2.2 Comparing PEMS with COPERT

The Computer Program to Calculate Emissions from Road Transport (COPERT) is a software program developed by the European Environment Agency that can be used to calculate the emissions of a number of key pollutants as a result of on-road vehicle operation. Within COPERT, the emissions estimation is broken down by fuel type, Euro class and vehicle segment. Therefore, to compare PEMS data with the

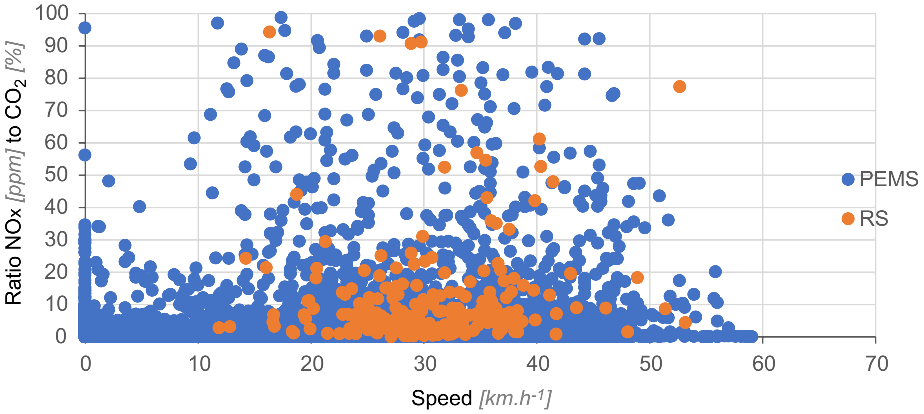


Figure 4.3. NO_x to CO_2 ratio over a range of vehicle speeds for RS and PEMS for a Ford Fiesta (Euro 5 petrol).

COPERT-generated data, we had to assign each vehicle to a bin. Each of these bins contained vehicles of a specific fuel type, Euro class and segment, i.e. a bin could contain all diesel Euro 6a/b/c large/sports utility/executive vehicles. Once all the 50 PEMS vehicles were assigned to a bin, the results obtained using PEMS and COPERT could be compared.

To compare emissions data obtained using COPERT and PEMS, a number of steps first had to be taken. Within each of the PEMS bins was a number of data points. Each of these points related to emissions from a vehicle fitted with PEMS while driving on a 1-km section of road. To create the best-fit curve for these points, a second dataset had to be generated. In this dataset, for example, all PEMS values within a 5 km/h window, and all NO_x emissions for vehicles within the 20–25 km/h range, were averaged in terms of both speed and emissions. This gave us a set of data points, with each point corresponding to each 5 km/h window.

NO_x results

The analysis revealed that COPERT provided an accurate estimate of the NO_x EFs of a number of subcategories of vehicles on Dublin roads. Figure 4.4 shows that this was the case for Euro 5 diesel large/SUV/executive vehicles. Similar trends were observed for Euro 4 vehicles. This shows that COPERT can effectively be used to estimate NO_x emissions in vehicles in these categories on Irish roads.

Figure 4.5 shows a less satisfactory comparison between the COPERT and PEMS NO_x emissions for small Euro 6d petrol vehicles, as COPERT overestimated the NO_x emissions of these newer

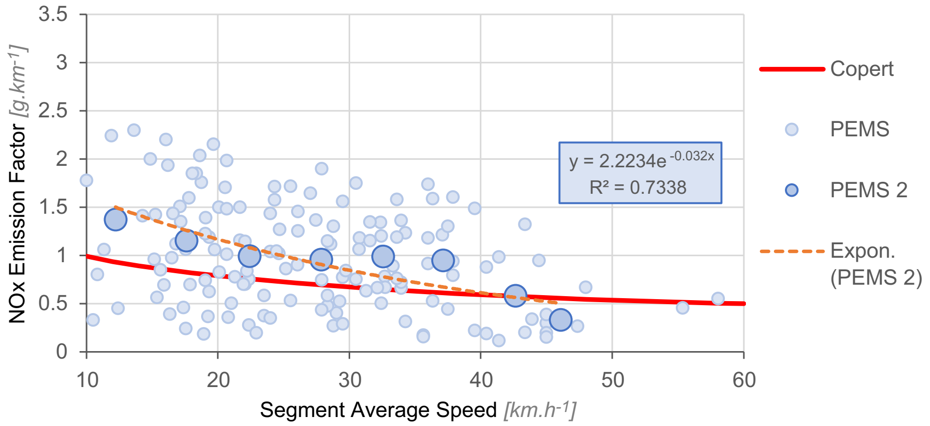


Figure 4.4. Comparison between COPERT and PEMS emissions for Euro 5 diesel large/SUV/executive vehicles.

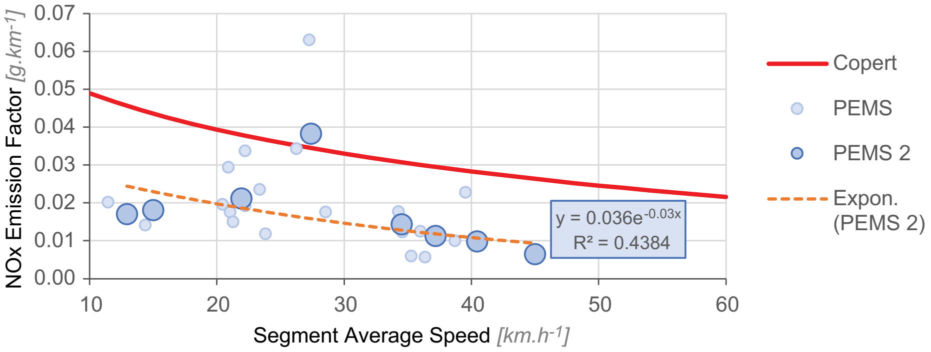


Figure 4.5. Comparison between COPERT and PEMS emissions for Euro 6d petrol small vehicles.

models. Similar findings were also observed for other vehicle types. In fact, COPERT was found to consistently overestimate the NO_x emissions of Euro 6 vehicles, regardless of fuel type or segment.

CO results

As for NO_x emissions, the CO EF of PEMS and COPERT can be compared and, again, a difference was evident between vehicles produced in accordance with the Euro 4 and Euro 5 standards and those produced after the implementation of Euro 6 (Figures 4.6 and 4.7). Once again, COPERT accurately predicted the CO EF only of vehicles produced prior to the implementation of Euro 6. This trend was also apparent across different vehicle types (i.e. petrol and diesel vehicles) and sizes (ranging from small vehicles to LGVs). As with NO_x emissions, COPERT overestimated the CO emissions of vehicles produced after the implementation of Euro 6. This led

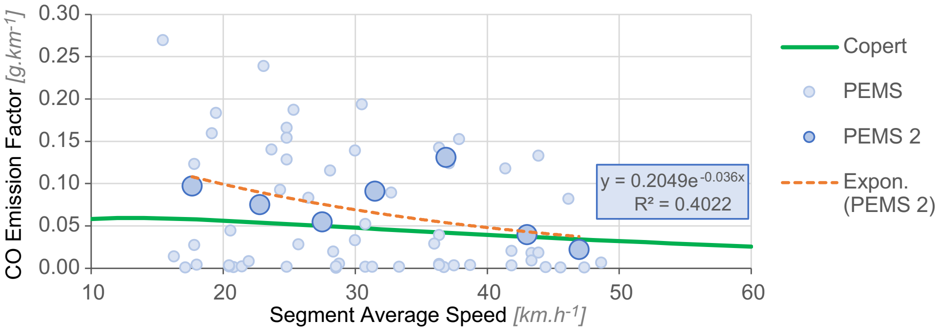


Figure 4.6. Comparison between COPERT and PEMS CO emissions for Euro 6a/b/c diesel medium-sized vehicles.

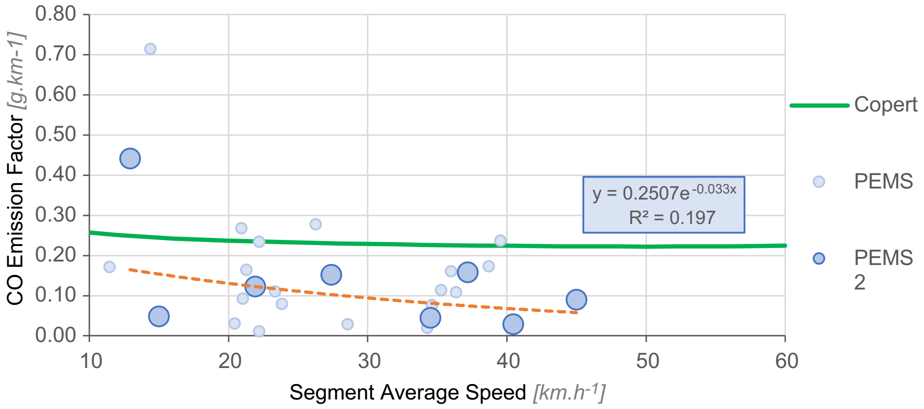


Figure 4.7. Comparison between COPERT and PEMS CO emissions for Euro 6d petrol small vehicles.

to the COPERT-derived CO EF being consistently higher than the PEMS-derived EF for similar vehicles.

4.3 Equivalence of PEMS and Remote Sensing Data

By matching the PEMS data to data of similar vehicles within the RS dataset, the data recorded in the PEMS measurements could be extrapolated to all vehicles of similar type. This was done with the goal of generating values for fleet-wide emissions for in-use vehicles on Dublin's roads. The RS fleet statistics gave a good indication of the mix of vehicles in the real-world road fleet. By assigning all of the valid RS vehicles to relevant PEMS bins, more accurate PEMS data could be used alongside the RS data, which were broader in scope.

To assign each accurately measured RS data point to a relevant PEMS vehicle, a number of steps had to be taken, the first of which was to match vehicles. All vehicles in the RS dataset were matched with one of the PEMS vehicles in terms of make, model, Euro class and engine size. Having done this, the remaining vehicles were then assigned based on manufacturer. As an example, a Euro 5 diesel Volkswagen Jetta could be assigned to the Euro 5 diesel Volkswagen Passat bin, as these vehicles share the same manufacturer and there was no PEMS bin associated with the Jetta model.

Any RS data points left unassigned were then sorted by manufacturer group, that is, vehicles produced by the same corporation. For example Audi, Skoda and Volkswagen vehicles were grouped, as it is often the case that manufacturers in the same group share powertrains. By this point, the majority of RS data points had been assigned to a bin, with the final sorting parameter being the engine size. This entailed the remaining RS vehicles being assigned to the PEMS bin containing vehicles with the same Euro class, fuel type and segment and the most similar engine size. Having run through these parameters, all valid RS data points were assigned to a relevant PEMS bin, in turn allowing the extrapolation of the PEMS EFs.

4.3.1 Estimating emissions within the Dublin fleet

To ensure that the emissions were most representative of the Dublin fleet, it was important to account for the mileage covered by different vehicle types in a given year. Therefore, vehicle mileage data were required. The RS database does contain some mileage data, but these are based on the last recorded figure from a National Car Test and could be up to 2 years out of date. For this reason, using figures provided by the Central Statistics Office (CSO) is more useful (CSO, 2019a).

The CSO mileage data are highly granular and are broken down by fuel type (petrol or diesel), vehicle type (passenger cars, public service vehicles or LGVs) and engine size, and also take into account the average mileage of each county. All vehicle types are differentiated by fuel type and engine size. For example, petrol vehicles with an engine capacity up to 1000 cc have an average mileage of 11,720 km, compared with an average mileage of 18,594 km for diesel vehicles with a similar-sized engine. Small public service vehicles, such as taxis, and LGVs had their mileage figures assigned based on their own relevant tables.

Once each vehicle had been assigned an average annual mileage, the next step was to offset this so that it more closely matched the distance travelled by vehicles within Dublin. To do this, we divided each vehicle's mileage by the national average – 16,352 km for passenger cars – and then multiplied this figure by the Dublin average, which is 13,337 km for passenger cars. In many cases this resulted in a reduction in the mileage, such as for passenger cars. However, in some cases, offsetting to Dublin averages resulted an increase in the average mileage; for example, offsetting resulted in an increase in the annual mileage of LGVs from 22,121 km to 23,512 km.

With each vehicle having an average mileage, it was then possible to calculate a vehicle-kilometre (V km) value for each of the Euro classes (Table 4.1). This entailed calculating the number of vehicles within each of the assigned bins and then multiplying this value by the average mileage across vehicles in that bin. This produced a V km value representative of the number of kilometres that the vehicles within a particular bin would cumulatively be expected to cover over a given year.

By multiplying the calculated EFs from both PEMS and COPERT by these V km values, it was possible to ascertain which vehicle segment on Irish roads was

Table 4.1. Estimated V km for individual vehicle bins

Vehicle bin	Number of vehicles	Average mileage (km)	V km (million)
Petrol hybrid – Euro 5	883	25,293	22.3
Petrol hybrid – Euro 6a/b/c	368	10,288	3.8
Petrol – Euro 5	4047	10,110	40.9
Petrol – Euro 6a/b/c	5908	9971	58.9
Petrol – Euro 6d-temp	414	10,017	4.2
Petrol – Euro 6d	813	9853	8.0
Diesel – Euro 4	1380	16,779	23.2
Diesel – Euro 5	11,279	19,435	219.0
Diesel – Euro 6a/b/c	9464	18,623	176.0
Diesel – Euro 6d-temp	588	16,951	10.0
Diesel – Euro 6d	386	18,468	7.1
Van – Euro 5	2130	26,887	57.3
Van – Euro 6a/b/c	616	28,885	17.8
Van – Euro 6d-temp	126	25,796	3.3

contributing the greatest proportion of emissions of a given pollutant.

As seen in Figures 4.8 and 4.9, the diesel passenger fleet on Dublin roads was responsible for the majority of the total emissions of both NO_x and CO. In the case of CO emissions, COPERT underestimated the effect of diesel vehicles, with the PEMS data showing values that were 250% higher; however, in the case of both petrol and petrol hybrid vehicles, emissions were estimated more accurately by COPERT. Examination of the values presented in Figure 4.9 shows that the opposite is true of NO_x emissions, as in this case COPERT overestimated the contribution of diesel to overall NO_x emissions, by almost 50%. These figures encapsulate the entire fleet, but it would also be possible to perform this comparison on the latest Euro 6d vehicles only.

Figures 4.10 and 4.11 show that the trend among newer vehicles differs from the fleetwide trend. The overall emissions of both CO and NO_x produced by Euro 6d vehicles were significantly lower than had been estimated by COPERT. Although the RS data recorded here were heavily weighted towards Euro 6d petrol vehicles (of which there were 813, compared with 386 Euro 6d diesels), this was offset by the higher annual mileage of the diesel vehicles. As a result, the NO_x emissions of both Euro 6d diesel vehicles and Euro 6d petrol vehicles are strikingly similar. Also clear from Figures 4.10 and 4.11 is that the emissions derived from COPERT were higher than

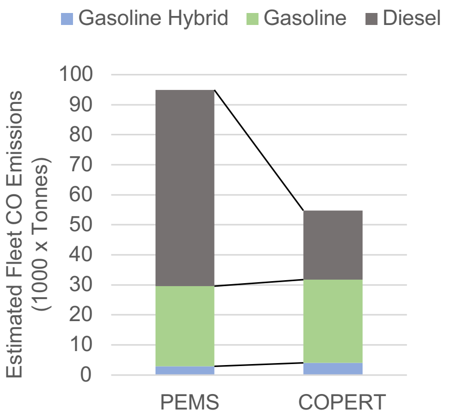


Figure 4.8. Annual CO emissions (tonnes) for the measured Dublin fleet as estimated by both PEMS and COPERT.

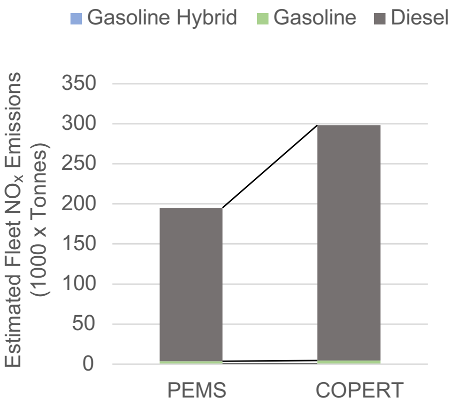


Figure 4.9. Annual NO_x emissions (tonnes) for the measured Dublin fleet as estimated by both PEMS and COPERT.

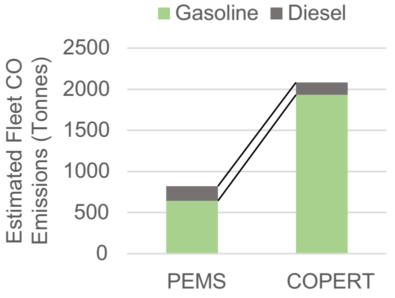


Figure 4.10. Annual CO emissions (tonnes) for the measured Euro 6d Dublin fleet as estimated by both PEMS and COPERT. Note the change in vertical scale relative to Figure 4.9.

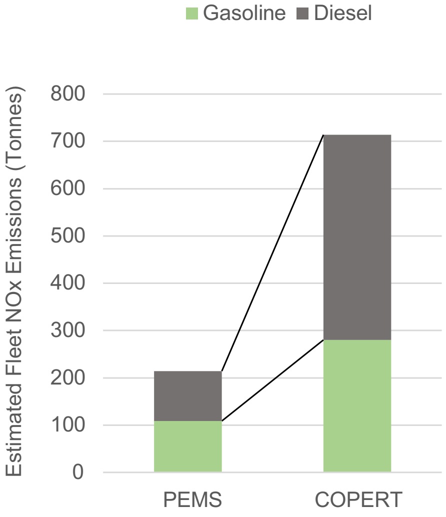


Figure 4.11. Annual NO_x emissions (tonnes) for the measured Euro 6d Dublin fleet as estimated for both PEMS and COPERT. Note the change in vertical scale relative to Figure 4.9.

those witnessed in the real-world PEMS testing. In this scenario, the COPERT Euro 6d CO emissions were comparable to those obtained from real-world PEMS testing, but the estimated NO_x emissions for the same vehicle type were over three times higher.

This trend towards lowered emissions within successive Euro classes can be easily seen by generating a marginal abatement cost curve. Marginal abatement cost curves plot the percentage that each vehicle type contributes towards the entire fleet V km against the EF. This enabled us to create a graph wherein the blocks with the largest area represent the vehicles contributing the most to the overall emission of a given pollutant.

As shown in Figure 4.12, there was a constantly decreasing trend among newer vehicles regardless of the fuel type. Of the nine lowest-emitting bins, only one did not contain solely Euro 6 vehicles. In this case the sole outlier was a Euro 4 diesel vehicle.

The effect of the advent of the Euro 6 standard is more evident in Figure 4.13; diesel emissions can be seen to halve between the implementation of Euro 4/5 and Euro 6/b/c. This trend continues, with an even greater relative reduction observed with the introduction of the Euro 6d-temp and Euro 6d standards. This trend was also observed for LGVs, as the NO_x emission value for diesel vans greatly decreased between the implementation of the Euro 5 and the Euro 6a/b/c and Euro 6d-temp standards. This trend was not observed for petrol vehicles, however, which exhibited only a small variation in NO_x EF regardless of Euro standard.

With respect to the light-duty (car and van) fleet, replacing all Euro 4 diesels with Euro 6d equivalents would reduce diesel NO_x emissions by 4.9% and overall NO_x emissions by 4.8%. Diesel CO emissions would drop by 0.9% and overall CO emissions by 0.7%. Replacing both Euro 4 and Euro 5 diesels (i.e. all diesel cars and vans over 8 years of age) with new

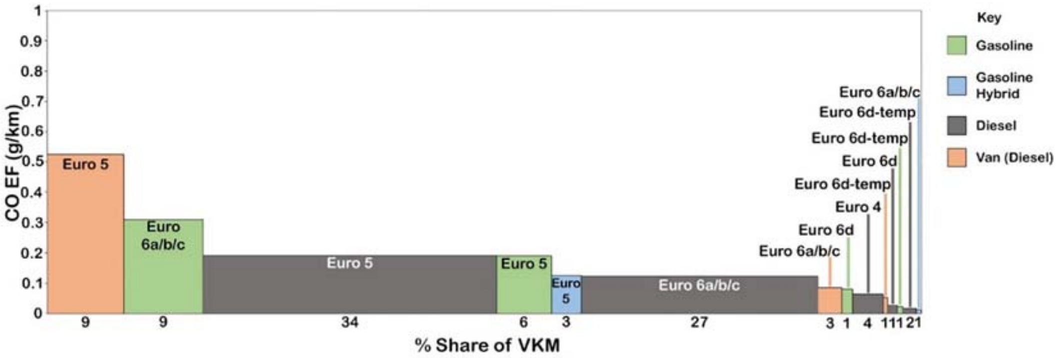


Figure 4.12. Cumulative NO_x emissions, by Euro class, for the Dublin fleet based on PEMS data.

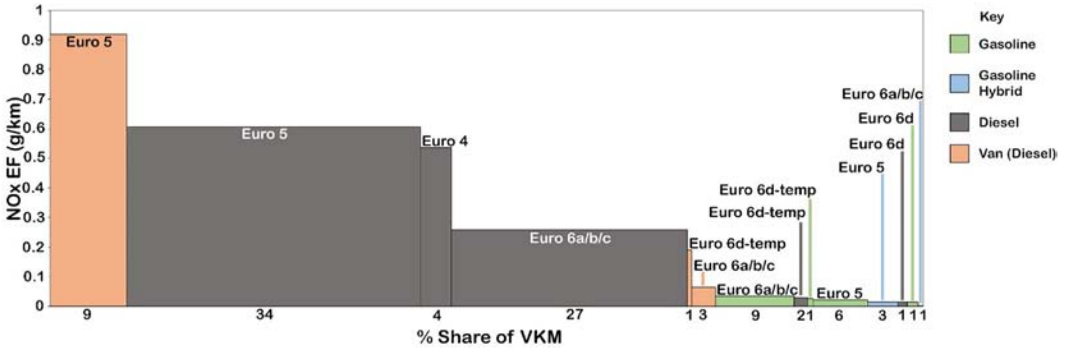


Figure 4.13. Marginal abatement cost curve for PEMS NO_x EF against share of V km.

equivalents would reduce diesel NO_x emissions by 74% and overall NO_x emissions by 73%.

4.4 Conclusions

The determination of EFs using RS gives values that are approximately in line with those generated by the more accurate PEMS. RS gives an accurate picture of the emissions from vehicles in use on Dublin roads, whereas using the more in-depth and cycle-based PEMS measurements is preferable when ascertaining the exhaust emissions produced by a given vehicle. This is because of the constraints inherent to RS-based measurement: each vehicle measurement is the value of emissions produced at a singular, instantaneous time point. Having only one data point means that assumptions have to be made in order to derive an EF; in contrast, in a PEMS analysis, all necessary data for a derivation are held within the PEMS dataset. Another advantage of PEMS is that emissions values can be recorded over the full range of vehicle speed and load, allowing the whole driving cycle to be analysed. In contrast, when using RS, owing to the nature of the technology, vehicles must be under acceleration at the time of measurement, such as is the case after exiting from a junction or roundabout. This means that all measurements obtained are recorded under the same conditions.

The PEMS analysis showed that the majority of overall emissions came from vehicles produced prior to the introduction of the Euro 6 standard. Despite constituting 45% of total diesel vehicles, Euro 6 diesels contributed only 29% of diesel NO_x emissions and 33% of diesel CO emissions. Similarly, the latest Euro 6d vehicles constituted 1.6% of all diesels, yet contributed only 0.3% of total diesel CO and 0.01% of total diesel NO_x emissions. The same was not true for petrol vehicles: the overall emissions of each Euro class of petrol vehicles were consistent with the share of that class among the petrol vehicle population. Replacing older vehicles with modern Euro 6d vehicles would clearly yield substantial reductions in emissions totals for the Irish fleet. The cost and life cycle implications must, however, be considered.

4.4.1 Policy recommendations

We recommend that any policy-based study that needs to determine, to the highest degree of accuracy, the EFs produced by a given set of vehicles use PEMS data rather than RS data. This is because the PEMS device records multiple parameters that contribute to emissions – values that are left to assumptions in the RS data.

For diesel emissions in particular, the impact of technologies implemented in line with the Euro 6d standard is clear and abundant. It is also evident that the COPERT model does not reflect these accurately, and overestimates CO and NO_x emissions from the most recently produced vehicles. Switching as many vehicles as possible to these newer standards would result in a drastic decrease in overall exhaust emissions.

5 Emission Inventory and Concentration Modelling

5.1 Introduction

This chapter describes the emission inventory developed for Ireland using the COPERT emission model. A concentration model was also developed for Dublin using an atmospheric dispersion modelling system (ADMS), which provides the concentration of pollutants at different locations in the city. This model was later applied to perform various case studies, including the introduction of a LEZ and the pedestrianisation of College Green.

5.2 Emission Model Development

The emission model was developed using COPERT (version 5.5.1). This software is commonly used for modelling emissions from motor vehicles in Europe. The software is comprehensive and requires detailed input data related to the study location and vehicle fleet. The vehicle fleet information includes the number of vehicles of different categories (cars, trucks, vans, etc.), fuel type (petrol, diesel, etc.), size (small, medium-sized, etc.) and Euro standard. Table 5.1 provides a summary of the input data required and the source of these data. As seen from the table, the input data include travel-related information such as the trip length and activity. For this study, the trip length and trip duration were 12 km and 0.25 hours, respectively. The vehicle activity data consider the mean distance travelled for each vehicle category, fuel type, segment and Euro standard.

Table 5.2 presents the emission inventory for Ireland considering the vehicle fleet of passenger cars, LGVs and trucks in 2020. The pollutants considered included CO, CO_2, NO_x, $PM_{2.5}$ and PM < 10 μm in aerodynamic

Table 5.1. Summary of input data sources

Data	Source	URL
Temperature data	Dublin Airport monthly data; Data.gov.ie (2018)	https://data.gov.ie/dataset/dublin-airport-monthly-data?package_type=dataset
Humidity data	World Weather & Climate Information (no date)	https://weather-and-climate.com/average-monthly-Humidity-perc,Dublin,Ireland
Trip length	National Travel Survey (CSO, 2019b)	https://www.cso.ie/en/releasesandpublications/ep/p-nts/nationaltravelsurvey2019/
Activity data	Sustainable Energy Authority of Ireland (no date)	https://www.seai.ie/data-and-insights/seai-statistics/key-statistics/transport/#comp00005b3f76b800000073d52ac1
Vehicle stock	Motorstats (2024)	https://stats.beepbeep.ie/
Circulation data	Brady and O'Mahony (2011)	–
Speed data	Free speed study survey report; Road Safety Authority (2018)	https://www.rsa.ie/docs/default-source/road-safety/r4.1-research-reports/speed/free-speed-survey-2018.pdf?sfvrsn=b5b52479_3

Table 5.2. Emission inventory (in tonnes) for Ireland for 2020

Pollutant	Passenger cars	LGVs	Trucks	Total
CO	45,566.85	2275.24	785.10	48,627.19
CO_2	6137,154.92	1090,433.46	486,475.88	7714,064.26
NO_x	11,688.54	7152.03	3600.40	22,440.97
$PM_{2.5}$	805.08	538.88	126.03	1469.99
PM_{10}	1166.63	635.90	183.57	1986.10
Volatile organic compounds	4625.32	570.62	137.65	5333.59
Non-methane volatile organic compounds	4172.45	553.43	107.64	4833.52

diameter. As expected, the highest contribution of CO_2 was from passenger cars, because they are much more numerous than other vehicle types. However, although the number of trucks was small, NO_x emissions from trucks were more than 30% of the total NO_x emissions from passenger cars.

5.3 Concentration Modelling

The concentration model was developed using ADMS Roads, which is a software developed by Cambridge Environmental Research Consultants. The information that can be input to ADMS Roads includes emission sources (roads), emission profiles, meteorological data, traffic flow data and background pollutant concentrations. The model can be used to determine the pollutant concentrations for a wide range of emission sources, including industries. However, the only sources we considered were roads. In our case, the model had 218 road sources, which included all the major roads in Dublin (Figure 5.1). The traffic volume and speed data input to the model were based on the National Transport Authority travel demand model. Meteorological data (Casement) and background concentration data (Rathmines) were obtained from the EPA, Ireland. Both of these datasets were hourly sequential datasets for the year 2019. The output from the concentration model is presented in terms of NO_x emissions.

The default EFs in the ADMS Roads software are based on the UK Emission Factors Toolkit (version 10.1). It is also possible for users to input EFs for vehicles. The software's in-built road types are urban, rural and motorway in England, Scotland, Wales and Northern Ireland. In this study, the option of Northern Ireland was chosen as the road type.

The ADMS model was used to test several cases based on EF and transport policy using default EF values, COPERT EF values and real-world EF values obtained from the PEMS dataset, as described in Chapter 4. This led to a total of nine case studies, as shown in Table 5.3. The entire network of roads is shown in Figure 5.1. In the case of the LEZ scenario, it was assumed that all the vehicles inside the hypothetical LEZ were Euro 6 compliant. Furthermore, in the case of the pedestrianised College Green, it was assumed that there was no traffic in College Green and Dame Street, as proposed in the plan by Dublin City Council.

Table 5.3. Case studies based on EF and transport policy

EF	Entire network	LEZ	Pedestrianised College Green
Default	Case study 1	Case study 4	Case study 7
COPERT	Case study 2	Case study 5	Case study 8
Real world	Case study 3	Case study 6	Case study 9

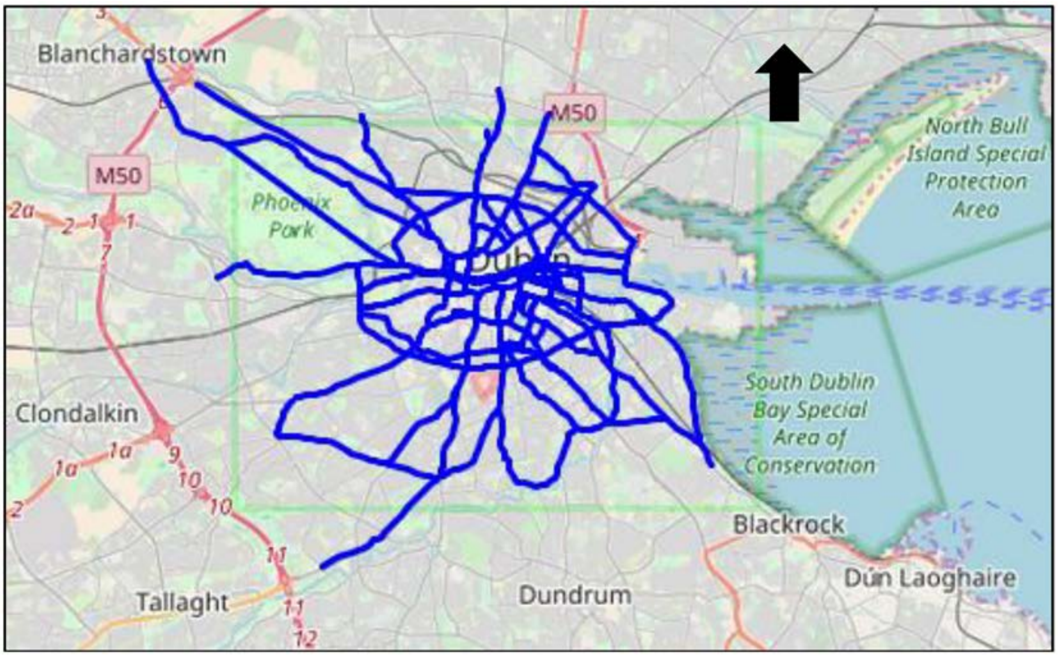


Figure 5.1. ADMS concentration model of Dublin with the major roads shown in blue colour.

Figure 5.2 shows the concentration of NO_x throughout the road network, in Dublin city centre and at locations with high concentrations. The highest concentrations, ranging between 80 and 120 μg/m^3, were seen along the quays in the city centre. However, the concentrations decreased significantly outside the canal cordon (Figure 5.2a), with only the locations along the roads having relatively high concentrations.

Figure 5.3 shows the NO_x concentrations with COPERT EFs for the entire road network, city centre and locations with high concentrations. The concentration in general was similar to those obtained with the default ADMS EF values, with higher concentrations seen within the canal cordon, and the highest concentrations seen along the quays.

Finally, Figure 5.4 shows NO_x concentrations obtained using real-world EFs from the PEMS dataset. From Figure 5.4a and b, it can be seen that concentrations were higher along the roads and that most locations inside the city centre had NO_x concentrations ranging between 40 and 80 μg/m^3. From Figure 5.4c, it can be seen that the locations along the quays and around Trinity College had concentrations higher than 80 μg/m^3.

Figure 5.5 shows the comparison of the average NO_x concentrations at different locations using the default, COPERT and real-world EFs. The locations chosen for comparison were College Green, Connolly Station, O'Connell Bridge, Phibsborough, Rathmines and Victoria Quay. The highest concentrations were observed using the COPERT EFs and real-world EFs at all locations. We also found that College Green and Victoria Quay had relatively high concentrations compared with the other locations. This shows the effect of the chosen EF on the modelling results.

The introduction of a LEZ is a commonly adopted strategy for reducing the air pollutant concentrations within a city centre. This approach is based on creating a zone which can be accessed only by low-polluting vehicles. As per the Clean Air for Europe Directive, local authorities are bound to keep air pollutant concentrations below certain threshold limits, and LEZ is a measure that could be used to limit emissions from road traffic. Many cities in Europe, including London, have successfully adopted this approach. However, LEZs are not currently used in Ireland. To evaluate the potential benefits of LEZs, concentration modelling using ADMS was used with a hypothetical cordon around the city centre.

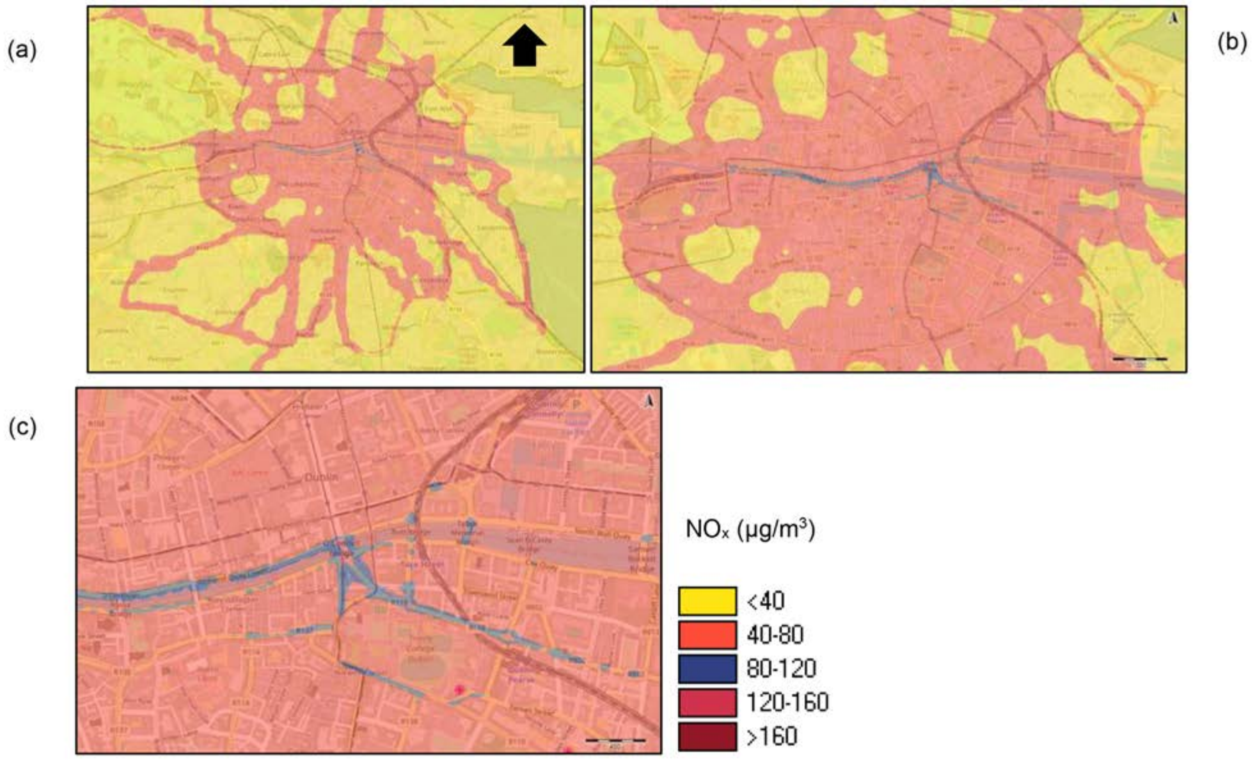


Figure 5.2. Baseline NO_x (μg/m^3) concentrations obtained from the ADMS (a) throughout the road network, (b) in Dublin city centre and (c) at locations with high concentrations.

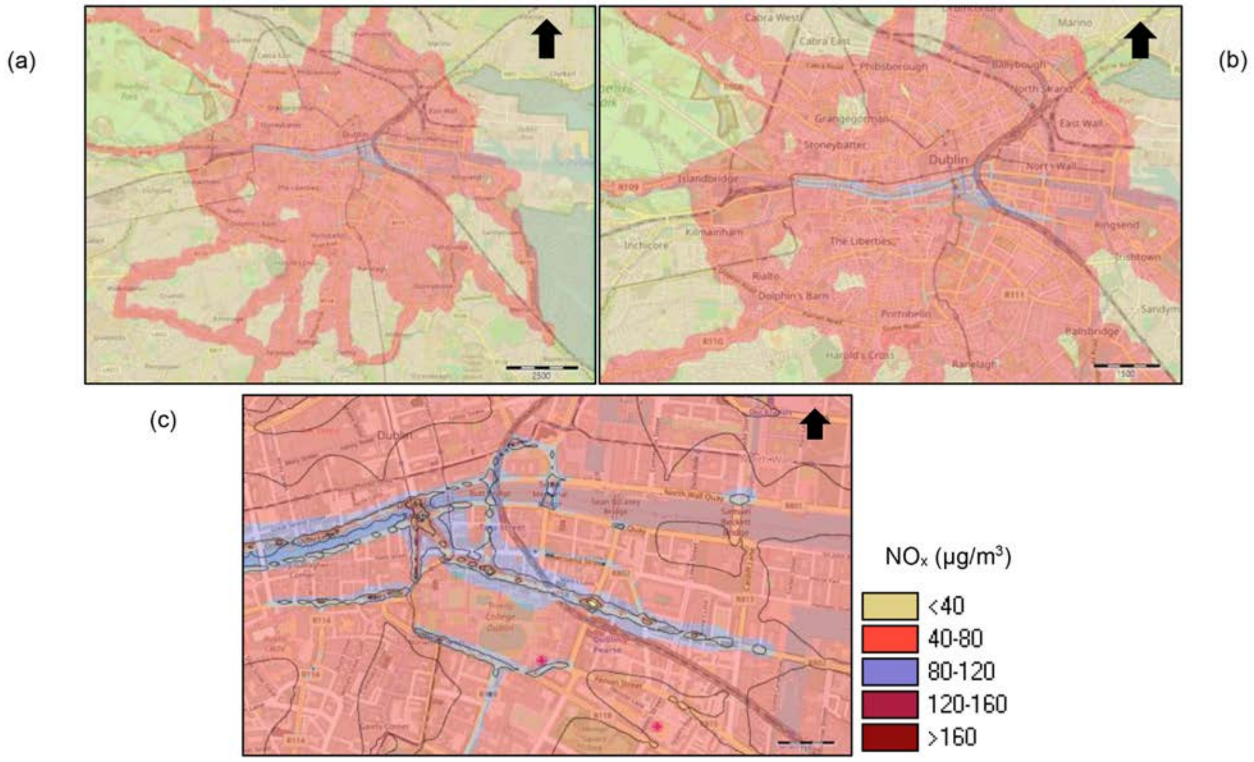


Figure 5.3. NO$_x$ (µg/m^3) concentration obtained from COPERT EFs (a) throughout the road network, (b) in Dublin city centre and (c) at locations with high concentrations.

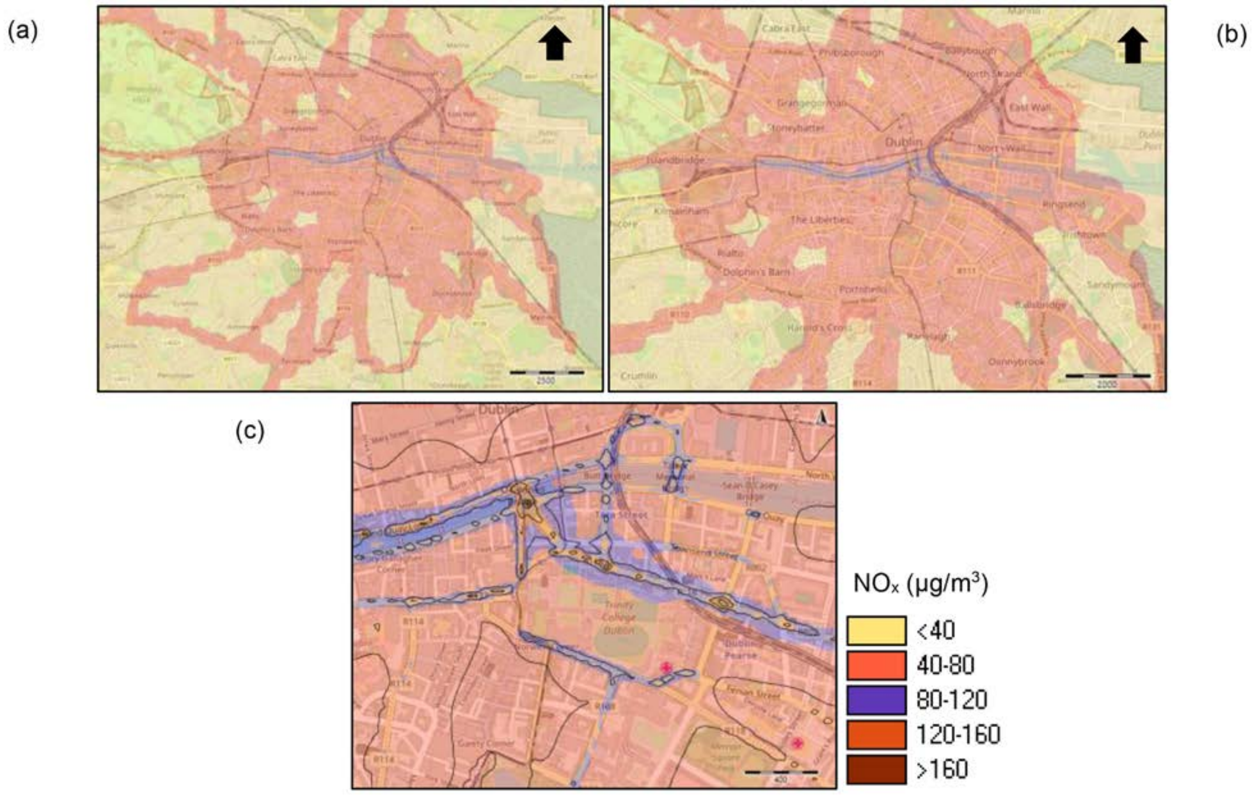


Figure 5.4. NO$_x$ (µg/m^3) concentrations obtained from real-world EFs (a) throughout the road network, (b) in Dublin city centre and (c) at locations with high concentrations.

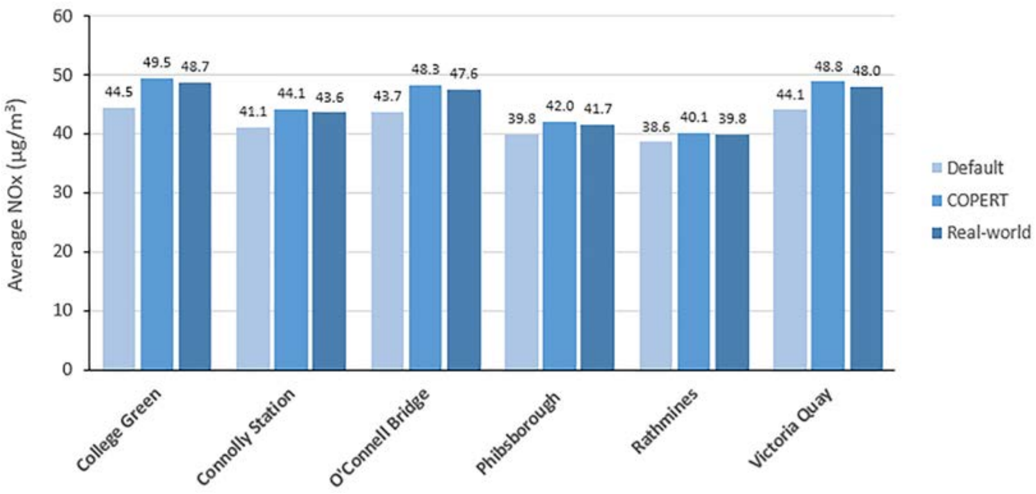


Figure 5.5. Effect of EFs on average NO_x concentrations at different locations.

Figure 5.6 shows the effect on NO_x concentration in the city centre after introducing a LEZ (shown by the dashed line). The post-LEZ NO_x concentrations inside the city centre were significantly lower than the baseline concentrations. However, the concentrations along the quays remained high owing to the high volume of traffic relative to the other roads. On comparing the concentration values at College Green and Connolly Station for baseline case with the LEZ case, the percentage reduction observed was 9.5% and 6.0%, respectively. Overall, a significant reduction (~20%) in NO_x concentrations was observed after the introduction of a LEZ.

Recently, Dublin City Council announced the College Green pedestrianisation project (or College Green Plaza), which aims to reroute buses that currently pass through College Green and Dame Street onto alternative routes. This measure is expected to improve the air quality and reduce noise levels in College Green and Dame Street, thus improving the pedestrian experience. The location of the proposed project is outside the main entrance of Trinity College Dublin.

The effect on NO_x concentrations of pedestrianising College Green was modelled using ADMS and the results are shown in Figure 5.7. It can be seen that there was no significant reduction in NO_x concentrations in College Green. Furthermore, comparison of the results obtained using different EFs showed that NO_x concentrations obtained using the COPERT and real-world EFs were about 20% higher than those of the model using default EF values. The highest average NO_x concentration was 49.4 µg/m³, which was obtained using the COPERT EFs. In contrast, the NO_x concentration was lowest (41.2 µg/m³) when using default EFs.

Figure 5.6. Concentration of NO_x (µg/m³) (a) at baseline and (b) after the implementation of a LEZ.

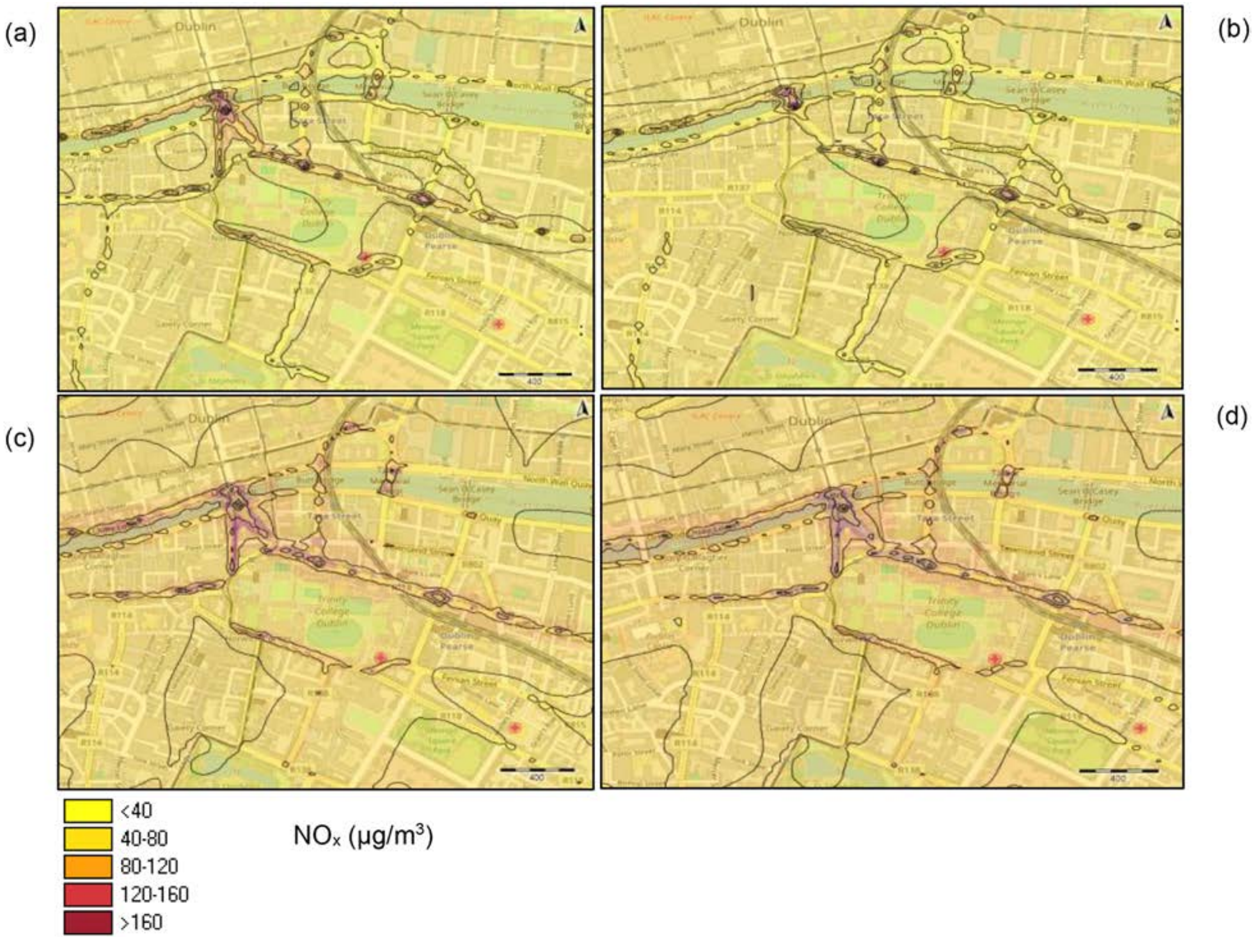


Figure 5.7. Effect of College Green pedestrianisation on NO$_x$ concentrations (µg/m^3) (a) at baseline, (b) determined using default EFs, (c) determined using COPERT EFs and (d) determined using real-world EFs.

6 Conclusions and Policy Recommendations

The following conclusions and policy recommendations have been drawn from the final report:

- *RS.* The RS technique for measuring emissions of key pollutants (including NO, NO_2 and PM) from in-use vehicles was successfully applied for the first time in Dublin. The data collection campaign, conducted in two phases, provided a comprehensive dataset comprising different vehicle types (cars, taxis, vans and buses) of varying makes, mileage, fuel types and Euro classes. This dataset was used to determine the EFs of CO, HC, NO and NO_2 from the fleet of vehicles in Dublin. The Euro classes of the vehicles ranged from Euro 3 to Euro 6, and the dataset included a large number of the latest Euro 6 vehicles. Thus, the dataset can be considered representative of the current fleet of vehicles in Dublin, and the findings provide evidence for the benefits of fleet renewal. However, since the study was restricted to Dublin, which may have a newer fleet of vehicles than other areas in Ireland, older vehicles may be underrepresented. Based on the findings from this study, it is recommended that similar RS-based emission measurement studies should be carried out in other cities in Ireland, which would help make the quantification of emissions from in-use vehicles more accurate. This could in turn form the basis for suitable emission mitigation measures for that particular city.
- *NO_x emissions.* Emissions of NO_x from diesel cars were found to be higher than those from petrol cars of the same vehicle registration year. NO_x emissions from diesel cars decreased with registration year after 2015. This can probably be attributed to more stringent emissions limits for Euro 6 vehicles. NO_x emissions recorded during the summer and winter campaigns were similar, with only the differences being slightly higher values recorded for some vehicles (mainly LGVs) and some registration years during the summer campaign. NO_x emissions from buses decreased considerably after 2013, which can probably be attributed to introduction of Euro VI buses towards the end of 2013. This is similar to the findings regarding emissions from buses in the UK. It was also found that emissions of NO_x were high for buses registered in 2012 and 2013. It is therefore recommended that buses registered before 2014 are phased out at the earliest opportunity.
- *Effect of Euro 6 standards.* The trends in NO EFs were similar for diesel cars, vans and taxis, with Euro 6 vehicles having the lowest values and Euro 5 having the highest. In addition, among the three vehicle types, taxis had a slightly higher EF than cars and vans of the same emission standard. This could be because taxis have, on average, a relatively high mileage and taxi drivers have a more assertive driving style than car and van drivers. In the case of buses, a significant reduction in NO EF was observed for Euro 6 vehicles (0.5 g/kg fuel) compared with Euro 5 (25.6 g/kg fuel) vehicles. It is therefore recommended that Euro 3- and Euro 4-compliant cars and Euro V-compliant buses are phased out as soon as possible.
- *Petrol cars.* The NO EF was 43.5% lower for Euro 6 cars than for Euro 5 cars. The HC EF increased from Euro 3 to Euro 4 vehicles, and then decreased, with a very low value observed for Euro 6 vehicles (1.0 g/kg fuel). The NO_2 EFs for Euro 5 and Euro 6 cars were similar, and significantly lower than those of Euro 3 and Euro 4 cars. In general, an overall decreasing trend in NO and NO_2 EFs with improving emission standards was observed.
- *Effect of manufacturer.* In the case of NO, an increasing trend was observed for some manufacturers up to 2012, after which a decrease was observed. Audi, BMW and Mercedes-Benz vehicles showed consistently low EF values, which decreased with the year of registration. Ford, Nissan and Hyundai vehicles had relatively high EF values compared with vehicles produced by other manufacturers. In the case of NO_2 EFs, most vehicles had a value of 2.5 g/kg fuel up to 2016, and vehicles from most manufacturers showed a declining trend from 2016 on.
- *PEMS.* Within the PEMS analysis, the majority of overall emissions were found to come from

vehicles produced prior to the introduction of the Euro 6 standard. Despite constituting 45% of total diesel vehicles, Euro 6 diesel vehicles contributed only 29% of diesel NO_x emissions and 33% of diesel CO emissions. Similarly, the latest Euro 6d vehicles constituted 1.6% of all diesels yet contributed only 0.3% of total diesel CO emissions and 0.01% of total diesel NO_x emissions.

- *NO_x concentrations.* NO_x concentrations were higher along roads, and at most locations inside the city centre the concentration was between 40 and 80 µg/m^3. Moreover, at locations along the quays and around Trinity College, concentrations were higher than 80 µg/m^3. Suitable mitigation measures, such as the introduction of LEZs, are recommended to prevent further increases in NO_x concentrations in the city centre, as higher levels could have a significant health impact.
- *College Green pedestrianisation and the introduction of a LEZ.* The proposed pedestrianisation project did not lead to significant improvements in the NO_x concentrations in College Green. However, the introduction of a LEZ resulted in concentrations inside the city centre being significantly reduced compared with baseline levels. Conversely, the concentrations along the quays remained high because of the large volume of traffic relative to the other roads. Overall, a reduction (about 20%) in NO_x concentrations was observed after the introduction of a LEZ. It is therefore recommended that a LEZ be put in place to mitigate air pollution inside the city centre.

In summary, the benefits of upgrading the vehicle fleet to newer emission standards (Euro 6d) are apparent from an air quality perspective. This is reflected in the proposed Euro 7 standards (European Commission, 2022), which make very minor adjustments to the emission limits for pollutants already regulated under Euro 6d, but extend the standards to include non-tailpipe emissions (brake and tyre wear) for the first time. The proposal also broadens the range of driving conditions that are covered by on-road emission tests (including temperatures of up to 45°C) and sets minimum durability requirements for batteries powering electric vehicles. Future work could be aimed towards quantifying and assessing the impact of new Euro 7 standard vehicles on the air quality in Dublin and other European cities.

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Abbreviations

ADMS	Atmospheric dispersion modelling system
COPERT	Computer Program to Calculate Emissions from Road Transport
CSO	Central Statistics Office
DPF	Diesel particulate filter
EF	Emission factor
Euro	European emission
GPS	Global positioning system
HC	Hydrocarbon
HGV	Heavy goods vehicle
LEZ	Low-emission zone
LGV	Light goods vehicle
PEMS	Portable emission measurement system
PM	Particulate matter
RS	Remote sensing
Vkm	Vehicle-kilometre

An Ghníomhaireacht Um Chaomhnú Comhshaoil

Tá an GCC freagrach as an gcomhshaol a chosaint agus a fheabhsú, mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ar thionchar díobhálach na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialáil: Rialáil agus córais chomhlíonta comhshaoil éifeachtacha a chur i bhfeidhm, chun dea-thorthaí comhshaoil a bhaint amach agus díriú orthu siúd nach mbíonn ag cloí leo.

Eolas: Sonraí, eolas agus measúnú ardchaighdeáin, spriocdhírithe agus tráthúil a chur ar fáil i leith an chomhshaoil chun bonn eolais a chur faoin gcinnteoireacht.

Abhcóideacht: Ag obair le daoine eile ar son timpeallachta glaine, táirgiúla agus dea-chosanta agus ar son cleachtas inbhuanaithe i dtaobh an chomhshaoil.

I measc ár gcuid freagrachtaí tá:

Ceadúnú

- Gníomhaíochtaí tionscail, dramhaíola agus stórála peitril ar scála mór;
- Sceitheadh fuíolluisce uirbigh;
- Úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe;
- Foinsí radaíochta ianúcháin;
- Astaíochtaí gás ceaptha teasa ó thionscal agus ón eitlíocht trí Scéim an AE um Thrádáil Astaíochtaí.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil

- Iniúchadh agus cigireacht ar shaoráidí a bhfuil ceadúnas acu ón GCC;
- Cur i bhfeidhm an dea-chleachtais a stiúradh i ngníomhaíochtaí agus i saoráidí rialáilte;
- Maoirseacht a dhéanamh ar fhreagrachtaí an údaráis áitiúil as cosaint an chomhshaoil;
- Caighdeán an uisce óil phoiblí a rialáil agus údaruithe um sceitheadh fuíolluisce uirbigh a fhorfheidhmiú
- Caighdeán an uisce óil phoiblí agus phríobháidigh a mheasúnú agus tuairisciú air;
- Comhordú a dhéanamh ar líonra d'eagraíochtaí seirbhíse poiblí chun tacú le gníomhú i gcoinne coireachta comhshaoil;
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Dramhaíola agus Ceimiceáin sa Chomhshaol

- Rialacháin dramhaíola a chur i bhfeidhm agus a fhorfheidhmiú lena n-áirítear saincheisteanna forfheidhmithe náisiúnta;
- Staitisticí dramhaíola náisiúnta a ullmhú agus a fhoilsiú chomh maith leis an bPlean Náisiúnta um Bainistíocht Dramhaíola Guaisí;
- An Clár Náisiúnta um Chosc Dramhaíola a fhorbairt agus a chur i bhfeidhm;
- Reachtaíocht ar rialú ceimiceán sa timpeallacht a chur i bhfeidhm agus tuairisciú ar an reachtaíocht sin.

Bainistíocht Uisce

- Plé le struchtúir náisiúnta agus réigiúnacha rialachais agus oibriúcháin chun an Chreat-treoir Uisce a chur i bhfeidhm;
- Monatóireacht, measúnú agus tuairisciú a dhéanamh ar chaighdeán aibhneacha, lochanna, uiscí idirchreasa agus cósta, uiscí snámha agus screamhuisce chomh maith le tomhas ar leibhéil uisce agus sreabhadh abhann.

Eolaíocht Aeráide & Athrú Aeráide

- Fardail agus réamh-mheastacháin a fhoilsiú um astaíochtaí gás ceaptha teasa na hÉireann;
- Rúnaíocht a chur ar fáil don Chomhairle Chomhairleach ar Athrú Aeráide agus tacaíocht a thabhairt don Idirphlé Náisiúnta ar Ghníomhú ar son na hAeráide;
- Tacú le gníomhaíochtaí forbartha Náisiúnta, AE agus NA um Eolaíocht agus Beartas Aeráide.

Monatóireacht & Measúnú ar an gComhshaol

- Córais náisiúnta um monatóireacht an chomhshaoil a cheapadh agus a chur i bhfeidhm: teicneolaíocht, bainistíocht sonraí, anailís agus réamhaisnéisiú;
- Tuairiscí ar Staid Thimpeallacht na hÉireann agus ar Tháscairí a chur ar fáil;
- Monatóireacht a dhéanamh ar chaighdeán an aeir agus Treoir an AE i leith Aeir Ghlain don Eoraip a chur i bhfeidhm chomh maith leis an gCoinbhinsiún ar Aerthruailliú Fadraoin Trasteorann, agus an Treoir i leith na Teorann Náisiúnta Astaíochtaí;
- Maoirseacht a dhéanamh ar chur i bhfeidhm na Treorach i leith Torainn Timpeallachta;
- Measúnú a dhéanamh ar thionchar pleananna agus clár beartaithe ar chomhshaol na hÉireann.

Taighde agus Forbairt Comhshaoil

- Comhordú a dhéanamh ar ghníomhaíochtaí taighde comhshaoil agus iad a mhaoiniú chun brú a aithint, bonn eolais a chur faoin mbeartas agus réitigh a chur ar fáil;
- Comhoibriú le gníomhaíocht náisiúnta agus AE um thaighde comhshaoil.

Cosaint Raideolaíoch

- Monatóireacht a dhéanamh ar leibhéil radaíochta agus nochtadh an phobail do radaíocht ianúcháin agus do réimsí leictreamaighnéadacha a mheas;
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha;
- Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta;
- Sainseirbhísí um chosaint ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Ardú Feasachta agus Faisnéis Inrochtana

- Tuairisciú, comhairle agus treoir neamhspleách, fianaise-bhunaithe a chur ar fáil don Rialtas, don tionscal agus don phobal ar ábhair maidir le cosaint comhshaoil agus raideolaíoch;
- An nasc idir sláinte agus folláine, an geilleagar agus timpeallacht ghlan a chur chun cinn;
- Feasacht comhshaoil a chur chun cinn lena n-áirítear tacú le hiompraíocht um éifeachtúlacht acmhainní agus aistriú aeráide;
- Tástáil radóin a chur chun cinn i dtithe agus in ionaid oibre agus feabhsúchán a mholadh áit is gá.

Comhpháirtíocht agus Líonrú

- Oibriú le gníomhaireachtaí idirnáisiúnta agus náisiúnta, údaráis réigiúnacha agus áitiúla, eagraíochtaí neamhrialtais, comhlachtaí ionadaíocha agus ranna rialtais chun cosaint chomhshaoil agus raideolaíoch a chur ar fáil, chomh maith le taighde, comhordú agus cinnteoireacht bunaithe ar an eolaíocht.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil

Tá an GCC á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóir. Déantar an obair ar fud cúig cinn d'Oifigí:

1. An Oifig um Inbhunaitheacht i leith Cúrsaí Comhshaoil
2. An Oifig Forfheidhmithe i leith Cúrsaí Comhshaoil
3. An Oifig um Fhianaise agus Measúnú
4. An Oifig um Chosaint ar Radaíocht agus Monatóireacht Comhshaoil
5. An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tugann coistí comhairleacha cabhair don Ghníomhaireacht agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

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