

## **Influence of Vehicle Mass on RDE tailpipe emissions from over 1000 vehicles**

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**Einfluss der Fahrzeugmasse auf die RDE-Abgasemissionen von über 1000 Fahrzeugen**

## **Abstract**

A wide variety of factors can affect emissions from a vehicle. In this study, carbon dioxide and pollutant emissions (carbon monoxide, particle number, and nitrogen oxides (NO<sub>x</sub>)) from over 1000 vehicles are measured over Real Driving Emissions (RDE) test cycles from vehicles spanning the Euro 3 to Euro 6d regulations. These are presented in order to observe fleet-wide correlations. Vehicle mass is found to be a strong predictor of carbon dioxide emissions but a weak predictor of pollutant emissions. In addition, non-regulated pollutants including nitrous oxide (N<sub>2</sub>O), formaldehyde, combined aromatics, alkanes, PAHs and alcohols are measured and presented. Overall, there is no obvious link between higher vehicle mass and these unregulated emissions. In this paper, the link between other vehicle characteristics - Euro emissions classification, powertrain type (gasoline/diesel/hybrid etc), and engine size will also be explored. The findings show that vehicle mass is a good predictor for carbon dioxide emissions, but not for pollutant and other non-regulated emissions. Engine size is also a good predictor of carbon dioxide emissions. However, there are no other vehicle characteristics that can predict the pollutant emissions particularly better either. Vehicle mass may also be a useful indicator of other measures of the environmental impact of a vehicle. This may lead towards a future vehicle regulation system where in a world of diverse powertrains, mass can be used as a future metric for a simple system of assessing the environmental impact of a vehicle.

## **Kurzfassung**

Eine Vielzahl von Faktoren kann die Emissionen eines Fahrzeugs beeinflussen. In dieser Studie werden die Emissionen von Kohlendioxid sowie Schadstoffen (Kohlenmonoxid, Partikelanzahl und Stickoxide (NO<sub>x</sub>)) von über 1000 Fahrzeugen während Real-Driving-Emissions (RDE)-Testzyklen gemessen. Die untersuchten Fahrzeuge entsprechen den Emissionsnormen von Euro 3 bis Euro 6d. Die Ergebnisse werden präsentiert, um flottenweite Korrelationen zu analysieren. Es zeigt sich, dass die Fahrzeugmasse ein starker Prädiktor für die Kohlendioxidemissionen ist, jedoch nur ein schwacher Prädiktor für Schadstoffemissionen.

Zusätzlich werden nicht regulierte Schadstoffe wie Distickstoffmonoxid (N<sub>2</sub>O), Formaldehyd, kombinierte Aromaten, Alkane, polyzyklische aromatische Kohlenwasserstoffe (PAKs) und Alkohole gemessen und dargestellt. Insgesamt lässt sich keine eindeutige Verbindung zwischen einer höheren Fahrzeugmasse und diesen nicht regulierten Emissionen feststellen.

In dieser Arbeit wird zudem der Zusammenhang zwischen weiteren Fahrzeugeigenschaften – der Euro-Emissionsklassifizierung, dem Antriebstyp (Benzin/Diesel/Hybrid etc.) und der Motorgröße – untersucht. Die Ergebnisse zeigen, dass die Fahrzeugmasse ein guter Indikator für Kohlendioxidemissionen ist, jedoch nicht für Schadstoffemissionen oder andere nicht regulierte Emissionen. Auch die Motorgröße erweist sich als zuverlässiger Prädiktor für Kohlendioxidemissionen. Allerdings gibt es keine weiteren Fahrzeugeigenschaften, die Schadstoffemissionen signifikant besser vorhersagen können.

Die Fahrzeugmasse könnte zudem ein nützlicher Indikator für weitere Umweltwirkungen eines Fahrzeugs sein. Dies könnte in Zukunft zu einem neuen Regulierungsansatz führen, bei dem in einer Welt mit vielfältigen Antriebstechnologien die Fahrzeugmasse als einfache Metrik zur Bewertung der Umweltwirkung eines Fahrzeugs herangezogen wird.

## **Introduction**

All vehicles equipped with an internal combustion engine must undergo official certification before they can be legally sold in their respective countries. In the United Kingdom and the European Union, certification for carbon dioxide (CO<sub>2</sub>) emissions is currently conducted in accordance with the Worldwide Harmonized Light Vehicles Test Procedure (WLTP). In contrast, the certification process for pollutants such as carbon monoxide (CO), nitrogen oxides (NO<sub>x</sub>), and particle number (PN) follows a combination of WLTP, which is conducted under controlled laboratory conditions, and the Real Driving Emissions (RDE) test, an on-road assessment, conducted with a portable emissions measuring system (PEMS) [1], designed to ensure that real-world emissions align closely with laboratory results [2]. Compliance with both WLTP and RDE is mandatory for all regulated pollutants.

However, the implementation of WLTP and RDE was introduced progressively from approximately 2018 onwards [3]. The exact timeline varies, as the introduction of these test protocols followed a staggered approach, with differing implementation dates depending on the pollutant, vehicle category (passenger cars versus vans, for example), and regional regulations. Prior to this transition, vehicle certification relied exclusively on the New European Driving Cycle (NEDC), a simplified laboratory-based test [4, 5]. The shift from NEDC to WLTP/RDE represents a fundamental change in emissions assessment. The NEDC, in place before 2018, was widely recognized as an undemanding test that was conducted solely in laboratory settings. Moreover, its regulatory framework contained ambiguities that allowed for significant interpretative flexibility. As a result, emissions values obtained under the NEDC were often highly optimistic, with vehicle manufacturers leveraging legal loopholes and technical optimizations to achieve artificially low emissions results. While some of these strategies complied with regulatory requirements, others were subject to legal scrutiny, and as of 2025, litigation concerning their validity remains ongoing in courts across Europe.

The transition to the combined WLTP and RDE testing framework was largely driven by the Dieselgate scandal and aimed to close regulatory loopholes while imposing more stringent and representative testing conditions. In contrast, the United States adopted a more rigorous approach earlier, tightening its emissions certification process in 2008 through the introduction of the "five-cycle method," which mitigated many of the weaknesses associated with earlier European testing protocols [6].

While Portable Emissions Measurement Systems (PEMS) facilitate real-time detection of vehicular emissions, their applicability is restricted to a limited set of pollutants, including nitrogen monoxide (NO), nitrogen dioxide (NO<sub>2</sub>), carbon monoxide (CO), carbon dioxide (CO<sub>2</sub>), and total hydrocarbons (THC). The latter category encompasses a broad spectrum of hydrocarbons; however, PEMS lacks the capability to speciate and identify individual volatile organic compounds (VOCs), such as aldehydes. This limitation is particularly significant given that aldehydes are classified as "probably carcinogenic" by international health agencies and are associated with organ damage in humans. Despite these health risks, aldehydes remain largely unregulated worldwide, with Brazil being one of the few countries to impose limited restrictions [7, 8]. Consequently, a detailed characterization of emissions, particularly in relation to different driving conditions, is crucial for informing future regulatory frameworks that better reflect real-world emissions profiles.

Recent advances in RDE measurement techniques have enabled a more comprehensive analysis of hydrocarbon speciation, supplementing the capabilities of conventional PEMS [9]. These developments have facilitated the identification of hazardous pollutants such as formaldehyde, acetaldehyde, acetone, acetic acid, benzaldehyde, toluene, and nitrous oxide ( $N_2O$ ). With the exception of  $N_2O$ , these pollutants are typically classified as non-methane volatile organic compounds (NMVOCs). Research indicates that road transport is a significant contributor to atmospheric NMVOC emissions, accounting for approximately 16% of total NMVOC emissions [10]. More specifically, in urban environments, Liu et al. [11] reported that road transport contributed 33.8% of NMVOCs in Beijing, China, with gasoline-powered vehicles responsible for two-thirds of these emissions and diesel vehicles accounting for the remaining third. Additionally, oxygenated volatile organic compounds (OVOCs), including formaldehyde and acetaldehyde, can constitute approximately 40% of NMVOCs [12]

In some senses, the link between vehicle mass and  $CO_2$  emissions for internal combustion engine vehicles is obvious. The higher the vehicle mass, the more energy it will take to propel it – and that energy will come from the fuel which ultimately ends up as  $CO_2$ . This is born out in many theoretical studies of both light- and heavy-duty vehicles [13-15]. However, many other factors may influence  $CO_2$  emissions from internal combustion engine vehicles such as engine power, vehicle size (or frontal area), engine size, engine torque, fuel type (gasoline or diesel and whether there are any bio- components in there), and powertrain type (e.g. hybridisation). However, no link has been comprehensively established between real (i.e. RDE)  $CO_2$  emissions and vehicle mass.

With regard to pollutant emissions, the link with mass is less clear. Certainly, in many circumstances, engine-out emissions of pollutants will be linked to vehicle mass [16], but with the advent of many different aftertreatment technologies, these links are less clear for tailpipe emissions [17, 18]. In reality, tailpipe emissions of pollutant emissions are more linked to the choice of aftertreatment and the space available to package this as well as its cost. This is determined by the certification class of the vehicle (i.e. the vehicle age) [19, 20] and the vehicle manufacturer [21]. However, since the fallout from the dieselgate scandal, and the introduction of the Euro 6d standards, all but a very small number of vehicles are found to be compliant with the standards, demonstrating very low RDE tailpipe emissions, regardless of vehicle size or mass [22].

This study, then, will investigate the link between vehicle mass and both  $CO_2$  and other regulated and unregulated pollutant emissions over independent RDE test cycles for over 1000 vehicles.

## **Methodology**

In this work, results from independent RDE tests are considered. The dataset, which has been gathered since 2011 by Emissions Analytics using regulatory-grade measurement equipment [23], comprises RDE emissions from 1,190 European vehicles. These vehicles are model year 1999-2023, from 41 different brands, and are a mixture of gasoline, diesel as well as different types of hybrids (see Senecal and Leach [1], for the definitions of hybrids adopted in this work). Throughout this work, where vehicle mass is referred to, we are using the mass in running order, commonly known as kerb weight.

Each of the vehicles was tested over Emissions Analytics' standard EQUA™ Index test cycle. This cycle lasts for around three hours in a set mix of cold start, urban, rural and

motorway driving, the latter three phases conducted with a warm engine. It contains boundary conditions of speed, acceleration, idling, and gradients, providing good repeatability. To achieve representative driving, dynamic criteria are applied to ensure urban driving is sufficiently 'stop-start' and includes some congestion, and that motorway driving is fast enough. Extreme weather conditions are avoided, and driving styles kept as consistent as possible, while using human drivers. This test route is around twice as long and has a wider range of dynamic driving modes compared to the certification RDE test [24]. The distances for the cold-start, urban, rural, and motorway conditions were 4.0 miles, 26.6 miles, 11.3 miles, and 38.7 miles, respectively, totalling approximately 80.8 miles on average. The higher speeds on the test were achieved during the motorway condition where the speed limit is 70 mph (112 km/h). The mean speeds of the cold-start, urban, rural, and motorway conditions are approximately 28 mph, 19 mph, 29 mph, and 65 mph on average, respectively, although this can vary with traffic conditions.

On-road tailpipe exhaust emissions were quantified utilizing the SEMTECH-LDV Portable Emissions Measurement System (PEMS) developed by Sensors Inc. [25]. The SEMTECH-LDV PEMS is designed to meet the measurement accuracy and linearity requirements established by both the European Union (EU) and the United States of America (USA) for emissions testing, demonstrating performance comparable to laboratory-based testing systems [26, 27]. The SEMTECH-LDV was configured with a comprehensive suite of components, including a tailpipe attachment, heated exhaust lines, a range of gas analysers, a Global Positioning System (GPS) receiver, an ambient weather station, and an interface with the vehicle's on-board diagnostic (OBD) system [27].

Gas concentrations were measured using specific sensor technologies: a non-dispersive infrared (NDIR) sensor for CO and CO<sub>2</sub>, and a non-dispersive ultraviolet (NDUV) sensor for nitrogen monoxide (NO) and nitrogen dioxide (NO<sub>2</sub>). The concentrations of NO and NO<sub>2</sub> were subsequently summed to calculate total nitrogen oxides (NO<sub>x</sub>). All gaseous emissions data were recorded at a frequency of 1 Hz. Additionally, the GPS receiver provided real-time data on vehicle speed, geographic coordinates (longitude and latitude), and altitude [28].

The PEMS operation did not interfere with engine performance, as it was powered independently by batteries. Although the added weight of the PEMS was consistent across all tests, it may have influenced the vehicle's power-to-mass ratio. Prior research indicates that this added mass could result in an increase of up to 3% in CO<sub>2</sub> emissions [26]. Further technical details regarding the installation of the PEMS and the operational parameters of the SEMTECH-LDV system are available in the literature [29].

A small (31) subset of vehicles also had additional sampling of non-regulated hydrocarbon emissions. The concentrations of VOCs, semi-VOCs, hydrocarbons ranging from two to at least forty-four carbon atoms (C<sub>2</sub> to C<sub>44</sub>), formaldehyde (CH<sub>2</sub>O), nitrous oxide (N<sub>2</sub>O), and various other species were quantified using a novel, patent-pending system [24, 30]. This proprietary VOC measurement system collected real-world exhaust emissions onto sampling tubes, which were subsequently analysed in a laboratory using gas chromatography. Specifically, a two-dimensional gas chromatography (GC×GC) system coupled with a time-of-flight mass spectrometer (TOF-MS), developed by SepSolve Analytical (UK) and Markes International (UK), was employed. The TOF-MS facilitated both identification and quantification of the compounds, with additional detection supported by an electron capture detector (ECD) for nitrous oxide (N<sub>2</sub>O). Formaldehyde (CH<sub>2</sub>O) was

quantified using the 1220 Infinity II high-performance liquid chromatography (HPLC) system from Agilent Technologies.

The VOC measurement system allowed simultaneous sampling onto multiple tubes, each configured for specific compounds. For example, formaldehyde was collected using tubes containing a 2,4-dinitrophenylhydrazine (2,4-DNPH) cartridge, which converted  $\text{CH}_2\text{O}$  into a chemically stable derivative for efficient capture. In contrast,  $\text{N}_2\text{O}$  was collected using molecular sieve tubes. This approach enabled the detection and quantification of a broad spectrum of compounds with high sensitivity, including those present at trace concentrations. By integrating the VOC measurement system with a PEMS, which provided exhaust flow rates and GPS data, the measured concentrations of VOCs were converted into mass values and subsequently used to calculate distance-specific emission rates, expressed in milligrams per kilometre.

However, this sampling approach inherently resulted in cumulative data collection, preventing the acquisition of second-by-second emissions data and potentially introducing bias into the calculated average concentrations. To address this limitation, a proprietary onboard constant volume sampling and proportional flow dilution system was employed. This system, combined with a geofencing mechanism that automatically switched between sampling tubes at pre-defined geographical locations during the test cycle, allowed for a more detailed analysis of emissions associated with specific driving modes [24]. This has the capability of dividing the emissions (still cumulatively) into four categories, corresponding to cold-start, urban, rural, and motorway driving.

## **Results and Discussion**

### **Emissions by vehicle mass**

Figure 1 is a box and whisker plot showing the  $\text{CO}_2$  emissions for 1,190 vehicles tested, broken into vehicle mass classifications. The vertical axis represents real-world emissions measured over the complete Real Driving Emissions (RDE) test cycle. The five distinct bars correspond to different vehicle mass classifications, where ' $500 \leq m < 1000$ ' denotes vehicles with a mass of at least 500 kg but less than 1000 kg. Each mass category, with the exception of the heaviest classification, spans a 500 kg range.

The box plot illustrates the distribution of emissions within each mass category. The interquartile range (IQR), represented by the shaded box, encompasses the middle 50% of the data, excluding the lowest and highest 25% of values. Within this range, the horizontal line indicates the median value, while the 'x' symbol represents the arithmetic mean. The whiskers extend to capture the entire data range, excluding the most extreme 5% at both the upper and lower ends. Outliers, defined as the most extreme 5% of values beyond the whiskers, are represented by individual dots, highlighting cases that may exert disproportionate influence on the overall distribution.

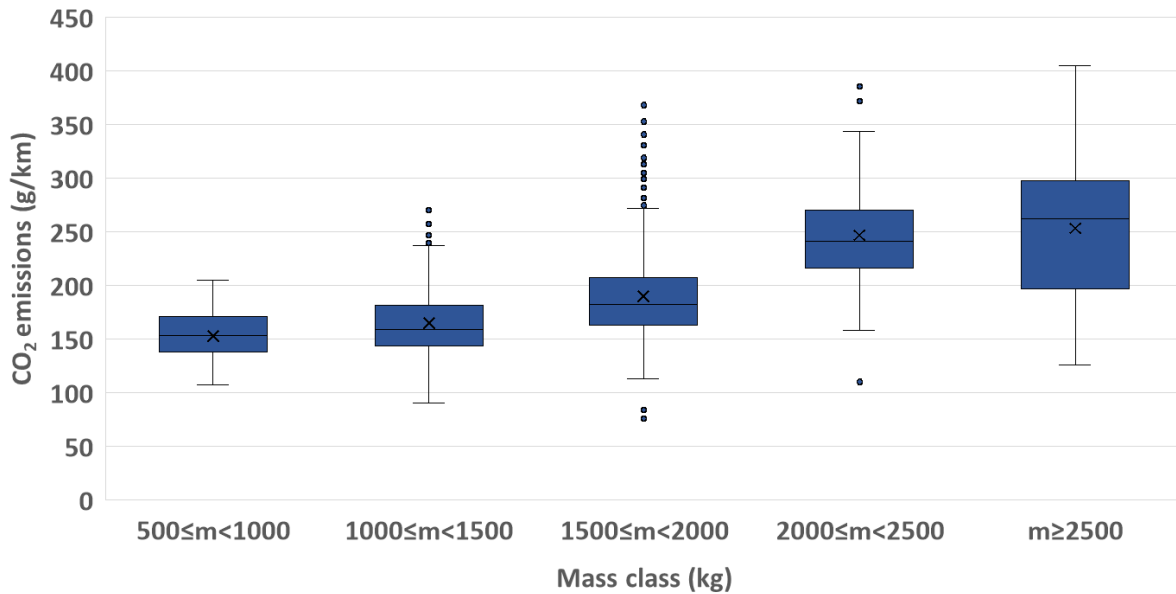


Figure 1: Carbon dioxide emissions for different internal combustion engine vehicle mass classes for 1,190 vehicles

Figure 1 illustrates the relationship between vehicle mass and real-world CO<sub>2</sub> emissions, demonstrating a clear upward trend in emissions as vehicle weight increases. Although considerable variability exists within each mass category, the overall pattern remains evident. The mean CO<sub>2</sub> emissions for vehicles in the 1.0–1.5 tonne category is 165 g/km, whereas vehicles in the 2.0–2.5 tonne category exhibit an average of 247 g/km. This represents a 50% increase in emissions associated with an approximately 80% increase in vehicle mass.

Further analysis of the distribution reveals that only 1% of the recorded emissions values within the lighter category exceed 247 g/km, while just 4% of observations in the heavier category fall below 165 g/km. One potential explanation for lower emissions within the heavier vehicle class is the prevalence of diesel-powered vehicles. Diesel engines, on average, produce approximately 15% lower CO<sub>2</sub> emissions than their gasoline counterparts. However, diesel vehicles tend to be of greater mass due to the structural requirements of compression ignition engines, as well as their frequent use in high-torque applications such as pickup trucks and sport utility vehicles (SUVs). Conversely, vehicles exhibiting higher emissions within the lighter mass category are often gasoline-powered, as gasoline engines typically generate higher CO<sub>2</sub> emissions per unit of fuel consumed. Overall, despite the observed variability, the data strongly supports the assertion that vehicle mass is a key determinant of real-world CO<sub>2</sub> emissions.

Figure 2 presents the relationship between vehicle mass and real-world CO emissions, revealing no clear correlation between the two variables. If any trend exists, it suggests a slight tendency for heavier vehicles to produce lower CO emissions. In addition to the absence of a strong relationship, the data exhibits considerable variability within each mass category, particularly in the mid-range weight classes.

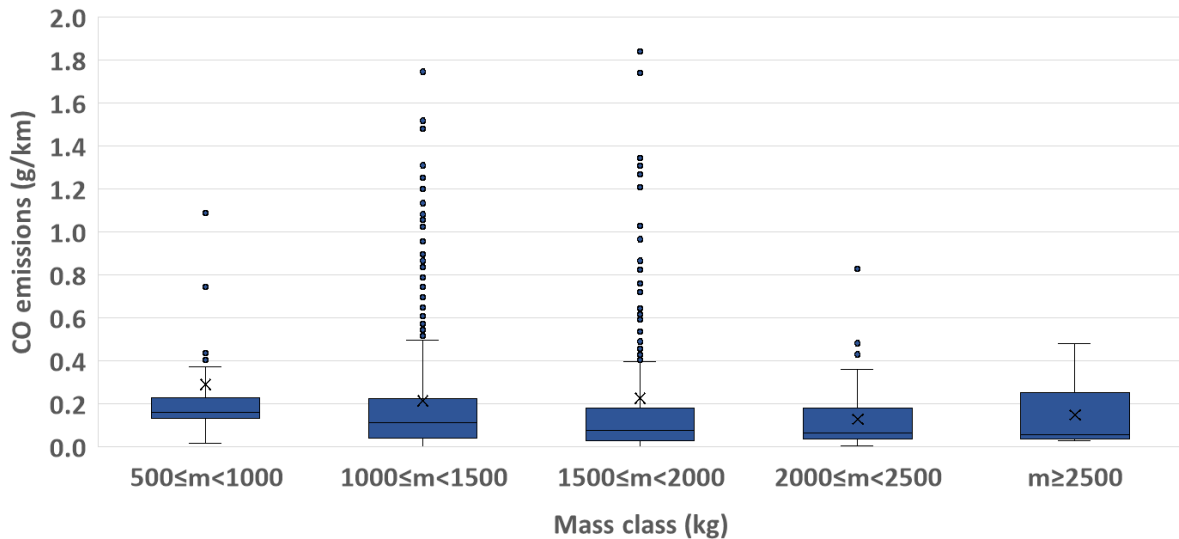


Figure 2: CO emissions for different internal combustion engine vehicle mass classes for 1,190 vehicles

Two primary factors contribute to this lack of correlation. First, diesel engines inherently produce lower CO emissions due to the nature of their combustion process, as discussed earlier. As noted before, given their higher torque output, diesel engines are well-suited for heavier applications and are consequently overrepresented in the higher mass categories. Second, CO emissions are largely mitigated through the use of aftertreatment systems, specifically three-way catalytic converters (gasoline) or diesel oxidation catalysts (diesel), which are designed to oxidize CO into CO<sub>2</sub> [1]. The effectiveness of these converters depends on their size, material quality, and calibration. More expensive vehicles, which tend to be heavier, are often equipped with higher-quality catalytic converters that optimize CO reduction.

As a result, the data suggests that vehicle mass is not a reliable predictor of real-world CO emissions, as factors such as engine type and exhaust aftertreatment technology play a more significant role in determining emission levels.

Figure 3 illustrates the relationship between vehicle mass and real-world NO<sub>x</sub> emissions, revealing a strong negative correlation. Specifically, larger vehicles exhibit lower NO<sub>x</sub> emissions, a finding that may initially appear counterintuitive. This is particularly notable given that diesel engines, which are more prevalent among heavier vehicles, have historically been associated with higher NO<sub>x</sub> emissions.

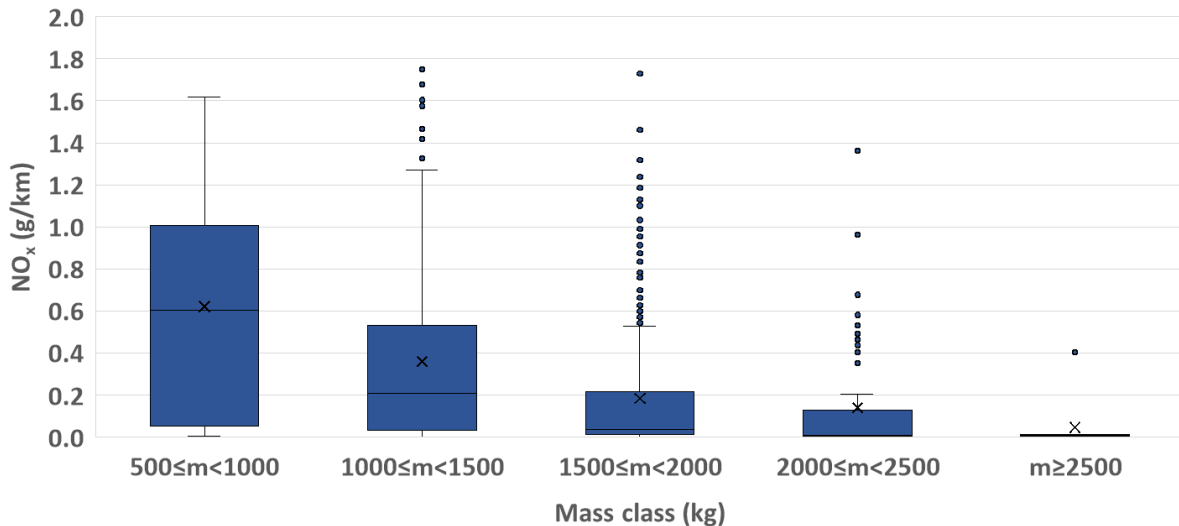


Figure 3: NO<sub>x</sub> emissions for different internal combustion engine vehicle mass classes for 1,190 vehicles

A key factor contributing to this trend is the widespread adoption of selective catalytic reduction (SCR) systems following the introduction of the revised emissions testing regime in 2018 [31]. Since this regulatory shift, all major manufacturers have implemented SCR technology, which has proven to be highly effective in reducing NO<sub>x</sub> emissions. As a result, the heavier vehicles analysed in this study – more representative of the current vehicle fleet – are predominantly composed of diesel vehicles equipped with SCR systems, as well as gasoline vehicles that inherently produce low NO<sub>x</sub> emissions. In contrast, the lighter vehicle categories include a higher proportion of older, small, and lower-cost diesel cars with inferior aftertreatment systems, thereby elevating the average NO<sub>x</sub> emissions within this group.

Consequently, this analysis demonstrates that, even more so than in the case of CO emissions, vehicle mass does not serve as a reliable predictor of NO<sub>x</sub> emissions. Instead, the presence and effectiveness of emissions control technologies play a far more significant role in determining real-world NO<sub>x</sub> output.

The final regulated pollutant we will consider is particle number (PN). The dataset for PN is smaller at only 184 tests, and the results are shown in Figure 4. Although data on the lightest vehicle categories is unavailable, and the overall sample size for PN emissions is smaller compared to other pollutants examined in this study, a discernible trend remains evident. Specifically, there is a weak negative correlation between vehicle mass and PN emissions, with greater variability observed in the lighter vehicle category (1500-2000 kg). One possibility for this trend is the likelihood of higher-quality filtration systems being installed in more expensive vehicles, which tend to be heavier on average.

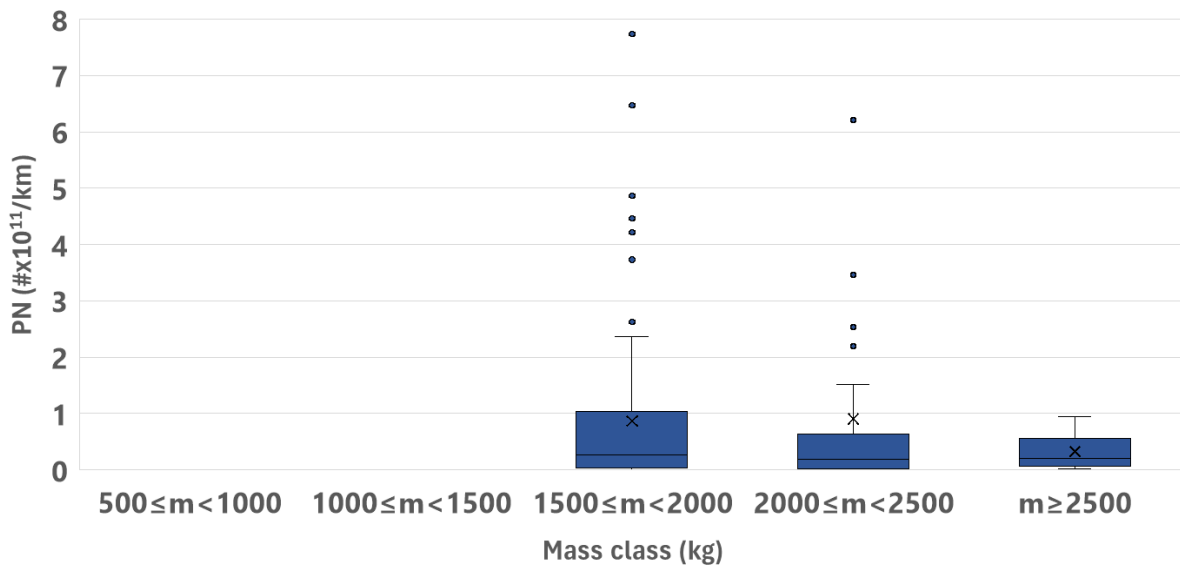


Figure 4: PN emissions for different internal combustion engine vehicle mass classes for 184 vehicles

Additionally, regulatory requirements have played a significant role in shaping PN emissions trends. Since the implementation of the Euro 5 standard in 2009, diesel vehicles have been effectively mandated to incorporate diesel particulate filters (DPFs) [32]. In contrast, no such requirement exists for gasoline vehicles, and as a result, only approximately 50% of gasoline-powered vehicles in Europe are currently equipped with gasoline particulate filters (GPFs). Consequently, the lower PN emissions observed in heavier vehicles can be attributed to a combination of improved emissions control technology in higher-cost vehicles and a greater prevalence of diesel engines within this category.

All the emissions discussed thus far are subject to regulation in Europe, the United States, and most other major automotive markets. However, a notable exception is the United States, where regulations pertain exclusively to particle mass rather than particle number [33]. Beyond these regulated emissions, it is also of interest to investigate a range of unregulated gases that may have potential health implications. Figure 5 presents the mean values and variabilities for nitrous oxide (N<sub>2</sub>O), formaldehyde (CH<sub>2</sub>O), total alkanes, total aromatics, total polycyclic aromatic hydrocarbons (PAHs), and total alcohol emissions, as measured across a sample of 30 vehicles. There are weak, if any, correlations either way with these unregulated emissions. Overall, there is no obvious link between higher vehicle mass and higher unregulated emissions.

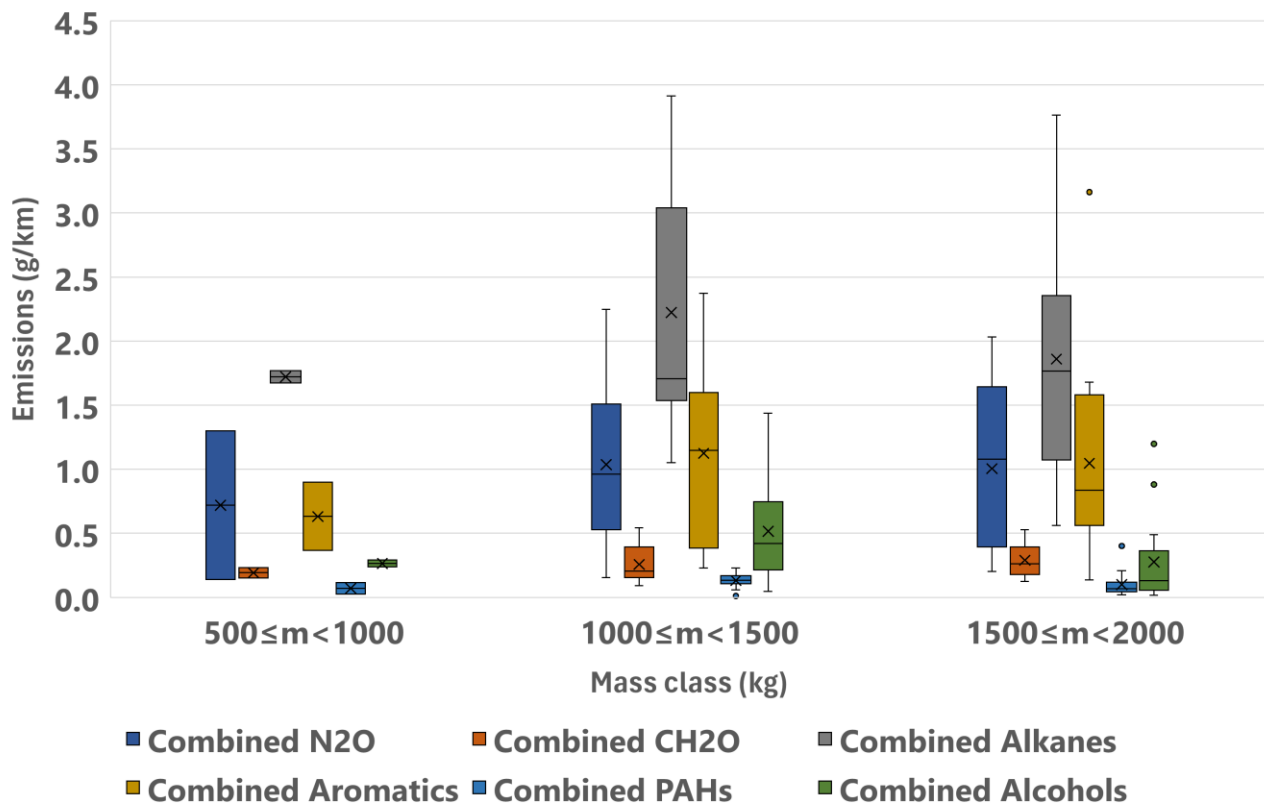


Figure 5: Non-regulated emissions for different internal combustion engine vehicle mass classes for 30 vehicles

## Emissions by vehicle Euro certification

Grouping the real-world test into these Euro categories, we can see the relationships between those stages and emissions in Figures 6-9. It can be seen that the Euro stage is no predictor of CO<sub>2</sub>, CO, or PN emissions, but it is a reasonably good predictor of NO<sub>x</sub>. Euro standards do not attempt to regulate CO<sub>2</sub> emissions (these are regulated on a fleet-average basis by different legislation) so it is not surprising that they predict CO<sub>2</sub> emissions poorly. However, it is of interest that CO and PN are poorly predicted. In the case of CO, it is the case that the overall levels are low and hence the variations seen here are broadly noise, and in the case of the PN emissions the number of vehicles tested is low, and the majority are Euro 6 (pre or post RDE) so the sample is not representative enough to make an assessment.

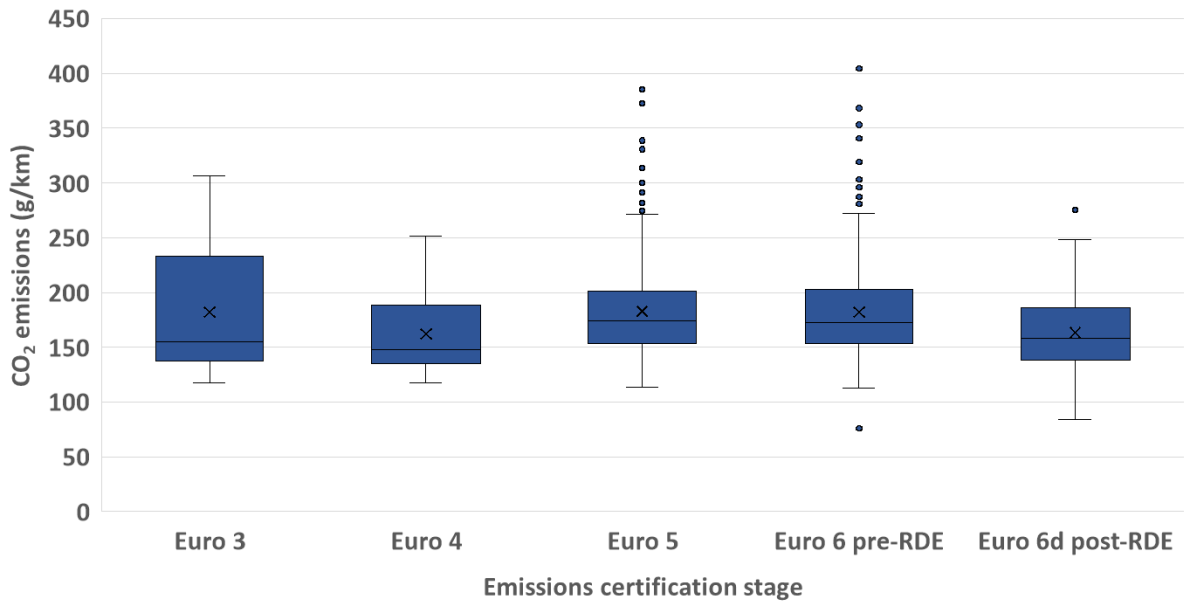


Figure 6: Carbon dioxide emissions for different internal combustion engine vehicle Euro standard classes for 1,189 vehicles

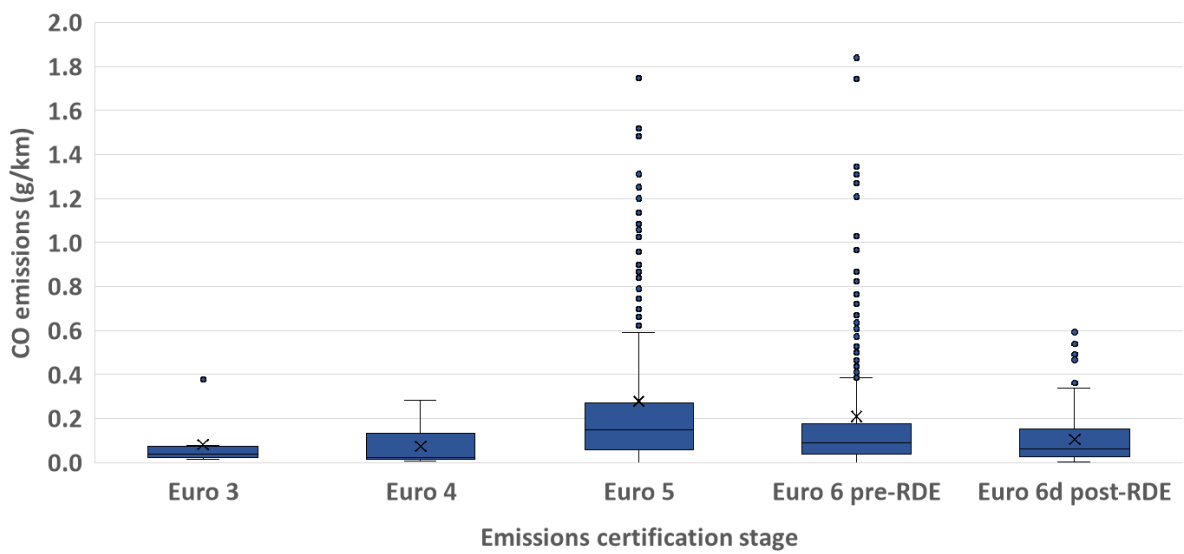


Figure 7: CO emissions for different internal combustion engine vehicle Euro standard classes for 1,183 vehicles

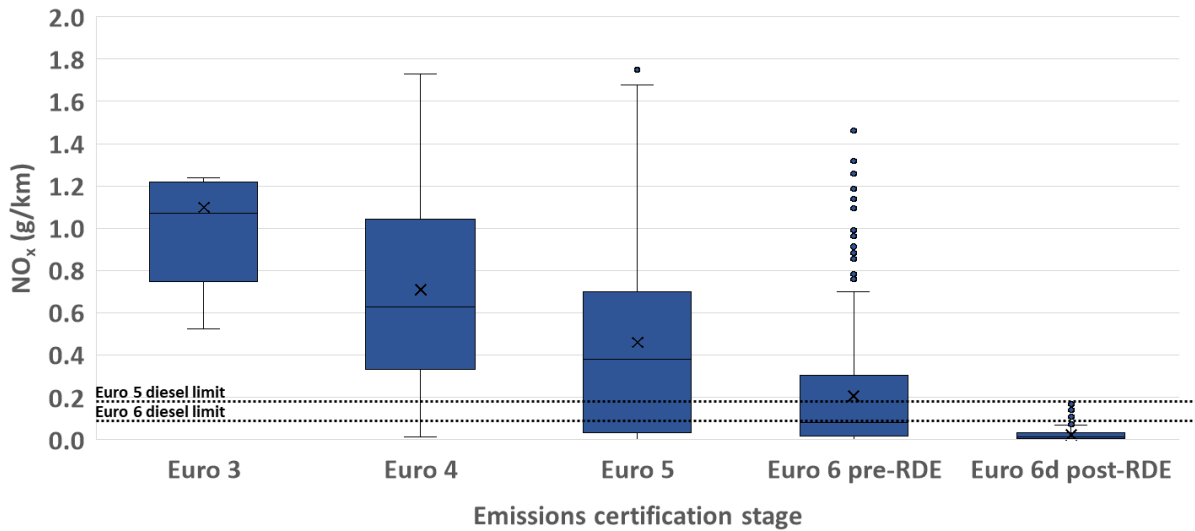


Figure 8: NO<sub>x</sub> emissions for different internal combustion engine vehicle Euro standard classes for 936 vehicles

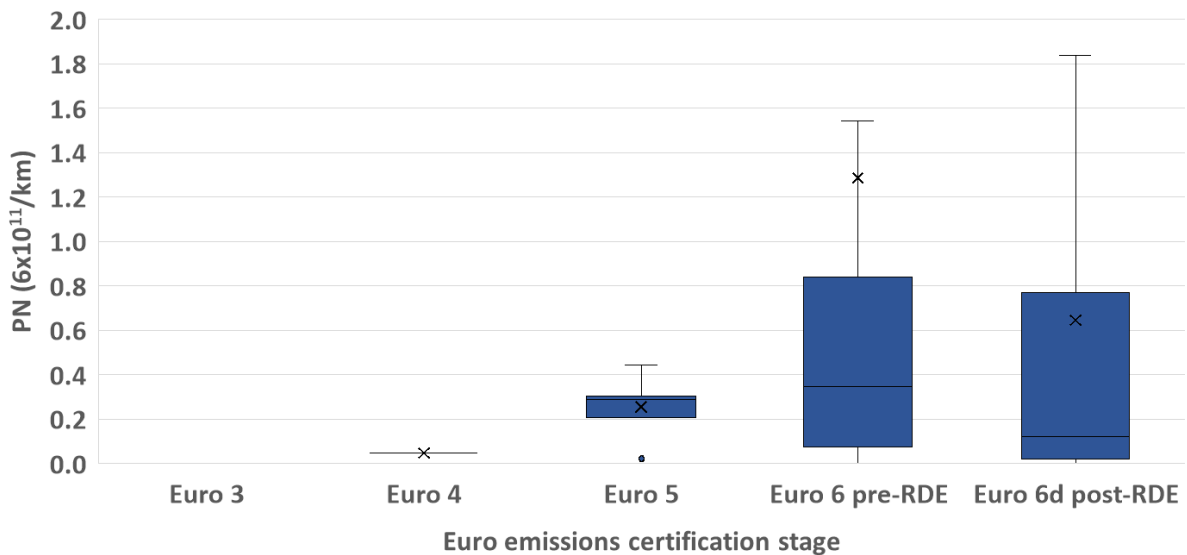


Figure 9: PN emissions for different internal combustion engine vehicle Euro standard classes for 183 vehicles

It is important to note that only vehicles meeting the Euro 6d standard consistently comply with both the Euro 5 and Euro 6 NO<sub>x</sub> emissions limits under RDE testing. A particularly striking observation is that Euro stage classification does not serve as a strong predictor of NO<sub>x</sub> emissions, despite the fact that these regulatory stages are explicitly designed to control such pollutants.

Analysis of the data reveals considerable variability in NO<sub>x</sub> emissions within each Euro stage category, attributable to two primary factors. The first is the diverse powertrain mix within each category, which includes gasoline, diesel, and hybrid vehicles. As previously discussed, gasoline engines typically produce significantly lower NO<sub>x</sub> emissions compared to their diesel counterparts. However, this factor alone does not account for the full range of variability observed.

A more substantial source of variation stems from the discrepancy between certification results and real-world emissions performance under RDE conditions. Regulatory limits

specify a maximum permissible NO<sub>x</sub> emission of 0.180 g/km for Euro 5 vehicles and 0.080 g/km for Euro 6 vehicles. However, empirical studies, including this analysis, have shown that a significant proportion—approximately 50%—of diesel vehicles from the pre-RDE Euro 6 era exceeded these regulatory limits in real-world driving conditions, often by factors ranging from three to ten [34]. Similar findings have been reported in existing literature.

Consequently, while Euro stage classifications provide a general framework for expected NO<sub>x</sub> emissions, they do not reliably predict emissions performance across all pollutants. The effectiveness of individual aftertreatment systems and the specific engine technologies employed within each vehicle category play a far more influential role in determining real-world emissions outcomes.

### Emissions by vehicle powertrain

Figure 10 presents the CO<sub>2</sub> emissions for the vehicles in the dataset, categorized by powertrain type. A discernible trend is evident, with gasoline-powered vehicles exhibiting higher average CO<sub>2</sub> emissions than their diesel counterparts. This difference in emissions was a key factor behind the European policy shift in the 1990s that encouraged the adoption of diesel vehicles [1]. The data also indicate that hybridization of gasoline powertrains results in a substantial reduction in CO<sub>2</sub> emissions, with an average decrease of 29% compared to conventional gasoline vehicles. However, despite these general trends, significant variability is observed within each powertrain category. This suggests that while powertrain type provides a broad indication of CO<sub>2</sub> emissions, it is not a precise predictor of a vehicle's real-world emissions performance.

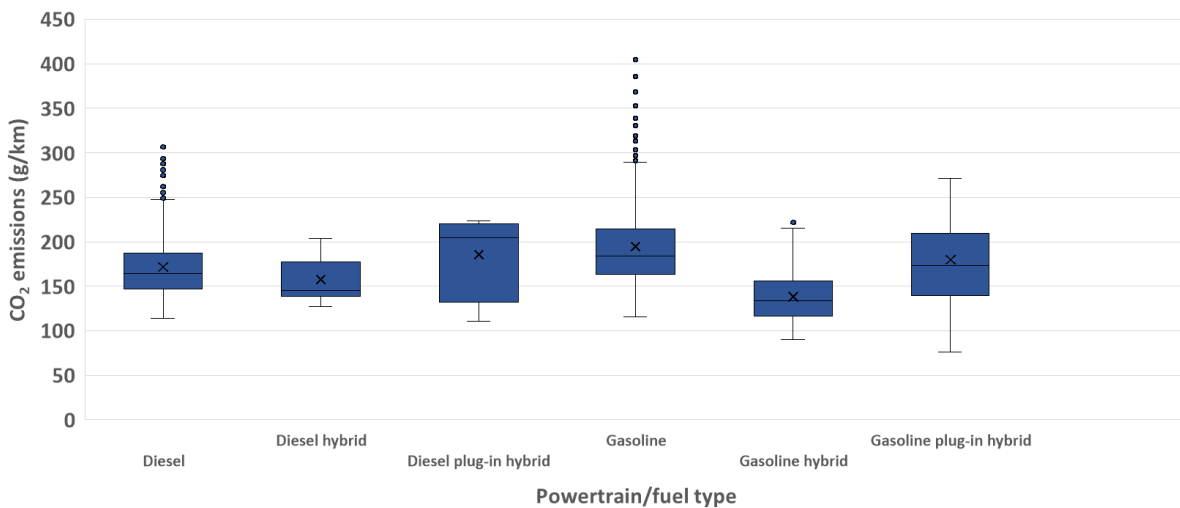


Figure 10: Carbon dioxide emissions for different powertrain types for 1,189 vehicles

A similar pattern emerges when examining CO emissions, as illustrated in Figure 11. The primary takeaway from this segmentation is that gasoline vehicles generally exhibit higher CO emissions than their diesel counterparts—a well-documented phenomenon that aligns with established combustion characteristics. Conversely, the opposite trend is observed for NO<sub>x</sub>, with diesel vehicles emitting significantly higher levels than gasoline vehicles, as shown in Figure 12. PN emissions (Figure 13) exhibit a less distinct pattern; however, the results broadly support existing knowledge regarding the effectiveness of DPFs. Diesel vehicles equipped with DPFs demonstrate significantly lower particulate emissions than gasoline

vehicles on average. This is largely due to the fact that many of the gasoline vehicles in this dataset are not equipped with gasoline particulate filters (GPFs), further reinforcing the established efficacy of DPF technology in mitigating particulate emissions [35].

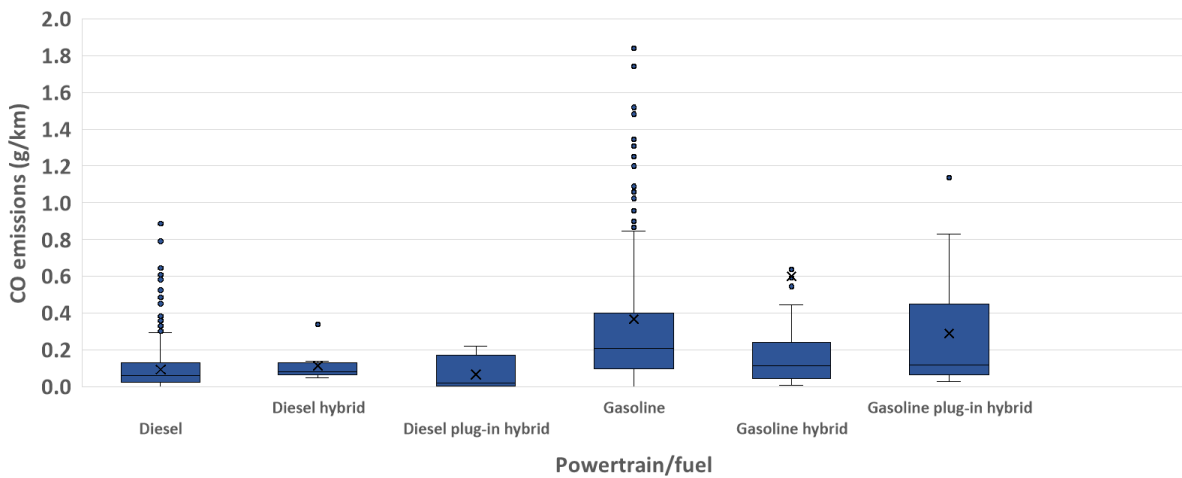


Figure 11: CO emissions for different powertrain types for 1,183 vehicles

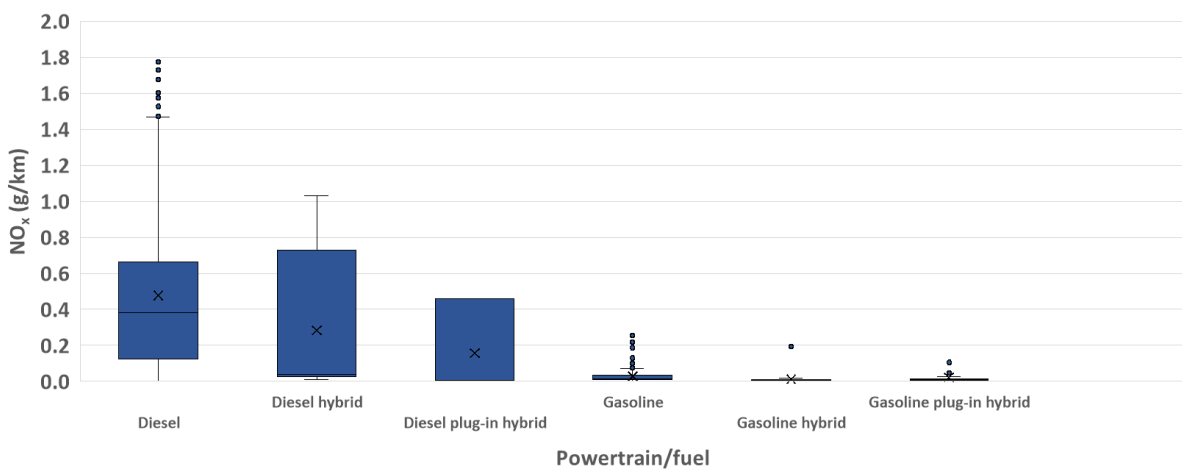


Figure 12: NO<sub>x</sub> emissions for different powertrain types for 936 vehicles

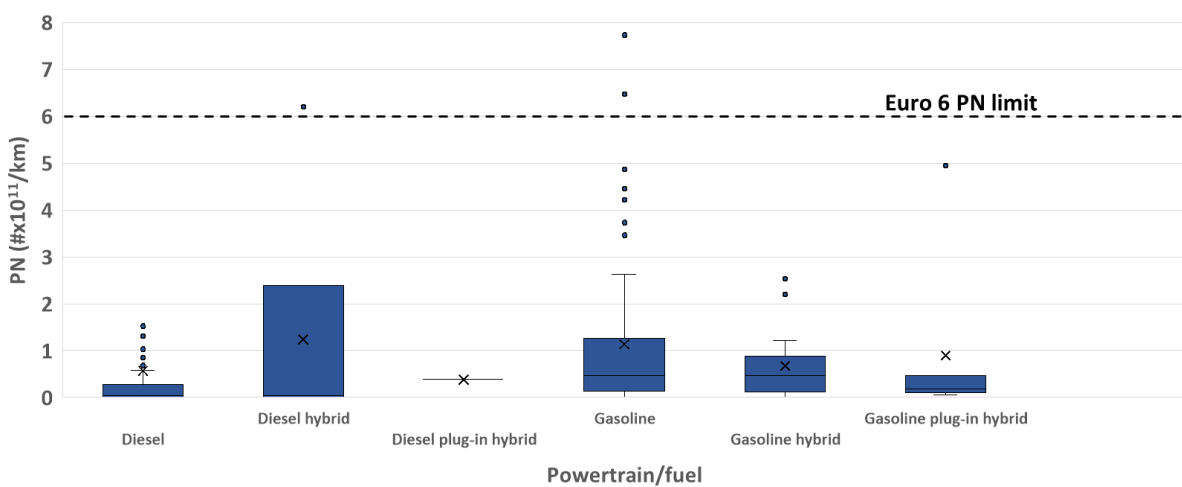


Figure 13: PN emissions for different powertrain types for 183 vehicles

## Emissions by vehicle engine size

Figure 14 shows that there is a strong correlation between engine displacement and CO<sub>2</sub> emissions. Despite considerable variability within the mid-to-large engine size categories, the overall trend is both evident and expected, as larger engines generally produce more power and consequently consume greater amounts of fuel, leading to higher CO<sub>2</sub> emissions.

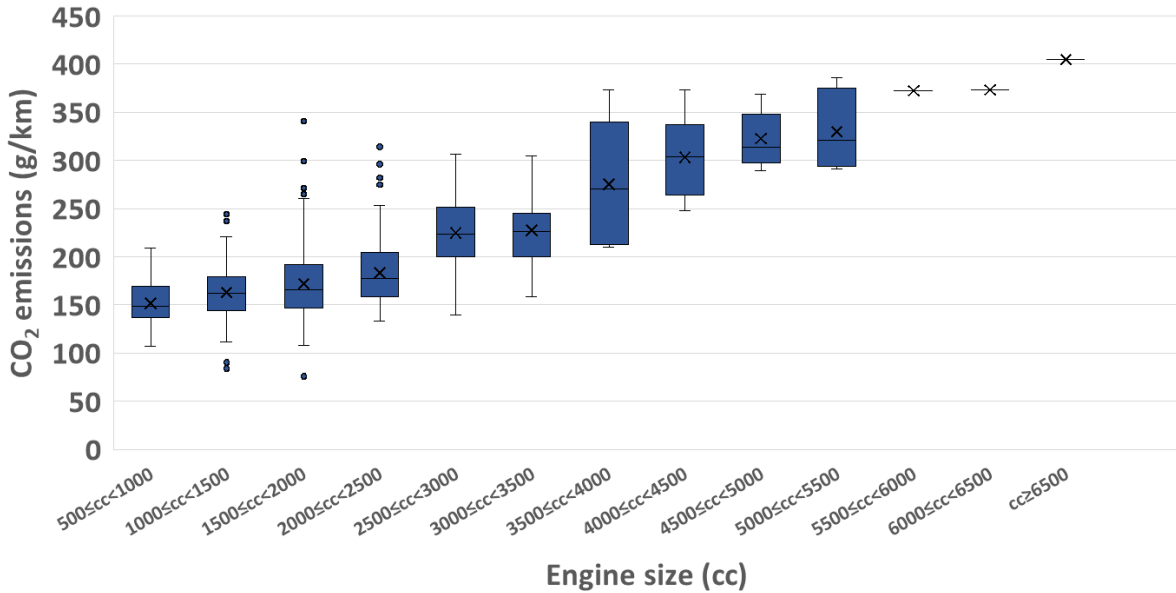


Figure 14: Carbon dioxide emissions for different engine sizes for 1,189 vehicles

In contrast, Figures 15–17 demonstrate the absence of a clear relationship between engine displacement and pollutant emissions. This lack of correlation can be attributed to the diversity of powertrain technologies within each engine size category, as well as the varying effectiveness of aftertreatment systems, as discussed in previous sections. These factors highlight the complexity of real-world emissions performance, where regulatory controls, vehicle calibration, and aftertreatment technology play a more significant role than engine displacement alone.

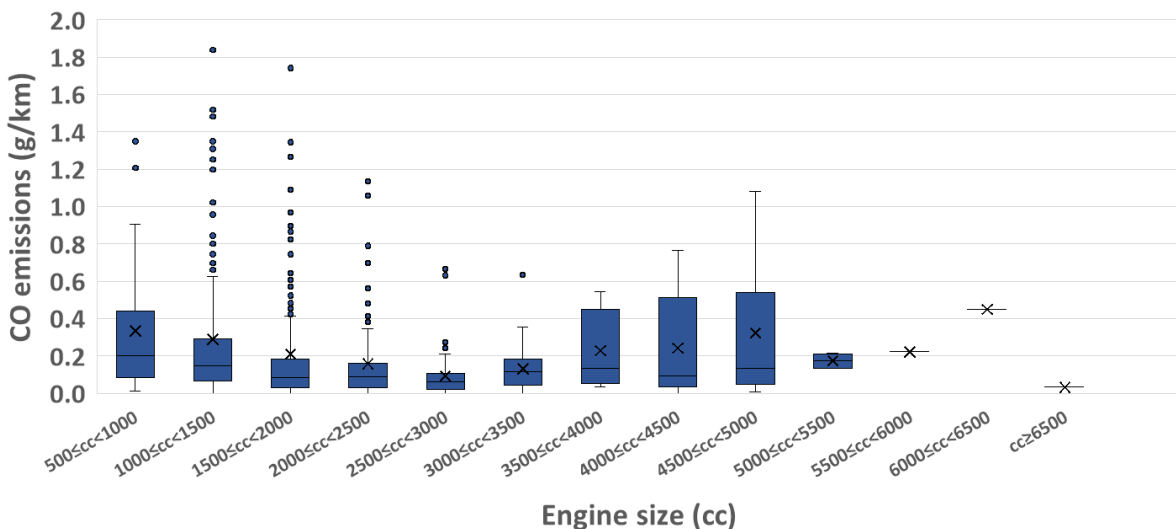


Figure 15: CO emissions for different engine sizes for 1,183 vehicles

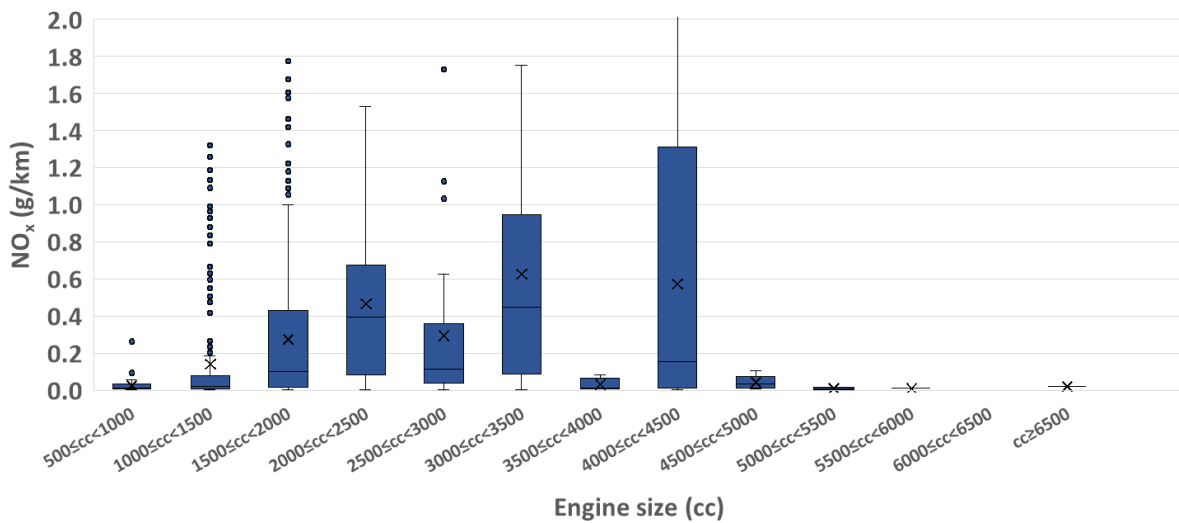


Figure 16: NO<sub>x</sub> emissions for different engine sizes for 936 vehicles

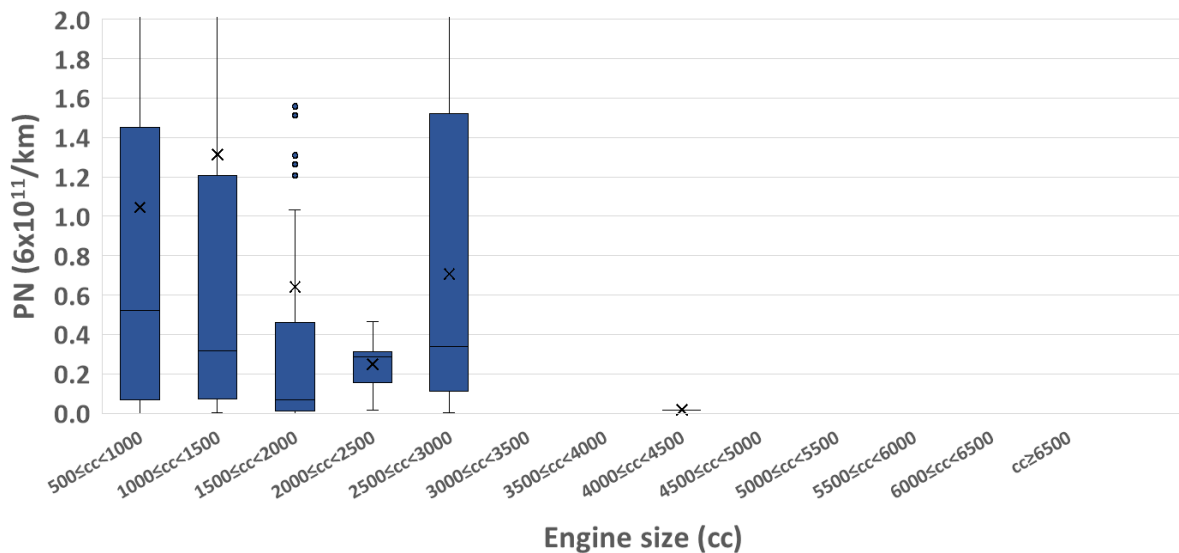


Figure 17: PN emissions for different engine sizes for 183 vehicles

## Conclusions

In this work, independent RDE tests have been carried out on 1,189 vehicles and the results assessed to examine the influence of vehicle mass, euro certification class, engine size, and powertrain type on CO<sub>2</sub> and pollutant emissions (both regulated and unregulated).

The results show that vehicle mass is a good predictor of CO<sub>2</sub> emissions, but a bad one for almost all pollutant emissions. The deployment of aftertreatment on the vehicle has decoupled the rate of fuel burn from the level of pollutant emissions. Engine size is in fact a somewhat better predictor of carbon dioxide emissions than vehicle mass – with a correlation coefficient (R<sup>2</sup>) of 0.41 compared to 0.24 for mass but again, the decoupling of engine-out and tailpipe emissions means that engine size is a poor predictor of pollutant emissions. Powertrain type can predict some trends in CO<sub>2</sub> emissions, but not of pollutant emissions, and there is a wide range of variation within powertrain classes.

Conversely, Euro certification stage is a better predictor of pollutant emissions but not of CO<sub>2</sub> emissions – as might be expected from the aim of this legislation. Indeed, the most modern vehicles (Euro 6d) are showing very low levels of pollutant emissions.

This work, then shows that vehicle mass can be used to predict CO<sub>2</sub> emissions from vehicles and that modern vehicles are not of concern for pollutant emissions. It is observed that the nature of the car fleet is fundamentally changing with electrification; if government policies in developed countries are successful, it is likely that cars on the road will be largely electric by 2050 [36]. In that world, tailpipe emissions become entirely irrelevant. We will have a world where emissions are dominated by those from manufacturing and non-exhaust sources. If we now introduce battery electric vehicles into the analysis, with their zero tailpipe emissions, even the positive correlation between mass and carbon dioxide breaks down as by definition (even if not by reality) they emit zero carbon dioxide. Due to the weight of their batteries, 61% of battery electric vehicles currently on the market fall into mass categories from two tonnes upwards [37]. While internal combustion engine vehicles in this weight range have the highest carbon dioxide emissions, their electric counterparts have zero emissions at the (non-existent) tailpipe. This leads towards a future where perhaps vehicle mass could be used as a proxy for the environmental impact of vehicles and where, with some adjustments between vehicle powertrain classes, it could be a universal metric, regardless of powertrain type, for all cars. This idea has been developed into a potential new taxation system by the authors in a recent book [38].

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## **Definitions, Acronyms, and abbreviations**

2,4-DNPH	2,4-dinitrophenylhydrazine
CH <sub>2</sub> O	Formaldehyde
CO	Carbon Monoxide
CO <sub>2</sub>	Carbon Dioxide
DPF	Diesel Particulate Filter
ECD	Electron Capture Detector
EU	European Union
GCxGC	Two-dimensional Gas Chromatography
GPF	Gasoline Particulate Filter
GPS	Global Positioning System
IQR	InterQuartile Range
N <sub>2</sub> O	Nitrous Oxide
NDIR	Non-Dispersive InfraRed
NDUV	Non-Dispersive UltraViolet
NEDC	New European Driving Cycle
NMVOC	Non-Methane Volatile Organic Compounds
NO	Nitrogen Monoxide
NO <sub>2</sub>	Nitrogen Dioxide
NO <sub>x</sub>	Nitrogen Oxides
OVOC	Oxygenated Volatile Organic Compounds
PAH	Polycyclic Aromatic Hydrocarbons
PEMS	Portable Emissions Measuring System
PN	Particle Number
RDE	Real Driving Emissions
SCR	Selective Catalytic Reduction
SUV	Sport Utility Vehicle
THC	Total Hydrocarbons
TOF-MS	Time-of-Flight Mass Spectrometer
USA	United States of America
VOC	Volatile Organic Compounds
WLTP	Worldwide Harmonized Light Vehicles Test Procedure

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