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Analysis of the 2019 Flemish remote sensing campaign

Final report

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ANALYSIS OF THE 2019 FLEMISH REMOTE SENSING CAMPAIGN

Deze studie geeft een overzicht van de voornaamste bevindingen uit de eerste Vlaamse *remote sensing*-meetcampagne, die in 2019 doorging. De resultaten tonen aan dat Euro 6d-Temp dieselwagens op vlak van hun NOx uitstoot gevoelig beter presteren dan hun voorgangers, terwijl benzinewagens op snelwegen soms een hoge NOx uitstoot laten optekenen. Deze inzichten zijn nieuw gezien er nooit eerder aan teledetectie langs snelwegen werd gedaan. Algemeen gezien blijven dieselvoertuigen de voornaamste bron van NOx, waar het gros van de benzinevoertuigen hier weinig toe bijdraagt.

Specifieke aandacht gaat in dit rapport naar het detecteren en analyseren van zogenaamde '*high-emitters*', een klein percentage van de vloot dat een aanzienlijk deel bijdraagt aan luchtconcentraties van schadelijke polluenten. Hieruit blijkt voornamelijk dat voor fijnstof (PM10), zo'n 10% van de '*high-emission events'* door dieselvoertuigen verantwoordelijk is voor 80% van de cumulatieve emissie van de personenwagenvloot (Euro 5-6). Voor benzinewagens zien we dan weer dat zo'n 7% van zulke '*high-emission events'* iets minder dan de helft (41%) van de waargenomen NOx emissies veroorzaakt. Voor vrachtwagens rijdt naar schatting 9,5% en 4,8% van de respectievelijke Euro V en VI voertuigen rond met ofwel beschadigde ofwel met opzettelijk gemanipuleerde nazuiveringssystemen voor uitlaatgassen. Hun impact wordt ingeschat op een extra NOx uitstoot van respectievelijk 24% en 67%. Op snelwegen blijken de recentste Euro VI vrachtwagens zeer lage concentraties aan NOx uit te stoten.

COLOFON

Verantwoordelijke uitgever
Peter Cabus
Departement Omgeving
Vlaams Planbureau voor Omgeving
Koning Albert II-laan 20 bus 8, 1000 Brussel
vpo.omgeving@vlaanderen.be
www.omgevingvlaanderen.be

Auteurs
Hooftman Nils – Vrije Universiteit Brussel, MOBI-onderzoeksgroep
Ligterink Norbert E. – TNO
Bhoraskar Akshay – TNO

Wijze van citeren
Hooftman N., Ligterink N., Bhoraskar, A., (2020) Analysis of the 2019 Flemish remote sensing campaign. Commissioned by the Flemish Government - Flanders Environment Agency - Team Air quality policy

PARTNERS

VUB mobi MOBILITY, LOGISTICS & AUTOMOTIVE TECHNOLOGY RESEARCH CENTRE

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EXECUTIVE SUMMARY

In June 2019, a remote sensing campaign was performed on five locations across Flanders during which nearly 190,000 valid samples were registered. This campaign consisted of new elements, bringing forward new information compared to earlier measurements performed throughout Europe. As such, the results presented in this report are the first with a substantial share of motorway driving conditions, providing more complete coverage of everyday vehicle use. Consequently, the results differ significantly from other test campaigns that were run in urban and suburban conditions only. Even between motorways, i.e. high-speed limit locations, differences are observed.

Since late autumn 2018, new passenger cars must satisfy real-driving emissions (RDE) legislation during on-road tests (Euro 6d-Temp). Given their significant representation in the Flemish dataset, we can for the first time see **lower NO_x emissions than what has been reported for previous generations of diesel passenger cars**. **Pre-Euro 6d-Temp diesel cars, however, remain a topic of concern** when it comes to NOx emissions, confirming findings from other studies. The same is true for the whole set of sampled **diesel light-commercial vehicles (LCV), for which we report very high real-world NOx emission for each Euro class**. The reported improvement for LCVs from Euro 6 onwards, on the one hand, can only be explained by the public attention for NOx emission by diesel vehicles following the 2015 diesel scandal. RDE legislation for LCVs, on the other hand, is lagging that of passenger cars, and no RDE-compliant LCV was reported during the measurements for this study. Concerning heavy goods vehicles (HGV), Euro VI technology proves its high efficiency in NOx reductions, although most HGVs were sampled during motorway drives with optimally functioning selective catalytic reduction (SCR) systems. **A small set of urban HGV samples, however, confirms that urban NOx emissions for this vehicle category remain an issue that requires attention in future test campaigns**.

Petrol vehicles, known to be the cleanest vehicles with combustion engines for years in many respects, do show **some increased nitrogen oxides (NO_x) emission** correlated with motorway conditions. This increase is the result of a relatively limited number of high-emitting vehicles, presumably caused by occasional technological deviations from traditionally stochiometric three-way catalyst (TWC) systems. These results indicate the need for **higher power demands to be better represented during type-approval testing**. Moreover, significantly higher NO_2/NOx shares are reported for petrol cars compared to what has been reported in other remote sensing studies, i.e. a 13% average relative to a commonly assumed 7%. Nonetheless, results confirm that petrol NOx emissions are generally very low, albeit that the averages are heavily influenced by a small share of high-emitters.

The Flemish study also involved the Federal police during a **roadside inspection campaign** to investigate issues with improperly lagging repair and tampering with heavy-duty vehicles. Due to the implementation of motorway sampling, a substantial number of heavy-duty vehicles populate the dataset to an extent that has not been witnessed yet in earlier studies. High emissions by heavy-duty vehicles resulting from improper behaviour of the vehicle owner are considered illegal in Flemish law, thus several fines were given during the campaign. The **scanning of the fleet with remote sensing increased the detection success rate from 9% to 83%**, while 9.5% Euro V and 4.8% Euro VI vehicles were deemed to have been tampered with or to be circulating with a defective SCR. As such, on fleet-level, their NOx emissions have increased by 24% and 67%, respectively, compared with a compliant fleet. This test-trial indicates the **potential for similar campaigns checking HGV diesel particulate filter (DPF) malfunctions**. For passenger cars, there is a lack of straightforward links between high-emitting events and tampering/wear as for many diesel vehicles, NOx emissions are already high without showing wear or tampering impacts. However, as general NOx emissions in recent diesel vehicles seem to be improving due to better emission control systems, the potential to distinguish tampered vehicles from regular ones by roadside measurements increases. **A suitable NOx threshold should be further investigated by combining remote sensing emission readings with immediate police action during a roadside inspection**. For vehicles that are on average expected to comply with a stringent emission limit, a single exceedance of 5 times the emission limit will select mainly those vehicles with defects and tampering. For Euro 5 diesel vehicles, such a criterion is pointless for NOx. By design, most vehicles will have such exceedances in normal operation.

The motorway anti-tampering campaign indicated the potential for effectively scanning large fleets. Recent diesel vehicles with SCR emission control systems (i.e. from Euro 6d-Temp onwards for passenger cars and from Euro VI onwards for heavy goods vehicles) should work optimally during motorway cruising situations, emphasizing the potentially high detection rate for those individual vehicles with (illegally) malfunctioning emission control systems. Next to sampling on motorways, it remains important to diversify in test locations so the largest possible engine operating range can be covered using remote sensing.

A large number of measurements on the full range of vehicles present on the road also provides many detailed insights into the relative contributions of the different categories and vehicle brands. This can be a starting point to more detailed investigations to the nature and the cause of emission-related problems, e.g. as a part of **market surveillance activities**. A distinction has to be made in systematic problems occurring either for a whole group of vehicles (e.g. pre-Euro 6d-Temp diesel cars) or originating from intermittent problems, for which a smaller fraction of high-emitters can be held responsible for a large share of that group’s cumulative emissions. This cause can be tampering, emission control system malfunctions, or limited robustness of the emission control system. Each of these reasons requires different mitigation actions. Nonetheless, it must be clear that high-emission events are first and foremost an indication of **inferior technology**. On the one hand, this can directly lead to high emissions due to insufficient emission control. On the other hand, poor emission control durability is often a cause for tampering, thus indirectly leading to problematic real-world emissions.

Setting different **threshold limits** in remote detection of these different causes of emission issues is important. An exceedance of **three times the emission limit with a confidence level of 95%** could be an initial limit for **in-service conformity**. An exceedance of **five times the limit** would suffice for **tampering** as emission levels are typically higher. The lowest limits are those related to technology effectiveness and durability, and refer only to the manufacturer’s responsibility. For this issue, data of different vehicles, models, or even manufacturers can be combined to provide enough evidence and confidence to pursue further investigations. **Remote sensing**, and other information linked to emissions in normal use and air quality, can help to retain the sense of impact and relevance. It can also play a pivotal role to assess risks and urgency, and thus **ensure an efficient organisation of market surveillance activities**.

There are at least seven methods in which remote sensing can support emission mitigation policies. Each method has its requirements and characteristics.

1. Based on first principles, without underlying data, **tampering and defects** could be uncovered with a **single passage** with **5 times** the exceedance of the emission limit. A location, like a stretch of motorway, should be selected as such that emission control technology, like SCR and DPF, should function properly. The false-positive results, i.e. an

incidental high emission, will be limited in that case. This is linked to direct action, e.g. by the police, to catch the perpetrator in the act.

2. In the case of **multiple passages and a subsequent request to visit** a periodic technical inspection (PTI) test centre, multiple measurements and a lower average exceedance of **a factor 3** will be more appropriate. Both methods 1 and 2, however, were not included in the scope of the original test campaign. Therefore, they should be investigated further.

Once an extensive set of remote sensing data is collected, alternative approaches using **statistical methods** are possible.

3. The **tampering detection limit** can be refined by using the typical spread (σ) in emissions for clean vehicles in the given vehicle category. Taking **twice this spread** is an appropriate detection limit for outliers like tampered and defective vehicles:
$$X_{threshold\ "\sigma=2"} = 2 \times X[84\%] - X[50\%]$$
4. Likewise, the method for **requesting a PTI** can be refined by the use of remote sensing data of the vehicle category. All the data from multiple passages provide **an estimate of the typical spread** in this data, and therewith the reliability of a single or very few measurements for the determination of the average emission behaviour. It will prevent an **unwarranted request for a PTI test** as emissions often vary for the same car and twice, or three times, a high emission can still be a coincidence. In the case of tampering, a vehicle can be restored to the original state before it is offered for PTI testing. Therefore, anti-tampering policies, particularly for SCR, should be generally based on direct enforcement, i.e. in a single passage.

Three other uses of remote sensing data for mitigation policies involve **high-emission events**. For cleaner vehicles, it is observed that a small fraction of high-emission events substantially affects the average emissions of a vehicle category. Therefore, it is relevant to act upon this.

5. A detection limit similar to the one used for tampering detection (i.e. twice the average spread) can also be used as an indication of high-emission events. This can either be **undetected deterioration or malfunctions,** which would not lead to failure on the current PTI tests but require further investigation that may lead to an adaption of the PTI requirements or resolve issues related to in-service conformity.
6. A second issue with high emissions are certain vehicle makes and **models that underperform** compared to similar vehicles in the same category. This can indicate a compliance issue and can be a cause to perform follow-up **ISC tests** and to focus **market surveillance** initiatives on. Following an analysis presented on Euro 6b/c diesel vehicles, a specific Renault engine proves to be a clear candidate for mitigation actions, i.e. recalls and software updates.
7. Thirdly, observed high emissions in particular circumstances or conditions can bring to the surface relevant **limitations of the procedures of RDE tests and heavy-duty PEMS-ISC tests**.

On the last three topics, it has to be noted that high-emission events represent a substantial contribution to the total emissions of clean vehicles, a relevance that will further increase when fleets start consisting of more such clean vehicles. Further investigation is warranted as the mitigation policies in these cases need to be developed, given the new responsibilities of the national authorities. Specifically, only follow-up emission testing can properly distinguish **the causes of unacceptable real-world emissions and possible mitigation actions.**

In this report, we propose a **framework for organising market surveillance and in-service conformity testing (ISC)**. Therefore, we focus on the **engine type** rather than on a vehicle's make or model, given that the same engines are often used by different manufacturers. A **long-term** market surveillance framework is proposed to consist of gathering indications from both remote sensing, third party testing, roadside and periodic technical inspections. This requires quite some practical and legal changes on a regional level for Flanders to align all contributing sources to the market surveillance authority. In the **shorter term**, the most effective approach consists of remote sensing as direct input for market surveillance. This allows categorising models/engines that require follow-up emission testing to make sure they comply in real-world conditions. Overall, market surveillance may be an effective initial deterrent for manufacturers to have reduced emission control in normal use. However, if nobody is taking up the task of following up on indications of inferior emission control, this deterrent will soon evaporate. Moreover, the first vehicles under new regulations generally tend to perform better than the later generations. So, the first RDE-compliant (Euro 6d-Temp) vehicles, even without compliance criteria, are likely much cleaner than later generations.

The detection of **high-emitters**, related to tampering and malfunctions, has been a central issue in the presented analyses of the remote sensing data. “Typical” emissions, or the most common/modal results, are represented by the midpoint or median value. There is a normal variation around that typical value related to variations in conditions and details of the technology. However, there are also very high values observed, outside the normal, expected variation in emissions. When a vehicle category like a petrol car or a Euro VI truck is typically very clean, a small group with malfunctions or tampering, or maybe just a temporary failure of the emission control system, may affect the average of the category significantly. Pre-Euro 6d-Temp diesel cars generally perform poorly NOx-emission-wise, which calls for air quality policies that apply to the general fleet. If hopefully, new diesel vehicles are eventually proven to be clean, tampering and malfunctions will be the remaining cause of high emissions, calling for more focussed policies, dedicated detection and research. The difference between typical emissions and the contribution by high-emitters can be seen in Figure 1-1.

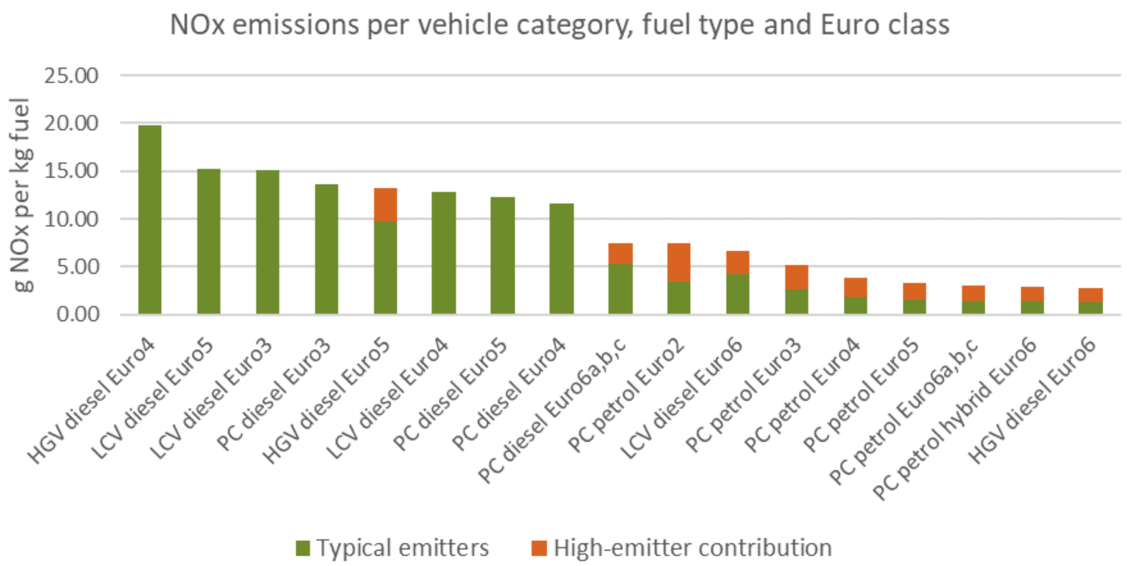

Figure 1-1: The typical emission bars represent the median values for those vehicle categories with more than 1,000 measurements. The high-emitter contribution is considered to be the difference between the average and the median and is highlighted when the contributions of high-emitting events are over 22%. This percentage serves as a simple distinction between the typical skewness of measurements and the contribution of high-emitters to the total emissions of a given category. If this 22% threshold is not reached, the contributions are considered to be part of the typical emissions, albeit a somewhat skewed distribution. Skewness can be understood as the asymmetry or distortion in a symmetrical bell curve that characterises a normal distribution in statistics.

In terms of outliers, the cleaner the 'typical' vehicles of a category get, the higher the contribution of the high-emitters to the average emissions. A small fraction of vehicles, i.e. a few percent, may increase the average emissions from the typical vehicles of a given category by 15% or more. Note that this is only true if the typical emissions are low to start with. For vehicle categories with higher typical emissions, the contribution of high-emitters in that group is less relevant. Based on probability distributions, high-emitters of typically cleaner and less clean vehicle categories seem to be similar in emission levels. This can be explained by the fact that if emission control fails, typical emissions are based on the physical characteristics of combustion, which lead to the same general maximal levels, irrespective of the typical emission levels.

The **identification of high-emitters can be at the basis of dedicated policies, improved inspection, or police enforcement**. Moreover, limitations to the emission control system, leading to temporary high emissions, should lead to mitigation procedures that involve the vehicle manufacturer. In the current analyses, we estimate how large the contribution of high-emitters is, and how they affect the averages per category. This shows us the effectiveness of targeting specific problems with high-emitting vehicles. Clearly, for pre-Euro 6d-Temp diesel cars with typically high NO_x emissions, the group of outliers (i.e. high-emitters), is hardly visible nor relevant within the whole group of high-emitting vehicles (see e.g. 'PC diesel Euro5' in Figure 1-1.). In this case, the whole group could be targeted for their impact, rather than focusing on the outliers only. **For petrol cars, an averaged 6.9% of high-emitter events contribute 41.1% of the NOx emissions**, indicating that petrol car emission results depend more on properly functioning three-way catalyst (TWC) technology than diesel cars depend on SCR technology. Concerning **diesel PM emissions, about 10% of the high-emission events observed in the sampled Euro 5 – 6a,b,c car fleet contributes 80.4% of the total PM emissions**. If this near-total contribution would be extrapolated to the entire fleet driving on Flemish roads, the impact of targeting this small share of high-emitters and enforcing repair (e.g. through PTI) could be very substantial.

Rural and motorway driving emissions are major contributions to the large-scale background concentrations covering entire regions. Motorways generate bands of substantially increased concentrations around them, often several kilometres wide. Therefore, it is relevant to quantify emissions in these specific circumstances, given the typically high share of kilometres travelled on Flemish motorways and the traffic intensity, a situation that can be generalised for many EU member states. On the other hand, people and cars occupy the same urban space, and spikes in pollutant concentrations near dwelling areas of people are often associated with narrow and busy **urban streets and congested traffic situations**. Hence, emissions from both types of roads are relevant for assessing air quality.

This remote sensing campaign covers both parts and some road types in between. In Ghent, urban conditions are covered with a 50 km/h road near junctions and traffic lights. Near Bruges, a rural road was the basis for the measurements, although the frequent start/stop traffic made it relate more to urban driving. Near the Antwerp Kennedy tunnel exit and Aalst, motorway traffic was sampled in different conditions, albeit that the steady cruising speeds in Aalst make this location the only 'pure' or typical motorway setting for comparisons. Also, the Aalst test site proved to be a good example for future remote sensing testing, due to driving conditions allowing for optimal emission control system functionality, which makes such a location ideal to select vehicles for roadside inspections as well. The site also allows for large numbers of vehicles that can be sampled on short notice. Whereas parameters like velocity or ambient temperature varied, the impact of the location and its characteristics (e.g., traffic density, congestion, road inclination) itself was found to be the key factor explaining the differences in emissions per vehicle category. The average emissions of vehicles vary depending on the vehicle category, but also the **location and the local driving conditions** will **affect** these **emissions significantly**. These variations, nonetheless, are still less than those observed between different vehicle categories. As such, diesel vehicles before Euro VI for heavy-duty (i.e. before 2015) and before Euro 6d-Temp for light-duty (i.e. before 2019) have the highest NO_x emissions in relation to their fuel consumption.

Fuel consumption is roughly proportional to the weight of the vehicle and should be taken into account when comparing the emission performance of different vehicle categories. In general, it is to be expected that heavy trucks have higher emissions in mg/km. However, per tonne of total vehicle weight CO_2 emission increase less than proportional. When fuel consumption is expressed per tonne of weight, the heaviest trucks of about 40 tonnes only burn a quarter of the fuel compared to a passenger car driving the same distance. Such trucks consume about 30 litres of diesel per 100 kilometres. In terms of NOx, this means these very heavy Euro VI trucks have about 0.5 g/km emissions, similar to pre- Euro 6d-temp diesel passenger cars at a fraction of the weight and engine power.

In terms of air quality problems related to nitrogen dioxide (NO_2), petrol cars, Euro-6d-Temp diesel cars and Euro VI diesel trucks combined contribute about one-quarter of the emissions, per kilogram fuel, compared to the other diesel vehicle categories like vans, older trucks, and older diesel cars. This is the global picture. Further nuance is that **in urban conditions, NO_x emissions by petrol cars are another 30% lower than the average based on all locations**. On the contrary, **NO_x emissions by Euro VI trucks in urban conditions are three times the average NO_x** emissions of this group of vehicles on all road types combined. **This indicates a flaw in heavy-duty ISC PEMS legislation, in which there is limited coverage as low engine load is excluded from the evaluation**. This legislation was designed to cope with Euro V emission problems, caused by shutting down the SCR at low engine load. It seems the heavy-duty ISC PEMS legislation only partially solved this problem. Figure 1-2 highlights the NOx reduction potential if the ISC PEMS legislation were to be improved, improving SCR reliability for the sampled vehicle categories for both the urban and the average (urban+rural+motorway) situations.

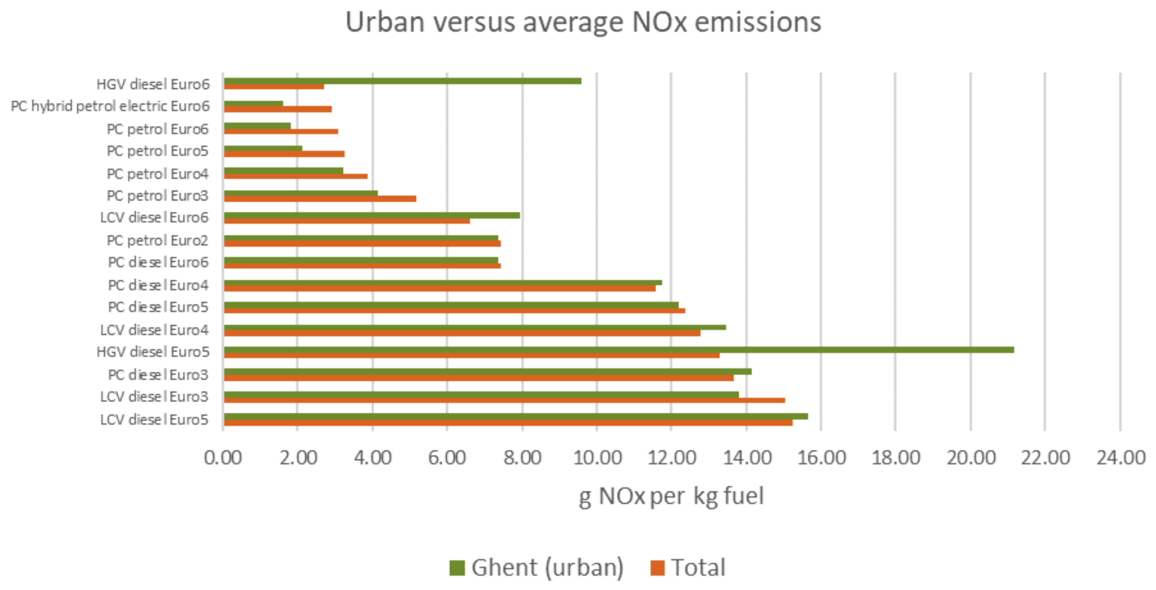

Figure 1-2: While NOx emissions of petrol vehicles, from Euro 3 onwards, are typically lower during urban driving than the average emissions including the other road types, urban NO_x emissions by diesel vehicles are normally higher. For diesel vehicles with SCR systems, and limited regulation of low power operation, urban emissions are significantly higher, as indicated by the heavy goods vehicle (HGV) categories for the (urban) Ghent measurements.

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1 INTRODUCTION

1.1 HOW THIS REPORT FITS IN THE LARGER PICTURE FOR FLANDERS

In spring 2017, the EMIS/Dieselgate Commission of Inquiry set up by the European Parliament completed her investigations and published several recommendations that pointed to both policy and enforcement shortcomings to prevent fraud and high emissions in real-world operation, both at the level of the European Commission and of individual member states. With the sixth Belgian State Reform in 2014, Flanders became competent in the field of road safety and vehicle type-approval. As such, Flanders started exploring its competencies (and subsequent responsibilities) in the context of unauthorised emissions from road vehicles.

Taking the above into consideration, the Flemish Government has issued a call for tenders - in a public procedure - to explore action perspectives and to define policy strategies for the improvement of air quality in Flanders. The focus was limited to the emissions of hazardous exhaust gases from road traffic, in particular from passenger cars, light commercial vehicles (LCV), and heavy goods vehicles (HGV).

The assignment consisted of four parcels, which were put out to tender individually. Within parcel I, an exploration of the context was carried out, specifically looking at both the scope and limitations offered by the European, Belgian, and Flemish regulations for taking action in terms of enforcement and the parties that are competent for this matter. In parcel II, policy strategies for dealing with high traffic emissions in real driving conditions were elaborated. As such, there has been a strong interaction between the legal research of parcel I and the strategic policy work carried out in parcel II. In parcels III and IV, the information on road traffic emissions is updated for the situation in Flanders, so that relevant and priority policy strategies can be elaborated in parcel II. Whereas parcel III is aimed at translating existing data sources to the Flemish situation, this report, covering parcel IV, consists of an analysis of measurements that were performed using remote sensing (RS) to gain further insight into the actual emissions of road traffic in Flanders.

In the light of EU Regulations 2018/858 and 2018/1832, appropriate measures to perform market surveillance on the vehicles registered within its borders are to be taken by Flanders as a competent authority in the field of road safety, and this since September 1st, 2020. This includes in-service compliance tests to take place on those vehicle categories that should comply with the aforementioned regulations, i.e. Euro 6d and Euro 6d-Temp-ISC passenger cars, as well as a mandatory fleet monitoring to perform risk-based analyses to pinpoint those vehicle types that require in-service compliance testing. By doing so, Flanders can evaluate the effectiveness of relevant vehicle emissions regulations (e.g. RDE) and post-emission exhaust treatment strategies by conducting and evaluating real-world emissions monitoring. Also will this very first remote sensing campaign to have taken place in Flanders allow for the latter to grow experience and expertise with vehicle emissions monitoring by remote sensing, which facilitates numerous policy strategies developed in the wake of the parcel II investigations.

1.2 OBJECTIVES

With this study, an update is given to the international CONOX database on remote sensing throughout Europe. As such, the database will be enriched with samples from thousands of passenger cars qualified according to Euro 6d-temp regulation. Thus, it offers a very first glimpse of how they relate to previous emission technologies in terms of pollutant emission reductions. Besides that, the following objectives are put forward:

- What emission trends do we see for the specific Flemish fleet, in which so-called “salary cars” have been representing a substantial share throughout the last years. Do these match with what we see in other studies?
- In this study, remote sensing is applied for the very first time on motorways. Will motorway emissions significantly alter the trends we have seen in previous studies? What will this mean for the different Euro classes, specifically for Euro 4 to 6 NOx and PM emissions, for different technologies (fuel, post-emission treatment strategy, …), makes, and models?
- Can we properly define and identify high-emitters based on remote sensing samples?
- Is there a more suitable way for converting g/kg fuel emissions to the generally better-understood unit of g/km?
- Can we assess and estimate the occurrence and extend of vehicle tampering (SCR and DPF fraud/malfunctions) by remote sensing

2 DESCRIPTION OF THE TEST EQUIPMENT AND LOCATIONS

2.1 EDAR

In this test campaign, samples were taken by two EDAR remote sensing devices provided by project partner HEAT. EDAR is an eye-safe, laser-based technology capable of remotely detecting and measuring the infrared absorption of environmentally critical gases coming out of a moving vehicle. This NASA spin-off device is an innovative technology that accurately detects and quantifies various gases being emitted from the tailpipe of a moving vehicle in real-time with two-dimensional spatial resolution. EDAR uses the DiAL method, or Differential Absorption Spectroscopy LiDAR, to directly detect and quantify gases such as but not limited to, carbon monoxide (CO), carbon dioxide (CO_2), nitrogen monoxide (NO), nitrogen dioxide (NO_2), nitrogen oxides (NOx), hydrocarbons (HC), and particulate matter (PM). The EDAR system also has the unique capability of measuring the temperature of the exhaust the moment it exits the tailpipe and utilises this temperature measurement to determine whether the vehicle is in a cold start, or any other low-temperature exhaust gas operation. This capability prevents incorrect high-emitter classifications as vehicles in cold starts tend to emit higher concentrations of hazardous pollutants. Additionally, the EDAR device is an unmanned system capable of detecting emissions, unattended for 24 hours a day, seven days a week, 365 days a year. It includes the sampling unit, an electrical panel, an automatic number plate reader (ANPR), a speed and acceleration detection unit, and a weather sensor.

EDAR produces a report for every vehicle detected and evaluated. As displayed in Figure 2-1, the unit captures a 2D image, similar to a finish-line photo in sports, of the vehicle and its exhaust plume for the detected gases as well as the date, time, speed, acceleration, license plate number, temperature, barometric pressure, humidity, wind speed, and emissions readings. The matching of plumes of pollutant and CO_2 emissions will lead to a better separation of signal and background compared to a single absorbance from a laser across the road, used in other systems.

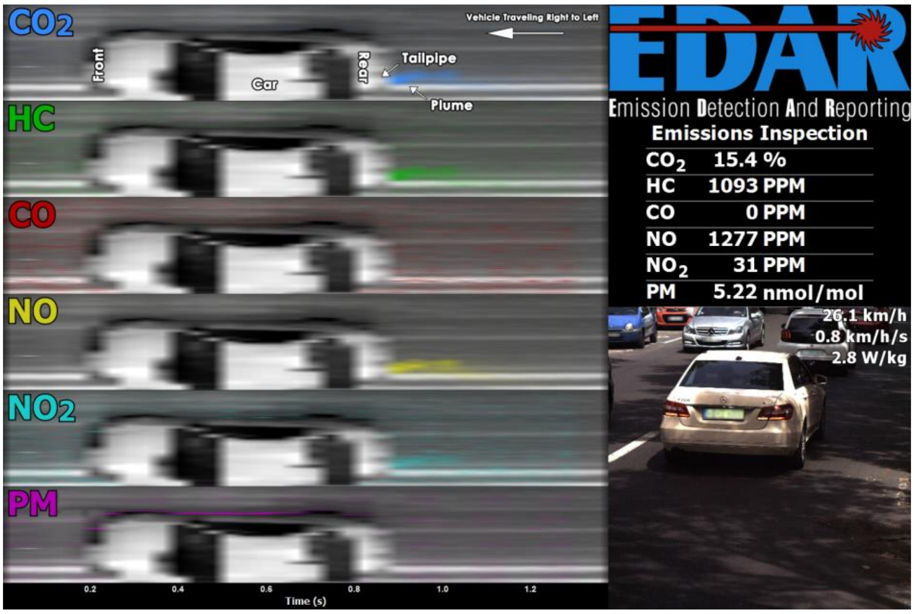


Figure 2-1: An example of a 2D image of a sampled passenger car, combined with the measurement read-out

EDAR has undergone multiple validation tests proving its accuracy in detecting emissions and is proven highly accurate. The technology uses principles similar to space satellites to detect and quantify gases in the Earth's atmosphere using lasers and the DiAL method, which is highly precise. EDAR's R^2 accuracy is shown in Table 2-1. Note that an "R squared" of 1 means a perfect fit and, an "R squared" of zero indicates no fit. Table 2-1 shows the accuracy characteristics per pollutant measured.

Table 2-1: Accuracy details are shown as the tolerance and the r-squared value

Gas	Accuracy	R^2
NO	± 10 ppm	0.998
CO	± 50 ppm	0.996
HC (Hexane equivalent)	± 50 ppm	0.996
NO_2	± 10 ppm	0.974
CH_4		0.983
PM		0.937

Note that for portable emissions measurement systems (PEMS), which measures higher gas concentrations directly in the exhaust gas from the tailpipe, the requirement is below 5 ppm accuracy for NOx in RDE testing. After exiting the tailpipe, the exhaust gas is diluted, so a remote sensing system at the same stringency level would have an accuracy of a few ppm.

Due to the absolute nature of EDAR's spectroscopic measurements, it can measure the targeted pollutants without explicit field calibration and remain within standard specifications. Due to the DiAL method, which uses lasers that are locked into a particular wavelength and have narrow bandwidths to differentiate between extremely narrow absorption features. This method is well-known in satellite technologies where direct calibrations cannot be performed and uses lasers to continuously subtract out the background radiation, changes in ambient conditions, and instrument noise. Therefore, allowing EDAR to operate 24 hours a day, seven days a week, unmanned, without any drift. This increases the reliability compared to other technologies using non-laser light sources, such as the non-dispersive infrared (NDIR) technologies, which require calibration due to changes in ambient conditions, instrument drift, and noise. In a blind study performed by ERG and US EPA, the EDAR system proved to have no drift, allowing for the unit to run continuously, collecting accurate data without any need for calibration[1].

[1] Tim DeFries (ERG), Carl Fulper (USEPA), Jim Kemper (CDPHE), Sandeep Kishan (ERG), Jim Sidebottom (CDPHE), "Independent Testing of EDAR Accuracy and Sensitivity Performed by EPA, Colorado, and ERG," Denver, Colorado, January 2, 2016.

2.1.1 EDAR System Equipment

Figure 2-2: Overview of the combined EDAR system

EDAR Unit
Measures CO, CO_2, NO, NO_2 (NOx), HC, and PM being emitted from vehicles

Laser-Based Speed and Acceleration Unit
Determines the speed and acceleration of vehicles

Automatic License Plate Recognition Camera (ALPR /ANPR)
Detects and transcribes the license plates of the vehicles measured by EDAR

Security Camera
Allows for remotely checking on the security of the system

Retro-reflector
Reflects the light up to the EDAR system

Electrical Panel
Conditions incoming AC power to operate all system components

Mounting
The EDAR unit, laser-based speed and acceleration unit, weather sensor, and cameras are mounted above the road. The system can be mounted on a permanent pole, gantry, or temporary movable truss system.

2.2 AUTOMATIC NUMBER PLATE RECOGNITION

The collection of license plates along with the emissions data was a requirement of the data deliverables outlined in this program. License plate data are captured using a license plate recognition camera as part of the EDAR system components. HEAT's custom-built cameras have a high valid automatic transcription rate, eliminating the need for any further manual transcription.

After the data is collected, the processing time is immediate due to the software's automated transcription algorithms. Traditionally, commercially available license plate recognition cameras normally have an accuracy rate of around 70% - 80%. By increasing the quality of the optics in the license plate reader and developing novel imaging algorithms, HEAT has significantly increased the average capture rate as proven in its recent deployments around Europe. Furthermore, all license plate data is automatically anonymised, following all data protection guidelines according to the General Data Protection Regulation (GDPR).

This anonymisation process is discussed further in 2.4 'Sources of data and data collected'.

2.3 ANALYSIS OF COLLECTED DATA

2.3.1 Validation and Screening Process

The following screening checks were applied to the measurements to ensure the data used for fleet evaluation were reasonable, consistent, and within the required parameters.

2.3.1.1 Screening of Exhaust Plumes

Since the EDAR system measures the exhaust plume with a sheet of laser light scanning across the roadway, it can construct two-dimensional images of passing vehicles and their respective emission plumes. One axis of the image depicts the length across the road, while the other axis depicts the passage of time. As such, a 2D passive infrared image of a vehicle is created as it moves underneath the unit. The vehicle image can show the shape of the vehicle, its lane position, the position of its tailpipe, and assist in the determination of vehicle type (e.g. light-duty or heavy-duty) based on the measurements of the vehicle. This indication is calculated in real-time.

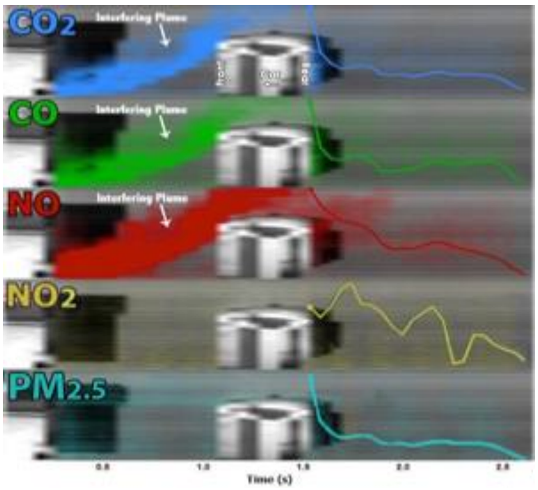


Figure 2-3: An example of interfering exhaust plumes

Also, the EDAR system forms an active image of a vehicle's emission plume showing the quantity of pollutant emissions detected per unit area or optical mass in moles/m², summing all concentrations in the vertical column. The plume image shows the position of the plume for each pollutant as well as the dispersion rate of the plume.

To determine valid reads, the linear correlation coefficient or Pearson's correlation criteria (R), which is the ratio mole/mole measurements for each scan, is applied between the CO_2 measurements and the CO, NO, and NO_2 measurements. If the pollutant is present and the correlation factor is relatively high, with a minimum threshold per gas, the measurement is considered valid. This signifies that there are no interfering plumes (see Figure 2-3). Interfering plumes usually have different ratios of pollutants to CO_2. Therefore, the linear correlation coefficient drops in value. The highest linear correlation coefficient is 1.0, whereas values near zero indicate no correlation and negative 1.0 indicates a complete negative correlation. Correlation values are ignored when gas readings are near zero for CO, NO, and NO_2, due to the lack of presence of those gases. This is an indication that the vehicle is decelerating/not being power at the moment it passes the EDAR lens.

2.4 SOURCES OF DATA AND DATA COLLECTED

2.4.1 Data Processing and Handling

Table 2-2: The data enrichment by the Flemish agency for information (AIV), supplying the vehicle registration characteristics

Vehicle technical data required from the registration agency	
Vehicle model	Fuel type
Model year	Engine displacement
Make	Maximum power output
Body style	Vehicle curb weight
Vehicle category	Vehicle mileage
Euro class	

All data collected by the EDAR system was stored on a secure local computer in Flanders with multiple layers of security. During the collection process, all emission data was compiled on one central computer at HEAT's local office in Belgium. Only authorised personnel were able to access the system within the country. When retrieving the data from EDAR, HEAT engineers download the data to a highly secure, encrypted hard drive that requires a physical PIN code to be entered on the outside of the device to operate for any data downloads or transfers. Only authorised HEAT personnel were made aware of the secret PIN code and were allowed to handle the hard drive. As soon as the data was retrieved by the engineers it was manually transported to HEAT's local office in Belgium and stored on an isolated, secure computer that was not connected to the internet. After the transfer was complete, all data was deleted from the transported hard drive. This process is designed to ensure that no data is ever uploaded into a cloud environment or provide an opportunity for a data breach. The data needed for the vehicle technical data retrieval from the motor vehicle registration authority was securely transferred to the project partner, in this case the Flemish AIV, for further data enrichment with the characteristics shown in Table 2-2. Table 2-3 shows the various parameters that are the output of the EDAR's measurements.

Table 2-3: An overview of the data linked to each vehicle by the EDAR post-processing

Data collected by EDAR		
CO	g/kgCO_2 ratios	Ambient rel. humidity (%)
CO_2	ppm concentrations	Wind speed (m/s)
NO	Exhaust temperature	Wind direction (°)
NO_2	Speed (km/h)	Date + time
NOx	Acceleration (m/s²)	Test location
Total hydrocarbons	VSP (kW/tonne)	Longitude
PM	Ambient temperature (°C)	Latitude
g/kg emission rates	Ambient pressure (mbar)	Altitude

3 STUDY DESIGN

3.1 DEPLOYMENT METHOD

3.1.1 Setup Configuration

3.1.1.1 Truss

At four of the five deployment locations for the Flemish campaign, the HEAT team utilised a movable truss system (*see* Figure 3-1) which can be easily and securely installed near the roadway. When the truss system is deployed in its intended configuration and all components are installed, the system runs unmanned 24 hours a day, 7 days a week without human intervention. The EDAR system is monitored remotely and alerts technicians of any anomalies. When the truss is erected to its full structure, EDAR sits approximately 5.5 meters or higher above the roadway.

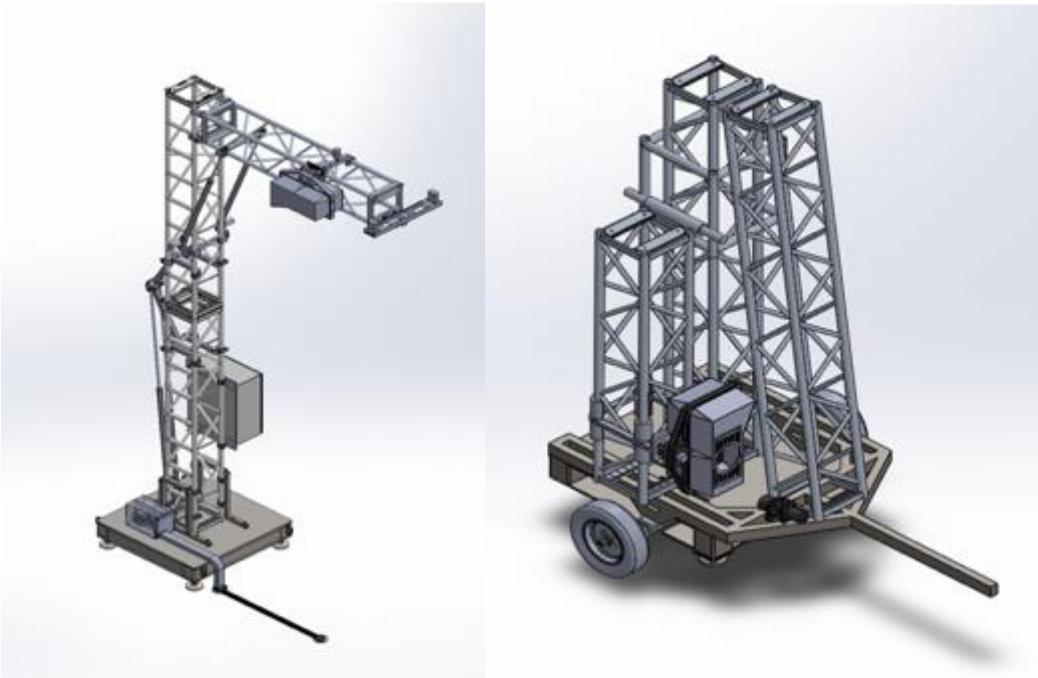


Figure 3-1: The truss system when fully deployed (left) and when stowed back for transport (right)

Directly below the EDAR device is a retro-reflective strip affixed to the roadway. This can be seen in the right-bottom corner of the fully deployed truss system in Figure 3-1 (left). The retro-reflector is installed by attaching it to the truss base and then securely adhering the strip transversely across the roadway using butyl. This specially designed retro-reflector ensures optimal operating time since it allows EDAR to continue detecting emissions in light rain or misty conditions. More information on the reflector can be found in section 3.4.

3.1.1.2 Gantry

At the location on the E40 in Aalst, the EDAR unit, laser-based speed and acceleration unit, weather sensor, and ANPR were mounted above the roadway using a specialised gantry mount designed for multi-lane, highspeed roadways. During operation, the EDAR unit is located approximately 6.5 m above the road surface. This mount is over-dimensioned for safety and securely attaches to the gantry or bridge. An image of the gantry deployment is shown in Figure 3-2.

Figure 3-2: The EDAR unit mounted on a gantry

3.2 MEASUREMENT SITES

Two EDAR units were implemented throughout Flanders in June 2019. The location references as well as the duration of the measurements at these sites are given in Table 3-1.

Table 3-1: Overview of the measurement sites and the duration of the on-site campaigns

Site	Dates	# of Days	EDAR System
Antwerp Site 1 (N186)	June 7 – 12	6	1
Aalst	June 8 – 17	10	2
Bruges	June 14 – 28	15	1
Ghent	June 18 – 24	7	2
Antwerp Site 2 (Tunnel)	June 24 – 28	5	2

3.2.1 Location description

For the reader to understand the specific context at each location where we set up our testing equipment, we try to describe the 500 metres before and after the remote sensing device concerning the profile of the road slope as well as potential changes in the speed limit. For the latter, the limit up- and downstream of the device are important as sudden changes in maximum allowed speeds, for instance due to a junction, intuitively cause a driver to adjust his/her speed. This can have an impact on the snapshot measurements performed in this study. In most studies on remote sensing, this information is limited to the speed and the road slope at the specific location of the remote sensing device. By broadening this perspective, we tend to bring more information to enhance the reader's understanding of the context in which we performed this test campaign.

3.2.1.1 Bruges – N31, extra-urban ring road, 90 km/h

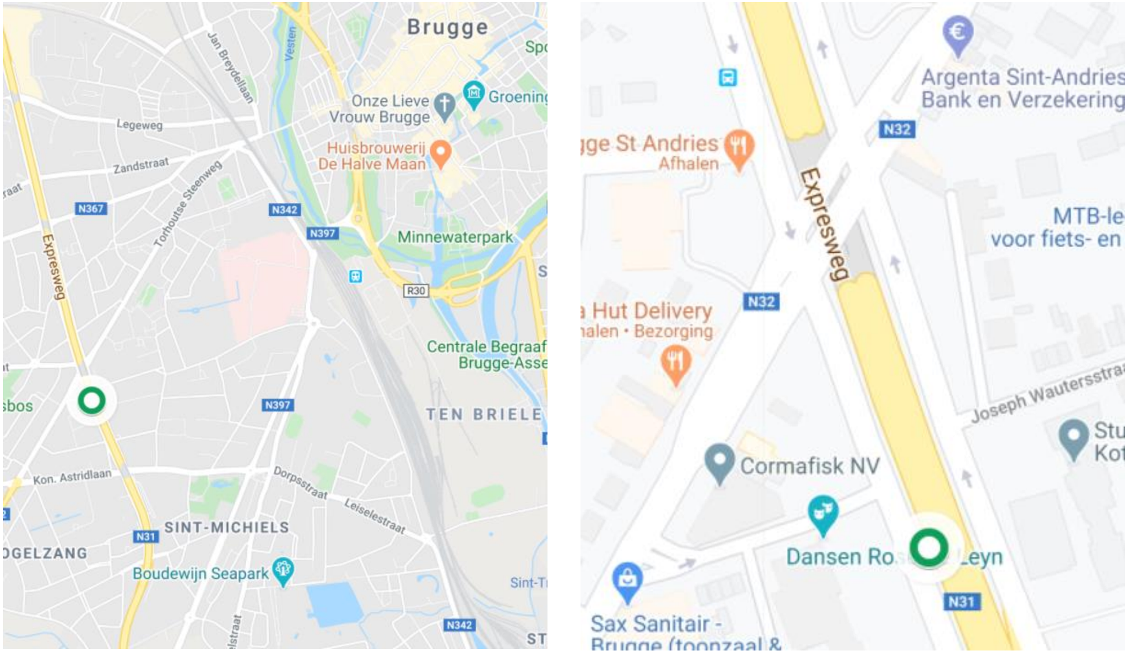


Figure 3-3: Test location near Bruges, by the N31 moving away from Zeebrugge

Figure 3-3 shows where the Bruges test campaign was located, i.e. by the side of the N31 moving away from the commune of Zeebrugge. The N31 is part of the 2x2 primary ring road around Bruges that is characterised by maximum speeds of 90 km/h, with the remote sensing device placed by the right-hand side lane of a positive slope where the N31 takes a passage underneath the crossing N32. In the 500 metres before the device, there is one exit lane before the N31 takes the under-passage. From its lowest point (9.25 m above sea-level) up until the measurement device (12.25 m above sea-level), 3 altimeters are covered over about 150 metres, indicating a 2% slope of the road. In the following 500 metres after the test location, another exit lane is present before the N31 takes the next passage below the roundabout on the *Koningin Astridlaan*. Generally, traffic can flow freely here.

3.2.1.2 Ghent – R40 Charles de Kerckhovelaan, urban, 50 km/h

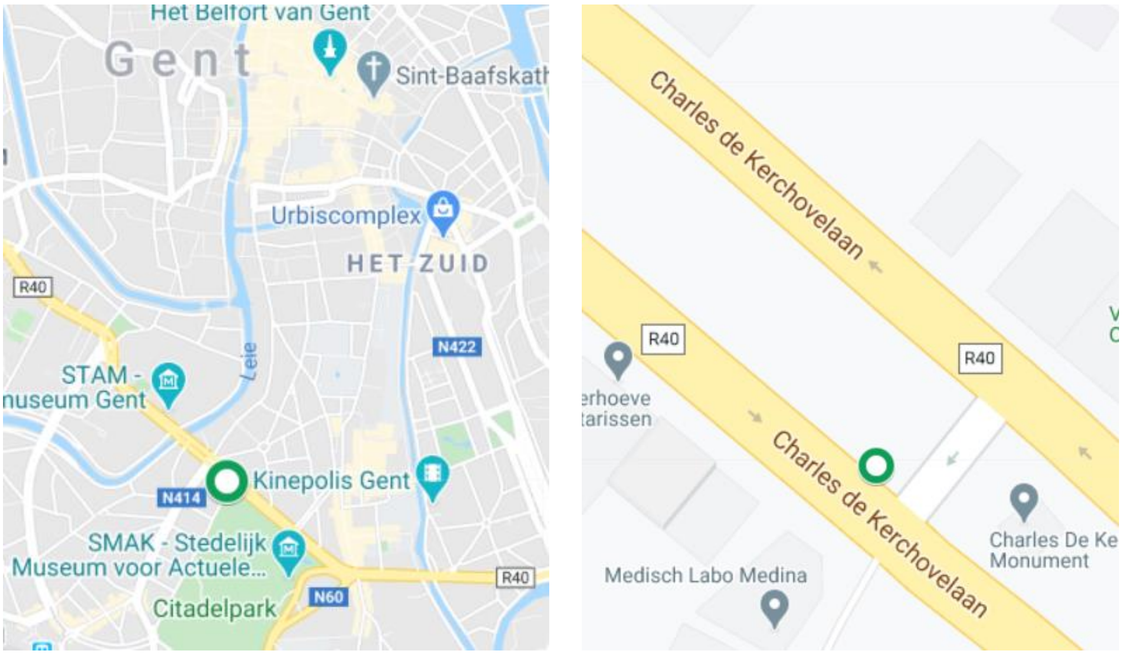


Figure 3-4: Test location near Ghent, by the Charles de Kerckhovelaan (R40)

The specific test location near Ghent is shown in Figure 3-4. Here, the remote sensing device is placed in the middle section of the urban R40 road, with separated lanes after a traffic light with a maximum speed of 50 km/h. HEAT's sampling unit was placed over the left-hand side lane of this double lane track. In the 500 metres before the sampling unit, the R40 shows a straight track during which a height of 10,8 m is climbed, indicating an average road slope of 2.16%. At the location of the EDAR system, the slope was higher, at 5%. There is a junction about 80 m before the device that is characterised by traffic lights, indicating that for a substantial share of the measurements, the sampled vehicles have been either accelerating from a standstill or taking the corner near the junction road. In the 500 metres after the sampling unit, the road slope continues while no junctions occur. As this is an urban road with traffic lights, traffic will often not flow freely.

3.2.1.3 Aalst – E40, motorway, 120 km/h, right lane

Figure 3-5: Test location near Aalst, by the E40 motorway towards Gent

The Aalst E40 test site is characterised by a motorway road section with a maximum speed of 120 km/h. Over the last 500 metres, slightly curved, before the sampling unit, the road height increased roughly 4.2 m, indicating a slope of 0.84%. The slope at the EDAR location was 1.9%. There are no changes to be expected in the speed of the drivers passing by the unit as there are neither entries nor exits or junctions in the roadway ranging from 500 m before to 500 m past the unit. This might indicate that drivers use the cruise control option of their vehicles when free-flowing traffic is possible. The motorway at this location has three lanes. The EDAR was over the right lane. This lane is mainly used by slower heavy-duty vehicles, while faster traffic, i.e. mostly light-duty vehicles, uses the middle and the left lane.

3.2.1.4 Antwerp – N186, extra-urban, 90 km/h to 70 km/h

Figure 3-6: Test location near Antwerp, by the N186 towards the city centre

The fourth test site is shown in Figure 3-6 and highlights the N186 road towards the Antwerp city centre. This road is characterised by several changes in the speed limit as in the 500 m before the sampling unit drivers can originate from three different road types. First, there's the motorway entry taking the curve towards the A112, with a maximum allowed speed of 120 km/h. Second, there's an urban road (i.e. the *Jan de Voslei*) that enters the A112 with a maximum speed of 50 km/h. Third, there's the traffic coming from the A12 motorway that splits to the A112 motorway and convenes with the two other roads via the *Jan de Vos* tunnel (A112), where a maximum speed of 90 km/h should be respected. The latter speed limit of 90 km/h is maintained up until the sampling unit, after which immediately, the drivers are prompted to lower their speed to 70 km/h as the double-lane convenes to a single-lane some 50 m past the unit. Given the convening of three roads earlier on the route, drivers typically reduce their speed for safe lane-shifting by other road users, which made this specific location inappropriate for remote sensing. From the moment the entry towards the city centre is taken, however, drivers will accelerate again if traffic allows it. This is mostly the case. Concerning the road slope, the track before the unit runs downhill while a climb starts some 20 m before the unit, starting from a height of 0.2 m above sea-level. This climb takes the driver to a height of 6.3 m after 250 m, indicating a slope of about 2.4%. The slope at the unit's location is 2.1%.

3.2.1.5 Antwerp – E34 exit Kennedy tunnel, motorway, 120 km/h, left lane

Figure 3-7: Test location nearby Antwerp, at the Kennedy tunnel exit by the E34

The fifth test site is located by the Kennedy tunnel exit on the E34 towards Ghent. The E34 is a European 3x3 motorway by which the sampling unit was positioned on the left-hand side, in the far-left high-speed lane of the slope. The tunnel has a platform in its middle-section that slightly runs down to a maximum depth of -20.8 m, after which an inclination starts over a length of roughly 420 m with a height increase of 13.2 m up until the sampling unit. The inclination does not entirely run linear as the last 200 m show a slope of 2.9%, while at the sampling site this is reduced to 2.1%. Concerning the speed limitations in the 500 m before the sampling unit, one has to take into account that these are dynamic. Due to the frequently congested traffic in front of the tunnel entry, the speed mostly has to be reduced to 50 km/h (or 70 km/h). Upon leaving the tunnel, this speed limit is typically increased to 100 km/h, as this was the case during the test campaign, indicating that next to accelerating to overcome the slope, drivers tend to reach this maximum speed swiftly. Whereas in front of the tunnel the road mostly starts to congest due to the 50 km/h speed limit, there typically is free-flowing traffic when leaving the tunnel. There is an exit about 500 m after the sampling site although this does not influence the traffic (and the average speeds) significantly.

3.3 WEATHER CONSIDERATIONS

During the deployment, there were variable periods of heavy rain which would block the signal of EDAR and cause data collection to cease. EDAR's reflector system, which is described in more detail in the section below, allowed for minimal interruptions in data collection since it lets the sampling unit recover signal quickly through its advanced mechanism.

3.4 THE REFLECTOR SYSTEM

Directly below each EDAR unit, a retro-reflective is strip installed on the roadway to reflect the laser light up to the system as part of the remote sensing emissions testing process. The retro-reflector is narrow and easily installed for either temporary or permanent deployments.

For temporary deployments, like the ones in Flanders, the retro-reflector is installed by securely adhering its components to the roadway using strong asphalt butyl tape specifically created for bonding objects to the road surface, such as car counting sensors. The reflector has a low profile on the road surface and is unobtrusive to the flow of traffic. The reflector system, shown in Figure 3-8, is designed in such a way that allows EDAR to continue taking data in misty conditions and to also recover signal quickly after a rain event. These enhancements contribute to a reduction in downtime due to adverse weather conditions.

Figure 3-8: The practical implementation of the retro-reflective strip

3.5 LIMITATIONS OF THE STUDY

Not every vehicle that passes the EDAR sampling unit results in a valid measurement. This is largely due to external factors that cause the instrument to work in a sub-optimal state or that render the readings false. In the former case, we typically talk about heavy rainfall or snow, which did not occur during our campaign. What caused invalid readings were mainly:

- interfering exhaust plumes from other vehicles driving on different lanes in multiple lane locations (n=2,330);
- low CO_2 readings, associated with low engine power, i.e., deceleration (n=18,493), and;
- insufficient readability of the license plates (n=457).

A total of 21.280 readings were excluded from the dataset, although they did provide proper emission readings. The Antwerp N186 location had by far the highest fraction of invalid readings of 60% (with a total number of 4,636 valid readings) due to issues discussed in 3.2.1.4. The other locations had typically 4%-12% invalid readings, leaving 188.966 valid readings for analyses.

Another limitation of the present study is that only Belgian and Dutch samples were further processed in this analysis, although vehicles registered in other countries passed the lens as well. The data processing before analysis requires to link the emission readings with vehicle-specific data. As this data was only readily available from Belgian and Dutch registration services, data processing for this campaign could only occur for those vehicles. Nonetheless, these represent most vehicles sampled. As can be seen in Table 3-2, nearly 88% of the total sample was retained for further analysis.

Table 3-2 – Overview of the sampled vehicles per country of registration

Country of registration	Number	Share
Belgium	161,849	83.0%
The Netherlands	9,117	4.7%
France	4,127	2.1%
Germany	3,864	2.0%
Poland	2,839	1.5%
Romania	2,633	1.4%
United Kingdom	1,815	0.9%
Unknown	1,731	0.9%
Latvia	1,266	0.6%
Bulgaria	795	0.4%
Other	4,897	2.5%

4 DATA ANALYSIS

4.1 INTRODUCTION

In the following sections, we start with a presentation of the statistics for the entire dataset before more in-depth analysis takes place. A difference between the general statistics and the latter is the number of available samples per sub-group/category, for instance Euro 5 diesel vehicles. Whereas the general overview discusses minimum sample sizes of 300 measurements, the in-depth analyses are based on a sample size starting from 10,000 measurements. This arbitrarily chosen threshold is deemed necessary if we want to draw conclusions that are representative of entire fleets. Some signals, like NO_x for older diesel vehicles, do not require that many individual measurements, although in some cases the spread in the data is about ten times the average result. Given the $N^{1/2}$ rule for the confidence in the average (see further on), thousands of measurements are needed to have sufficient confidence in the presented average results, where the spread is less than 20% of the average for all components. Although some signals have limited spread, other signals have a spread up to tenfold the average value. To bring the uncertainty down for all these measurements, a generic number of measurements $N^{1/2}= 10{,}000^{1/2} = 100$, will generate confidence by reducing the spread in the average down by a factor close to 100. However, it should be noted, that the $N^{1/2}$ rule is based on the assumption of normal distributions. **Some care must be taken not to take that for granted when considering vehicle emissions**. For example, for measurements falling into clearly distinct groups, the $N^{1/2}$ rule does not apply and more detailed analyses are needed. Thus, for generic conclusions for all categories and gaseous exhaust components, thousands of measurements are needed. In more specific cases, in particular with a lower spread in the measurements, lower numbers will suffice.

Large standard deviations originate from the fact that there is a very sizable number of vehicles with very low amounts of pollutants (which represent regular vehicles with correctly designed and functioning emission control systems) and typically few large outliers (cases of poorly designed emission treatment, malfunctions, and tampering) disproportionately affecting the mean and standard deviation. Also, the dynamic range of some pollutants (e.g. CO) contributes to the standard deviation.

The evidence and conclusions hence depend on the amount of data and the typical spread in the data. Three elements have to be considered.

1. If all data of a particular vehicle category and emission components show similar high readings, with limited bandwidth, it can be concluded that the evidence is sufficient.
2. If the spread in the data is large, more data is needed to determine the average with sufficient confidence
3. If the average is significantly affected by a limited number of vehicles with high emissions, special care must be taken to draw a conclusion.

In the last case, it may be appropriate to separate the category's typical emissions from a smaller subset of the data with high-emission events, to then report on each separately. This third approach is best suited to analyse emissions of vehicle categories which, as mentioned before, consist of a sizable amount of rather homogeneously low-emitting vehicles on one hand, and a limited number of vehicles with significantly higher emission readings on the other hand. With a lower standard deviation per sub-group, the required sample size to reliably determine an emission average decrease. Also, the emission performance of regular vehicles can be analysed separately from the emission from high-emitters, avoiding a situation in which a few high emitters skew the average emission of the total group. This approach is taken up further in the report with the high-emitter analyses.

To allow for comparison with other remote sensing studies, we moved away from discussing measurements in their 'purest' form, i.e. expressed in grams per kg of CO_2 (gpkg CO_2) emitted, to the (in remote sensing analyses) commonly applied unit of grams per kilogram of fuel burned (gpkg). After an overview of the more general emission trends reported for the Flemish fleet, however, a novel way of converting gpkg emissions to the more understandable unit of grams per kilometre is discussed as this unit is used for official reporting on vehicle emissions following the WLTP and/or RDE-test. The reason hereto is that, to date, there is no transparent way of making a proper conversion based on real-world CO_2 emissions.

There is a rather direct relation between CO_2 and fuel, given the almost complete conversion to CO_2 of the carbon atoms in the fuel. Apart from that, some carbon is emitted as hydrocarbons, some as carbon monoxide, and some as particulate matter. In the conversion from the measured CO_2 back to the fuel, particulate matter is not included, but the gaseous components are, as well as some assumptions on the fuel composition, which may contain oxygen related to the bio-admixture, e.g. with bio-ethanol and biodiesel. All of these elements generate a minor correction to the relation between the measured CO_2 and the calculated associated fuel.

Real-world fuel consumption data is needed to translate the pollutant per kilogram fuel to the pollutant per distance travelled. It is long known that type-approval fuel consumption and CO_2 emission data fail to properly represent the real-world results. In that respect, the measured fuel consumption is the best starting point for the translation from grams per kg of fuel to grams per kilometre. Although many conversion models, which are based on laboratory tests and coast-down experiments, are discussed in other remote sensing studies[2], they do not properly predict the observed fuel consumption.

In this conversion method, MILE21 data is used as an input. In the European project MILE21, a reasonable estimate of the real-world fuel consumption is derived from the refuelling data of half a million vehicles[3] (see Figure 4-1). Based on this dataset, vehicle fuel-type, weight, and age are found to be the best estimators for realistic fuel consumption over a wide range of vehicles. The relation between CO_2 emissions to vehicle weight for each age is assumed to be linear. The age-dependent offset of this function is related to the increased engine efficiency over the years. The offset to this linear function with weight has reduced by 30 gCO_2/km over the years, also due to these improvements in engine efficiency. The change in average weight has a small, opposite effect as for every 100 kg vehicle mass the CO_2 emissions increase by about 8 g/km. For individual cars, however, fuel consumption can be very different due to their size and weight. Pollutant emission limits are irrespective of this weight, indicating that for heavier vehicles the pollutant emission per kg fuel should be less to meet compliance. As such, the variation in fuel consumption and CO_2 emissions across the passenger car fleet can easily be 80%. Therefore, when g/km results based on remote sensing data are envisioned, it is important to make the best possible estimate of the fuel efficiency, since this affects the conversion from the measurements expressed as g per kg CO_2. Generic fuel consumption data for a category of vehicles, e.g. Euro 5 petrol vehicles, do not have enough differentiation to limit the bias based on weight.

2 See, for instance, Bernard, Yoann et al. 2018. Determination of Real-World Emissions from Passenger Vehicles Using Remote Sensing Data.
3 See TNO Report 2019 R10872: "*More information, Less emissions - Estimating the real-world CO_2 emissions of passenger cars based on vehicle properties*".

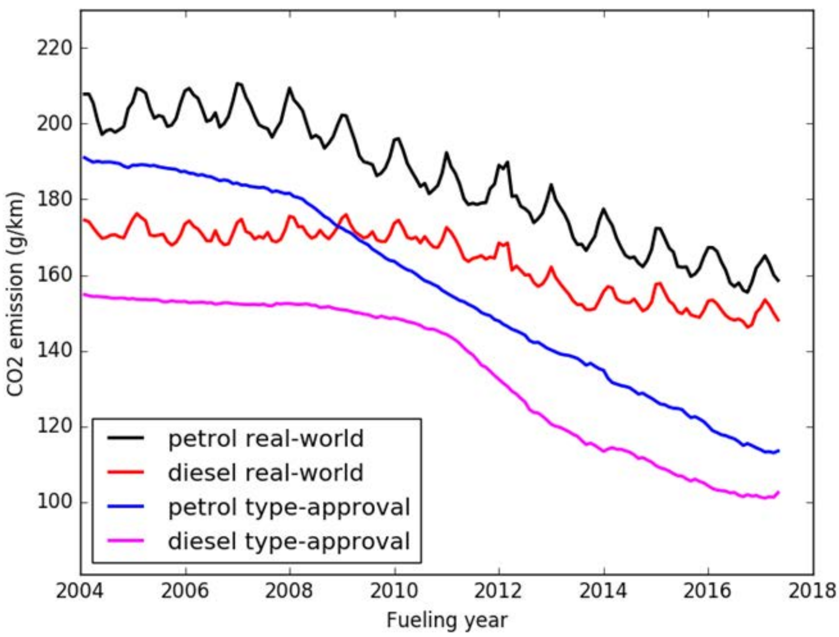


Figure 4-1 There is a clear downward trend in fuel consumption and CO_2 emissions of vehicles, despite the increase in weight, with seasonal variations. These reductions, however, do not follow the trends set out by type-approval results. The real-world CO_2 discrepancy amounts to about 30 g/km, while for diesel vehicles this is reduced by the increase in weight[4]

For most of this report, the unit of g per kg fuel is retained, to have analyses based on the purest possible emission data, and thus not influenced by fuel consumption modelling. Only for average results, the conversion to g/km is made and should be treated as an estimation. Given that two-thirds of the fuel consumption is related to the vehicle weight, limited benefit from engine efficiency improvements may be expected, because weight reductions are negligible. If the proper average weight is used to determine the average fuel consumption, the average g/km will be approximately right. But brands that sell heavier cars will have an underestimation of their g/km, due to the higher fuel consumption. Therefore, using an average fuel consumption rather than a vehicle-specific fuel consumption will generate a larger spread and it may generate a bias for vehicle brands that are heavier or lighter than average. For these reasons, it is appropriate to use a good estimate of the vehicle fuel consumption for individual vehicles.

Vehicle mass will also affect the emission rates itself, as shown for the Flemish remote sensing dataset in Figure 4-2. For Euro 5 diesel cars, NOx emissions increase with weight and power demand from 11 to 16 g NO_X per kg fuel. For Euro 6 diesel cars, with more constant emissions per kilometre (and thus fulfilling the legal requirements better, as heavier vehicles need to comply with a lower emission limit when it is expressed in gNO_X/kg fuel), the NOx to fuel emission ratio is considerably lower, i.e. going: from 9 to 5 g NO_X per kg fuel from the lightest to the heaviest vehicles.

[4] See TNO report 2018 R10371

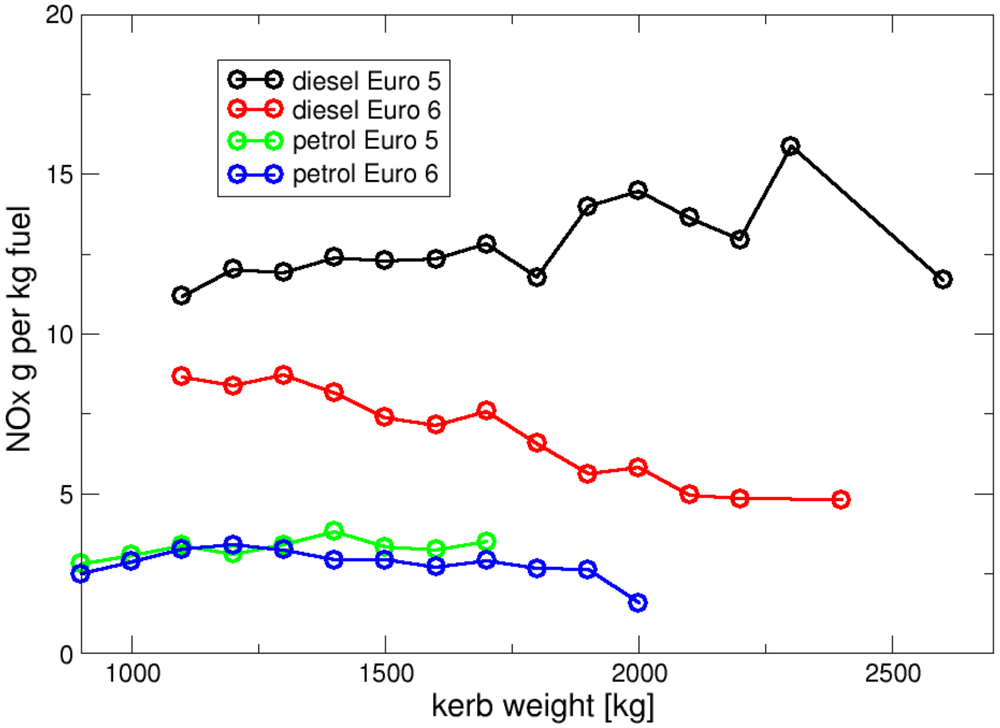


Figure 4-2 Average emission ratios per weight class[5]. Data derived from the Flanders remote sensing dataset. Only weight classes with 100 or more measurements are included.

[5] Kerb weight is the total mass of a vehicle with standard equipment and all necessary operating consumables

4.2 THE GENERAL STATISTICS FOR THE FLEMISH DATASET

In this overview, we present the most important findings from the general statistics and discuss the trends that are reported for the Belgian and Dutch motorised vehicle fleet. Table 4-1 consists of background information on the test campaign, for which two EDAR units were consecutively used on the five different test locations across Flanders.

Table 4-1: EDAR Data statistics for Flanders

Flemish RS Campaign	
EDAR units	2
Test locations	5
Data collection days	22
Attempted measurements	210,246
Interfering exhaust plumes	2,330
Low CO_2 emission	18,493
Unreadable license plate	457
Valid measurements	188,966
Unique vehicles identified	146,365
Unique vehicles identified twice	18,895
Unique vehicles identified three times	5,227
Unique vehicles identified more than three times	3,382
Number of samples for vehicles sampled more than once	70,105

A graphical presentation of the distribution of the valid samples per vehicle category and fuel type is given in Figure 4-3. Note that passenger cars represent most of the dataset, although heavy goods vehicles (HGV) show a significant share of the total as well. This is mainly due to the sampling along motorways as this was done in Aalst and Antwerp. In this way, HGVs are for the first time sampled in such large numbers, while the higher engine loads of every vehicle category during motorway driving can also have an impact on the emissions sampled, as discussed further on. As expected, diesel technology represents a vast share of the measurements as it remains the most prominent fuel type in Flanders.

Whereas we distinguish passenger cars (PC), light-commercial vehicles (LCV), heavy goods vehicles (HGV), and buses, we also reported a minor share of powered two-wheelers (PTW) consisting of mopeds and motorcycles. Given their low sample size, we did not include buses and PTWs in our analysis. The same counts for registrations of vehicle categories O and T. The exclusion of this group of vehicles results in a mismatch between the total valid samples highlighted in Table 4-1 and the total depicted in Table 4-2.

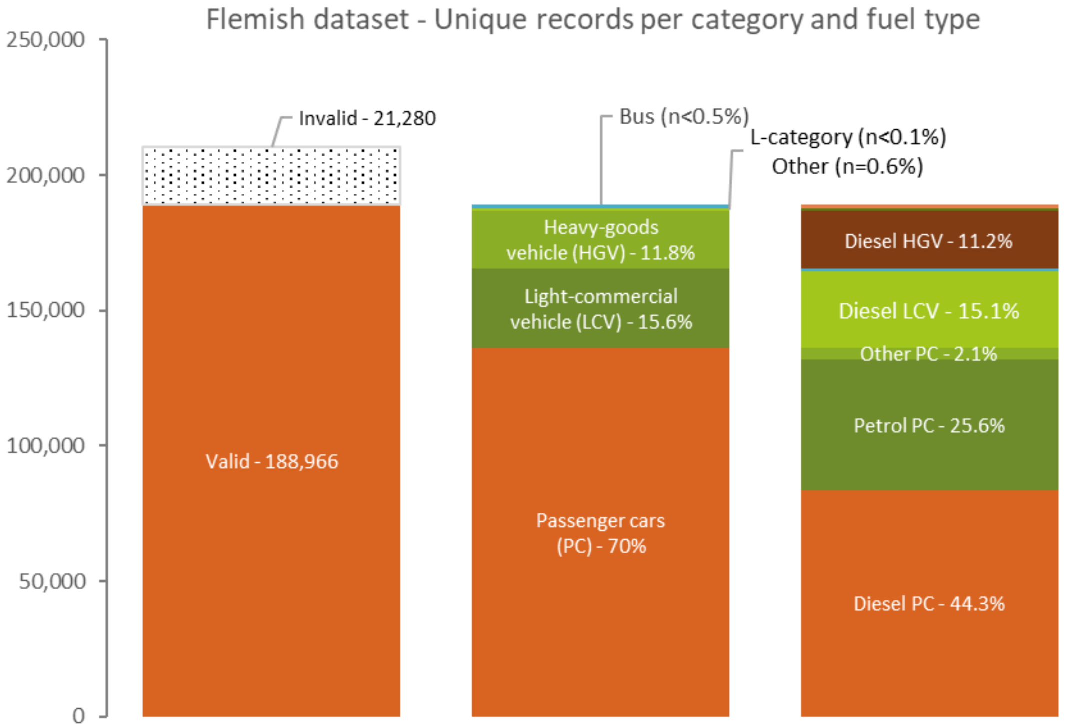


Figure 4-3: Overview of the vehicles registered in Belgium and the Netherlands, which were sampled in the Flemish remote sensing campaign

4.3 CHARACTERISTICS OF THE SAMPLED FLEET

Table 4-2 summarises the distribution of the sampled vehicles according to the Euro class and fuel type. This distribution is further visualised in Figure 4-4. Note that, for passenger cars, we report a relatively young fleet with nearly half of the sampled cars belonging to the Euro 6 sub-classes. This can be explained by the large number of salary cars registered in Flanders[6]. For LCVs and HGVs, a similar trend is seen. Moreover, most of the substantial set of HGVs is observed on motorways. In comparison, the number of trucks in urban conditions was very small.

Table 4-2: Overview of the sampled vehicles per vehicle category, fuel type, and Euro class

Vehicle category	Fuel type	Pre-Euro	Euro 1	Euro 2	Euro 3	Euro 4	Euro 5	Euro 6 a,b,c	Euro 6d-temp	Euro 6d	No data	Subtotal
PC	**PC total**	**428**	**384**	**1,915**	**5,038**	**23,121**	**38,097**	**55,206**	**11,272**	**233**	**295**	**135,989**
	diesel	116	84	563	3,498	14,999	26,887	32,642	4,781	82	125	83,777
	petrol	312	300	1,352	1,539	8,095	10,730	19,923	5,755	117	169	48,292
	hybrid petrol/electric					14	394	2,292	514	34		3,248
	hybrid diesel/electric						50	216	142			408
	CNG				1	12	32	132	80		1	258
	flex-fuel E85					1	2	1				4
	No data						2					2

[6] For more information visit www.ecoscore.be

LCV	**LCV total**	**82**	**70**	**333**	**1,487**	**4,663**	**10,710**	**11,586**	**200**	**8**	**291**	**29,430**
	diesel	73	65	313	1,468	4,609	10,575	11,017	166	8	289	28,583
	petrol	9	5	20	19	53	122	469	27		1	725
	CNG					1	13	95	5		1	115
	hybrid petrol/electric							4				4
	hybrid diesel/electric							1	2			3
HGV	**HGV total**	**34**	**18**	**131**	**852**	**1,187**	**5,426**	**13,626**			**69**	**21,343**
	diesel	34	18	131	852	1,187	5,424	13,531			69	21,246
	CNG						2	94				96
	petrol							1				1
No data	**No data total**										**1,089**	**1,089**
	no data										1,076	1,076
	petrol										8	8
	diesel										5	5
Bus	**Bus total**		**2**	**8**	**60**	**52**	**268**	**503**			**3**	**896**
	diesel		2	8	60	52	268	496			3	889
	CNG							6				6
	hybrid diesel/electric							1				1
MC	**MC total**	**4**	**2**	**10**	**61**	**43**	**1**	**4**			**2**	**127**
	petrol	4	2	9	61	43	1	4			2	126
	diesel			1								1
O2	**O2 total**										**61**	**61**
	no data										61	61
O4	**O4 total**										**28**	**28**
	no data										28	28
T1	**T1 total**										**1**	**1**
	diesel										1	1
L1	**L1 total**				**1**							**1**
	petrol				1							1
O3	**O3 total**										**1**	**1**
	no data										1	1
Total		**544**	**474**	**2,387**	**7,437**	**29,023**	**54,499**	**80,921**	**11,472**	**241**		**186,998**

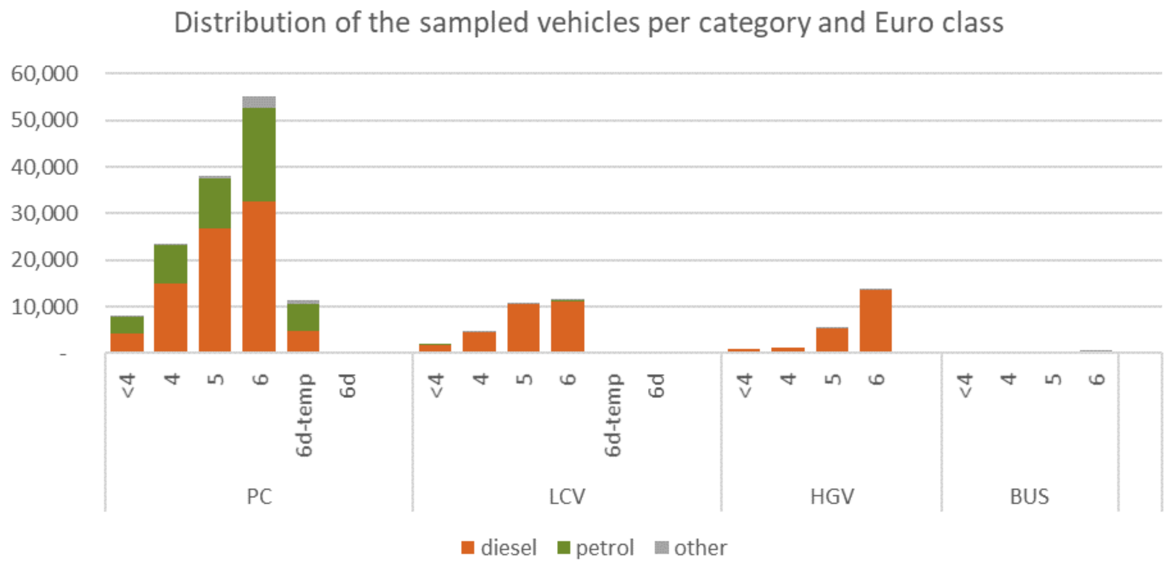
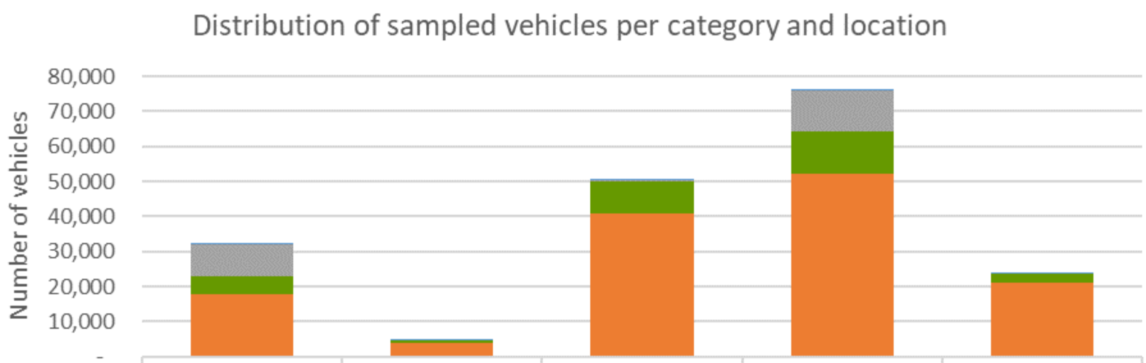


Figure 4-4: Graphical overview of the distribution of the measurements per category, fuel type, and Euro class

Note that a low number of Euro 6d vehicles was sampled during this campaign, although for Euro 6d diesel samples at least, there is no certainty that they effectively belong to this group. The reason here can be a faulty data transfer by the national vehicle registration service. Therefore, no analysis will take place on the Euro 6d passenger cars present in the dataset.



	Aalst	Antwerp N186	Antwerp Tunnel Exit	Bruges	Ghent
Bus	387	42	23	388	56
HGV	9,266	30	80	11,913	54
LCV	5,283	470	9,225	12,061	2,391
PC	17,638	4,054	40,948	52,216	21,132

Figure 4-5: An overview of the number of vehicles per category that passed the sampling unit per location

Figure 4-6: Speed distributions per test location

4.3.1 Average emission ratios

The official date for transitioning to the new WLTP and RDE emission legislation was September 1st, 2018. As such, all vehicles registered after that date should comply with the new legislation. In reality, there are several loopholes to that requirement, for example the end-of-series registration that can last up to a year, and the fact that vehicles can have partial compliance to the new legislation. This means that for the majority of the vehicles, the real transition to the new legislation occurred in the third quarter of 2018 (see Figure 4-7). As such, cleaner vehicles entered the market from December 2017 to Spring 2019. Consequently, 2019 was the first year of RDE-compliant vehicles. Given this introduction of Euro 6d-Temp vehicles, it is unlikely Euro 6d vehicles were introduced far ahead of the official date of 1 January 2020.

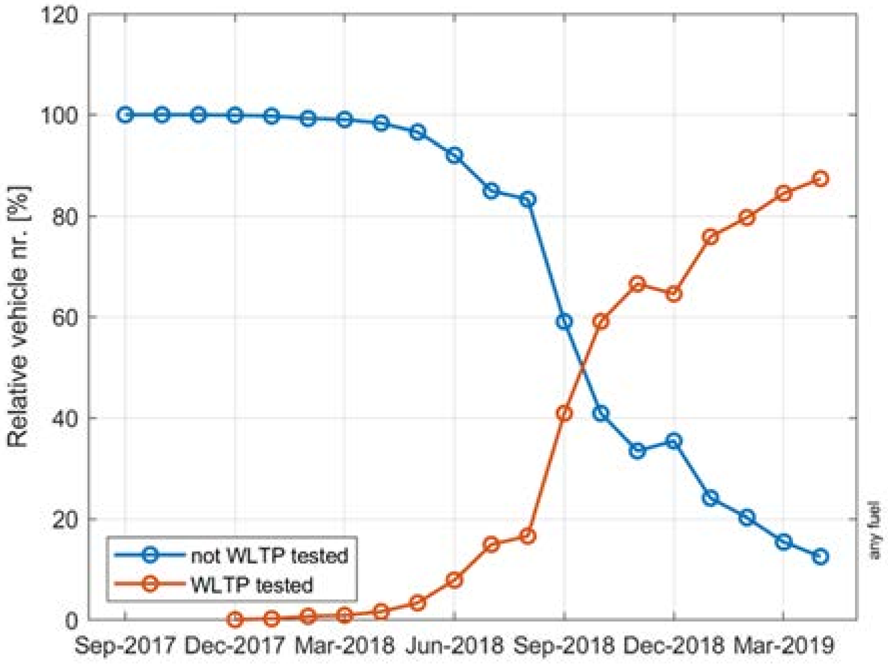
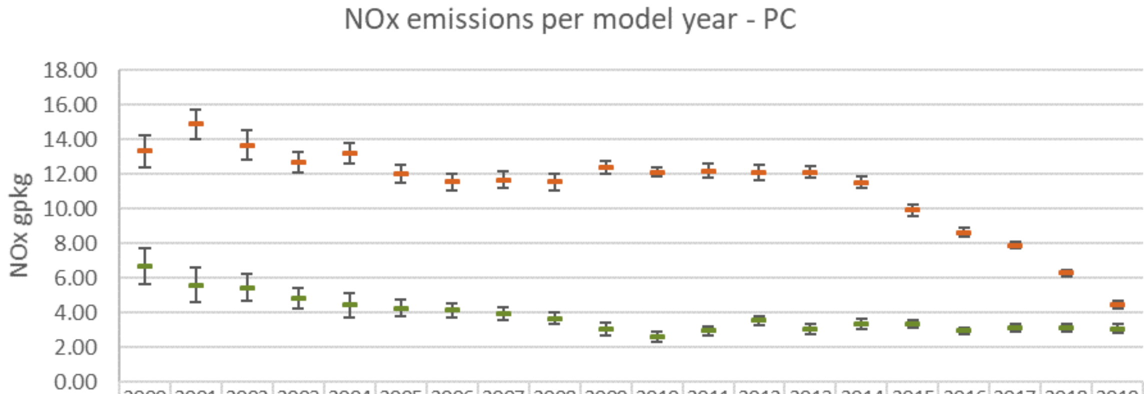


Figure 4-7 The registration in the Netherlands of vehicles complying with the new legislation, WLTP, and for most vehicles also RDE.

It is expected that diesel vehicles registered in 2019 should be substantially cleaner than vehicles introduced in the years before. Current vehicles must comply with RDE legislation, including a temporary NOx limit of 168 mg/km (considering a conformity factor of 2,1), over a full trip and the urban part of the trip. These are average emissions that translate into about[7] 3.4 g NOx per kg fuel (with 20 km on 1 kg of fuel, or 17 km per litre diesel fuel). On a short trip, or in a snapshot during remote sensing campaigns, emissions can nonetheless be higher although this does not have direct consequences in terms of compliance. That is because an RDE not-to-exceed limit applies to average emissions from the vehicle concerned, and this over a full valid trip and the full urban part separately. Thus, a snapshot measurement is insufficient to prove a non-compliance of the manufacturer. Some of the high emissions could be attributed to defective (or tampered) vehicles being driven. However, when a significant number of elevated emissions is observed for a particular vehicle model, this should give rise to follow-up investigations to rule out a possible non-compliance of the model concerned with the type-approval legislation. The recently introduced in-service conformity (ISC) framework provides member states and other stakeholders with the possibility to perform such tests on vehicles subject to RDE-ISC legislation (i.e. Euro 6d). European legislation also obliges member states to organise market surveillance including such ISC emission tests. It may however be that these vehicles satisfy the RDE requirements but do perform worse in normal use. Hence, the restrictions of the RDE tests can also be the cause of the observed difference.

[7] As mentioned in part 4.1, the conversion of the emission limit expressed in g NOx/km to g NOx/kg fuel results in a variation of the limit which depends on fuel consumption (and thus, vehicle weight).

4.3.1.1 Nitrogen oxides (NOx)



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Diesel	13.3	14.8	13.6	12.6	13.2	12.0	11.5	11.6	11.5	12.4	12.1	12.1	12.1	12.1	11.5	9.91	8.64	7.89	6.29	4.47
Petrol	6.70	5.59	5.46	4.80	4.44	4.27	4.15	3.94	3.68	3.03	2.62	2.97	3.54	3.03	3.36	3.37	2.95	3.12	3.14	3.09

Figure 4-8: Overview of the evolution of NOx emissions for passenger cars over the different model years sampled. The results show the model year averages for petrol (green) and diesel (orange), for which a spread is given representing the 95% confidence interval.

The fact that the diesel passenger cars registered in 2019 show an average emission of 4.47 g NOx per kilogram fuel raises some concern. This is about 30% above the 168 mg/km RDE-limit for compliance or about 3.4 g/kg for a diesel passenger car with an average fuel consumption of 5 l/100 km. Nevertheless, the measurements do not meet the RDE test requirements in any way. The reasons for the elevated average measurement result can be numerous. There can be a bias in the test, such that the measurement result deviates from the average emission obtained over longer driving. For obvious efficiency reasons, remote sensing installations are deployed on sites where emissions are likely to occur, preferably during a mild uphill slope. Such driving conditions normally constitute only a minor part of an RDE test. Vehicle manufacturers may also have optimised the vehicles specifically towards these RDE test requirements, where, for example, velocities over 60 km/h only occur after half an hour of driving. Moreover, a 90-minute RDE test has sections of very low NOx emissions when the engine is not under load. The average of this test will, therefore, be lower than a measurement under load as it is typically seen in remote sensing. On the other hand, the results are an indication that, even if these vehicles meet the RDE requirements, the RDE results generally do not translate into real-world emission performance nor do they reflect the requirement in Euro 5/6 that vehicles should meet the emission limit in normal use, throughout the normal lifetime. This plot basically says that if one deviates from the RDE test protocol, you will find other, higher results. If any conclusion can be drawn regarding the NOx emission of diesel vehicles from 2019, it is that the RDE legislation is neither robust nor transparent.

Nonetheless, we do report a further reduction of the average NOx emission by diesel passenger cars over the model years. As such, these findings confirm the general trends seen in other studies, while offering insights into the recent Euro 6d-Temp technology's potential. What catches the eye is how diesel and petrol car averages seem to converge, indicating that stricter RDE requirements tend to have a positive impact. For petrol cars, no significant changes can be seen over the last 10 - 15 years, given that three-way catalyst technology for bringing down NO_x (and CO and HC) is robust and petrol NOx emission limits have not changed over the last decade. Occasionally, petrol vehicles are equipped with special technologies that deviate from the traditional stochiometric three-way catalyst systems, e.g. with lean-burn operation and storage catalysts. They may give higher NO_x values, in particular on motorways. With RDE legislation, however, manufacturers are likely to use properly dimensioned and more robust systems again, as these vehicles can be tested in in-service conformity RDE tests by independent parties at higher power demands. The use of this kind of technology may affect vehicle emissions. Likewise, variations in durability can lead to varying results.

What also catches the eye in this campaign using EDAR equipment is a reported higher measured average percentage of nitrogen dioxide (NO_2) in petrol NO_x measurements than NO_2 estimations used in other remote sensing campaigns. For petrol cars, the NO_2 share constitutes 21% on average of the total NOx (Figure 4-9). This is in stark contrast to a share of about 7% which is typically used for calculating national emission inventories by EEA[8]. This may also explain, in part, why the Flemish dataset shows higher petrol NO_x emissions, compared to datasets where NO_2 is not measured but estimated, using an assumed fixed fraction of 8%, as was the case for Euro-1 and Euro-2. For each vehicle category, the NO_2/NO_x ratios are given in Table 4-3. It is expected that with the ageing of the vehicles, the NO_2/NO_x ratio decreases as the oxidation catalyst's efficiency decreases. Diesel particulate filters typically rely on NO_2 for regenerating.

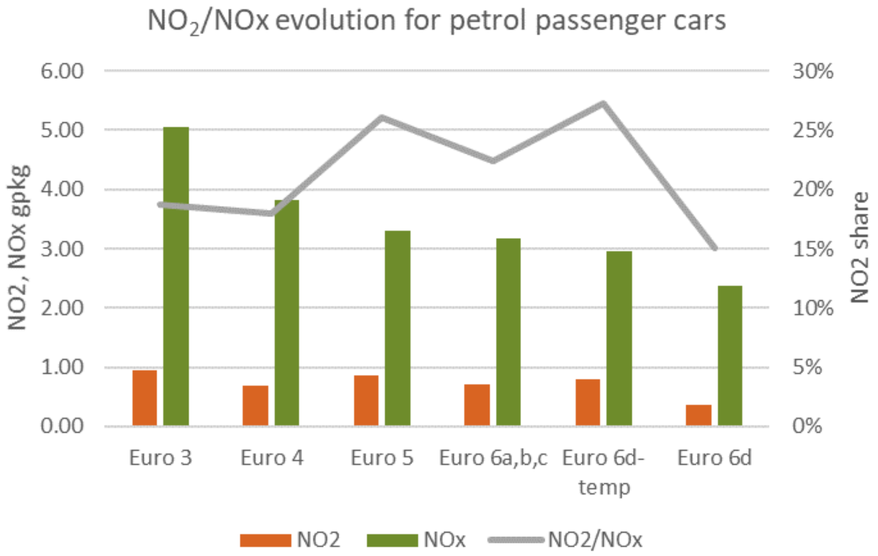
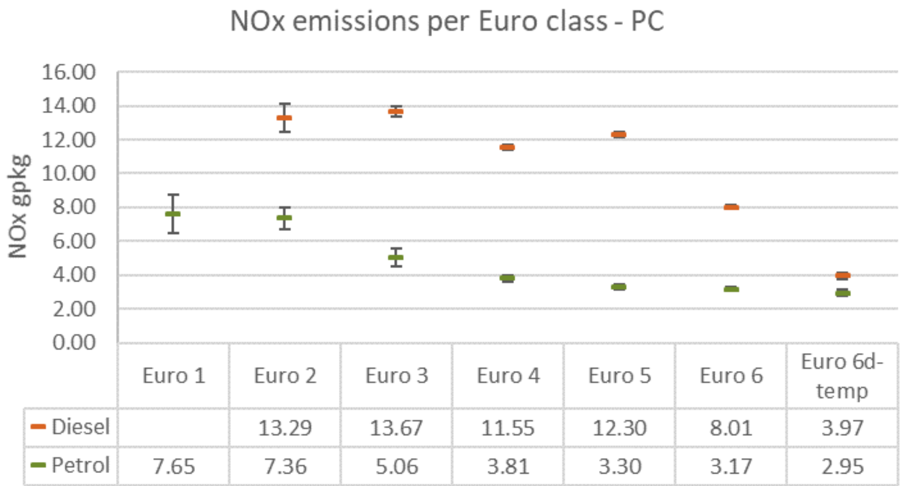


Figure 4-9: Overview of the average NO_2/NOx ratio per Euro class for petrol cars

Table 4-3 NO_2/NO_x ratios of all categories with sufficient measurements.

NO_2/NOx fraction	Heavy-duty			Light-duty	
	bus	truck	van	diesel	petrol
Euro 0					10.0%
Euro 1					6.4%
Euro 2		23.2%		14.7%	12.7%
Euro 3		7.2%	19.7%	22.9%	18.1%
Euro 4		10.2%	33.0%	31.9%	17.7%
Euro 5		10.3%	20.6%	23.3%	27.0%
Euro 6	23.2%	36.4%	26.3%	24.4%	23.4%

[8] See the EMEP/EEA Air pollutant emission inventory guidebook (Section 1.A.3.b.i-iv Road Transport 2019)



	Euro 1	Euro 2	Euro 3	Euro 4	Euro 5	Euro 6	Euro 6d-temp
Diesel		13.29	13.67	11.55	12.30	8.01	3.97
Petrol	7.65	7.36	5.06	3.81	3.30	3.17	2.95

Figure 4-10: Overview of the evolution of NOx emissions per Euro class for passenger cars. The results show the averages for petrol (green) and diesel (orange), for which a spread is given representing the 95% confidence interval.

Plotted per Euro class, the results in Figure 4-10 show average NOx emission rates for those Euro classes for which more than 300 samples were found in the Flemish dataset. As such, insufficient Euro 6d passenger cars were reported. Following the earlier given numerical example, a diesel car with a 5 l/100 km fuel consumption and emitting 168 mg NOx/km (which is the RDE emission limit, taking the applicable conformity factor into account), translates to approximately 3.4 g NOx/kg fuel. As such, the average Euro 6d-Temp diesel cars sampled in the Flemish test campaign are close to this value.

For petrol cars, the average NOx emission for Euro 6d-Temp is about 25% less than what is seen for diesel variants. As such, petrol car emissions are higher than expected. As discussed in section 4.5.3 ‘High-emitter impacts’, averages for petrol cars are heavily influenced by a small share of high-emitters. Also, the fact that a substantial part of the Flemish remote sensing campaign took place on motorways allows for new insights as previous studies focused on urban emissions. As such, motorways NOx emissions for petrol technology are found to deserve extra attention.

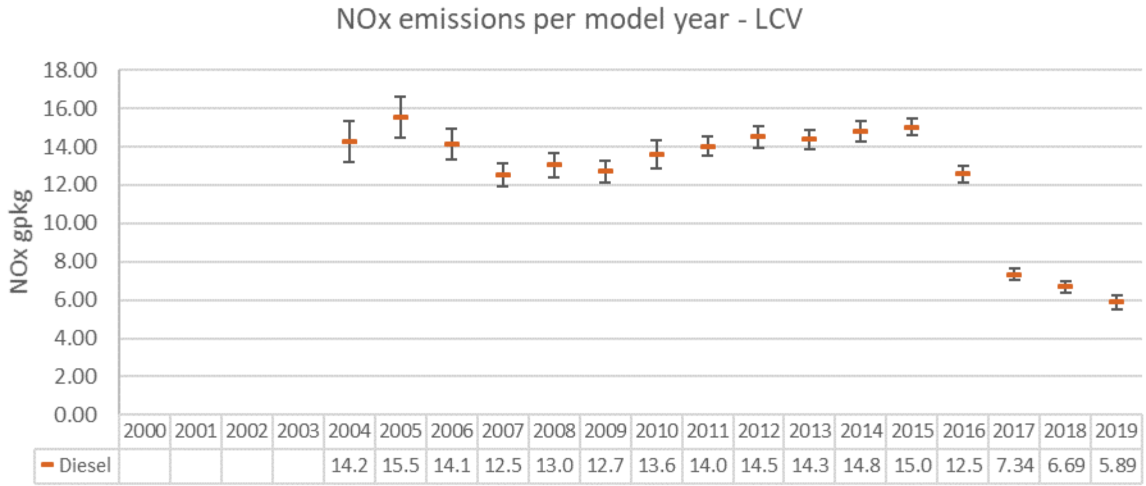


Figure 4-11: Overview of the LCV evolution per model year for NOx. The results show the model year averages for diesel technology (orange), for which a spread is given representing the 95% confidence interval.

Diesel light-commercial vehicles (LCV), or vans, have received little attention in the years leading up to 2014. Moreover, in emission legislation, vans have had more lenient emission limits, tests, and introduction dates. This is likely the reason why the sampled LCVs have very high real-world NOx emissions for each Euro class. On the other hand, Euro 6 legislation for LCVs was the first round of emission legislation to be released after the 2015 diesel scandal, with an all-vehicle registration date being September 2016. Despite similar legislation as for the 2014 first-generation Euro 6 passenger cars, Euro 6 LCVs perform better than the smaller diesel passenger cars that entered the market a year earlier, continuing in 2017. Nonetheless, both are well above any limit. The reported improvement can only be explained by the public attention for NOx emission by diesel vehicles. RDE legislation for LCVs, on the other hand, is lagging that of passenger cars, and no RDE-compliant LCV was on the road during the measurements.

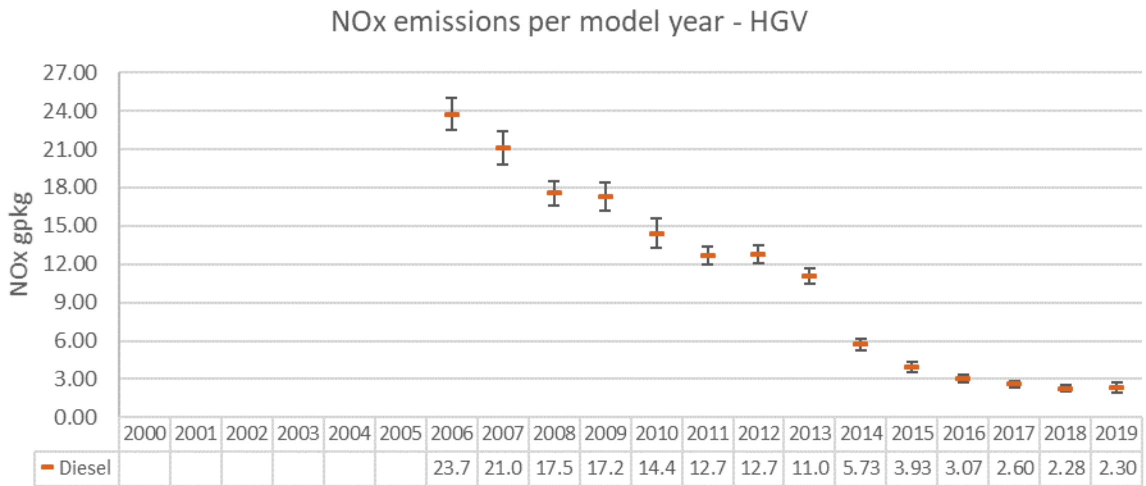


Figure 4-12: HGV evolution of NOx emissions per model year sampled. The results show the model year averages for diesel technology (orange), for which a spread is given representing the 95% confidence interval.

For heavy goods vehicles (HGV), the average NOx emissions reported per model year show a steady reduction to very low averages for Euro VI technology (as of 2014 for all new HGVs). This trend confirms that Euro VI legislation is respected, and emission control strategy works for both laboratory and real-world situations as this is also shown in other studies. It must be stated, however, that the heavy-duty emission averages presented here are dominated by measurements taken on motorways (i.e. near Aalst and Antwerp). Remote sensing data collected in urban conditions (site: Ghent) show much poorer Euro VI NO_X emission performance, although only 54 such measurements were performed, indicating that this might be a point of attention for future investigations.

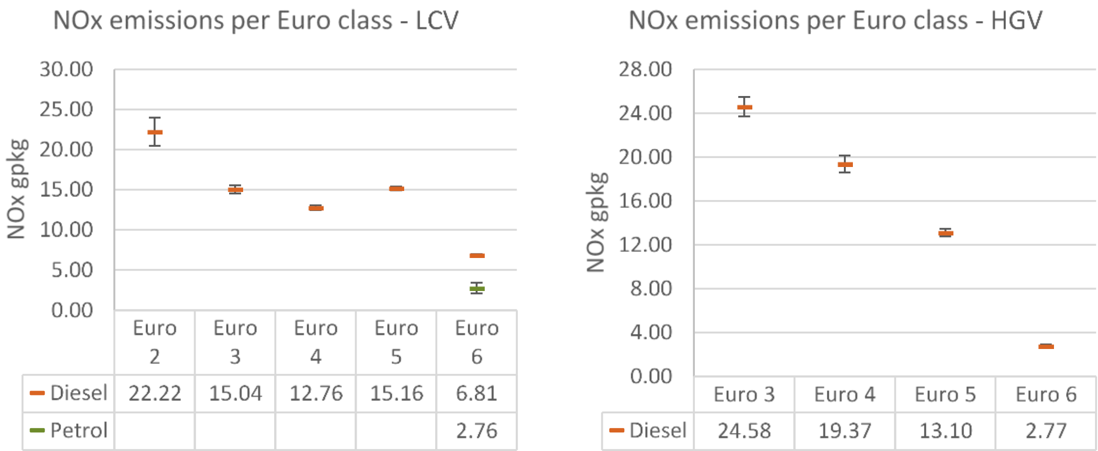


Figure 4-13: Overview of the evolution of NOx emissions per Euro class for vans (left) and trucks (right)

For light-commercial vehicles (LCV) and heavy-good vehicles (HGV), the distribution of the NOx emissions per Euro class shown in Figure 4-13 indicates how Euro 6 LCV emissions are significantly lower than for the previous classes, although the average remains high. Nearly 500 petrol-fuelled LCVs were sampled as well, for which the average NOx emission aligns with passenger car (PC) counterparts. For HGV, Euro VI technology clearly allows for very low NOx averages (during motorway driving).

4.3.1.2 Particulate matter (PM10)

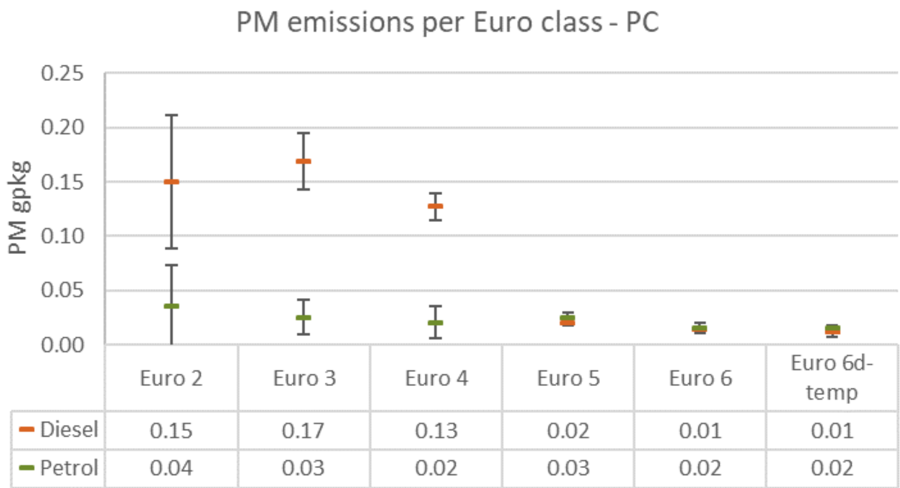


Figure 4-14: Overview of the evolution of PM emissions per Euro class for passenger cars

Concerning particulate matter (PM) emissions, Figure 4-14 clearly shows the effect of the diesel particulate filter's introduction from Euro 5 onwards, following the decrease in officially allowed PM emissions from 25 mg/km to 5 mg/km. As such, Euro 5 and 6 diesel cars, which typically have high engine-out particle emissions, end up having very similar PM emission as petrol cars, i.e. close to zero. As will be discussed in section 4.5.3 'High-emitter impacts', a small share of high-emitters tend to represent a substantial share of the cumulative emissions. This impact can be expected with extremely efficient technologies such as DPFs, as illegal removal of it (tampering) may lead to an increase in PM emissions by a factor of 100 – 200, while particle number (PN) emission may increase by a factor of 1,000 – 10,000[9]. Note that for the sampled Euro 4 fleet, a share of diesel cars was originally brought on the market without DPF technology as the 25 mg/km emission limit did not necessarily require it. Based on the Belgian and Dutch vehicle registration data, however, no distinction could be made between Euro 4 diesel cars with a DPF and those without it. For light-commercial vehicles (LCV) and heavy goods vehicles (HGV) a very similar effect of the DPF introduction is observed (see

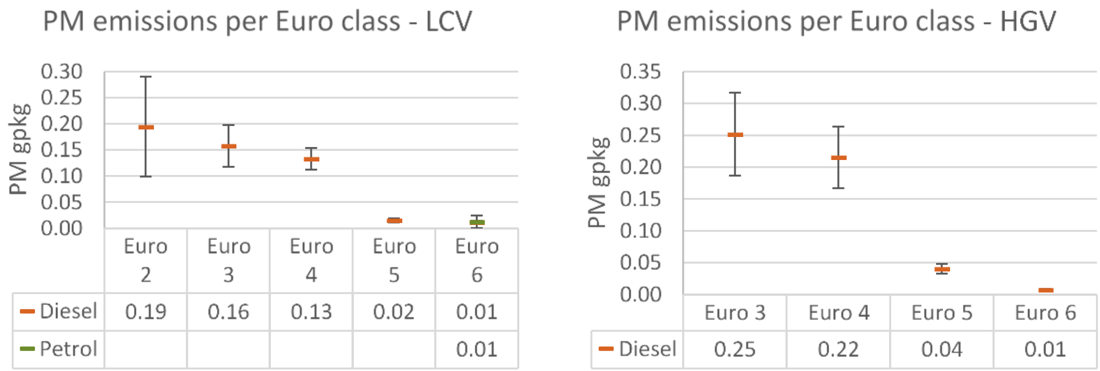


Figure 4-15 below).

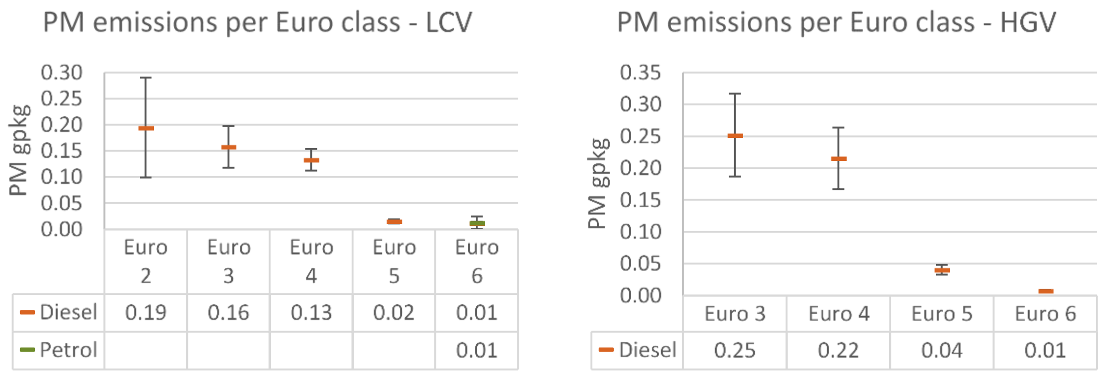


Figure 4-15: Overview of the evolution of PM emissions per Euro class for vans (left) and trucks (right)

4.3.1.3 Particle number (PN) relation to PM(10)

In the EDAR system, the light scattering of particles at different wavelengths is used to determine PM emissions. However, at the basis of this methodology are the particle numbers (#), based on scattering from small particles for which typical size and characteristics of diesel particles are used. So, the PM emissions have a direct relation to PN emissions:

$$1 \text{ mg (PM)} = 4.8 * 10^{12} \text{ \# (PN)}$$

The PN standard is used for the assessment of automotive particle filters. A broken filter will have a steep increase in particle numbers, in particular during idling and at low engine loads. In these cases, a functioning filter has about 1,000 #/cm^3, while a broken, or absent filter, easily leads to levels of 1,000,000 #/cm^3.

The observed PM emission levels for diesel passenger cars of 10 mg/kg fuel, or about 0.5 mg/km, would translate to 2.4 * 10^{12} #/km. The emission limit is 0.6 * 10^{12} #/km. This is very close to the

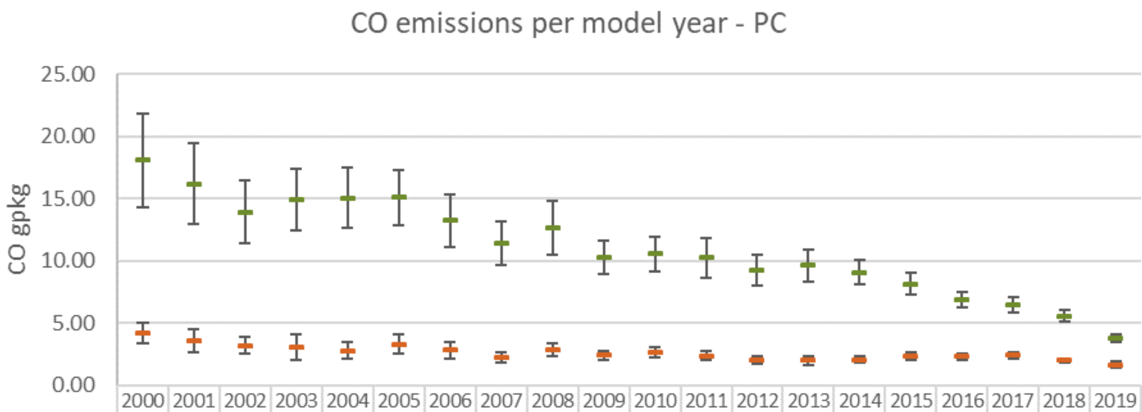
[9] See TNO 2019 R10825v2 Emissiefactoren wegverkeer - Actualisatie 2019

detection limit and the background emissions, e.g. from wear. The higher reported values, associated with defects and tampering, are more relevant in terms of enforcing proper vehicle maintenance. Here, remote sensing can help to select vehicles that should be invited for PTI testing of particle filters on the vehicles. This, nevertheless, only makes sense if a PN emission test takes place during PTI.

It must be noted that PM, and especially, PN emission measurements performed in the laboratory and with PEMS is underestimating the total PM and PN emissions in normal ambient conditions. In the laboratory, the exhaust gas is heated and, possibly, diluted before these measurements take place. Consequently, the more volatile particles, and volatile parts of particles, have been removed in standardised automotive measurements. In remote-sensing, it is expected that such contributions of volatiles add to the total. Therefore, they are deemed to be closer to real-world PM and PN emissions.

4.3.1.4 Carbon monoxide (CO)

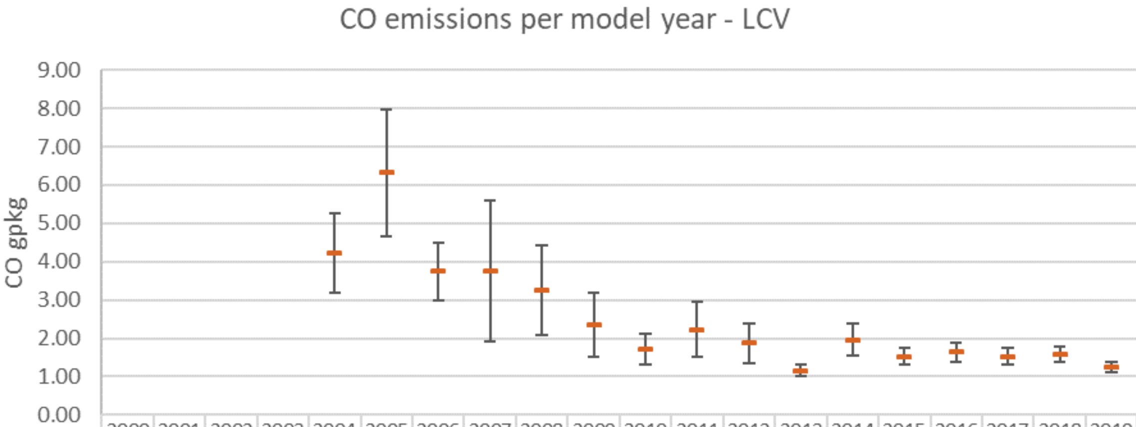
Concerning the emission of carbon monoxide (CO), the evolution per model year as per Euro class is shown in the figures below. Given the higher health impact of other pollutants released into the atmosphere such as NO_X and PM, currently, CO emissions do not enjoy the same focus. Generally speaking, remote sensing results for CO show measurements that are far below the applicable emission limit[10]. High emission events of this pollutant may indicate durability issues with, for example, catalysts and engines. Elevated CO emissions could also indicate the use of undesirable fuel enrichment strategies in petrol cars, which increase fuel consumption and thus adversely affect pollutant emissions. The introduction of RDE is considered to have played a role in limiting the use of such strategies in petrol cars.



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Diesel	4.19	3.56	3.18	3.08	2.78	3.27	2.80	2.23	2.82	2.40	2.66	2.37	2.00	1.99	2.04	2.35	2.32	2.41	1.97	1.66
Petrol	18.0	16.1	13.9	14.9	15.0	15.1	13.2	11.4	12.6	10.2	10.5	10.2	9.23	9.61	9.08	8.14	6.90	6.46	5.56	3.75

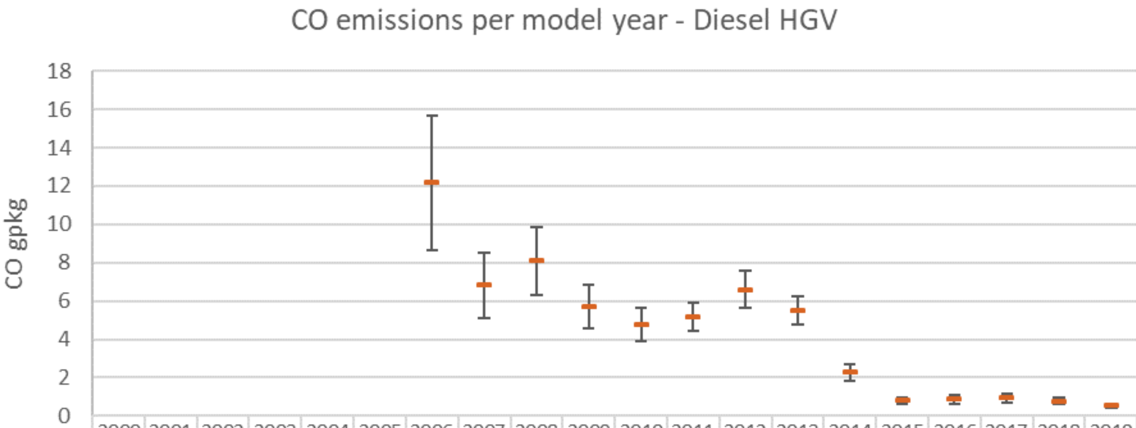
Figure 4-16: Overview of the evolution of CO emissions per model year for passenger cars. The error bars depicted show the 95% confidence interval.

[10] For a 7 l/100 km consuming petrol car, a CO-limit of 1 g/km equals about 19,3 g/kg. This limit has applied since Euro 4



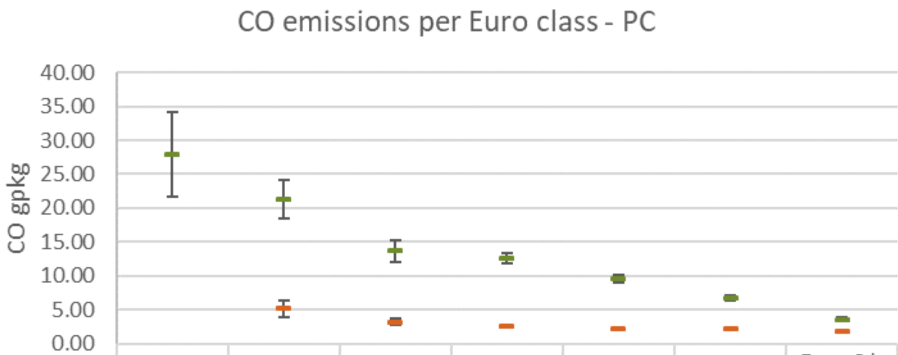
	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Diesel					4.23	6.32	3.74	3.75	3.25	2.34	1.72	2.23	1.87	1.16	1.96	1.52	1.63	1.53	1.59	1.24

Figure 4-17: Overview of the evolution of CO emissions per model year for light-commercial vehicles. The error bars depicted show the 95% confidence interval.



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Diesel							12.2	6.82	8.08	5.71	4.77	5.19	6.61	5.49	2.27	0.79	0.86	0.93	0.78	0.53

Figure 4-18: Overview of the evolution of CO emissions per model year for heavy goods vehicles. The error bars depicted show the 95% confidence interval.



	Euro 1	Euro 2	Euro 3	Euro 4	Euro 5	Euro 6	Euro 6d-temp
Diesel		5.16	3.23	2.59	2.16	2.28	1.78
Petrol	27.98	21.34	13.72	12.63	9.65	6.72	3.62

Figure 4-19: Overview of the evolution of CO emissions per Euro class for passenger cars. The error bars depicted show the 95% confidence interval.

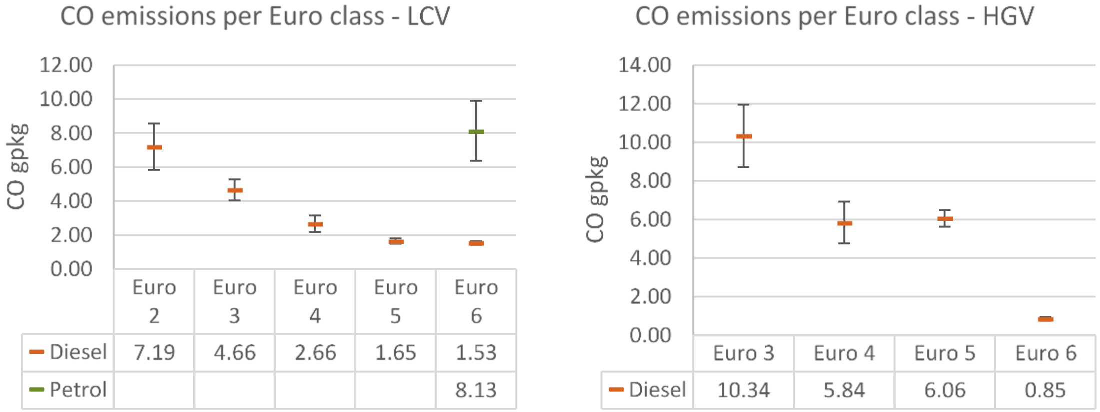


Figure 4-20: Overview of the evolution of CO emissions per Euro class for light-commercial vehicles (left) and heavy goods vehicles (right). The error bars depicted show the 95% confidence interval.

4.3.1.5 Hydrogen Carbons (HC)

For the emission of unburned hydrocarbons (HC), the evolution per model year as per Euro class is shown in the figures below. Given the low overall observed HC emissions, both in this campaign and during RDE PEMS tests, currently, these emissions enjoy less focus as well. High emission events of this pollutant may also indicate durability issues with, for example, catalysts and engines.

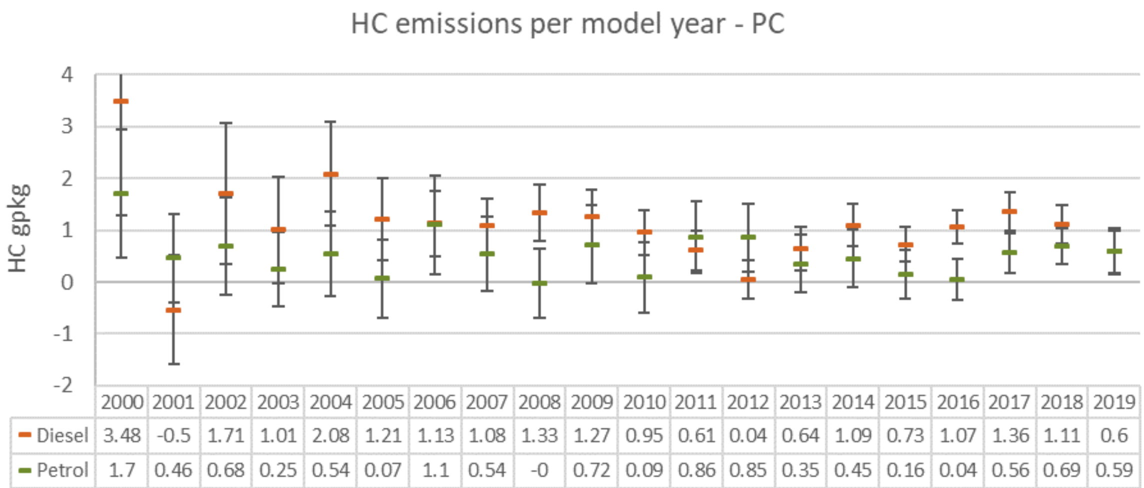


Figure 4-21: Overview of the evolution of HC emissions per model year for passenger cars. The error bars depicted show the 95% confidence interval

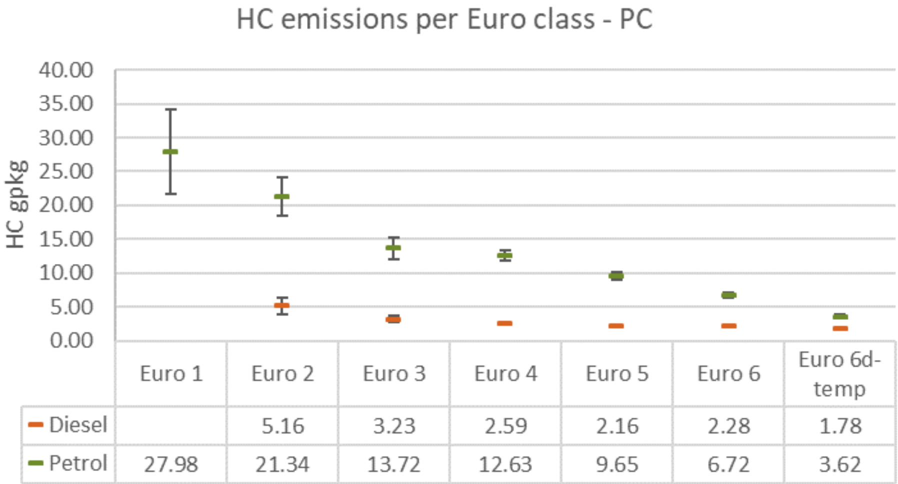


Figure 4-22: Overview of the evolution of HC emissions per Euro class for passenger cars. The error bars depicted show the 95% confidence interval.

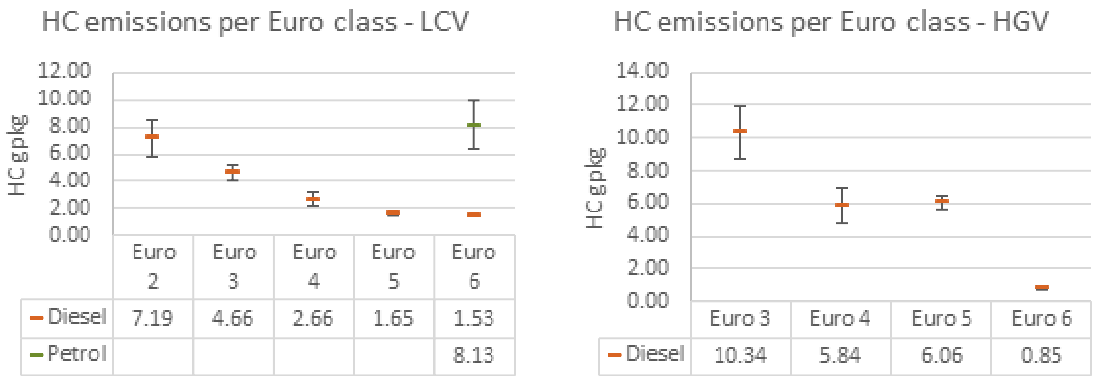


Figure 4-23: Overview of the evolution of HC emissions per Euro class for light-commercial vehicles (left) and heavy goods vehicles (right)

4.3.2 Conversion to mg/km

As discussed earlier in the introduction to chapter 4, a novel way of converting grams per kilogram fuel burned to grams per kilometre driven is proposed. Equation 1 shows how a vehicle-specific fuel consumption in grams CO_2 per kilometre is derived from a model year factor A and a mass factor B that is dependent on the fuel type. Table 4-4 presents an overview of the model year factors per fuel type, for which the situation in 2005 is applied for the four previous years as there were only negligible changes reported for these model years. Table 4-5 in turn shows the mass factor B per fuel type. Based on this equation, a more realistic CO_2 emission factor was calculated for those passenger cars sampled in the Flemish dataset, for which a mass in running order is known. Also, mass registrations exceeding 3,000 kg were deemed unrealistic and therefore excluded from the CO_2 conversion.

Equation 1: The MILE21 methodology for determining realistic CO_2 emissions based on a model year factor and vehicle mass

$$CO_2 = A_{model\ year} + B \times Mass\ in\ running\ order$$

Table 4-4: Model year factor A per fuel type

Year	Petrol	Diesel	Hybrid petrol/electric	Hybrid diesel/electric	Plug-in Hybrid petrol/electric
2005	75.14974	41.66894			

2006	72.55472	40.3163	42.2895058		
2007	70.25439	40.47701	42.60266145		
2008	68.35208	38.46222	47.49482778		
2009	64.44091	34.247	46.92744841		
2010	59.95869	31.28949	40.62240845		
2011	56.89881	29.8628	40.07106072		
2012	51.7704	27.8336	38.00942722		
2013	50.88273	26.7065	41.07286724	-4.974374236	5.39326202
2014	52.182	28.32758	43.6916082	-4.542615182	11.88423361
2015	54.5338	28.60317	39.34722307	-0.438553452	13.90056303
2016	55.11635	32.13934	39.10719573	0.9911797	14.02855696
2017	56.46276	32.3735	44.78461698	0.974513086	13.57212421
2018	52.94272	30.56773	43.70190726	0.974513086	13.30232229
2019	52.0282	30.8085	43.36053944	0.974513086	12.95831374
2020	57.24283	33.13934	60.16439563	0.974513086	13.43597237

Table 4-5: Mass factor B per fuel type

Fuel type	Mass Factor
Petrol	0.08449
Diesel	0.083023
Hybrid petrol/electric	0.06448
Hybrid diesel/electric	0.07504
Plug-in Hybrid petrol/electric	0.075034

Figure 4-24 presents the overview of the average CO_2 emissions per model year and fuel type for the sampled passenger cars, according to the MILE21 methodology. What is important in this figure is how petrol and diesel average converge, even though petrol vehicles typically emit about 17% more CO_2 if we would compare the same vehicles, e.g. a petrol VW Golf and a diesel VW Golf. Diesel vehicles, however, tend to be heavier and larger, annihilating their proclaimed advantage in terms of climate change. This tendency is likely to be at the base of the increasing CO_2 averages from 2012 onwards, with SUVs claiming a substantial share in the annual Flemish vehicle registrations (i.e. from 6% in 2012 to over 18% in 2019).

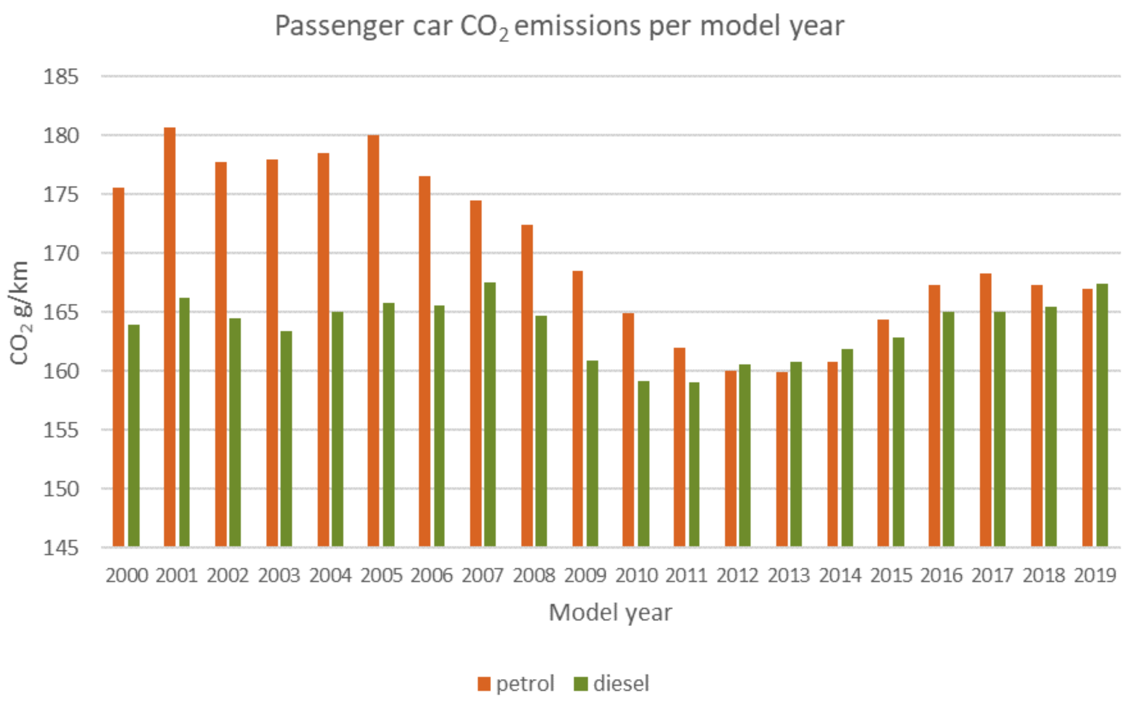


Figure 4-24: Overview of the model year CO_2 averages for petrol and diesel passenger cars according to the Flemish dataset

To determine the average NOx emission in grams per kilometre, beginning from the grams per kilogram fuel emission factors, we start from the model year average emission in g/kg and the conversion of the MILE21-based average CO_2 emission in g/km to a fuel economy expressed in km/kg fuel. Therefore, a fuel density of 0.835 kg/l and 0.74 kg/l is assumed for diesel and petrol fuel, respectively. In terms of CO_2 emissions produced per litre of fuel burnt, we assume 2.65 kg/l and 2.37 kg/l, respectively. The result of this exercise is displayed in Figure 4-25, showing the model year average NOx emissions in grams per kilometre driven for petrol and diesel passenger cars. These show on the one hand how the model year 2019 diesel cars (assumed to be consisting mostly of Euro 6d-Temp) are moving towards the 168 mg/km emission limit, although an exceedance factor of 1.4 remains. For petrol cars, on the other hand, we report an exceedance by a factor of 1.3 to the 120 mg/km emission factor for RDE-compliant vehicles. Nonetheless, these remain *estimations* that should be handled with care, given the significant differences between a remote sensing snapshot and a full RDE test performed on-road.

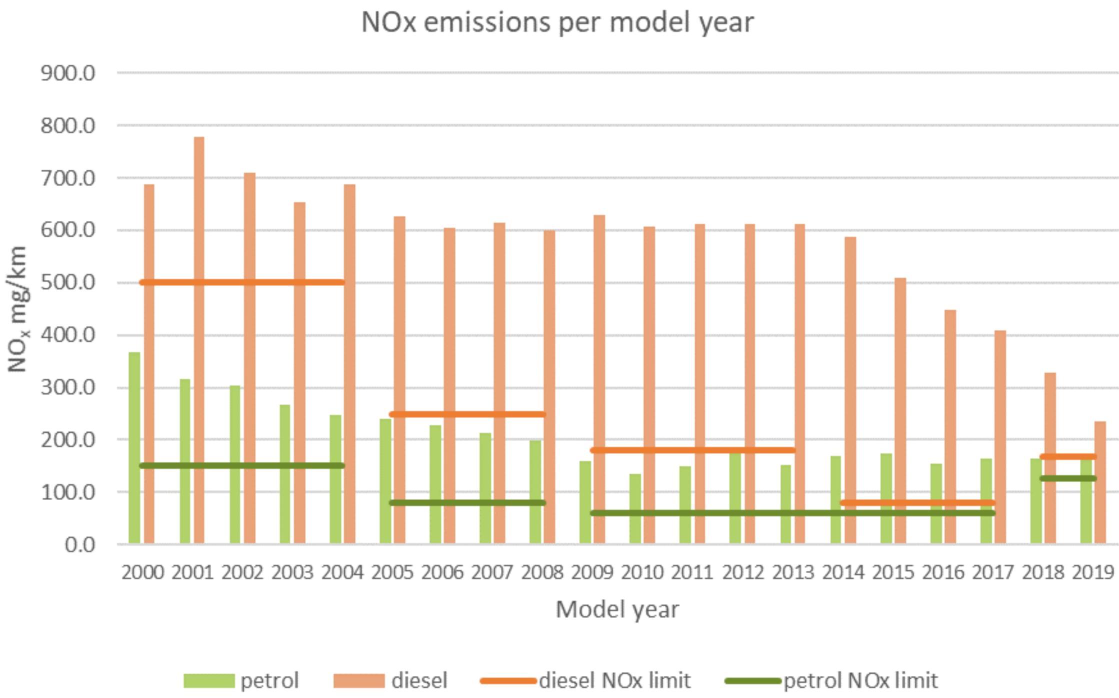


Figure 4-25: Passenger car NOx emission factors in mg/km based on the MILE21 methodology for deriving realistic CO_2 emission factors, per model year and per fuel type for the Flemish dataset. Note that the latest limits take the RDE conformity factor into account.

For heavy-duty trucks, CO_2 emissions and the conversion to a mg/km emission result depends strongly on the total weight of the truck. Since large trucks can carry more than their weight in goods, the emissions in mg/km can vary a factor two with the payload. Following a large monitoring program for heavy-duty trucks[11], Euro V fuel consumption can be estimated using Equation 2.

Equation 2

$$3.1 * FC\left[\frac{g}{km}\right] = CO_2\left[\frac{g}{km}\right] = 26.5 * (0.5 * weight[ton] + 0.05 * Engine\ Power[kW])$$

where FC is the fuel consumption in g/km.

A large tractor-semitrailer, the most common form of heavy goods truck in Belgium, will have an empty weight of 17 to 20 tonnes, depending on the type of semi-trailer. Fully loaded, this weight adds up to 40 tonnes. The rated engine power is around 320 kW. Consequently, CO_2 emissions vary. On motorways, this ranges between 700 g/km and 950 g/km, being a factor 5 to 10 higher than typical motorway CO_2 emissions for passenger cars. Nevertheless, given the large uncertainty of the payload, a conversion to mg/km is not made for heavy-duty vehicles. Euro VI trucks, however, with a typical NOx g per kg fuel of 2.77 g/kg, would have NO_x emissions in the range of 600 to 850 mg/km, similar to pre-euro 6d-Temp diesel passenger cars weighing substantially less.

[11] See TNO report 2016 R10449 Dutch CO_2 emission factors for road vehicles.

4.4 MARKET SURVEILLANCE AND IN-SERVICE CONFORMITY TESTING

On November 5th, 2018, the European Commission published its regulation (EU) 2018/1832 on how vehicle in-service compliance can be checked by independent parties. A year later, on September 1st, 2019, this regulation went into force with the introduction of Euro 6d, indicating that vehicles from this Euro class onwards are eligible for independent testing, i.e. RDE-ISC testing. The remote sensing campaign performed for the Flemish government took place in June 2019, which is why none of the vehicles sampled was yet eligible for further investigation of compliance issues, according to this newest standard. This, nonetheless, should not keep us from proposing a methodology for Flanders to take up this task diligently.

In-service conformity tests for passenger cars and light-commercial vehicles[12] consist of checking real-world tailpipe emissions against the emission limits throughout the normal life of the vehicles up to five years or 100,000 km, whichever comes first. Regulation (EU) 2018/1832 indicates how granting type-approval authorities (for Flanders: *Vlaams Huis voor de Verkeersveiligheid*, residing under the department *Mobiliteit en Openbare Werken* (MOW)) and vehicle manufacturers have shared responsibilities in making sure that from Euro 6d on, vehicles are clean in normal, real-world circumstances. The market surveillance authority's tasks, which are of interest in this study, consist of an information gathering and risk assessment of vehicles to be tested and to enforce remedial measures upon the manufacturer in case of non-compliance. A granting type-approval authority can also use such information to select vehicles it certified for in-service conformity testing. For market surveillance, a minimum of one in every 40,000 new motor vehicle registrations is to be checked, out of which at least 20% shall be emission-related. For in-service conformity, a minimum of 5% of the type-approvals needs to be tested.

In this section, a methodology for a suitable roll-out of measures in the framework of market surveillance is discussed. This is not only needed due to the European Commission's requirements for each member state to take its responsibility in this task but also to stay focused on real-world emissions. The reason hereto is that, generally, the first vehicles under new regulations tend to perform better than the later generations. So, the first RDE-compliant (Euro 6d-Temp) vehicles, even without compliance criteria, are likely much cleaner than later generations. Once the attention slackens and member states consider their type-approval RDE-ISC and market surveillance testing a mere routine task, there will be a sliding scale. Once the first major manufacturer is held responsible by authorities to a lower standard, other manufacturers will follow suit. Therefore, it is important to maintain a higher standard with pro-active surveillance. Remote sensing, and other information linked to emissions in normal use and air quality, can help to retain the sense of impact and relevance. It can also play a pivotal role to assess risks and urgency, and thus ensure an efficient organisation of market surveillance activities.

4.4.1 The potential for implementing remote sensing

High-emission events in a particular group of vehicles, belonging to a fuel and Euro class combination, a specific manufacturer, a specific vehicle model, using a specific engine, or, in the case of RDE-compliant vehicle; a PEMS family, are first and foremost an indication of inferior technology. If, on the other hand, high-emission events occur for a specific individual vehicle only, and this in multiple passages by a remote sensing unit, such events should be related to that vehicle but not necessarily to the technology applied in the vehicle.

[12] LCV class II and III are included, albeit delayed

Inferior technology has many different aspects. A less than robust emission control technology may fail on occasions, leading to temporary high emissions. Moreover, inferior technology will lead to malfunctions, also associated with high-emission events, and possibly to improper repair that causes further problems and subsequent high-emission events. Tampering is generally a way to avoid costly repair of malfunctions, with high emissions as a result. So, in the end, high-emission events that seem systematic for a group of vehicles are very likely caused by a range of problems related to inferior technologies, cascading down in the usage and repair, leading to further increases of emissions.

Therefore, it makes sense to consider cases of tampering also an issue of durability in the framework of in-service conformity (ISC) tests, for which the manufacturer is at least partly responsible. As such, with increasing emission levels in high-emission events, only more responsible parties get involved. Setting different threshold limits in the remote detection of these vehicles is important. An exceedance of three times the emission limit with a confidence level of 95%, could be an initial limit for in-service conformity[13]. An exceedance of five times the limit would suffice for tampering, as emission levels are typically higher. To narrow down the 95% confidence level and obtain a workable cut-point, a sufficiently large remote sampling size would be required, which calls for the implementation of remote sensing over long periods. The lowest limit relates to technology effectiveness and durability, which are the manufacturer's responsibility. For this issue, data of different vehicles, models, or even manufacturers can be combined to provide enough evidence and confidence to pursue further investigations. Higher limits may link to periodic technical inspection (PTI) and refer to individual vehicles. These relate to illegal tampering and driving around in vehicles with a known malfunction, issues that involve the vehicle owner, and which call for police enforcement.

If the emission measurement data of a large group of vehicles are used, the underlying knowledge for deciding for follow-up actions improves. It may increase the confidence or lead to lower limits to be set. But there are few a priori rules on how to use such data. Below, some general principles are discussed.

There is no simple rule for how many measurements are needed for a given level of confidence. Standard statistical methods do not take the whole picture into account. To come up with proper evidence of problems with a certain technology, one needs to answer the following questions:

- How much spread is there in the data for the vehicles under investigation? Is the average sufficiently high compared to the spread? Is the average dominated by a few outliers?
- Is the effect systematic? Is the same result seen at different locations and under different conditions?
- Is the data of the vehicles under investigation significantly different from similar vehicles? Should the criteria of the group be adapted to include or exclude certain vehicles, which may be affected by the same problem? Are the selection criteria for identifying a group also supported by other information, like the technology used?

In principle, the typical variation of a group, i.e. 68% ($\sigma=1$ in a symmetrical distribution around the average, or 84% in a one direction distribution, see Figure 4-26) of the data within a standard deviation of 1 in the case of a normal distribution, can form the basis of initial investigations. The vehicles that have higher emissions than twice this distance from the average ($\sigma=2$), i.e. twice above

[13] For a Euro 6 diesel car the ISC threshold would consist of 240 mg NOx/km + half of the 95% confidence interval that applies to the data sample of the concerned model, resulting in a threshold of 360 mg/km.

the 84-percentile, are candidates for investigation as high-emitters. This is shown in Equation 3. For a normal distribution, this is will be about 2.3% of the data but for the actual data, it will deviate, based on the tail of the distribution.

Equation 3

$$X_{threshold\ "\sigma=2"} = 2 \times X[84\%] - X[50\%]$$

where X[%] represents the lowest emissions up to a given percentile. Samples with emissions above this value should be candidates for further investigation. If this points out that the vehicle has no malfunction or tampering, the investigation can focus on durability and compliance issues.

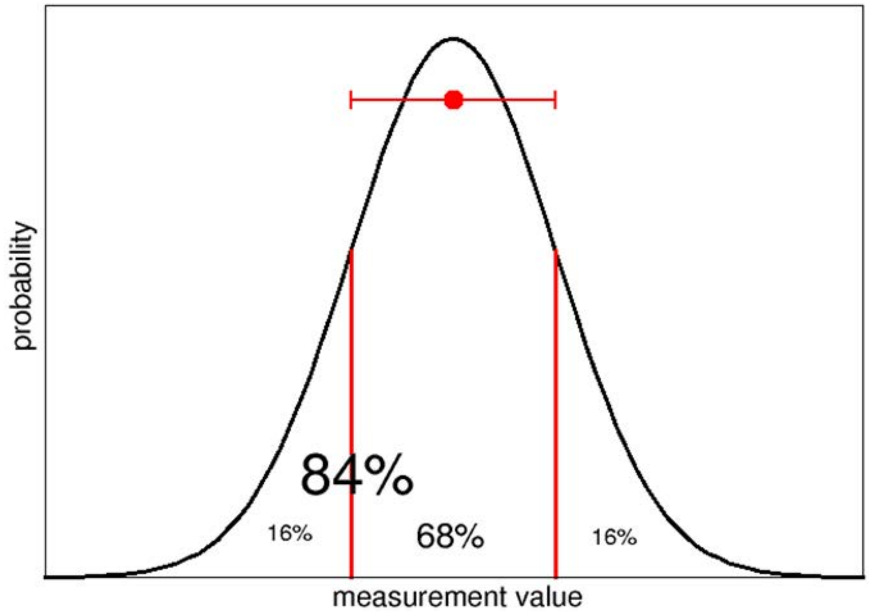


Figure 4-26: Graphical overview of the 1-σ percentile (red) for a symmetrical normal distribution (covering 68% of the data) and for a one-sided normal distribution (covering 84% of the data when excluding the right-hand side half of the bell curve).

In the specific case of the tampering campaign with trucks (discussed in section 4.5.6' Anti-tampering campaign' from p. 110 onwards), the result matches well with the described detection limit for Euro V trucks, based on experience. For Euro VI trucks, the detection limit is slightly lower than the estimate from the data itself, i.e. 7 g/kg instead of 10 g/kg, extrapolating the observed linear trend shown in the bottom graph in Figure 4-27. Based on analyses of the sampled emission data, 7 g/kg does seem an appropriate threshold for Euro VI on a motorway in free-flow conditions.

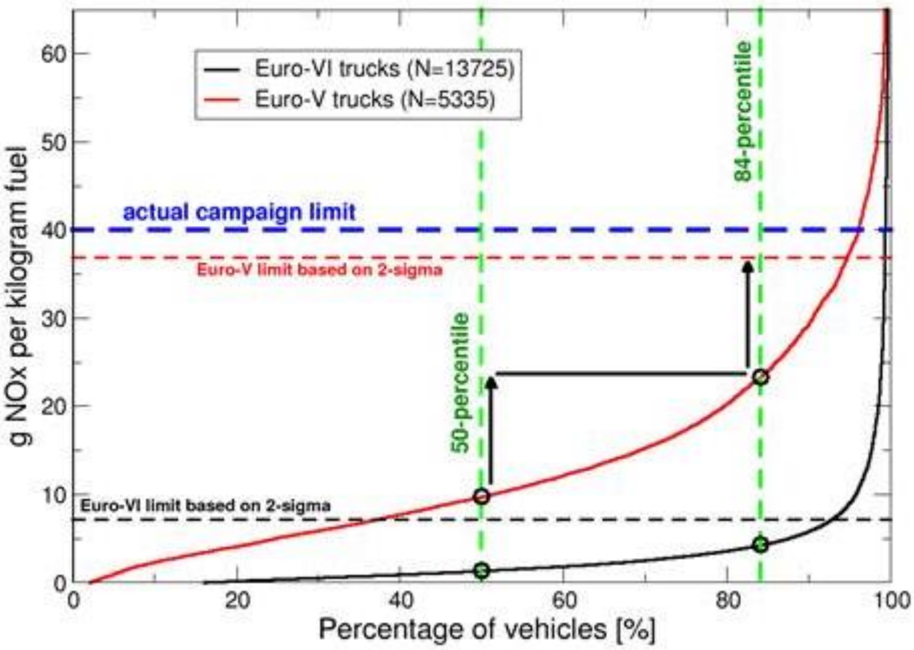


Figure 4-27: Using the difference in values between the 50% and the 84% percentiles as an extrapolation to a "2-σ" threshold for high-emitter identification, this will lead to a similar value that was used in the test campaign.

A similar detection limit for real-time measurements of passenger cars can be determined in future investigations, combining remote sensing with immediate police action during roadside inspections (RSI). Whereas the federal Belgian police already had sufficient experience with assessing tampering issues with heavy goods vehicles (HGV) during RSI, tampering with light-duty (passenger cars and vans) NOx conversion systems like SCR catalysts currently remains unexplored terrain. International experiences in this field should be shared to build up the necessary knowledge.

When market surveillance and anti-tampering campaigns start at a larger scale, each of these investigations can provide information that may allow us to conclude that the cause of a high-emission problem lies in another domain, like compliance, durability, or tampering. It is therefore important to exchange this information and follow up on indications of failure to meet the existing regulations. A dedicated emission database, containing all information systematically coming from roadside and periodic technical inspections, can become vital to this cause. Only with wide collaboration, covering the total use and lifetime of the vehicles, emissions can be curbed effectively.

4.4.2 Using remote sensing to identify problematic emissions

As mentioned earlier, the present dataset does not allow us to discuss insights on possible non-compliances for Euro 6d as the test campaign came too soon for sampling a sufficient amount of these vehicles. Therefore, as an example of typical problems that remote sensing can help to identify, it is better to look at the last pre-RDE diesel vehicles of which enough (minimum 10,000) samples were taken, i.e. those belonging to the Euro 6b class. One way of doing so is by comparing per vehicle make or even per model. In this exercise, a ranking is given for passenger car makes per fuel type and Euro class, as shown in Figure 4-28 and Figure 4-29. Note that only those combinations are considered for which at least 300 samples are found in the Flemish dataset.

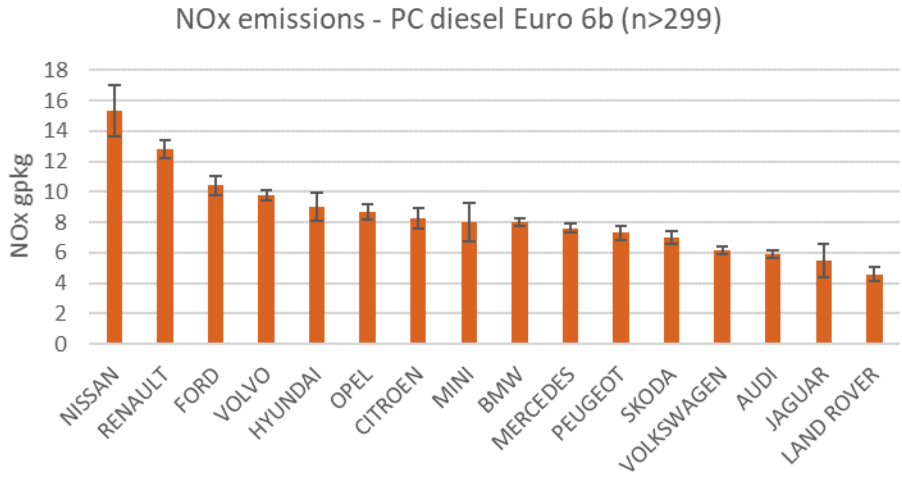


Figure 4-28: Passenger car NOx emissions per manufacturer, diesel Euro 6b

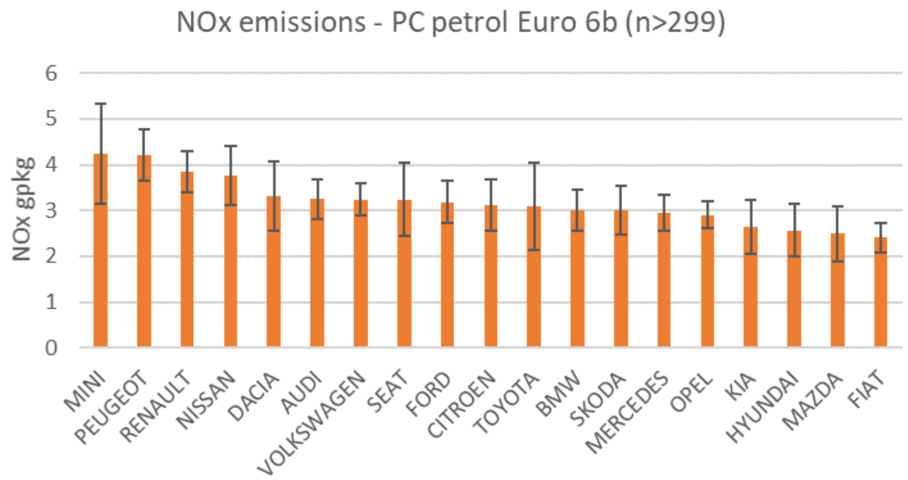


Figure 4-29: Passenger car NOx emissions per manufacturer, petrol Euro 6b

A similar approach for comparing makes and models is what European member states should develop in the light of market surveillance and in-service conformity (ISC) testing. For an ISC risk-based selection protocol, however, part of the necessary data is currently missing. To see if certain emission certificates raise concern, the most efficient approach is to group the measurement data according to the emission certificate, also known as the "PEMS family". Based on new legislation, i.e. the *transparency act*,[14] this kind of information should be available to market surveillance, type-approval authorities, and independent testers. Based on real-world monitoring such as remote sensing, they can see if certain PEMS families have higher emissions than others that must satisfy the same regulation. Note that vehicles from before 2019 are not eligible for independent ISC testing. For these vehicles, however, durability issues can be directed to the granting type-approval authority and the vehicle manufacturer since they are still responsible for the emission performance in normal use over the normal lifetime. In the above exercise of ranking vehicles per make, however, the manufacturer will eventually prove to be too broad a target, and the individual vehicle model, of which there are thousands, too small a target for investigations. Moreover, engines produced by one manufacturer are used widely in many different brands and models. Therefore, the best way to

[14] UNECE Global Technical regulation 15 Amendment 4 and European regulations EC/2017/1151 and EC/2018/1832

investigate issues with emissions and durability is to look at the engine performance in terms of emissions.

Since specific engine types cannot be distinguished via the vehicle registration data, a pragmatic approach is to deduce them from general vehicle characteristics like the Euro class, fuel type, engine volume, and possibly power rating. This procedure is, e.g., followed by the H2020 uCARe project to identify groups of vehicles[15]. Part of this work is a manual check if similar engines are identical, by looking at manufacturer information. This information is used for the analyses presented here. As such, there is a plausible way to identify inferior technology and emission control linked with high emissions. To improve air quality, focussing investigations and testing on vehicles with heavily polluting engines may have the largest impact.

Exemplary for this exercise is Figure 4-30, for which a distinction is made between engines based on their 'engine code'. This code is a compilation of the fuel type, Euro class, cylindric capacity, and vehicle make (i.e. the manufacturer). As such, e.g. the Renault 1,461 cc Euro 6b diesel engine is given as 'd_6b_1461_RENAULT'.

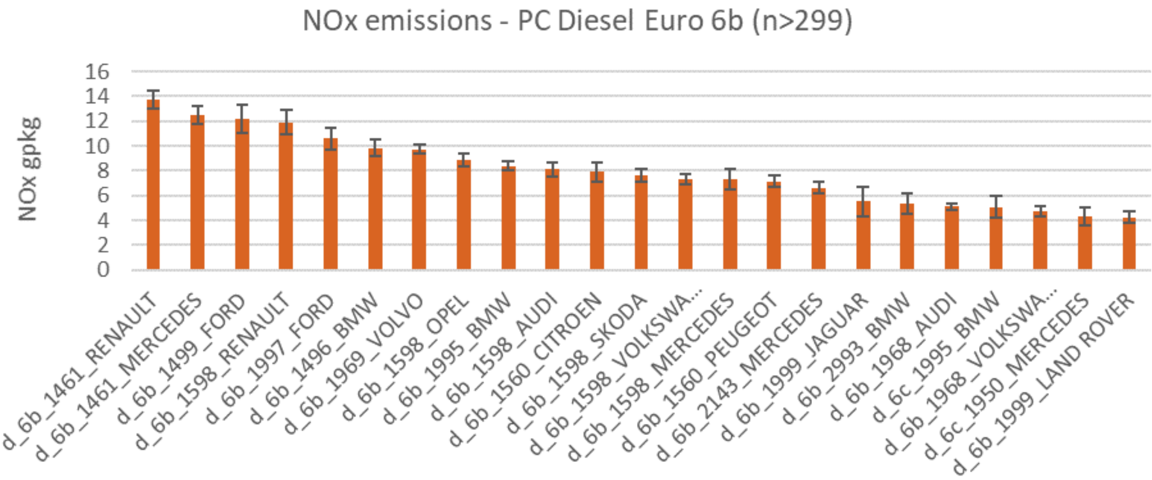


Figure 4-30: Overview of the diesel Euro 6b passenger car NOx emissions per engine type

It is this specific Renault engine that will be discussed in an example case for market surveillance authorities for acting towards a manufacturer. In the wake of the 2015 diesel scandal, many manufacturers implemented better performing emission control technologies. As such, the first generation of Euro 6 diesel light-commercial vehicles (LCV) outperformed the first generation of diesel Euro 6b passenger cars, despite being subject to less stringent NOx standards. Only a few manufacturers did not fully align with the new, perceived responsibilities. In all analyses performed, Renault stands out with the worst-performing Euro 6b diesel vehicles sampled in Flanders. These engines are also used in Nissan vehicles, which therefore have similar high emissions, although insufficient samples were present in the data to highlight this in Figure 4-30. One group of vehicles showing high NOx emissions as well appears to belong to Mercedes Benz, which turns out to have the same Renault engine. These findings on the specific Renault engine are supported internationally by other studies[16]. Despite this kind of evidence, little can be done given that these vehicles cannot be subject to ISC-RDE testing, which is required to determine compliance in a legally binding

[15] Available in uCARe deliverable D 1.1. Refer to: https://www.project-ucare.eu/project-results/deliverables/

[16] See for example, TNO Reports 2020 R10438, 2017 R11473, and 2016 R11177.

procedure. This problem differs from durability issues, where vehicle performance deteriorates. The new framework for market surveillance and independent testing should change that.

All the evidence shows the Renault diesel Euro-6b models, in particular with the 1,461-cc engine, are among the worst-performing diesel cars in Flanders for NO_x emissions in normal use, with limited change after the diesel scandal. The average NOx emission of the whole group of vehicles is 8.0 g/kg. Values above 12 g/kg (50% higher) for the Renault and the Mercedes Benz are not necessarily outliers given the spread in the group. Based on Figure 4-30, however, these vehicles do stand out. Also, they have a significant impact on air quality due to their prevalence. Despite any formal requirement, a market surveillance authority may consider investigating such a vehicle and act upon the findings. The British market surveillance authority has done so and has built up experience with market surveillance since 2017[17]. If such vehicles, vehicle groups, manufacturers, or manufacturer groups show up in future remote sensing campaigns and those vehicles are eligible for RDE-ISC, the procedure is in place to declare the vehicle's type-approval invalid and enforce remedies. Such a system may be an initial deterrent for manufacturers to have reduced emission control in normal use. However, if nobody is taking up the task of following up on indications of inferior emission control, this deterrent will soon evaporate. It may even be that vehicles in different countries may perform differently, based on the attitude of the national market surveillance and type-approval authorities. Already now, there seem to be differences in practice and standards among the different type-approval authorities, which seems to have led manufacturers to take their type-approval business to other member states. As such, a race to the bottom in terms of leniency during emission testing continues[18].

Given the long history of poor emission performance of vehicles in normal use, proper active market surveillance and a diligent type-approval authority seem needed to ensure that a high standard of emission control is maintained. This task will only work if indications, like those of remote sensing measurements, are available to steer investigations towards the vehicles and engines that do not comply with a standard that is considered appropriate for the protection of air quality and the environment. Without these general public interests of emission legislation in mind, other aspects may shift the focus to technical difficulties and economic interests. Therefore, broad, and representative measurements, like remote emission sensing, are needed, to provide the facts as a basis to act upon.

[17] See also https://www.gov.uk/government/publications/vehicle-market-surveillance-unit-programme-results-2018
[18] See Hooftman et al (2018): A review of the European passenger car regulations – Real driving emissions vs local air quality

4.4.3 Setting up a holistic market surveillance system

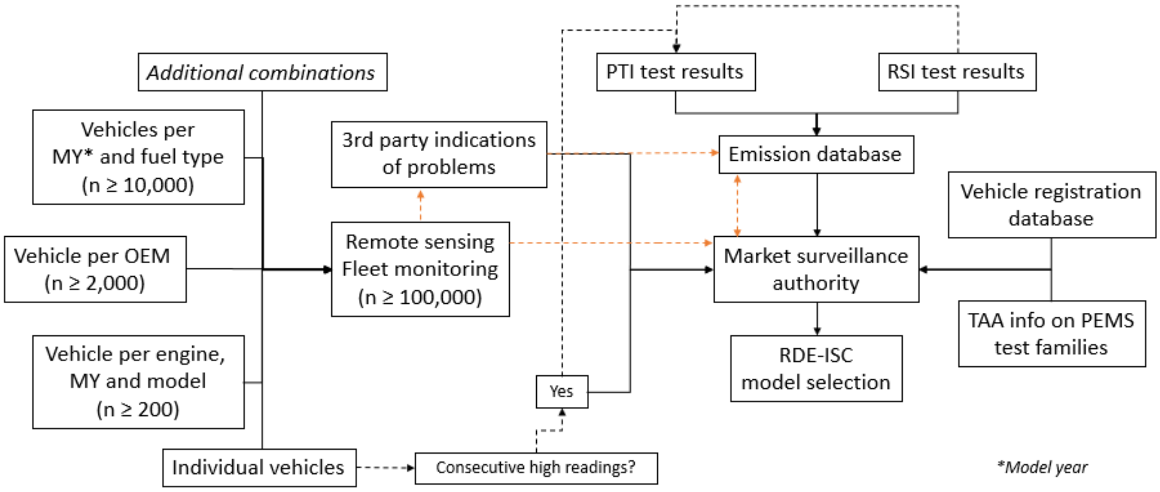


Figure 4-31: Flow chart for a data-driven market surveillance

A long-term market surveillance structure is presented in Figure 4-31, focussing on remote sensing on the one hand, and structured feedback from periodic technical and roadside inspections on the other hand. *Long-term*, because such a scheme requires quite some changes on a regional level for Flanders to align all contributing sources to the market surveillance authority, both practically as legally. Concerning remote sensing input, one must start with a sufficiently large test population. A minimum size of 100,000 is given, although a multitude is recommended according to the level of detail for the planned investigation. As such, insights in emission trends per model year and fuel type, as discussed for instance in Figure 4-25 on p. 55, require at least 10,000 samples to allow for solid conclusions. If investigations are to be focussed on specific manufacturers, at least 2,000 vehicles of that manufacturer should be sampled. Finally, if one wants to discuss the environmental performance of specific engine types and models per model year, at least 200 samples are recommended per combination. Again, these population sizes are minimum values, whereas higher amounts allow for better insights.

In the case of multiple passages of individual vehicles, consecutive high readings should be an incentive for inviting the owner for an additional periodic technical inspection (PTI). The multiple passages should ensure that there is sufficient confidence the vehicle has a problem that would lead to failure on the PTI test. Hence, the PTI tests determine the components to be assessed and thresholds for the limit. As discussed in parcel II of this study, also the PTI's emission test should evolve towards an effective tool to filter out high-emitting modern vehicles, including a particle number (PN) count for addressing diesel particulate filter (DPF) failures/removals and a novel test to make sure selective catalytic reduction (SCR) systems are in a proper state of operation. The same is true for petrol cars, which require a thorough check of the functionality of their three-way catalyst (TWC). Both PTI and roadside inspection (RSI) assessments should serve as an input to a structured emission database. Remote sensing data may help to provide further indications. As such, durability issues may come to light that require action by a market surveillance authority. Following regulation (EU) 2018/1832, third party indications of emission-related problems can serve as an important input to market surveillance as well. The orange dashed lines in Figure 4-31 indicate that remote sensing data also needs to be incorporated in the emission database, although post-processing of the data should take place first. Validation can be done by competent third parties and/or the market surveillance authority.

In the shorter term, a few parameters need further development and are therefore not of use, e.g. the structured feedback from PTI/RSI. Therefore, a first fall-back is the vehicle registration database for selecting vehicle models to be tested for ISC. This approach, however, is not what is desired as such a 'random' selection is not driven by indications of emission problems and would not comply with the notion of a robust risk assessment as required by Regulation (EU) 2018/858. A much more effective approach, which is readily available in short term, consists of remote sensing. This allows categorising models/engines that require follow-up testing to make sure they comply in real-world conditions.

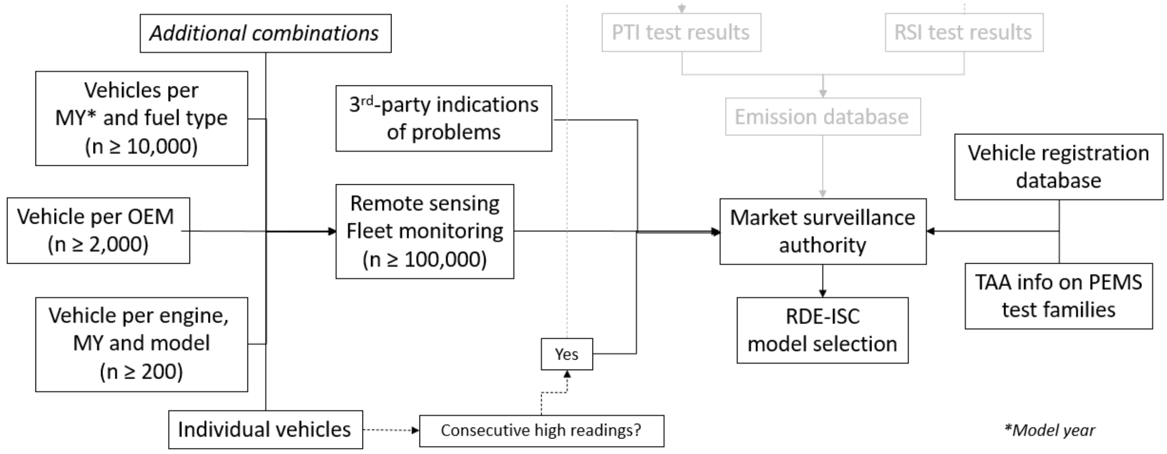


Figure 4-32: Short-term implementation strategy for market surveillance

A closer look at the consequences that can be given to a registered high-emission event is given in Figure 4-33. This flow chart has two major pathways, i.e. the RDE-ISC pathway and the police investigation one, in case of certain suspicion of tampering. For the former, we start with the question of whether the same individual vehicle showed high-emission events. If so, and if consistent high readings occur, a PTI test should be scheduled. In case the high-emission readings do not trace back to the same individual vehicle, it can be interesting to investigate whether similar high-emission events can be reported for the same vehicle *model*. If so, and if also here consistent high readings occur, such a vehicle model would be suitable for re-testing in case it is eligible for RDE-ISC (Euro 6d and younger). If an older vehicle appears on this radar, an investigation for durability can be instigated. Finally, in case no consistent high readings occur, the test conditions, during RDE-ISC testing where some freedom in testing exists, may need revision to check whether the problem returns for vehicles of the same category (e.g. Euro 5 diesel cars).

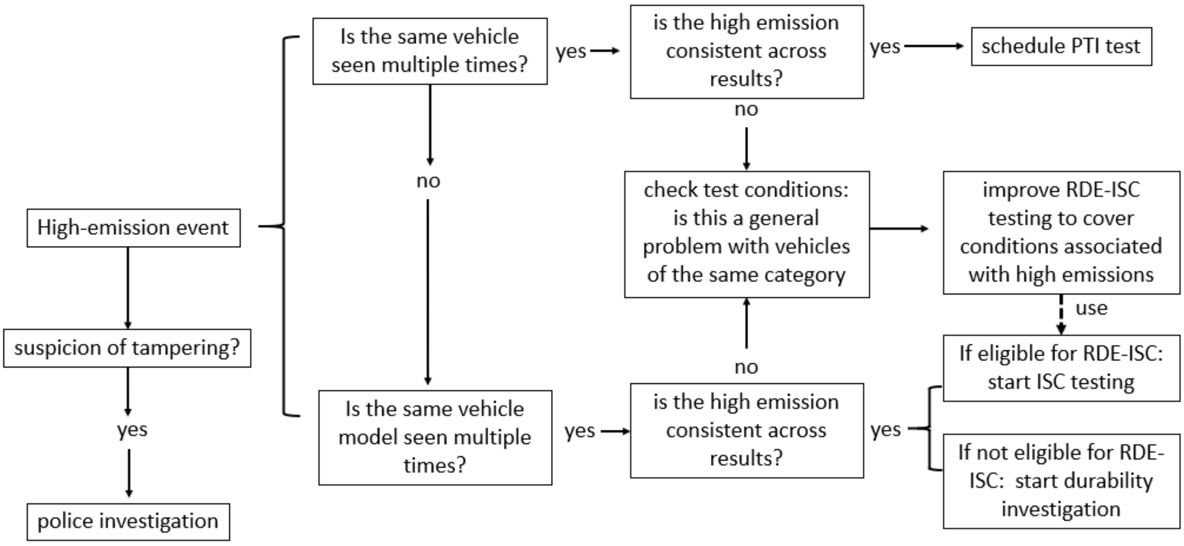


Figure 4-33: Close-up on high-emission events

4.5 TYPICAL VS. HIGH-EMITTERS

4.5.1 Assessing pollutant emissions using probability density functions

Whereas the previous figures in section 4.3.1 show generalised and averaged insights per Euro class and fuel type, a lot more information is hidden in the spread of emissions, for instance *within* a certain Euro class. To emphasize the weight of high-emitters on the outside boundaries of the spread, a presentation using the probability density function is proposed. If vehicles become cleaner, singular events or singular vehicles with high emissions become more relevant for the overall or average performance of a vehicle group. This may be linked to specific issues with emission control, malfunctions, tampering, or improper repair. Once vehicles are generally clean, addressing these problems is the next step to further reduce the impact of their emissions. The former is not the case yet, as diesel passenger cars before Euro 6d-Temp (and to a lesser extent these as well) are found to have high NOx emissions on average. Nonetheless will this section be dedicated to the impact of high-emitters on the total averages, so we can confirm whether a small percentage of (most likely tampered) vehicles may have a substantial impact.

The probability density function, i.e. the symmetrical bell curve, is generally assumed to follow from standard statistics, for instance to present a normal distribution. Applying such a probability density function on vehicle exhaust data, however, does not show the expected distribution. This probability density function was compared to Gamma distributions in the past[19], whereas for the analyses presented here, piece-wise exponential distributions were used. The reason is that today's emissions mitigation systems are more efficient than those studied when the Gamma functions were applied. As such, when they malfunction or break, the difference in emissions becomes more extensive, making the outliers contribute more disproportionally to the fleet average. Consequently, few events of high emissions may occur and affect the average significantly. In statistics, this is known as 'thick' and 'long' tails in distribution plots, i.e., a small group of high emissions, still large enough or with sufficiently high emissions to affect the average results.

Investigation on the emission performance of the vehicles represented in the Flemish remote sensing dataset shows that older diesel vehicles (pre-Euro 6d-Temp) with high NO_x emissions have tails that fall off rapidly, indicating that these tails contribute little to the overall results as the bulk of the emissions can be found around the average of the sample population. Here, the tails show an exponential decay of probability for higher values. For all other emissions and vehicle categories, the tails are thick and long, indicating that for older diesel vehicles NOx emissions are generally high and high-emitters have less impact on the averages compared to cleaner technologies. This, nonetheless, may not be misinterpreted in such a way that diesel cars seem to be clean in terms of NOx emissions. On the contrary, this shows that most of the pre-Euro 6d-Temp diesel cars produce (unacceptably) high emissions and require a continuous focus to bring these to acceptable levels.

In many cases, the probability of finding higher emission values tapers off with a power-law decay. Power-law decay curves can have much, even unbounded, emissions in the tail. As such, a few vehicles with very high emissions may dominate the average. In the example of all the sampled data combined in Figure 4-34, the emission levels above 60 g NOx per kilogram fuel are of specific concern. Given modern petrol vehicles typically doing a factor of 20 less, a few per cent of these extremely high-emitting vehicles will affect the total emissions significantly. It is assumed that

[19] Automobile Emissions Are Statistically Gamma Distributed, Y. Zhang, G.A. Bishop and D.H. Stedman, Environ. Sci. Technol., 28:1370-1374, 1994.

maximum NO_x emissions are limited to about 140 g NO_x per kilogram fuel, based on the physical principles of combustion following the Zeldovich equations[20]. With 3500 ppm NO_x and 10% CO_2, the expected maximum NO_x g per kg fuel is 110 g/kg fuel. Indeed, the emission measurement results taper off beyond these numbers.

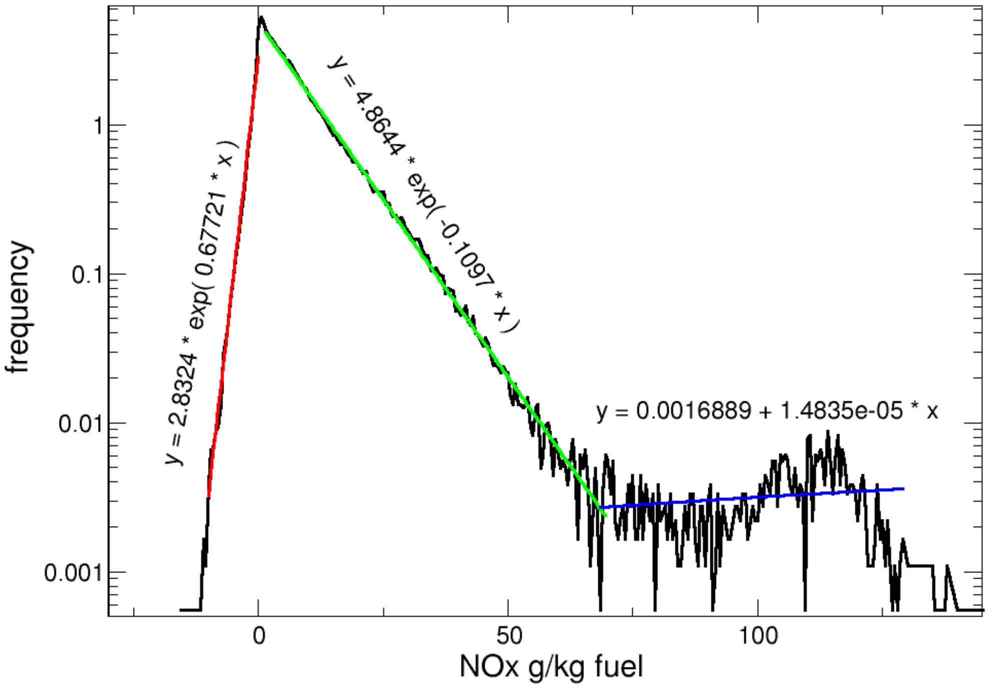
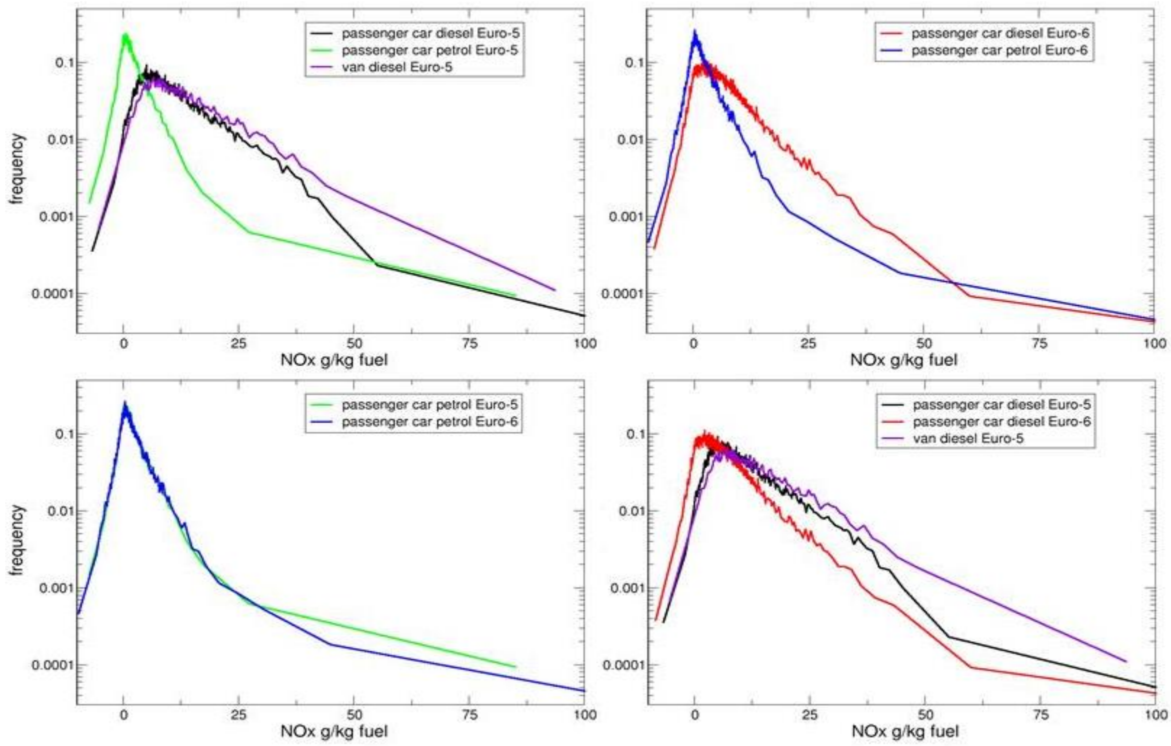
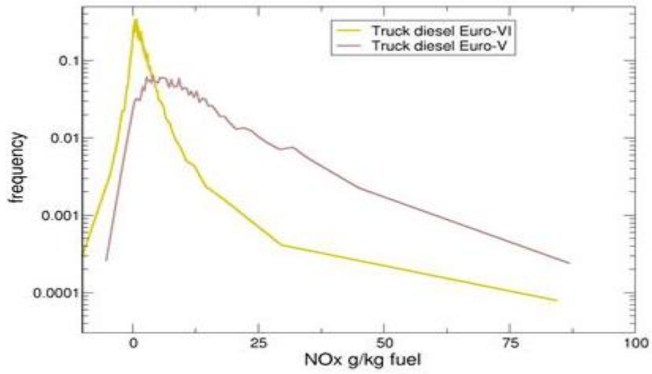


Figure 4-34 The distribution of NO_x emission ratios for all data combined. Around zero are two exponential trends. For negative values, the measurement accuracy could be deduced. The positive values show a much weaker slope, dominated by diesel vehicles. High values, ranging from above 60 g per kg to 140 g per kilogram seem to occur homogeneously. These values are associated with old-fashioned engine-out NO_x concentrations of 2000 to 3500 ppm.



[20] See Heywood, Combustion engine fundamentals



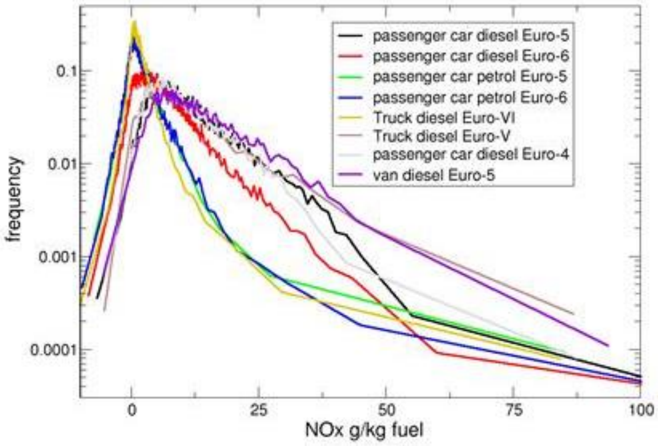


Figure 4-35: Probability density functions for the different test populations for which sufficient data was collected during the Flemish test campaign

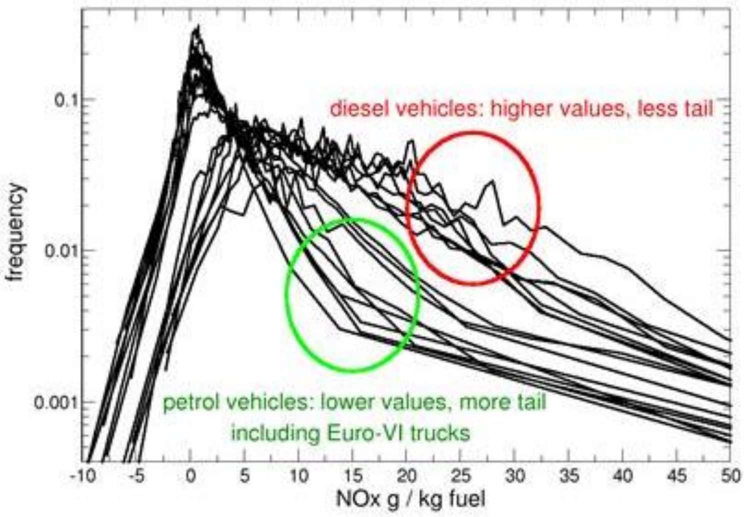


Figure 4-36: Another take on probability density functions for both petrol and diesel cars, vans, and heavy goods vehicles, cut-off at 50 g NOx/kg fuel. Here, the typical tail characteristics are highlighted.

One problem with long and thick tails in the probability distribution of vehicle emissions is the lack of confidence when the average emissions of a vehicle (sub-)group are determined, even with very large experiments. So, if 1% of the vehicles with high emissions may contribute half of the total emissions, several hundred vehicles must be measured to ensure this 1% is accurately measured. Within every hundred, only one high-emitter is expected, and at least five should be measured to have any idea of the real magnitude of an average among these high-emitting vehicles. This demonstrates the need for a monitoring scheme in which a large quantity of real-world emission data gets collected. The technique of remote sensing is particularly suited for this task, especially when deployed to cover longer periods to allow for a sufficient sample size to point out high-emitters effectively.

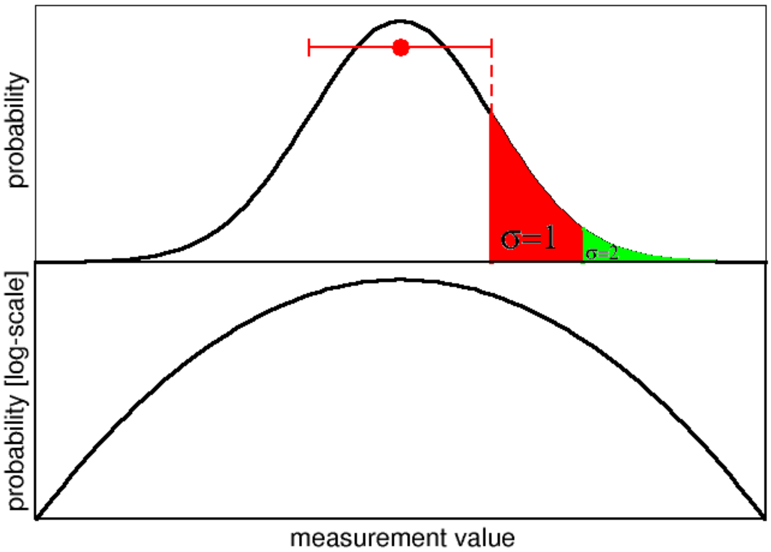


Figure 4-37: The normal distribution is symmetric (linear y-scale: above, logarithmic y-scale: below). The standard deviation $\sigma=1$, or spread, contains 84% ($\sigma=1$, bottom right) of the data. A one-sided $\sigma=2$ contains 97.7% of the data. If a large number of N draws from this distribution are used to determine the average, the average will be known with a typical accuracy of the $\sigma/N^{1/2}$. In a logarithmic scale normal distribution, the chances of encountering outliers fall off faster than for a linear scale due to an exponential relation. Data presented in this report clearly show a slower decrease.

One way to present the length and thickness of the tail is to express it as the deviation from the normal distribution (Figure 4-39). In a normal distribution, the median equals the average, and the 2-sigma point (i.e. 2.28% of the highest emissions) lies twice the distance of the 1-sigma point (i.e. 15.87% of the highest emissions). If the 2-sigma point lies further away (based on the median and the 1-sigma point), the tail is longer and thicker than for the normal distribution. For all data, except for the high NO_x emissions of older (pre-Euro 6d-Temp) diesel vehicles with generally high NO_x emissions, the 2-sigma point lies twice to six times further than would be based on the characteristics of normal distributions. This indicates that high-emitters can significantly distort the fleet average. Consequently, great care must be taken to interpret the results and to treat the statistics.

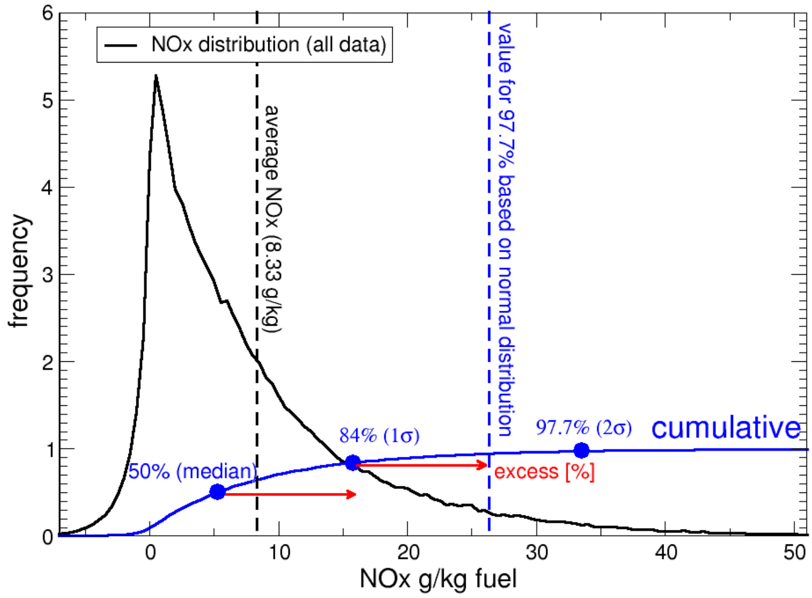


Figure 4-38: An example of the method to quantify the relevance of the tail of the distribution, relative to the tail of a normal distribution. The three percentiles are the average, the 1-σ and the 2-σ values of a normal distribution. In the case of a normal distribution, the two distances are equal. The relative excess distance of the second segment is reported in the tables below.

Moreover, if the 2-sigma point is twice away from the expected normal distribution value, it is expected that based on the normal distribution the contribution of these high values is also at least twice as large. The difference between the median and the average, the latter based on the appropriate accounting of high values, is also a good indication of the data in the tail. Again, except for generally high NO_x-emitting vehicles, these differences are very large (see Table 4-7). When 'typical' vehicles only emit very low pollutant levels, the measurement accuracy may become relevant to determine average emissions with sufficient confidence. A similar effect is observed in the results for PM and HC emissions. Due to very low emissions, the results from these pollutants are centred around zero but show a substantial spread compared to the average. This complicates the determination of the average emissions with sufficient confidence. Exemplary is the shape of the tails deviating from the normal distribution per vehicle category and fuel type for the given pollutants as given in Table 4-6, which serves as a summary for the more detailed overview in Table 4-7 and Table 4-8. Looking at the NOx figures in these tables, one must note that the higher the typical emissions are, the lower the tail deviation becomes. The opposite is true for emissions that are typically near zero (e.g. for PM and HC): the lower the typical emissions are, the higher the tail deviation becomes. The latter indicates the impact high-emitters can have on averages.

Table 4-6: Based on the typical spread, this table presents the positions of 2.3% (or 2-σ) percentile, expressed as the deviation from the normal distribution of their locations away from the median. Shown in this table is an overview of the tail deviations, or the difference between the 1-σ percentile and the 2-σ percentile compared to their respective distance in a normal distribution for the different test populations and measured pollutants. In a normal distribution, the 2.3% percentile (2-σ) is twice the distance of the 84% percentile (1-σ). The higher this value, the larger the contribution of high values to the average results. For high average emissions, tail deviations are low. The opposite is true for low average emissions, e.g. for PM or HC.

		NOx	PM	CO	HC
category	**count**	**tail deviation from a normal distribution**			
HGV diesel Euro4	1,145	20%	246%	360%	343%
PC petrol Euro2	1,383	104%	231%	187%	369%
LCV diesel Euro3	1,459	15%	206%	119%	602%
PC petrol Euro3	1,561	120%	273%	203%	321%
PC hybrid petrol electric Euro6	2,840	44%	207%	290%	300%
PC diesel Euro3	3,496	26%	213%	216%	462%
LCV diesel Euro4	4,573	15%	259%	194%	605%
HGV diesel Euro5	5,405	38%	469%	297%	446%
PC petrol Euro4	8,228	108%	288%	277%	263%
PC petrol Euro5	10,576	84%	290%	255%	383%
LCV diesel Euro5	10,670	19%	242%	120%	451%
LCV diesel Euro6	11,131	46%	297%	88%	491%
HGV diesel Euro6	13,629	144%	698%	197%	441%
PC diesel Euro4	14,945	19%	215%	242%	360%
PC petrol Euro6	25,776	81%	276%	288%	306%
PC diesel Euro5	26,976	23%	249%	172%	343%
PC diesel Euro6	37,484	55%	227%	145%	417%

The difference between the average and the median can thus serve as an indication of the contribution of the tail (Table 4-7, Table 4-8). With a limited number of samples, the average results tend to shift towards the median or even the modal value. Given that for petrol cars the NO_x average emissions are almost twice the median, this shows the impact of outliers. For comparison: without such outliers, in a normal distribution, the average and median values would be similar. As such, the treatment of the statistics (e.g. the removal of outliers) must be conducted with great care. Methods based on the assumption of a normal distribution of data have limited validity in these cases. If the highest few per cent of the data is more than twice the value that would arise from a normal distribution, the contribution of these results to the average are likely significant. The low values have little relevance for the average, so the median (instead of the average) and the percentiles (corresponding to 1-sigma and 2-sigma of a normal distribution) are better characteristics to estimate the contribution of high values. With more high values in the tail, the average increases significantly, but the median does not. Figure 4-39 shows a distinction between median and average emission values, with the difference between the two considered to be the high-emitter contribution. This indicates that the cleaner technologies get, the greater the impact of high-emitters becomes. Note that for diesel Euro 4 and 5 passenger cars, there is no visible difference between the median and the average results, indicating that NOx emissions are high for virtually every sample and that higher-emitters have a negligible influence on the already high averages. For diesel Euro 6 and petrol cars, NOx emissions are typically relatively low, leading to a more significant influence of high-emitters on the averages.

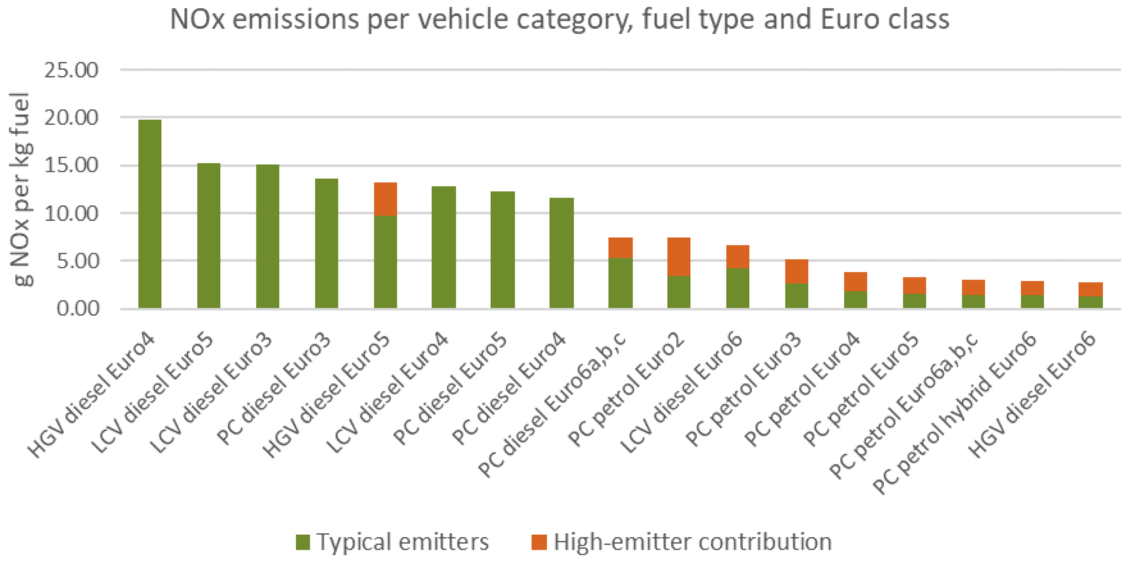


Figure 4-39: The typical emissions represented by the median (green) for those vehicle categories with more than 1,000 measurements. In case the average and median differ more than 22%, the high-emitter contribution is considered to equal the difference between the average and the median. As such, the top of the orange bars represents the average emission values. If the difference between average and median is less than 22%, high emissions are considered to be part of the typical emissions and no high-emitter contribution is displayed.

Table 4-7: Overview of the normal distribution parameters for the test populations and measured pollutants NOx and PM. Note that, next to the average and median per pollutant, also the 1-σ and 2-σ values are given, representing 84% and 97.7% of the data spread.

		NOx				PM			
category	count	average	median	1-σ (15.87%)	2-σ (2.28%)	average	median	1-σ (15.87%)	2-σ (2.28%)
HGV diesel Euro4	1,145	19.83	17.43	31.89	52.01	0.211	0.047	0.459	2.893
LCV diesel Euro5	10,670	15.25	12.32	25.69	44.08	0.014	0.001	0.045	0.302
LCV diesel Euro3	1,459	15.04	13.71	22.77	34.61	0.156	0.080	0.401	2.042
PC diesel Euro3	3,496	13.68	11.94	20.75	34.16	0.171	0.077	0.430	2.291
HGV diesel Euro5	5,405	13.28	9.68	23.22	46.98	0.038	0.001	0.047	0.524
LCV diesel Euro4	4,573	12.76	10.73	20.75	33.74	0.137	0.055	0.344	2.127
PC diesel Euro5	26,976	12.35	9.51	20.99	37.73	0.020	0.003	0.051	0.344
PC diesel Euro4	14,945	11.56	8.95	19.50	34.02	0.128	0.052	0.344	1.890
PC diesel Euro6	37,484	7.44	5.27	13.20	29.91	0.013	0.001	0.036	0.229
PC petrol Euro2	1,383	7.42	3.46	13.35	43.83	0.036	0.003	0.088	0.565
LCV diesel Euro6	11,131	6.60	4.26	12.13	27.24	0.011	0.000	0.031	0.245
PC petrol Euro3	1,561	5.18	2.64	8.80	29.75	0.026	0.001	0.064	0.469
PC petrol Euro4	8,228	3.85	1.87	7.00	23.21	0.021	0.001	0.051	0.387
PC petrol Euro5	10,576	3.27	1.53	5.76	17.12	0.026	0.001	0.056	0.429
PC petrol Euro6	25,776	3.09	1.49	5.81	17.18	0.016	0.001	0.040	0.293
PC hybrid petrol electric Euro6	2,840	2.90	1.42	6.09	14.89	0.012	0.001	0.038	0.225
HGV diesel Euro6	13,629	2.72	1.31	4.24	15.60	0.009	0.000	0.005	0.081

Table 4-8: Overview of the normal distribution parameters for the test populations and measured pollutants CO and HC.
Note that, next to the average and median per pollutant, also the 1-σ and 2-σ values are given, representing 84% and 97.7% of the data spread.

		CO				HC			
category	count	average	median	1+σ_1 (15.87%)	1+σ_2 (2.28%)	average	median	1+σ_1 (15.87%)	1+σ_2 (2.28%)
HGV diesel Euro4	1,145	5.80	1.75	5.97	40.63	0.64	-0.06	2.25	20.44
LCV diesel Euro5	10,670	1.64	0.47	2.35	8.75	1.06	-0.01	3.28	36.20
LCV diesel Euro3	1,459	4.84	1.46	7.72	28.88	2.31	0.03	3.99	55.58
PC diesel Euro3	3,496	3.23	0.92	3.96	20.12	1.64	0.03	4.22	47.04
HGV diesel Euro5	5,405	6.19	1.53	7.80	51.28	0.97	-0.02	2.96	32.47
LCV diesel Euro4	4,573	2.71	0.52	2.69	13.32	1.72	0.01	3.66	51.47
PC diesel Euro5	26,976	2.16	0.46	2.54	11.80	0.57	-0.02	3.45	30.71
PC diesel Euro4	14,945	2.59	0.49	2.69	15.51	1.19	0.03	4.05	37.01
PC diesel Euro6	37,484	2.22	0.59	2.96	12.20	1.08	-0.01	3.77	39.11
PC petrol Euro2	1,383	20.92	4.52	31.88	161.65	2.39	0.14	5.52	50.68
LCV diesel Euro6	11,131	1.52	0.48	2.49	8.01	0.73	-0.02	3.16	37.52
PC petrol Euro3	1,561	14.25	3.25	22.72	121.44	0.54	0.02	3.91	32.78
PC petrol Euro4	8,228	12.82	2.68	17.11	111.35	0.40	0.00	3.62	26.28
PC petrol Euro5	10,576	9.64	2.26	12.04	71.80	0.64	-0.04	3.43	33.46
PC petrol Euro6	25,776	5.89	1.73	6.95	42.19	0.44	-0.04	3.44	28.28
PC hybrid petrol electric Euro6	2,840	5.50	1.80	6.67	39.81	0.33	-0.05	3.18	25.88
HGV diesel Euro6	13,629	0.82	0.16	0.97	4.94	0.51	-0.03	2.62	28.61

4.5.2 Assessing multiple passages of individual vehicles

There are two approaches to multiple passages. First, without using other data to estimate the true average emission of a given vehicle that has passed several times. Second, using the existing data on similar vehicles to improve the confidence in the estimated average of the measurement data of that single vehicle. The current section focuses on the second approach. It rarely occurs that enough measurements are collected to make a confident decision on the true average. The spread in the data is generally too large. An indication of the typical spread, and how much higher the observed emissions are, will lead quicker to a decision to follow-up on that specific vehicle.

Most of the analyses in this section are to improve the estimate. Nevertheless, as multiple passages (especially with high numbers) are rare, the statistics are limited. This section provides basic numbers for categories where at least 30 passages are observed. These numbers can provide uncertainty levels if one, two, or three passages of the same vehicle are used to determine if this vehicle has unwarranted high emissions. It may, after all, be a coincidence that one or a few high values are observed.

Given the large set of data, also with vehicles that have passed the measurement location several times, it is possible to determine to what extent a single measurement predicts the general and average behaviour of a specific vehicle if it would be measured during multiple passages. The spread in the data of vehicles with multiple passages indicates the spread in measurements for individual vehicles. Of course, once a vehicle is seen multiple times, the actual, observed spread is the best indication of the confidence in the average emission behaviour. If an individual vehicle of interest, however, only has a single reading in the dataset, the current section provides an alternative method to determine confidence levels. This is based on the central limit theorem.

> *The central limit theorem is a key element of statistics. If one would throw a dice, or flip a coin, N-times over, the sum value (of dice values or number of heads) of many repetitions of N throws would form a normal distribution. Many processes with variable outcomes are considered to be built on several independent parts, like successive throws of a dice. Hence, a normal distribution is a common distribution of random values. Although, this is not always the case as the key element of this process, i.e. the ever-increasing accuracy of the average value with the increasing number of throws, is considered common. The sum of the number of heads increases with N, while the spread increases with* $\sqrt{N}$*. Say, after 10,000 throws, the number of heads is* $5000 \pm \frac{\sqrt{10000}}{2}$*, or 5000 +/- 50. Thus, the average number of heads is 0.5 +/- 0.01, with a small spread of the average. Therefore, the uncertainty in the average is expected to decrease with* $\frac{1}{\sqrt{N}}$*. This basic assumption, the* $N^{1/2}$ *or* $\sqrt{N}$ *rule, is used in the analyses below, using the whole dataset to determine the accuracy of a limited number of measurements.*

A hypothesis, e.g. that the true average value is in between a lower and upper bound, based on a limited number of measurements, always contains two elements. First, there's the range of values, like +/-20% from a given estimate. The second is the confidence level. The confidence level is linked to an assumption, like assuming a normal distribution. With a normal distribution, the common confidence level is 95%, meaning that in 95% of the cases the hypothesis is true. However, with unknown distributions of the data, it is more complicated to reach the 95% confidence level, and this because of outliers. Lower confidence levels are more easily fulfilled with less knowledge of the underlying distribution. In this case, the 84% confidence level is used as a basis to determine the accuracy with which the measured average, given a finite sample of data, is the same as the true average.

Some vehicles passed by the sampling unit multiple times for the different measuring locations, leading to a possibility to do statistics *per vehicle*. Only with a minimum of 30 samples per vehicle model, and multiple (see further down) passages for individual vehicles, the data is considered acceptable to draw any conclusions on the level of individual vehicles with sufficient confidence. Using the statistics per vehicle, weighted with the $N^{1/2}$ factor to account for individual vehicles with more passages, a typical confidence level of 1-sigma, i.e. 84% within these bounds were determined, based on the standard deviation. For higher confidence levels, the long tails in the distribution must be considered in more depth. Again, only for diesel vehicles with high average NO_x emissions, above 2 g per kg fuel, a single measurement can give a reasonable estimate of the average emissions of that vehicle within a range of 20%-40%, with 84% certainty or above a certain value with this certainty. In many other cases, vehicle categories and emission components, the spread increases to 100%. For these vehicles, one would require at least 4 passages of the same vehicle to reach the same confidence in the estimated emissions based on these measurements. For HC emissions, the situation is the worst. It would take hundreds to thousands of measurements to reach any reasonable estimate of the average. The result of this exercise is given in Table 4-9. It should be noted that the values observed in Table 4-9 are solely based on the selection of multiple passages. Their effect should be investigated further. As such, PEMS measurements may provide further explanations in these cases. This may for example show that emissions of a given component occur in a small number of high peaks throughout a full trip. This would explain the large tail, but also that there might be no consistency in the data of an individual vehicle.

The analyses presented in Table 4-9 are based on all multiple passages of unique vehicles in specific categories with sufficient data. The results displayed in the table give a general guideline on the number of measurements needed to achieve certain confidence in the result. For a single measurement, the percentages in the table give the typical variations one may expect with second or more passages. So, in the absence of further passages, a margin should be taken, based on the percentages in Table 4-9. For some emission components and categories, a single remote sensing measurement will not provide an appropriate estimate, given the large variations. For example, we will consider a specific Euro 5 diesel LCV with a single emission reading of 20 g NOx/kg fuel. This measurement may deviate 36% from the average emission if the vehicle is measured several times. Also note that if the spread is 30%, 9 passages will bring it down to about 10%, based on the $N^{1/2}$ rule (or $30/\sqrt{9}$). If more passages and measurements occur, the basic spread displayed in the table can be replaced by the observed spread for that specific vehicle. For example, with 5 measurements, the average maybe is 8 g NOx per kg fuel, with a standard deviation of 3 g per kg fuel. This would mean that there is an 84% chance that the average is 8 +/- 1.34 g per kg fuel, given the fact that $3/(5)^{1/2} = 1.34$.

In this way, Table 4-9 gives a basic indication of the spread in measurements for different vehicle categories and different pollutants, based on the multiple passages of the same vehicle. Given the significant spreads, a single passage in many cases does not provide conclusive evidence of the emission performance of a vehicle. Large spreads indicate that emissions are variable and vehicle emission behaviour is not captured by a single, or in some cases even several measurements of that vehicle. In particular, emissions of hydrocarbons and particulate matter do not seem to be consistent, but rather unsteady. On the other hand, the NOx emissions are more consistent in emission behaviour over time and repeated measurements.

Table 4-9: Overview of the average emissions of the measured pollutants for multiple passages, combined with the spread (σ=1, 84%) per pollutant per test population

			Spread						Averages					
			CO_gpkg	HC_gpkg	NO_gpkg	NO2_gpkg	NOx_gpkg	PM_gpkg	CO_gpkg	HC_gpkg	NO_gpkg	NO2_gpkg	NOx_gpkg	PM_gpkg
Bus	Diesel	Euro3	86%	327%	21%	50%	22%	638%	1.451	-0.149	4.364	0.219	4.583	0.0115
Bus	Diesel	Euro5	81%	165%	30%	46%	29%	461%	0.907	-0.326	2.731	0.165	2.896	0.0002
Bus	Diesel	Euro6	96%	244%	64%	108%	64%	184%	0.078	-0.276	0.466	0.116	0.582	0.0003
HGV	CNG	Euro6	53%	132%	73%	72%	56%	3110%	0.386	1.765	0.224	0.094	0.319	0.0000
HGV	Diesel	Euro2	65%	786%	23%	39%	24%	424%	2.555	-0.102	4.609	0.273	4.882	0.0171
HGV	Diesel	Euro3	64%	552%	22%	50%	21%	169%	1.861	0.158	3.862	0.257	4.119	0.0534
HGV	Diesel	Euro4	80%	6062%	28%	65%	29%	186%	0.866	0.014	2.961	0.334	3.295	0.0379
HGV	Diesel	Euro5	80%	535%	35%	93%	36%	211%	1.097	0.198	1.996	0.217	2.212	0.0071
HGV	Diesel	Euro6	137%	1335%	84%	155%	96%	206%	0.151	0.071	0.287	0.157	0.444	0.0010
LCV	CNG	Euro6	83%	215%	78%	156%	79%	76%	1.073	0.665	0.787	0.127	0.914	0.0115
LCV	Diesel	Euro2	57%	230%	19%	92%	25%	294%	1.393	0.633	3.789	0.491	4.280	0.0261
LCV	Diesel	Euro3	70%	388%	29%	43%	27%	285%	0.798	0.246	1.979	0.471	2.450	0.0201
LCV	Diesel	Euro4	100%	346%	32%	47%	32%	233%	0.465	0.286	1.441	0.723	2.164	0.0228
LCV	Diesel	Euro5	103%	1218%	36%	56%	36%	555%	0.277	0.076	2.040	0.523	2.563	0.0022
LCV	Diesel	Euro6	99%	960%	54%	86%	56%	542%	0.240	0.105	0.796	0.298	1.094	0.0015
LCV	Petrol	Euro5	94%	1039%	70%	181%	68%	3587%	1.380	0.083	0.317	0.070	0.387	0.0001
LCV	Petrol	Euro6	71%	1064%	105%	142%	109%	408%	1.410	0.085	0.351	0.204	0.555	0.0026
PC	CNG	Euro6	66%	1038%	78%	108%	79%	866%	0.665	-0.080	0.399	0.273	0.672	0.0017
PC	Diesel	Euro2	76%	658%	27%	63%	26%	261%	0.973	0.144	1.748	0.302	2.051	0.0256
PC	Diesel	Euro3	81%	532%	32%	59%	33%	240%	0.569	0.190	1.695	0.524	2.219	0.0264
PC	Diesel	Euro4	90%	597%	40%	56%	40%	265%	0.466	0.170	1.325	0.632	1.957	0.0226
PC	Diesel	Euro5	102%	1751%	39%	63%	40%	357%	0.356	0.052	1.600	0.474	2.074	0.0038
PC	Diesel	Euro6	98%	547%	50%	78%	51%	343%	0.361	0.203	0.936	0.308	1.244	0.0026
PC	hybrid diesel/electric	Euro6	92%	1073%	53%	95%	63%	4535%	0.607	-0.099	0.729	0.437	1.166	-0.0002
PC	hybrid petrol/electric	Euro5	72%	4997%	72%	289%	75%	1362%	1.006	-0.017	0.366	0.043	0.409	0.0007
PC	hybrid petrol/electric	Euro6	69%	469%	81%	129%	84%	297%	1.109	0.191	0.358	0.150	0.508	0.0033
PC	Petrol	Euro0	39%	159%	34%	135%	39%	481%	12.000	0.617	2.395	0.427	2.822	0.0054
PC	Petrol	Euro1	68%	689%	49%	159%	51%	910%	5.090	0.129	1.127	0.090	1.217	0.0021
PC	Petrol	Euro2	68%	304%	52%	145%	61%	400%	3.328	0.442	1.112	0.236	1.348	0.0050
PC	Petrol	Euro3	67%	25586%	60%	205%	65%	398%	1.967	0.004	0.646	0.070	0.716	0.0054
PC	Petrol	Euro4	70%	1448%	70%	153%	75%	344%	2.088	0.062	0.486	0.118	0.604	0.0037
PC	Petrol	Euro5	79%	867%	80%	166%	95%	310%	1.623	0.110	0.384	0.179	0.562	0.0053
PC	Petrol	Euro6	75%	2184%	87%	159%	93%	383%	0.949	0.041	0.355	0.124	0.479	0.0028

4.5.3 High-emitter impacts

When were refer to 'high-emitters' throughout this report, we refer to vehicles emitting significantly more than similar vehicles belonging to the same group (e.g. the same vehicle category, fuel type, Euro class, etc). When a vehicle is defined as a 'typical emitter', this does not necessarily mean that its absolute emissions are acceptable, it only means that the vehicle does not emit significantly more than most vehicles belonging to the same group. As such, entire groups can have high emissions, like pre-Euro 6d-Temp diesel cars in case of NOx.

High-emitters can substantially skew the average emissions of vehicle fleets, as discussed in the previous section. To quantify their impact on a fleet's total emissions, we must start with a definition of how to characterise high-emitters. In this approach, we propose to consider vehicles as high-emitters when their measured emission rate exceeds the upper bound as described in Equation 4. This upper bound is determined by the summation of the third quartile with a factor 1.5 times the interquartile range (IQR) of the whole set of samples within a particular vehicle group (e.g. diesel Euro 5 cars). The IQR is the difference between the 75^{th} (Q3) and 25^{th} (Q1) percentile and represents the middle 50% of the sample data of a given test population. This is visualised in Figure 4-40. It is important to stress once more that by doing so, we define high-emitters based on their emissions relative to that of similar vehicles belonging to the same group. The threshold values for high-emitters for those combinations of vehicle categories, Euro class, and fuel types for which an arbitrary minimum of 10,000 samples was registered are given in Table 4-10. Note that, based on the Flemish dataset, the NOx threshold for Euro 5 diesel cars exceeds the Euro 4 threshold, indicating that for the Euro 5 samples higher NOx emissions are reported in general. In the following discussion, those combinations for which less than 10,000 samples were registered are covered in the charts as well, although these should be considered as *indications*

Equation 4: Determination of the high-emitter threshold ('upper bound') value

$$Upper\ bound = Q3 + 1.5 \times IQR$$

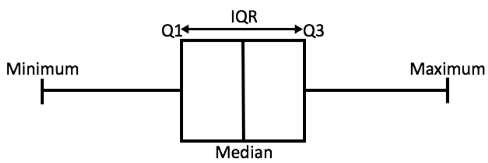


Figure 4-40: The principle of a box plot showing the interquartile range

Table 4-10: Thresholds to determine high-emitters for passenger cars (PC) and heavy goods vehicles (HGV)

Vehicle category	Fuel type	Euro class	NOx gpkg	PM gpkg
PC	Diesel	Euro 4	30.73	0.55
PC	Diesel	Euro 5	32.65	0.08
PC	Diesel	Euro 6a,b,c	23.19	0.06
PC	Petrol	Euro 5	9.76	0.09
PC	Petrol	Euro 6a,b,c	9.73	0.06
HGV	Diesel	Euro VI	6.94	0.01

4.5.3.1 High-emitters for PM

4.5.3.1.1 Diesel PC

For diesel passenger car PM emissions, 74,529 samples were eligible for analysis as they represent over 10,000 samples for each Euro class ranging from Euro 4 to Euro 6a,b,c, as shown in Figure 4-41 and Figure 4-42. Note that when applying the distinction between typical and high-emitting vehicles as described above, roughly 10 per cent is found to produce significantly higher PM emissions, and this for each Euro class discussed. Note also that Euro 6d-Temp diesel cars are included, although their sample size does not allow us to draw conclusions. Therefore, indicative results are presented in transparent colours.

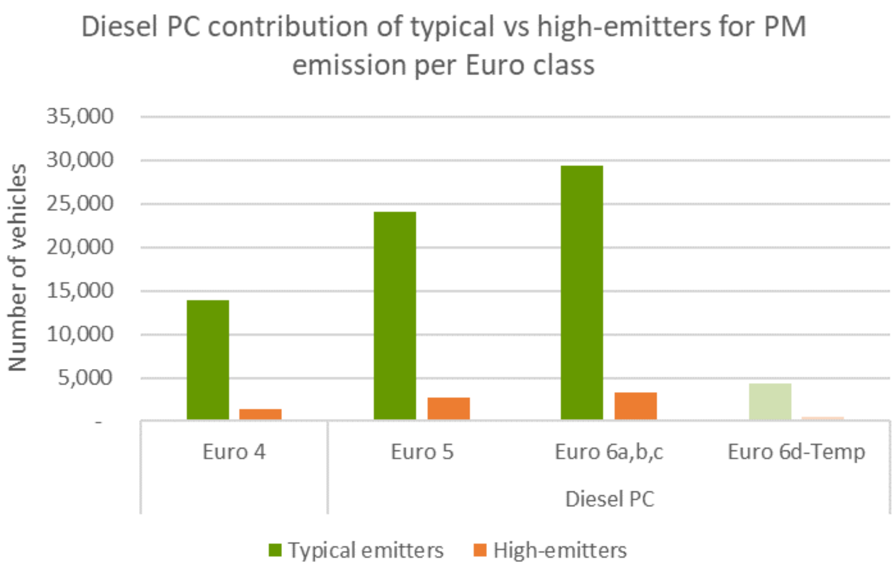


Figure 4-41: Overview of diesel passenger car PM emissions by high-emitters and typical emitters

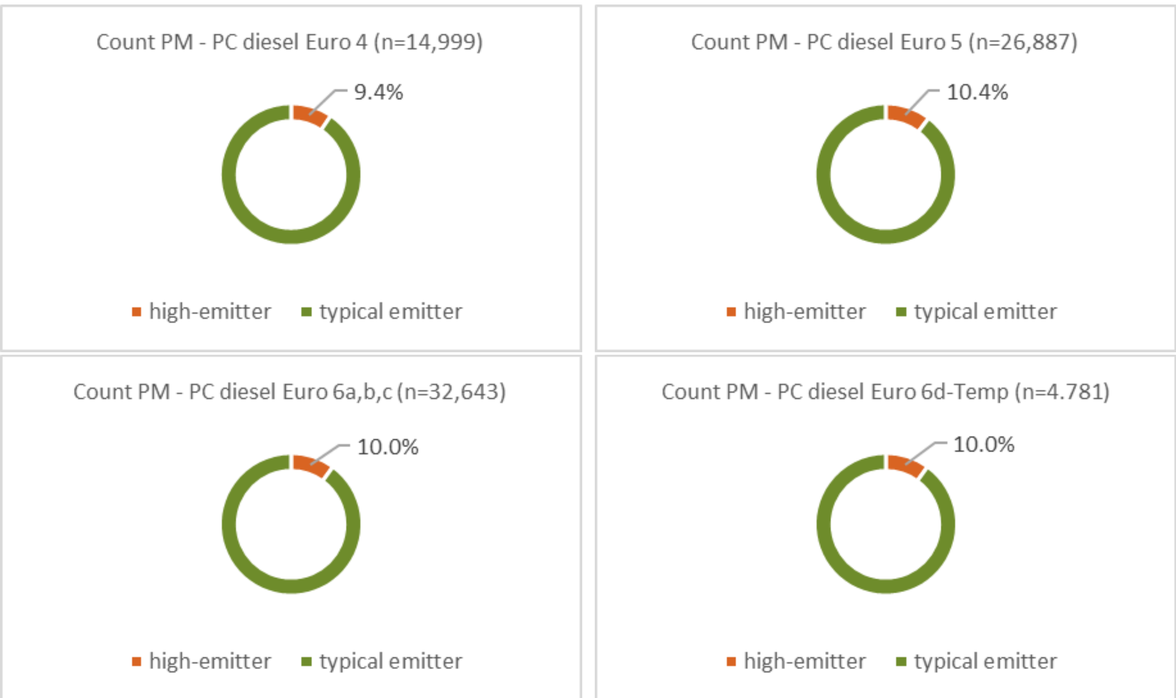


Figure 4-42: The distribution of typical and high-emitters for PM for diesel cars per Euro class

To assess the impact high-emitters have on the cumulative PM emission for the test population, we first look at the average PM emission rates, given in Figure 4-43. What should be noted is how average PM emissions for typical emitting Euro 4 diesel cars are an order of magnitude higher than what is seen for Euro 5 diesel cars. This may be explained by a higher emission limit for Euro 4 technology (25 mg/km) compared to Euro 5 and 6 (5 mg/km), which led to the introduction of diesel particulate filter (DPF) technology to be installed from Euro 5 onwards. Nonetheless, there is also a significant share of Euro 4 diesel cars that were originally equipped with a DPF, although we were not able to make this distinction based on the available vehicle characteristics obtained by the Belgian and Dutch vehicle registration services. The non-DPF variants may be the main reason for the high-emitter averages, although the test location (slight inclinations) combined with the ageing of aftertreatment technology might be the cause of higher Euro 4 average emissions as well. On average, Euro 4 high-emitters tend to emit up to 17 times larger amounts of PM than is the case for typical Euro 4 diesel cars.

For Euro 5 and 6a,b,c technology, this difference between typical and high-emitters increases substantially as typical PM emissions for cars with properly working DPFs are close to zero. As such, the impact of poor maintenance, DPF failures, or even tampering becomes substantial. This emphasizes the need for proper control over these events, for instance in a periodic technical inspection's (PTI) emission test focusing on a particle number count. Remote sensing can play a vital role to increase the effectiveness of such schemes if high-emitters are flagged in consecutive measurements. If subsequent checks of a given vehicle indicate a consistent emission limit breach, the vehicle should be marked as a suspicious emitter and could be targeted for additional PTI tests.

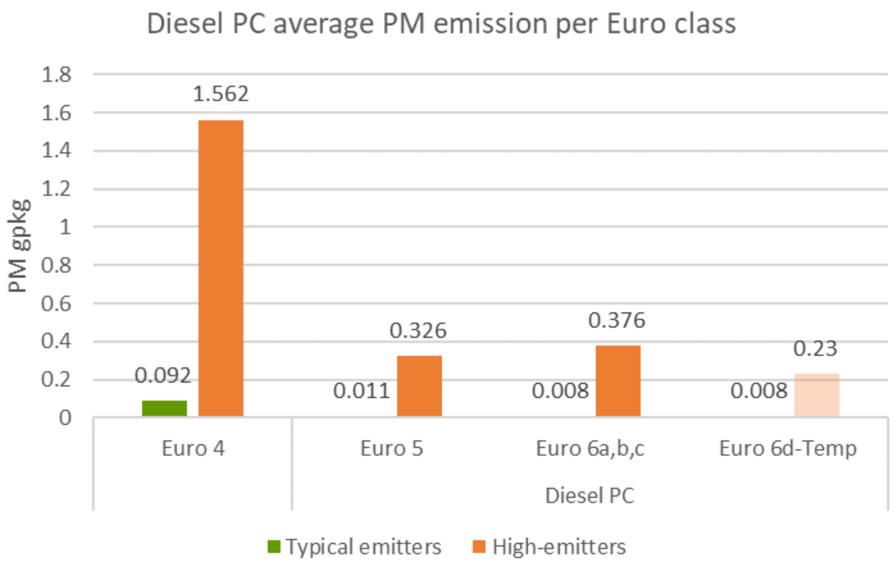


Figure 4-43: Overview of the average PM emission rates in g per kilogram fuel per Euro class

If we then look at the impact on the cumulative emissions by the test population, shown in Figure 4-44, it is clear that removing high-emitters from traffic can have a substantial impact when it comes to PM. In this comparison, we treat Euro 4 separately from the other Euro classes as the lack of data on DPF implementation would not allow for a fair comparison. Thus, Euro 4 high-emitters represent approximately two-thirds (64%) of the Euro 4 test population's contribution. This finding is in line with the expectation as a significant share of Euro 4 diesel cars has no DPF installed. For Euro 5 and 6a,b,c diesel cars, the high-emitters contribute 32.5% and 43.9% to the total test population's PM emission, respectively (Euro 5 – 6d-Temp, Figure 4-44). The preliminary results for Euro 6d-Temp show that high-emitters represent 3.9% of this Euro 5 – 6d-Temp population. In their population per

Euro class, high-emitters represent an averaged 80% of the totals, and this for both Euro 5 and 6b technologies (Figure 4-45). For Euro 6d-Temp, this share amounts to 76.4%. If we leave out the Euro 4 samples, we can estimate that **for the Euro 5 – 6d-Temp test population, about 10% contributes 80.4% of the total PM emissions**. If this near-total contribution would be extrapolated to the entire fleet driving on Flemish roads, the impact of targeting this small share of high-emitters and enforcing repair (e.g. through PTI) could be very substantial.

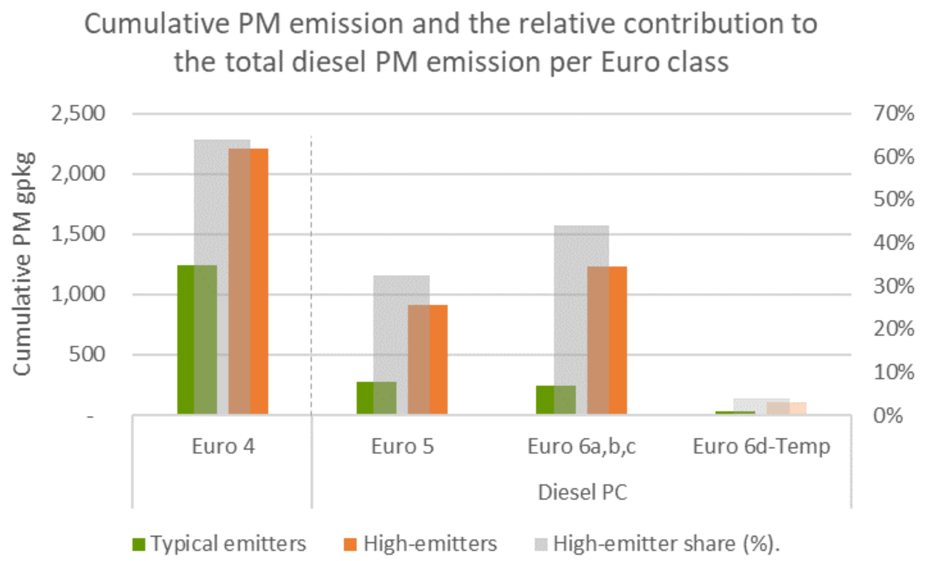


Figure 4-44: Cumulative diesel passenger car PM emissions per Euro class and the relative contribution to the test population's total PM emission (grey bars, right-hand side Y-axis), in which Euro 4 results are treated separately and the other Euro classes are grouped. As such, Euro 5 diesel car high-emitters account for 32.5% of the combined total Euro 5 – 6d-Temp emissions (typical + high-emitters). Cumulative PM emissions are expressed in grams emitted when all the vehicles concerned each burn one kg of fuel.

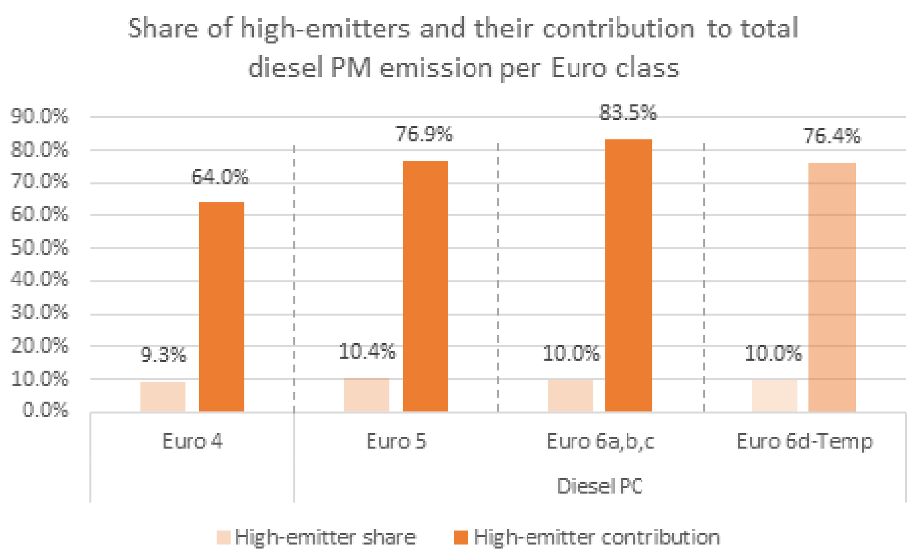


Figure 4-45: Relative contribution of the diesel passenger car high-emitters for PM per Euro class. In this figure, each Euro subclass is treated separately (Euro 5, 6a,b,c, and 6d-Temp are not grouped).

4.5.3.1.2 Petrol PC

If we re-do this exercise for petrol cars, only the Euro 5 and 6a,b,c population exceeded 10,000 measurements. Nonetheless, the smaller samples for Euro 4 (8,095) and Euro 6d-Temp (5,755) are added to indicate their performance. Similar to what is stated for Euro 4 diesel cars, we were not able to distinguish direct injection from port-fuel injection petrol cars, although the decreased particle number limit from Euro 6d-Temp onwards allows us to assume that the petrol cars belonging to this Euro class are equipped with a gasoline particulate filter (GPF) when direct-injection is used.

The distribution of typical and high-emitters is shown below in Figure 4-46 and Figure 4-47. In the Flemish dataset, high-emitting Euro 5 and 6a,b,c petrol cars both represent about 11% of the population. The same is true for the Euro 4 and 6d-Temp preliminary insights, which stresses the similarity to the distribution reported for diesel cars discussed earlier. Their average emissions, nonetheless, prove to be substantially higher than for normal range PM emitters, as shown in Figure 4-48, given that normal range PM emissions are also for petrol vehicles very close to zero. The combined contribution of high-emission events for the Euro 5 – Euro 6d-Temp petrol cars sampled is reported to amount up to an averaged 79.4% of the test population's total petrol PM emission (see the cumulation of the grey bars in Figure 4-49 right-hand side Y-axis). This cumulative share is nearly identical to what is reported for PM emissions of diesel cars with a filter, i.e., Euro-5 and Euro-6, but substantially lower than Euro 4 diesel vehicles without filter (Figure 4-44). Based on this exercise, both diesel and petrol Euro 5 – 6d-Temp high-emitters emit similar amounts of PM when averaged out, as shown in Table 4-11.

In many cases of black exhaust plumes being emitted from vehicles, we can associate this with engine problems. This can be a leaking turbo, a filthy fuel injector, or excessive wear that reduces the sealings in the engine. Tampering may also be a cause of high PM emissions. These kinds of problems occur in diesel and petrol cars alike. With very low typical emissions, problematic vehicles in terms of PM are likely to dominate the average results. In the high-emitter analyses, the large contribution of a small number of measurements does support the idea that malfunctions and, possibly, tampering are the main contribution to PM emissions nowadays, as DPFs are generally applied on diesel vehicles and gasoline particulate filters (GPF) on petrol cars with direct injection engines.

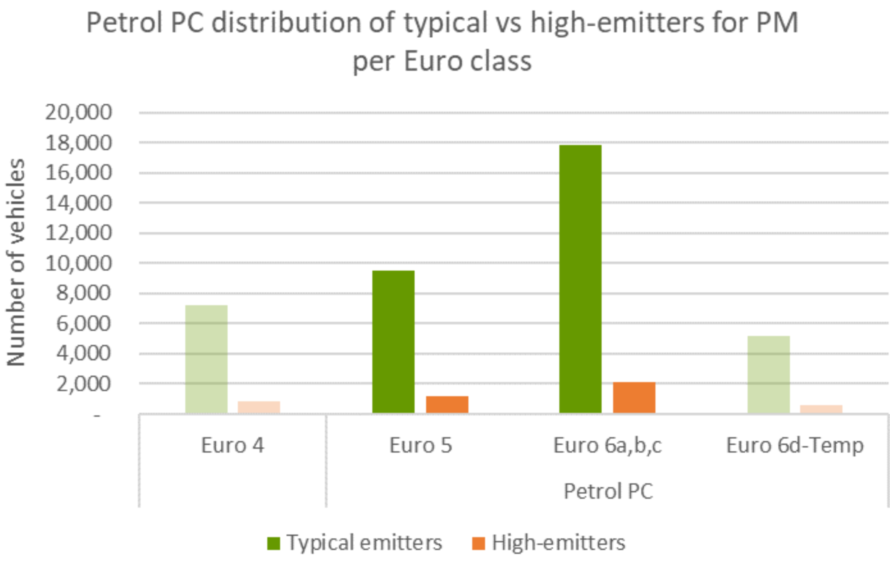


Figure 4-46: High- and typical range emitters for PM for petrol cars per Euro class

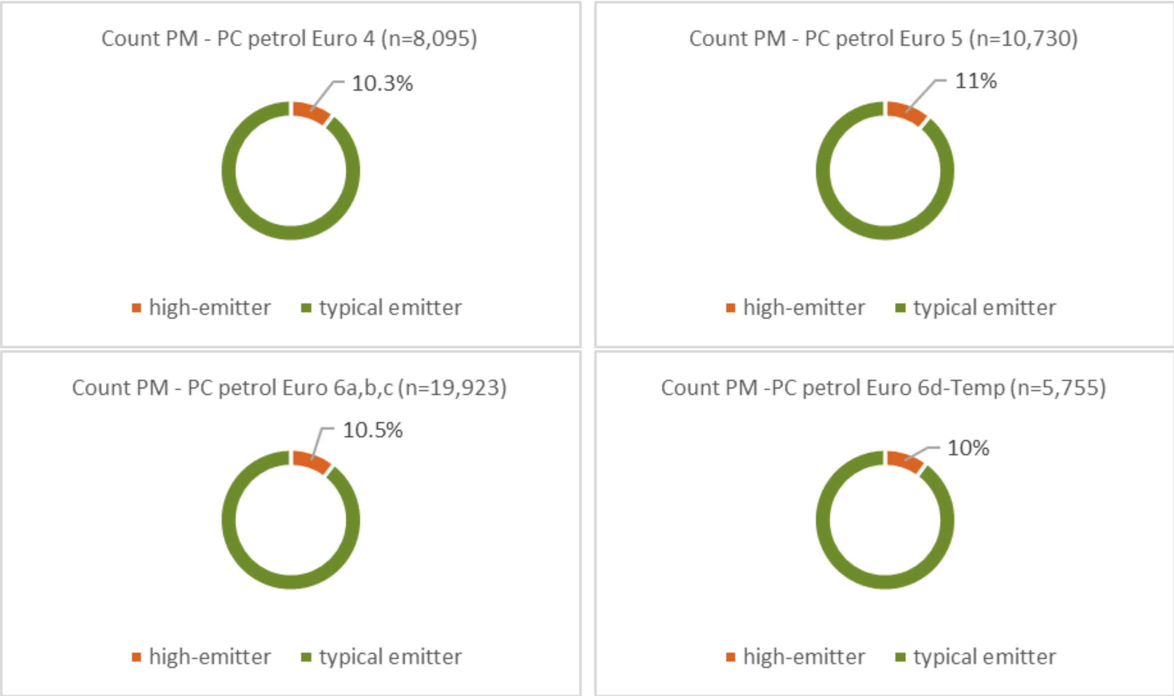


Figure 4-47: The distribution of typical and high-emitters for PM for petrol cars per Euro class

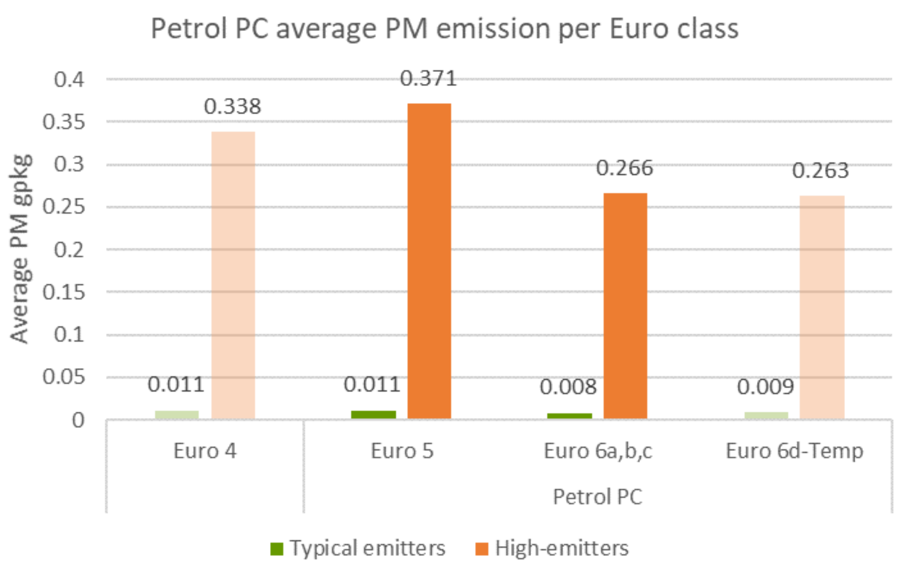


Figure 4-48: Average PM emissions for Euro 6b petrol high- and normal range PM emitters

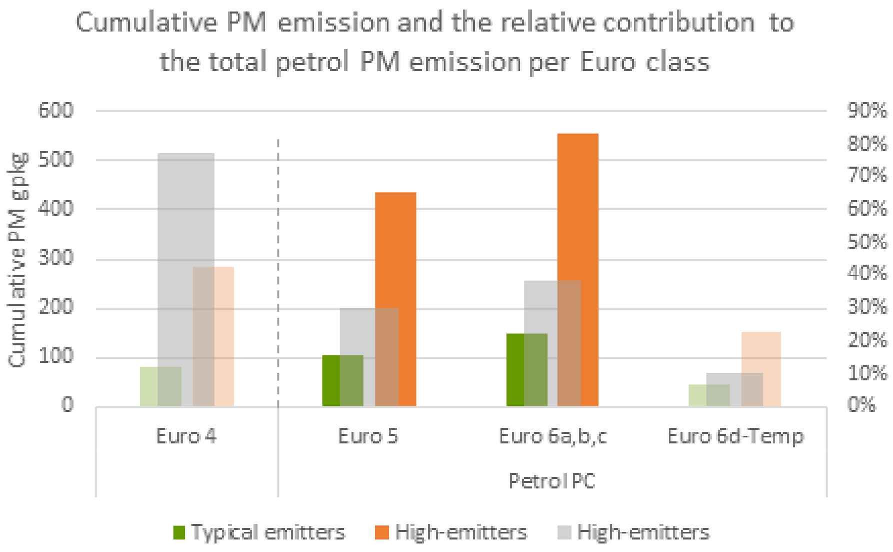


Figure 4-49: Cumulative petrol car PM emissions per Euro class, expressed in grams per kg of fuel burned. The relative contribution per Euro class to the total test population's PM emission is shown for Euro 4 separately, and for Euro 5 – 6d-Temp combined (grey bars, right-hand side Y-axis).

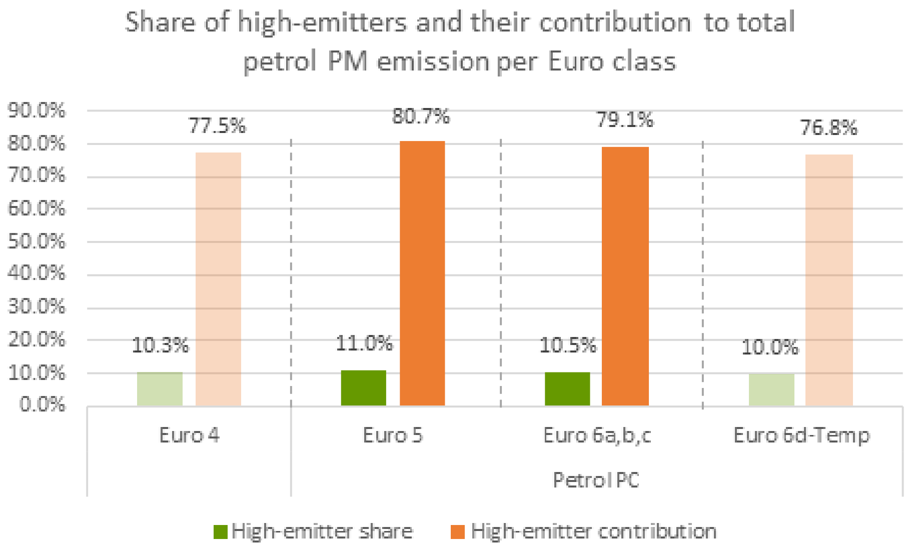


Figure 4-50: Relative contribution of the petrol passenger car high-emitters for PM per Euro class

Table 4-11: Overview of the average PM emission factors for the Flemish dataset, both for petrol and diesel passenger cars

AVG PM_gpkg	Petrol PM			Diesel PM		
	Normal range	High-emitter	Cumulative	Normal range	High-emitter	Cumulative
Euro 4	*0.011*	*0.338*	*365*	***0.092***	***1.562***	***3,454***
Euro 5	0.011	0.371	540	0.011	0.311	1,183
Euro 6a,b,c	0.008	0.266	703	0.008	0.236	1,473
Euro 6d-Temp	*0.009*	*0.263*	*198*	*0.008*	*0.230*	*144*

4.5.3.1.2.1 DPF problems vs regenerations

Every 400 to 700 kilometres, the DPF of a vehicle regenerates, causing a spike in particulate emissions. This is to be regarded as normal emission behaviour. One specific concern with assessing PM emissions through remote sensing sampling is that there is a need to distinguish filter regenerations from DPF defects (or removals). This because during normal operation, DPF-equipped vehicles emit PM levels that are near to zero. As such, the bulk of overall PM emissions occur during regenerations that are needed to keep the filtration systems operational. It would, however, be undesirable to assess a vehicle as 'failing' in terms of PM emissions when such a regeneration event takes place. Therefore, we briefly zoom in on a potential methodology to separate regenerations from failures.

Exhaust PM consists of small particles only. In air quality assessments the reference is made to PM10 and PM2.5, indicating the particulate mass of particles with an aerodynamic diameter smaller than 10 and 2.5 micrometres, respectively. The HEAT system uses multiple wavelengths and Mie scattering theory, i.e. spherical particles, to theoretically determine the particle mass and particle number. In these numerical simulations, a typical size-distribution of diesel particles is used, and the particles are assumed to consist of a refractive layer covering a light-absorbing core. Based on the light scattering results for multiple wavelengths, both particle numbers and mass are determined based on an assumed particle size distribution emitted by diesel engines. The assumptions are thus a given size distribution, fixed refractive properties, and a spherical nature of particles. These assumptions are compared to in-situ devices, for which test vehicles are used and the number per volume is compared to EDAR results. Then, adjustments are made to the theoretical model such as an index of refraction, etc. This method originates from Mazzoleni et al.[21], stating that the size distribution of diesel particles remains fairly consistent and therefore can be assumed. Any difference in shapes can be accounted for with the index of refraction.

A DPF regeneration will produce higher particle emissions, and possibly other gaseous emissions for a few minutes while covering distances of about 10 to 15 kilometres during higher-speed rural and motorway drives. This could wrongly be identified by remote sensing analysis as a removed or defective DPF if sampling units are located next to such road types. Hence, the quality of future remote sensing analysis could be improved by separating regeneration events from other cases of high PM emissions (defects, tampering, etc). DPF regeneration occurs at very high temperatures, typically 150 degrees Celsius above the normal exhaust gas temperature. The EDAR system can measure the exhaust gas temperature, so this would be a criterion to distinguish the two cases. Moreover, hot exhaust gas has a higher buoyancy, meaning it would tend more to move upwards. Therefore, the spatial distribution of the exhaust gas a few metres behind the vehicle may help to identify regeneration events. Spatial distribution can be explained by a CO_2 plume that should coincide spatially with the PM from the exhaust in case a regeneration takes place.

The spatial distribution method is illustrated below showing various 3D and 2D plots representing the values of CO_2 and PM at the same pixel or location in the exhaust plume scan. Note that for the specific purpose of this exercise, the converging of the two plumes is artificially simulated to identify (and separate) exhaust from non-exhaust emission sources. If the CO_2 only comes from the tailpipe and other pollutants come from a different source, the plumes do not overlap, see Figure 4-51. A PM plume moving gradually from the right-hand to the left-hand side of the vehicle, to eventually overlap with the CO_2 plume, is shown in the next four illustrations. As the plumes start to coincide with each other, the plots to their right-hand side change.

[21] *Monitoring Automotive Particulate Matter Emissions with LiDAR: A Review*, Claudio Mazzoleni et. al. Remote Sensing 2010, 2, 1077-1119

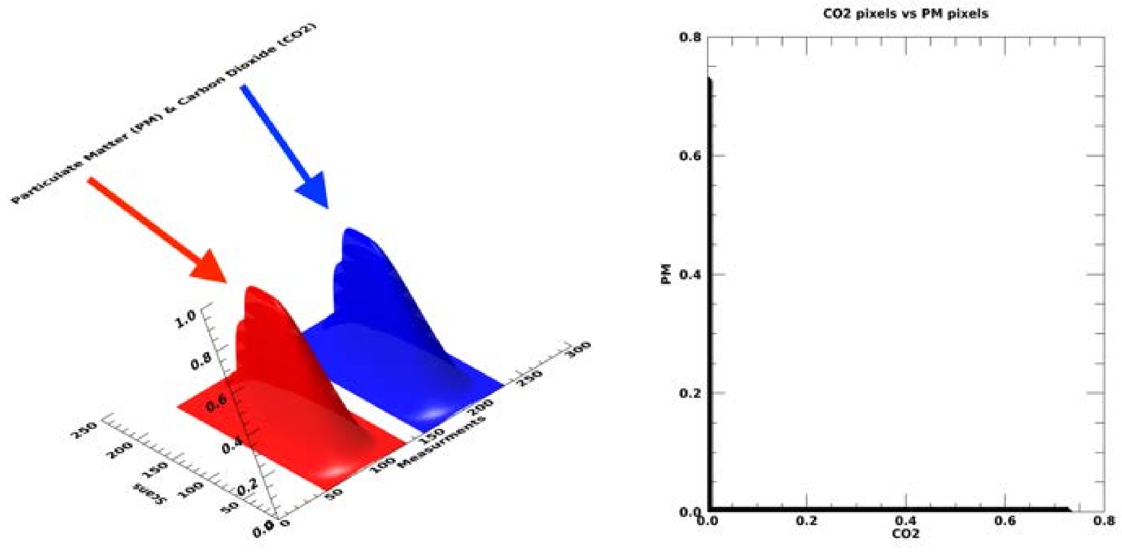


Figure 4-51: These are the plumes coming from the rear of the vehicle. The rear of the vehicle starts at scan 1. The PM plume is on the right-hand side of the car and the CO_2 plume is on the left-hand side. If the CO_2 and the PM come from different sides of the vehicle and do not overlap; the values of the plot are on their perspective axes. This means that the PM emissions do not originate from the exhaust.

If the two plumes slightly overlap, then values start to populate the lower left quadrant of the plot shown in Figure 4-52

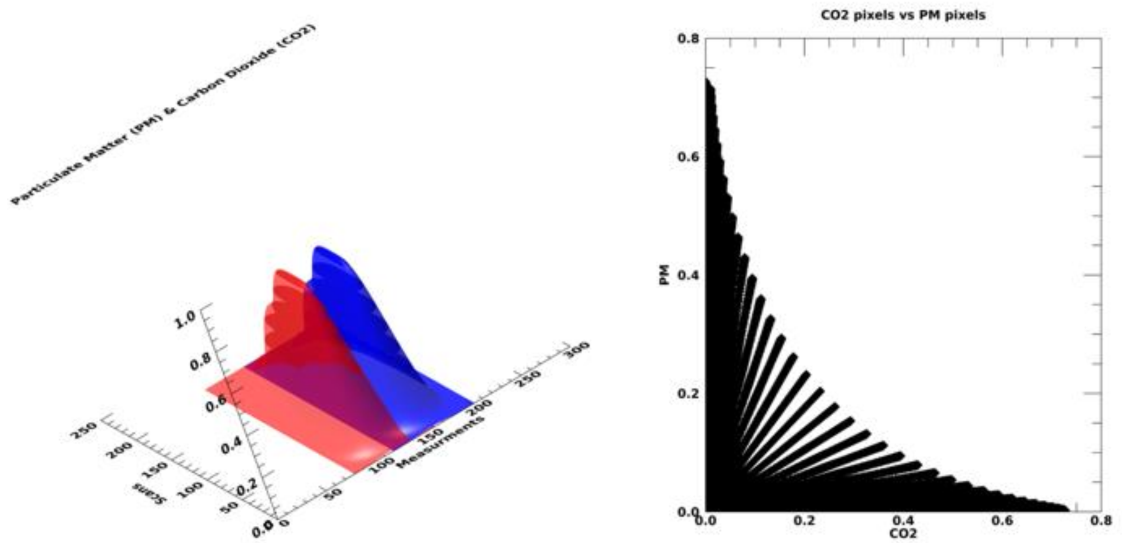


Figure 4-52: Start of overlap between the two plumes start, resulting in a population of the lower left quadrant of the 2D-plot to the right.

If the two plumes almost overlap, then the values populate the upper right quadrant of the plot and start to resemble one straight line as shown in Figure 4-53.

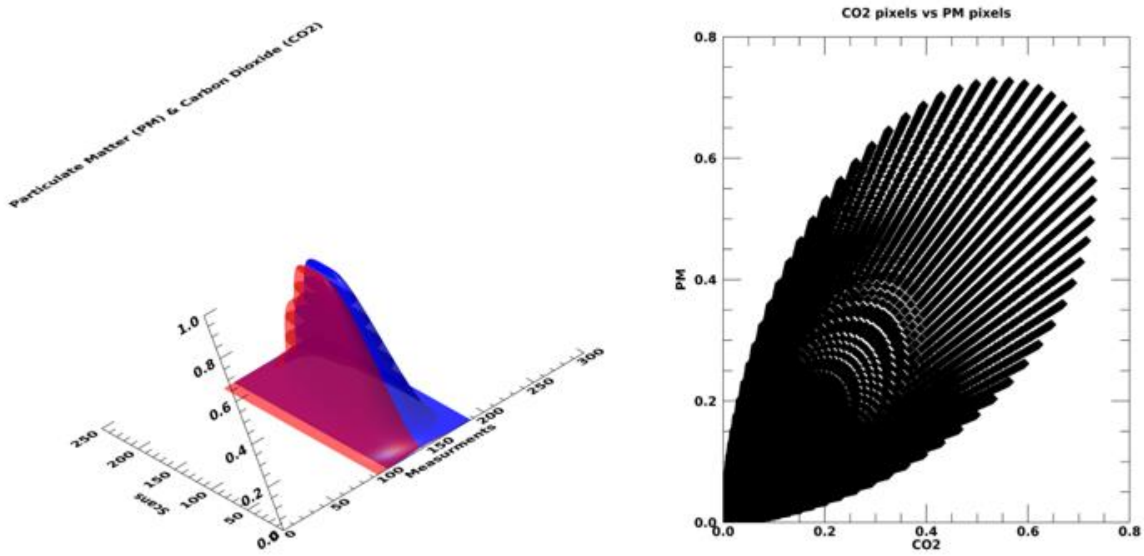


Figure 4-53: A near-complete overlap, leading the values to start populating the upper right quadrant of the plot

If the two plumes overlap exactly, the plot shows one straight line with the slope that equals the ratio of PM/CO_2

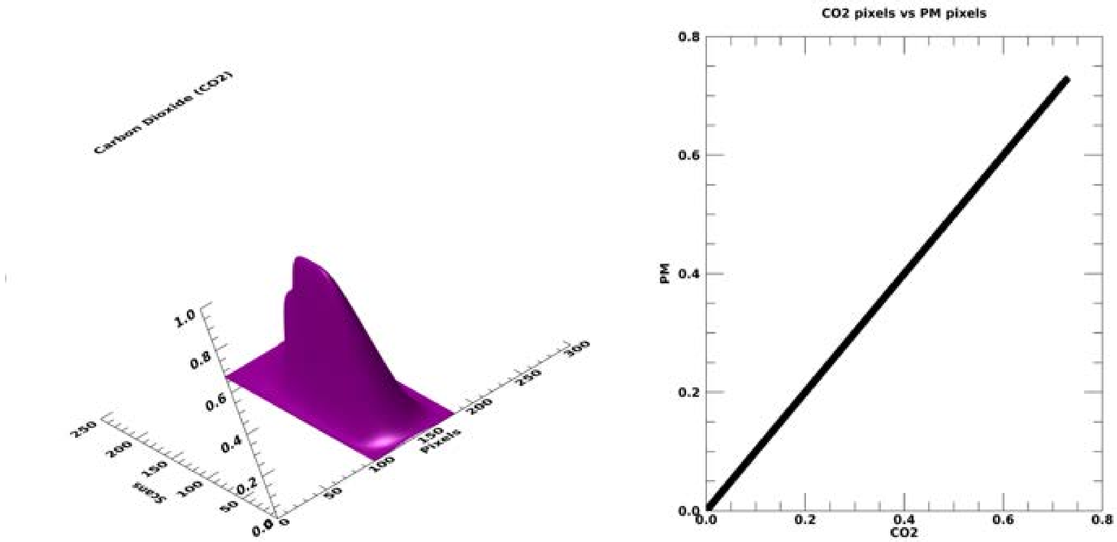


Figure 4-54: An exact plume overlap, resulting in a plot showing one straight line with the slope that equals the ratio of PM/CO_2

The spatial threshold can be automated by fitting the data to a straight line, making sure a significant amount of data is in the upper right-hand quadrant. This is shown in Figure 4-55. CO_2 and PM map a straight line when the measurements are plotted with each other, whose higher values are in the upper right corner. When the CO_2 is high, then the PM is high, and when the CO_2 is low, the PM is low. If the PM does not coincide with CO_2, the read is considered invalid as virtually no PM is deemed to originate from the exhaust in this case. This gives a more definitive threshold for spotting DPF failures.

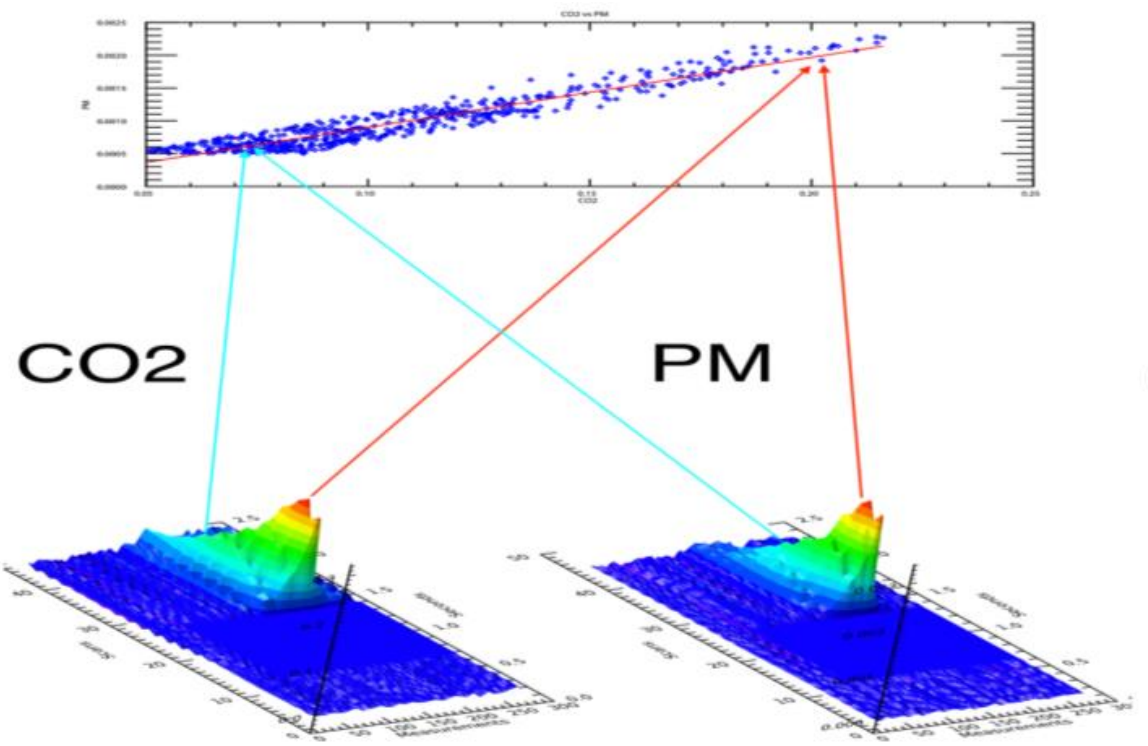


Figure 4-55: An example of the spatial distribution of CO_2 and PM during a high-PM event like a DPF regeneration

Apart from the spatial analysis, it is also possible to rule out a DPF regeneration event in the case of a high-emitting PM vehicle by having more than one remote sensing reading of that same vehicle. As such, EDAR can spot broken or removed DPF filters, ruling out DPF regeneration when consecutive readings show a high and a (very) low outcome. One example of a PM failure from the dataset that rules out DPF regeneration is a 2016 Volvo V60, diesel Euro 5b which failed twice for PM measurements. On the other hand, a 2014 Opel Astra diesel Euro 5 failed the first time it was seen with relatively high PM, while on a second pass it would not be considered a failure but could be flagged for future monitoring in case the DPF is failing. Figure 4-56 and Figure 4-57 are exemplary of a possible DPF regeneration, showing a 2018 Citroen diesel Euro 6de that was detected twice and failed once, pointing out to a possible regeneration. Please note that in Figure 4-57, the CO_2 stays near its axis in the 2D plot indicating no correlation with any PM. For the Flemish dataset, 15 DPF-equipped diesel cars were flagged for DPF failures. This number is low as such analysis requires at least two measurements of the same vehicle, indicating the need for extended remote sensing campaigns.

In summary, EDAR collects large amounts of data with its high sampling rate of over 100,000 Hz for each vehicle detected. This allows for the construction of a 3D image for each pollutant. By using spatial correlation or plotting pollutant positions versus CO_2 positions, a promising approach can be implemented to separate DPF regenerations from failures. This, however, requires to be validated in future remote sensing campaigns.

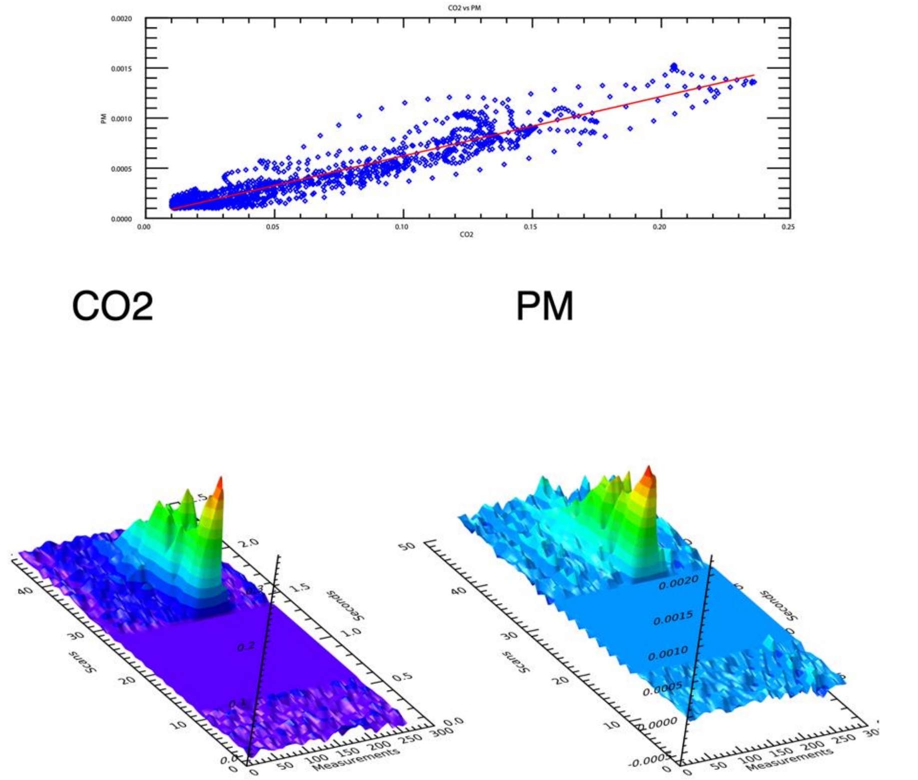


Figure 4-56: An example of a potential DPF regeneration event during the first detection of a 2018 Citroen diesel Euro 6de car, characterised by a high PM emissions

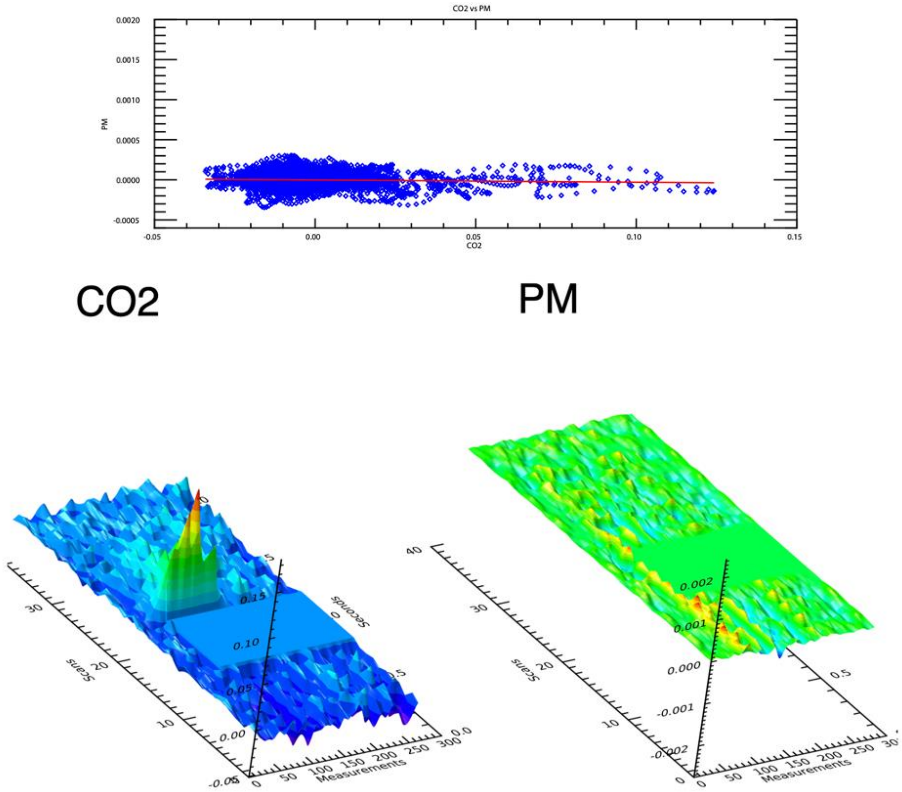


Figure 4-57: The second detection of the 2018 Citroen Euro 6de car, indicating that the high PM emissions during the first detection might be related to a DPF regeneration event

4.5.3.2 High-emitters for NOx

4.5.3.2.1 Diesel PC

Repeating the same exercise for diesel passenger car NOx emissions would at first glance suggest diesel high-emitters are far less represented in the Flemish dataset, as shown in Figure 4-58 and Figure 4-59. This distribution, however, results from the proposed methodology for defining high-emitters. As such, a high 75th percentile and interquartile range result in a high threshold for pointing out high-emitting vehicles. This is the case for the investigated diesel samples and explains why we should consider the entire test population as high-emitters, for which less than 5% is considered not to belong to the 'typical' emitter category.

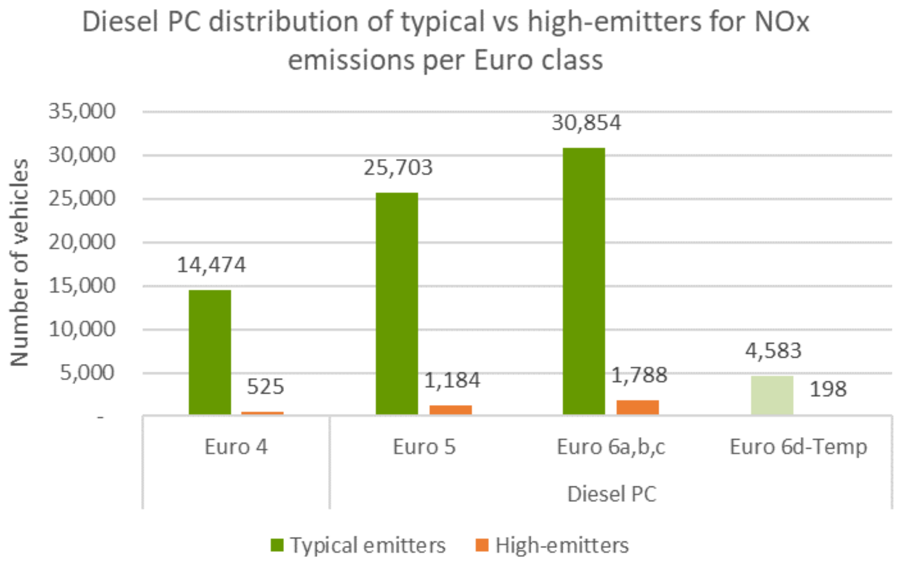


Figure 4-58: Distribution of normal range and high-emitter diesel NOx emissions for diesel passenger cars

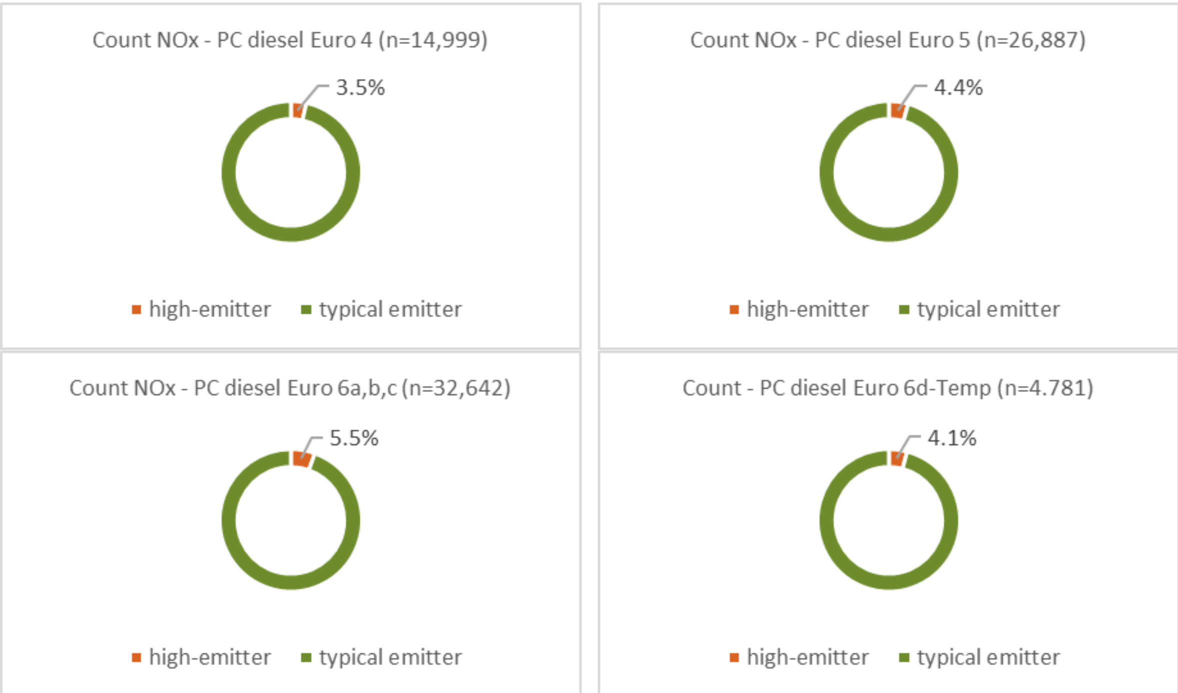


Figure 4-59: The distribution of typical and high-emitters for NOx for diesel cars per Euro class

The statement of considering most of the discussed diesel cars as high-emitters is strengthened by the average emission factors showed in Figure 4-60. Note that the typical emitting cars show a slight increase in average emissions from Euro 4 to Euro 5, indicating that the latter did not result in the desired reductions following the tightened emission limit. Nonetheless, we do report a substantial decrease from Euro 6 onwards. Remember that in this specific exercise Euro 6d-Temp diesel variants are displayed to give a preliminary indication of their potential emission profiles as their sample size did not reach the arbitrarily chosen threshold of 10,000. As discussed in section 4.3.1.1 'Nitrogen oxides (NOx)' on p. 43, a further reduction in average NOx emissions is seen for the latter technology. This indicates that the strict RDE regulation with on-road testing is showing a positive impact on real-world driving emissions. Keeping in mind that the 168 mg/km NOx limit during type-approval approximates 3.4 g NOx per kg fuel burned (for an average diesel car consuming 5 l/100 km), we see that the typical emitter's average for Euro 6d-Temp is below this threshold. However, high-emitters still cause problematic emissions in real-world driving conditions: these can either be caused by the vehicles concerned, or by limitations of the RDE regulation (such as limited scope for driving conditions during on-road testing).

Concerning the exceedance factor for the determined high-emitters relative to a typical emitter, no significant difference is visible between Euro 4 and 5 diesel cars, with an average exceedance of approximately a factor 4. For Euro 6 diesel car, this factor increases to over a factor 5,5. Keeping in mind that the current Euro 6a,b,c limit of 80 mg NOx/km equals approximately 1.6 g NOx/kg fuel for a diesel car with a 5 l/100 km fuel economy (i.e. 20 km on 1 kg of fuel, or 17 km per litre diesel fuel), we see that also the typical emitters for this technology tend to exceed the limit by almost a factor 4, and much more in case of high-emitters. This value is in line with the expectation and confirms what is reported in PEMS studies. As it is known from the literature, such discrepancies typically originate from calibrating engines and their exhaust gas aftertreatment systems specifically for type-approval testing, while applying a more relaxed strategy during non-test conditions. The additional emissions displayed by high-emitters on top of the already high typical emissions are most likely explained by critical failures in the emission control systems such as malfunctions and tampering or a failing emission control strategy. When advanced emission control technology fails, the emissions return to very high levels.

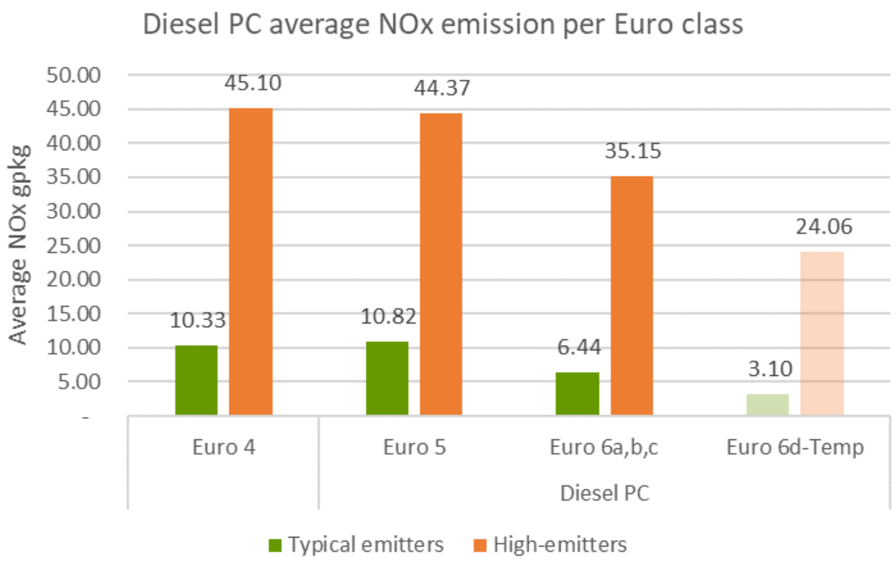


Figure 4-60: Average NOx emission rates in g/kg fuel for normal range and high-emitting diesel passenger cars

Considering the cumulative NOx emissions for the discussed sample populations (Euro 5 – 6d-Temp), Figure 4-61 illustrates how the defined high-emitter shares contribute a combined 19.7% of the total. For Euro 4 diesel cars, high-emitters contribute about 14% to the total of this sampled population. This is nonetheless a skewed representation of reality as typical emitters have a high NOx offset. Figure 4-62 finally shows the contribution of the high-emitters within the specific Euro classes. As such, note that the cleaner exhaust emissions get, the higher this impact becomes. Thus, a share of 4.9% Euro 5 – 6d-temp high-emitters contribute nearly one-fifth (19.7%) of the test populations NOx emissions, whereas the cumulative emissions show that the bulk of NOx is emitted by the typical emitters.

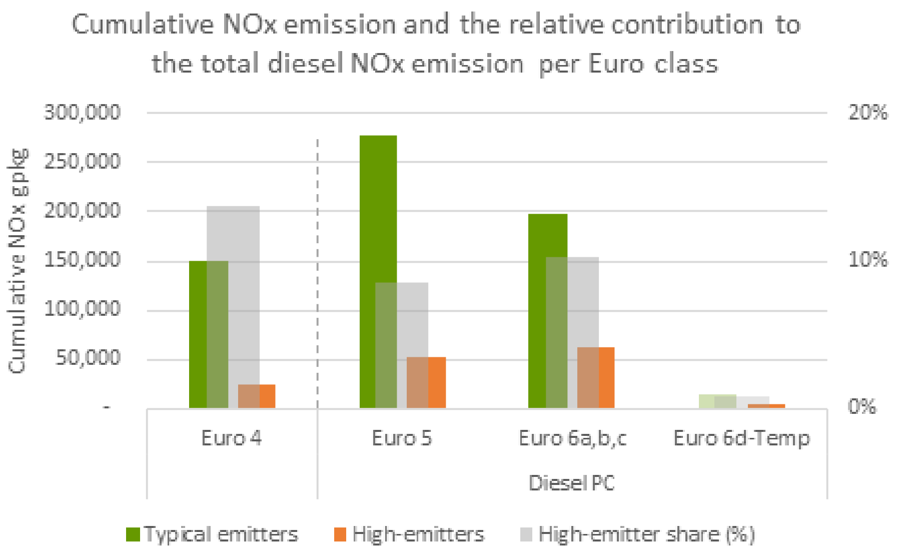


Figure 4-61: Total NOx contribution of the diesel passenger car high and normal range emitters (left-hand Y-axis), and the relative share of high-emitters in the Euro 4 class and the combined Euro 5 – 6d-Temp class, respectively (grey bars, right-hand Y-axis).

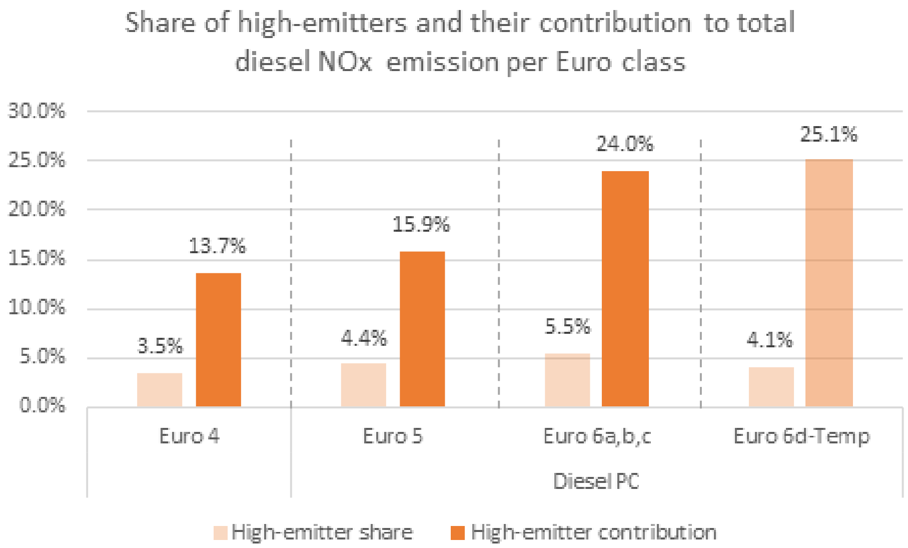


Figure 4-62: Relative contribution of the diesel passenger car high-emitters for NOx per Euro class

4.5.3.2.2 Petrol PC

For both the Euro 5 and 6a,b,c petrol population, for which more than 10,000 samples are registered, approximately 7% was categorised as a high-emitter. For the lesser populated Euro 4 and 6d-Temp categories, high-emitters represented 7.7% and 6.6%, respectively (Figure 4-66).

Looking at their average emissions, we see that also for petrol cars the high-emitters have a significant impact. As such, Euro 5 and 6a,b,c high-emitter samples show a difference by a factor 13 and 12, respectively, compared to typical emitters. For Euro 4 and 6d-Temp categories, these factors are 10.9 and 11.4, respectively. This is shown in Figure 4-63 and Figure 4-64. In terms of cumulative NOx emissions **for both Euro 5 and 6a,b,c petrol cars, an averaged 6.9% of high-emitter events contribute 41.1% of the NOx emissions**. This situation differs substantially from what is reported for the diesel counterparts, where high-emitters were found to have only little impact on the averages (since the average is already high). This indicates that **petrol car results depend more on properly functioning TWC technology than diesel cars depend on SCR technology**. As such, a small share of petrol vehicles significantly influences the total petrol averages for NOx. A small group with high emissions may indicate issues with three-way catalyst technologies, which could be, for example, malfunctions or reduced performance in real-world operation by design where power demand is higher than in the type-approval test. High petrol NOx emissions can also originate from ageing, failing or removed three-way catalysts, from rich engine operation, and (intentionally tampered) faulty lambda sensors.

What came to light in this specific remote sensing campaign is that certain petrol cars emitted very high concentrations of NO_x during motorway driving, an event that has been a blind spot in remote sensing studies so far as they typically address urban driving. Moreover, low-powered driving has been part of legislation and vehicle testing for a long time. High-powered driving, as would occur on the motorway, is not naturally included in the evaluation of emission behaviour. For diesel vehicles, this is less significant as their SCR systems should work optimally in motorway conditions, making this part of the RDE-test less challenging compared to petrol cars. The absence of significant high-powered motorway driving can nevertheless impact the emission performance of petrol cars. Even now, in RDE testing, the power demand is restricted, disqualifying any responsibility for the manufacturer, claiming it is ‘aggressive’ driving. As such, albeit that these conditions consist of nothing more than regular motorway driving, high emissions in such circumstances are currently considered the responsibility of the driver. In Table 4-12, an overview is given of the average NOx emission factors for both petrol and diesel cars, with a distinction based on the Euro class. Also, cumulative emissions are given.

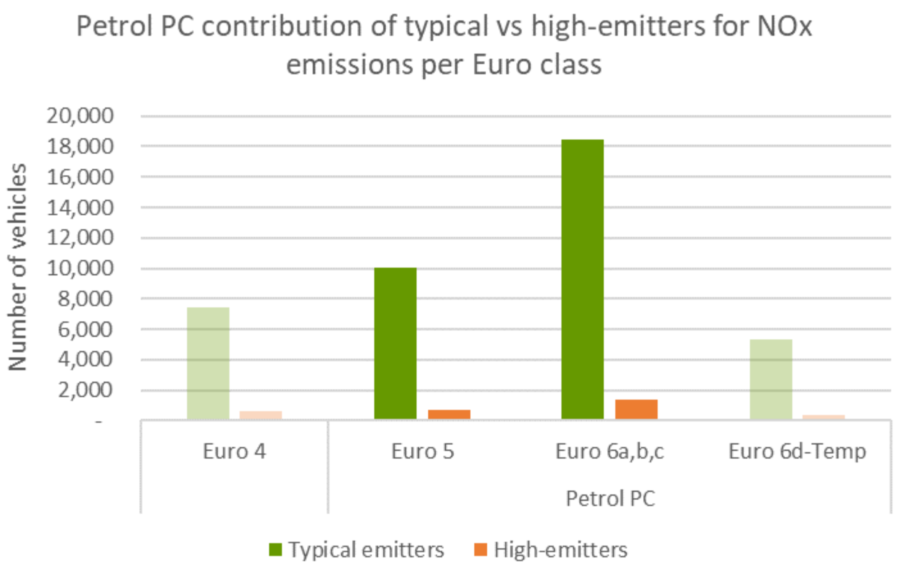


Figure 4-63: Distribution of normal range and high-emitter diesel NOx emissions for petrol passenger cars

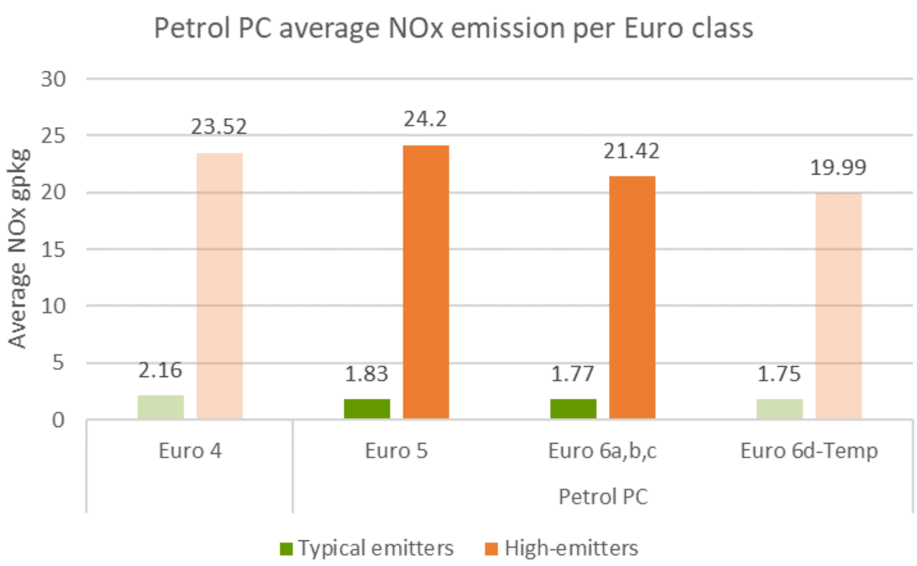


Figure 4-64: Average NOx emission rates in g/kg fuel for normal range and high-emitting petrol passenger cars

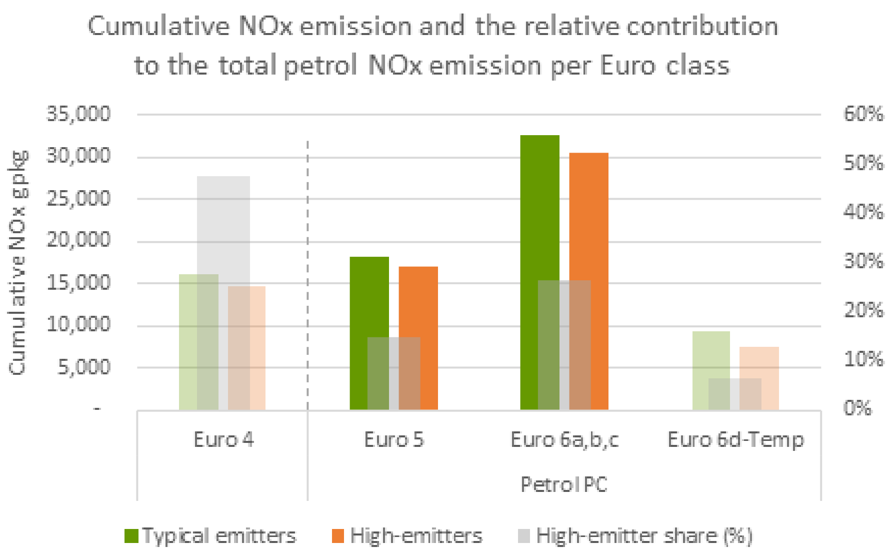


Figure 4-65: Total NOx contribution of the petrol passenger car high and normal range emitters per Euro class (coloured bars, left-hand side Y-axis), and the relative share of high emitters for Euro 4 separately and Euro 5 – 6d-Temp combined (grey bars right-hand side Y-axis)

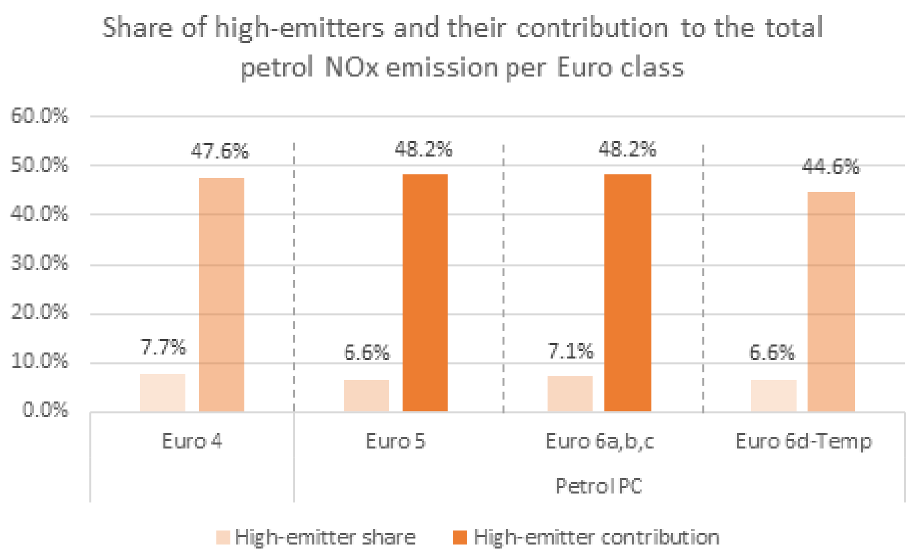


Figure 4-66: Relative contribution of the petrol passenger car high-emitters for NOx per Euro class

Table 4-12: Overview of the average NOx emission factors for the Flemish dataset, both for petrol and diesel passenger cars

AVG NOx_gpkg	Petrol NOx			Diesel NOx		
	Normal range	High-emitter	Cumulative	Normal range	High-emitter	Cumulative
Euro 4	*2.16*	*23.52*	*30,850*	*10.33*	*45.10*	*173,210*
Euro 5	1.83	24.20	35,378	10.82	44.37	330,700
Euro 6a,b,c	1.77	21.42	63,102	6.44	35.15	261,522
Euro 6d-Temp	*1.75*	*19.99*	*16,998*	*3.10*	*24.06*	*18,958*

4.5.3.3 Three-way catalyst functioning

In an attempt to find causes for high petrol NOx emissions, e.g. due to a broken or deteriorated catalyst, we performed a correlation analysis for the different measured pollutants (CO, NO, NO_2, NOx, HC, and PM). The reasoning behind this approach is that high NO_x emissions by petrol cars with a broken catalyst would also result in high CO and HC emissions if the lambda control is still functioning as a three-way catalyst typically keeps the three pollutants at very low levels when the engine runs stoichiometrically. This effect, however, was not to be seen from the results in the correlation matrix presented in

Table 4-13 below, as only poor correlations were found between NOx, CO, and HC. Similar matrices were compiled for diesel Euro 4-6b cars, as well as for HGV Euro VI, although no significant correlations were found. Such findings might have, for instance, pointed out durability issues related to oxidation catalyst. No such indications are found.

Table 4-13: Petrol Euro 6 passenger car correlation matrix for indicating three-way catalyst issues

	CO_gpkg	NO_gpkg	NOx_gpkg	NO_2_gpkg	HC_gpkg	PM_gpkg
CO_gpkg	1	0.016829	0.007423	-0.005052	0.01481	-0.0007
NO_gpkg	0.016829	1	0.755223	0.171919	0.013517	0.00573
NOx_gpkg	0.007423	0.755223	1	0.775546	0.131325	-0.00753
NO2_gpkg	-0.005052	0.171919	0.775546	1	0.184351	-0.01683
HC_gpkg	0.01481	0.013517	0.131325	0.184351	1	0.02549
PM_gpkg	-0.000702	0.005732	-0.007526	-0.016831	0.025489	1

4.5.3.4 Analysis of the impact of the test location

Also, for the different test locations, we compared the average NOx emissions for the same test population, although the Antwerp N186 site was not included as the number of measurements was too low to allow for proper conclusions. Figure 4-67 shows the average NOx emissions per Euro class for diesel passenger cars for the typical emitters, while Figure 4-68 shows to what extent the high-emitters exceed the former's impact. Note the scale on the Y-axis as the high-emitters had a far greater impact in the range of a factor 4 higher than what is seen for the typical emitters. What catches the eye is how high-emitters in Bruges show a larger impact relative to the typical fleet when compared to this situation for the other locations. The measurements by the Antwerp Tunnel exit show higher averages than those for other locations, something that might be explained by higher engine loads due to the long slope from the lowest point of the tunnel, combined with the typical change from congested to free-flowing traffic. The high-emitter contributions near Bruges may be explained by the frequent traffic jams at rush hours and/or accelerating on the relatively short slopes when exiting the under-passage by which the remote sensing unit was set up. Contrary to the steady engine operations in the Aalst motorway, the Bruges setting tends to lean closer to urban/rural driving. For Ghent, typical urban driving is represented, for which start/stop traffic and/or traffic lights may explain higher NOx emissions.

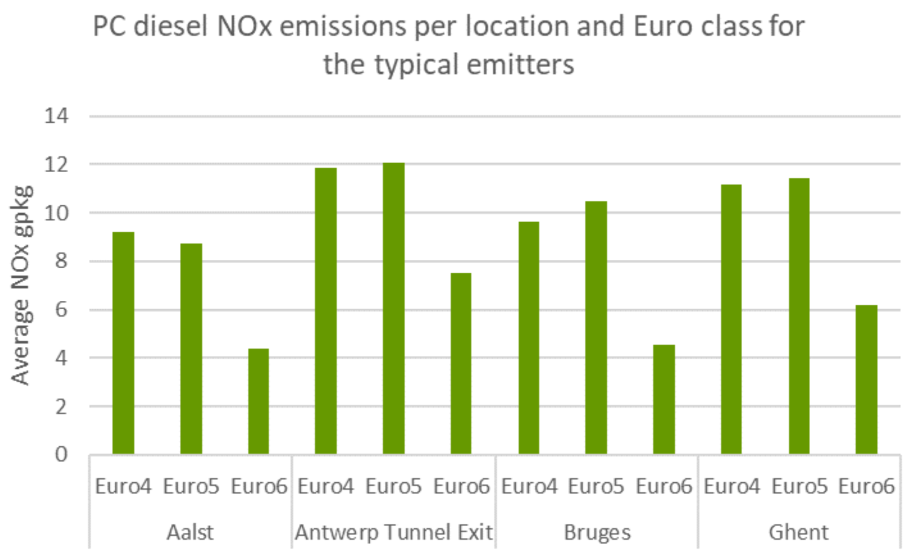


Figure 4-67: Typical emitter averages for NOx for diesel cars per test location

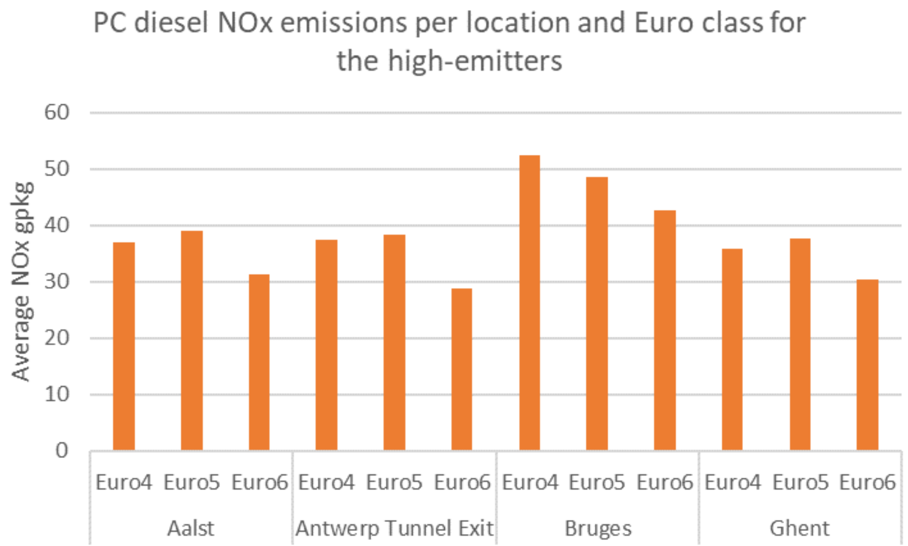


Figure 4-68: High-emitter averages for NOx for diesel cars per test location

For petrol cars, we see a far greater impact of the high-emitters, as an increase by a factor 10 compared to the normal range emitter averages is reported. Also here, the average impact in Bruges is emphasised, with the discrepancy increasing further to a factor of 20. This can be seen in Figure 4-69 and Figure 4-70.

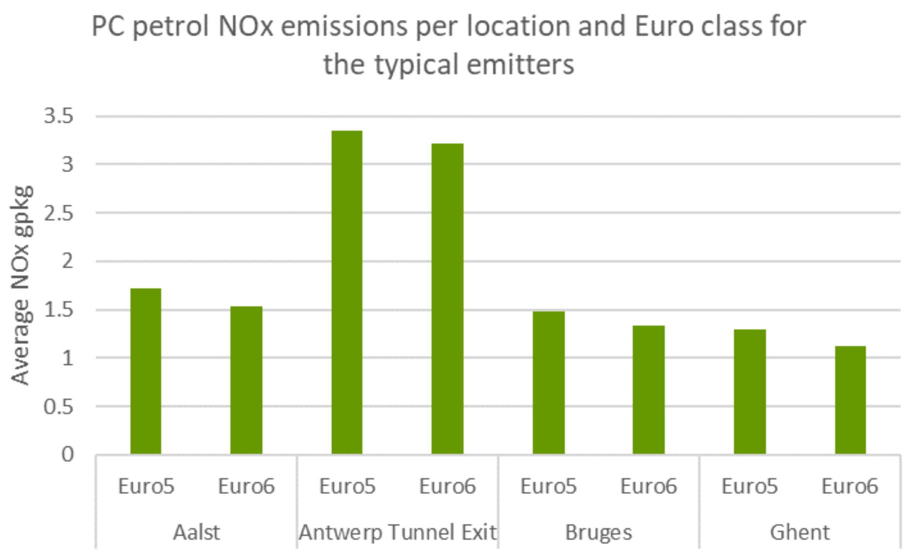


Figure 4-69: Typical emitter averages for NOx for petrol cars per test location

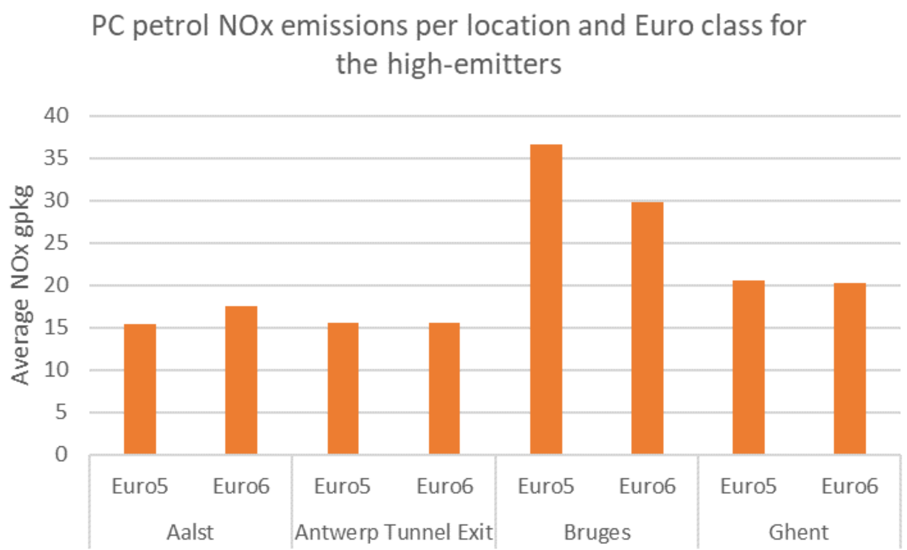


Figure 4-70: High-emitter averages for NOx for petrol cars per test location

4.5.4 Multi-regression for location, VSP, ambient temperature, and speed

In a remote sensing experiment, many elements are not under control and other elements need to be extrapolated to the average situation. Correlation studies and multi-regression analyses disentangle different dependencies and may prevent conclusions without underlying causal relation. Moreover, with a limited number of parameters to describe the state of the vehicle that passes a measurement location, too much importance may be assigned to these parameters. For example, measurements on a warm day and a specific location may have higher emission values. This may be related to the temperature but may just as well be related to the location or could even be related to the vehicles that are typically out on the road on warm days. This needs to be disentangled to ensure that effects are linked to the causes if this link is retained across different measurements. The simple assumption is that all aspects are uncorrelated and other aspects can be averaged over, but this turns out to be incorrect.

One way of looking for significant impacts of variables such as ambient temperature, vehicle-specific power, and/or vehicle speed on pollutants like NOx or PM is to cluster data and to look for 'fingerprints' from dependent variables. By doing so, one can look for strong correlations between parameters as these are typically seen in emission testing campaigns on dynamometers or using portable/smart emissions measurement systems (PEMS/SEMS)[22]. Examples of such correlations are:

- diesel particulate filter (DPF) regenerations, typically causing high exhaust gas temperatures (being about 150°C higher than in normal operation), combined with temporarily increased emissions of carbon monoxide (CO), unburned hydrocarbons (HC), and particle number (PN). Such regeneration events typically take place sporadically while driving on motorways and last for a few minutes (or 10-15 km);
- three-way catalyst (TWC) ageing, leading to a combined increase in petrol NOx, CO, and HC emissions;
- rich-burning petrol engines during high engine loads (i.e. fuel enrichment), leading to high CO and HC. Such events should indicate high vehicle-specific power (VSP) levels and high velocities;
- faulty lambda sensor activity, resulting in high petrol NOx emissions, and;
- NOx storage catalyst regenerations for diesel vehicles, typically produced between 2015 and 2019, characterised by a temporal fuel injection into the exhaust line, leading to spikes in HC and CO emissions.

In this exercise, we focus on the whole remote sensing dataset for those combinations of Euro class, fuel type, and vehicle category for which more than 10,000 samples were taken. This threshold has been chosen arbitrarily to allow for solid conclusions rather than looking at preliminary trends for technologies that are under-represented in the Flemish dataset. An example of such a technology is the Euro 6d passenger car segment, for which less than 300 samples can be found in the dataset (while the low number of diesel Euro 6d vehicles might even result from errors in the vehicle registration services' database). Next to a presentation of the whole dataset, we also focus on the specific impact of high-emitters on the total emissions.

For this fingerprinting method, a multi-regression model was used to see if there is a significant impact of different dependant variables (namely vehicle specific power (VSP, kW/tonne), ambient temperature, and/or vehicle speed) on the average emission of NOx and PM. These variables are used as inputs for a multi-regression model to predict the pollutant emissions per combination of

[22] See for example, TNO report 2013 R11891 Appendix B to see the typical combinations of emissions associated with LNT regenerations.

vehicle category, fuel type, and Euro class by evaluating the least squared errors. Linear regression models typically show polynomials that look like Equation 5 where y is the independent variable or the output, a_i is the coefficient for the dependent variables, and x_i is the dependent variable.

Equation 5

$$y = a_1.x_1 + a_2.x_2 + a_3.x_3 + a_4.x_4 + a_5.x_5 \ldots$$

In the dataset, the output (y) is NOx (or PM) and the dependent variables are the ambient temperature, VSP, and velocity. Locations are treated as constants since they are not continuous but discrete. This helps to remove the 'location-bias' that might creep in and makes the other dependent variables independent from location effects. For example, the average ambient temperature may have been higher at one location than at another one. The effect of the location, in turn, might be "transferred" to the ambient temperature. Because a range of ambient temperatures occurs at every location, a combined approach can separate the effects to a certain extent.

Table 4-14 and Table 4-15 make a distinction between vehicle category, Euro class and fuel type as comparing one to the other would cause errors. Each column represents the coefficient for the given variables. The results in Table 4-14 indicate a weak negative influence of the ambient temperature on Euro 5 petrol cars and Euro V HGVs, meaning that NOx emissions tend to drop very slightly with higher ambient temperatures. For all other combinations, we see no significant correlations with ambient temperature. Also, barely any impact from the VSP on NOx emissions is observed. For all three discussed Euro classes, there is a negligible relation with the vehicle speed. For diesel PM emissions, no significant impact is predicted from one of the three first dependent variables.

The location columns show the constant offset for the emissions. By introducing the constants for each of the locations, one overcomes the bias in measurements that might have occurred due to the location itself. For example, two locations may have a similar ambient temperature, velocity, and VSP, but still have different average emissions. This is associated with the location itself and aspects of traffic not linked to the measured parameters. As such, the predicted NOx emissions for a Euro 4 diesel car, at the E40 motorway near Aalst, would look like what is shown in Equation 6.

Equation 6

$$NOx = -0.06544\ x\ (AmbientTemp\ C) + 0.000106\ x(VSP) + 0.026467\ x\ (SpeedKPH) + 8.139342$$

Table 4-14: Multiple linear regression result for the whole test population including high-emitters

	Ambient Temp	VSP	Speed KPH	Aalst	Antwerp N186	Bruges	Ghent	Antwerp_ Tunnel exit
NOx Euro 4 Diesel PC	-0.065444	0.000106	0.026467	8.139342	9.796982	11.366275	12.116897	12.445968
NOx Euro 5 Diesel PC	-0.062553	-0.000927	0.044385	5.832788	9.38785	11.463109	11.684793	11.319188
NOx Euro 6 Diesel PC	0.071172	-0.001835	0.035825	0.137428	2.054782	3.554582	4.927376	5.100417
PM Euro 4 Diesel PC	-0.006048	-0.000847	-0.000765	0.354604	10.598475	0.345126	0.282716	0.330542
PM Euro 5 Diesel PC	-0.005036	-0.000299	-0.000623	0.195375	11.489018	0.183753	0.158117	0.196482
PM Euro 6 Diesel PC	-0.000259	-0.000077	0.000116	0.005748	0.021848	0.022054	0.007037	0.009264
NOx Euro 5 Petrol PC	-0.114087	-0.002272	-0.008684	5.49108	4.674361	6.495255	5.277776	8.881801
NOx Euro 6 Petrol PC	-0.063964	0.003087	-0.014099	4.709251	3.938161	5.267812	4.008412	7.526234
PM Euro 5 Petrol PC	0.00007	-0.00019	-0.000072	0.025958	1.773114	0.051088	0.004711	0.014285
PM Euro 6 Petrol PC	-0.001914	0.000036	-0.000872	0.141947	1.8027	0.121959	0.090225	0.122235
NOx Euro 5 Diesel HGV	-0.155136	-0.006389	-0.017384	16.364676	13.791376	18.821213	25.047688	25.108112
NOx Euro 6 Diesel HGV	-0.086567	-0.001753	-0.011154	5.1515	5.597479	5.516891	12.086574	10.433825
PM Euro 5 Diesel HGV	-0.000642	-0.00005	0.000396	-0.017675	0.012801	0.035345	0.029237	-0.003579
PM Euro 6 Diesel HGV	-0.000039	-0.000045	0.000103	-0.007923	-0.004616	0.009743	-0.00363	-0.00156

In most cases, the ambient temperature has a small negative correlation, indicating that with increasing temperatures, the emissions decrease. For VSP and speed, the effect is less consistent. The coefficients themselves do not provide much information. The combination of the coefficient with the typical range of the parameter indicates the typical variation of emissions associated with these parameters. Given a typical range of temperature, VSP, and speed, of 20^{o} C, 70 km/h, and a VSP of 30 kW/tonne, the effects of these parameters on the emissions, given in Table 4-14, are in the range of 0,1-2 NOx gpkg. **The effect of the location, not captured by velocity, VSP, and ambient temperature is therefore dominant in almost all cases**. Apart from the technical state (maintenance, quality of emission control, etc) of the vehicle, it seems that the measurement result depends on the traffic dynamics and the driving conditions in the last kilometre (or less) before the sampling point. To gain a better understanding of the emission performance of vehicles in different driving conditions, it is advisable to collect and combine measurements in different locations, each representing different driving conditions.

For high-emitters, given in Table 4-15, we see different influences from mainly the ambient temperature and, to a lesser extent, VSP and the vehicle speed. As such, NOx emissions from diesel passenger cars tend to increase with lower exhaust temperatures, possibly linked with ambient temperatures, which might point out poor aftertreatment efficiencies at such temperatures (if present). A similar influence of ambient temperatures on NOx emissions is shown on petrol Euro 5 cars, as well as for Euro V HGVs. However, in general, high emissions seem more likely to be linked with other aspects, like tampering or malfunctions, than any of the variables that have been registered in the remote sensing dataset.

Diesel PM emissions seem to be little influenced by these variables, indicating that high PM emissions are not caused by ambient nor driving conditions, but are likely the result of a broken, damaged, or removed DPF.

Table 4-15: Multiple linear regression result for the test population of high-emitters

	Ambient Temp	VSP	Speed KPH	Aalst	Antwerp N186	Bruges	Ghent	Antwerp Tunnel Exit
NOx Euro 4 Diesel PC	**-1.307136**	-0.045455	**-0.226331**	89.97795	76.122955	95.669345	78.355415	89.825433
NOx Euro 5 Diesel PC	**-0.829012**	-0.066327	**-0.142167**	72.999	68.69898	76.924374	65.792741	71.387531
NOx Euro 6 Diesel PC	-0.490532	-0.028356	-0.052092	49.4055	48.8467	56.815767	46.412357	49.078384
PM Euro 4 Diesel PC	-0.016381	-0.005203	0.001481	1.378514	10.84873	2.05772	1.67068	1.455182
PM Euro 5 Diesel PC	-0.007544	-0.000805	-0.000657	0.41372	10.547015	0.599516	0.430087	0.416971
PM Euro 6 Diesel PC	-0.005361	0.000864	0.002352	-0.081199	6.337108	0.277927	0.153099	0.077136
NOx Euro 5 Petrol PC	**-1.203424**	-0.049398	0.073389	34.87524	41.915686	58.502142	47.196439	42.794047
NOx Euro 6 Petrol PC	-0.674661	0.053994	-0.012508	30.01197	33.05759	44.206378	37.123679	33.25749
PM Euro 5 Petrol PC	-0.012853	-0.000916	-0.000319	0.484254	1.79154	0.74007	0.522038	0.538323
PM Euro 6 Petrol PC	-0.010117	0.000888	-0.003324	0.649773	3.398151	0.746443	0.556294	0.629235
NOx Euro 5 Diesel HGV	**-0.834903**	-0.021219	-0.047013	70.04809	61.897945	69.37512	60.343036	120.523533
NOx Euro 6 Diesel HGV	-0.547143	-0.031293	0.017966	24.40383	34.378181	31.111045	27.450696	28.471408
PM Euro 5 Diesel HGV	-0.011639	-0.001663	0.001613	0.216024	0.310833	0.527175	0.568821	0.280054
PM Euro 6 Diesel HGV	-0.000622	-0.000196	0.000078	0.031867	0.010069	0.091474	0.030205	0.043334

To get an idea of the impact of each of the parameters shown in Table 4-14 and Table 4-15, it is useful to convert the regression results into absolute bandwidths. For example, the velocity dependence is given by a coefficient, e.g. -0.22. The velocities themselves, however, may vary between 20 and 120 km/h. In that case, the emissions in g/kg fuel will decrease with the increasing velocity -0.22*(120-20) = -22 g/kg. So, the combination of coefficient -0.22, including the sign, and the range of velocities provides the typical effect. If the emission would increase with velocity, the sign would have been positive. As such, Table 4-16 and Table 4-17 show the impact ranges per variable for the whole fleet and the high-emitters separately, respectively. The average NO_x emission in g/kg fuel given in the second column is calculated as shown in Equation 7. The actual bandwidth provides the relative contribution of each of the parameters in the range of conditions observed in the whole measurement campaign.

Equation 7

$$\begin{aligned}\mathrm{NOx} = \mathrm{NOx}_{\mathrm{average}} &\pm \Delta\mathrm{NOx}\,(\text{ambient temperature}) \pm \Delta\mathrm{NOx}\,(\mathrm{VSP}) \pm \Delta\mathrm{NOx}\,(\text{velocity}) \pm \Delta\mathrm{NOx}\,(\mathrm{Aalst}) \\ &\pm \Delta\mathrm{NOx}\,(\mathrm{AntwerpN186}) \pm \Delta\mathrm{NOx}\,(\mathrm{Bruges}) \pm \Delta\mathrm{NOx}\,(\mathrm{Ghent}) \pm \Delta\mathrm{NOx}\,(\mathrm{Antwerp\_exit\_tunnel})\end{aligned}$$

Where:

$$\begin{aligned}\mathrm{NOx}_{\mathrm{average}} = (&a_1 * x1_{\mathrm{average}} + a_2 * x2_{\mathrm{average}} + a_3 * x3_{\mathrm{average}} + a_{\mathrm{Aalst}} * x_{\mathrm{Aalst,average}} + a_{\mathrm{AntwerpN186}} \\ &* x_{\mathrm{AntwerpN186,average}} + a_{\mathrm{Bruges}} * x_{\mathrm{Bruges,average}} + a_{\mathrm{Ghent}} * x_{\mathrm{Ghent,average}} + a_{\mathrm{AntwerpExitTunnel}} \\ &* x_{\mathrm{AntwerpExitTunnel,average}}\end{aligned}$$

And

$$\Delta\mathrm{NOx}\,(\text{ambient temperature}) = a_1 * \sigma_1$$

$$\Delta\mathrm{NOx}\,(\mathrm{VSP}) = a_2 * \sigma_2$$

$$\Delta\mathrm{NOx}\,(\mathrm{Velocity}) = a_3 * \sigma_3$$

$$\begin{aligned}\Delta\mathrm{NOx}\,(\mathrm{Aalst}) = a_{\mathrm{Aalst}} - (&a_{\mathrm{AntwerpN186}} * x_{\mathrm{AntwerpN186,average}} + a_{\mathrm{Aalst}} * x_{\mathrm{Aalst,average}} + a_{\mathrm{Ghent}} * x_{\mathrm{Ghent,average}} \\ &+ a_{\mathrm{Bruges}} * x_{\mathrm{Bruges,average}} + a_{\mathrm{AntwerpExitTunnel}} * x_{\mathrm{AntwerpExitTunnel,average}})\end{aligned}$$

$$\begin{aligned}&\Delta\mathrm{NOx}\,(\mathrm{AntwerpN186}) \\ &= a_{\mathrm{Antwerp186}} - (a_{\mathrm{AntwerpN186}} * x_{\mathrm{AntwerpN186,average}} + a_{\mathrm{Aalst}} * x_{\mathrm{Aalst,average}} + a_{\mathrm{Ghent}} \\ &* x_{\mathrm{Ghent,average}} + a_{\mathrm{Bruges}} * x_{\mathrm{Bruges,average}} + a_{\mathrm{AntwerpExitTunnel}} * x_{\mathrm{AntwerpExitTunnel,average}})\end{aligned}$$

$$\begin{aligned}\Delta\mathrm{NOx}\,(\mathrm{Bruges}) = a_{\mathrm{Bruges}} - (&a_{\mathrm{AntwerpN186}} * x_{\mathrm{AntwerpN186,average}} + a_{\mathrm{Aalst}} * x_{\mathrm{Aalst,average}} + a_{\mathrm{Ghent}} * x_{\mathrm{Ghent,average}} \\ &+ a_{\mathrm{Bruges}} * x_{\mathrm{Bruges,average}} + a_{\mathrm{AntwerpExitTunnel}} * x_{\mathrm{AntwerpExitTunnel,average}})\end{aligned}$$

$$\begin{aligned}\Delta\mathrm{NOx}\,(\mathrm{Ghent}) = a_{\mathrm{Ghent}} - (&a_{\mathrm{AntwerpN186}} * x_{\mathrm{AntwerpN186,average}} + a_{\mathrm{Aalst}} * x_{\mathrm{Aalst,average}} + a_{\mathrm{Ghent}} * x_{\mathrm{Ghent,average}} \\ &+ a_{\mathrm{Bruges}} * x_{\mathrm{Bruges,average}} + a_{\mathrm{AntwerpExitTunnel}} * x_{\mathrm{AntwerpExitTunnel,average}})\end{aligned}$$

$$\begin{aligned}&\Delta\mathrm{NOx}\,(\mathrm{AntwerpExitTunnel}) \\ &= a_{\mathrm{AntwerpExitTunnel}} - (a_{\mathrm{AntwerpN186}} * x_{\mathrm{AntwerpN186,average}} + a_{\mathrm{Aalst}} * x_{\mathrm{Aalst,average}} + a_{\mathrm{Ghent}} \\ &* x_{\mathrm{Ghent,average}} + a_{\mathrm{Bruges}} * x_{\mathrm{Bruges,average}} + a_{\mathrm{AntwerpExitTunnel}} * x_{\mathrm{AntwerpExitTunnel,average}})\end{aligned}$$

a_i are the coefficients obtained from the regression analysis in Table 4-14 and Table 4-15 and σ_i is the standard deviation of the measurements (AmbientTemp, VSP, and velocity). For the locations, we consider them as absolute deviations from the average location contribution.

Notable effects from the tables below include, firstly, very large effects of the locations, compared to other aspects. The outlier location for diesel light-duty vehicles is Aalst, where NOx emissions are substantially lower, while for Ghent the HGV NOx emissions are substantially higher, and likely the circumstances and dynamics also affect the Antwerp tunnel results. Ambient temperature effects remain for Euro 5 petrol cars and Euro V trucks, but the effects are less than 20%. Very notable is also the high PM at the Antwerp N186 location. It should be noted that for this site, only collected a small sample of valid results due to the specific local driving conditions, as pointed out in section 3.2.1.4.

Table 4-16: The regression analysis results with ranges for the whole dataset

	NOx/ΔPM avg.	ΔNOx/ΔPM (AmbientTemp.)	ΔNOx/ΔPM (VSP.)	ΔNOx/ΔPM (SpeedKPH.)	ΔNOx/ΔPM (Aalst)	ΔNOx/ΔPM (Antwerp N186)	ΔNOx/ΔPM (Bruges)	ΔNOx/ΔPM (Ghent)	ΔNOx/ΔPM (Antwerp Exit Tunnel)
NOx Euro 4 Diesel PC	11.5605	-0.3227	0.0033	0.6941	**-3.0721**	-1.4145	0.1548	0.9055	1.2345
NOx Euro 5 Diesel PC	12.2790	-0.3140	-0.0294	**1.1455**	**-4.8088**	-1.2537	**0.8215**	1.0432	0.6776
NOx Euro 6 Diesel PC	8.1706	0.3805	-0.0562	**0.8798**	**-3.7908**	-1.8735	-0.3737	0.9991	1.1722
PM Euro 4 Diesel PC	0.1510	0.0052	-0.0080	0.0082	-0.0382	-0.0541	0.0418	0.0055	-0.0493
PM Euro 5 Diesel PC	0.3385	-0.0253	-0.0095	-0.0161	-0.3083	**10.9853**	-0.3199	-0.3456	-0.3072
PM Euro 6 Diesel PC	0.0138	-0.0014	-0.0024	0.0028	-0.0071	0.0090	0.0092	-0.0058	-0.0036
NOx Euro 5 Petrol PC	3.2818	**-0.5456**	-0.0709	-0.2256	-1.0418	-1.8585	-0.0376	-1.2551	2.3490
NOx Euro 6 Petrol PC	3.1303	-0.3117	0.0954	-0.3619	-0.8232	-1.5943	-0.2647	-1.5241	1.9937
PM Euro 5 Petrol PC	0.0876	0.0003	-0.0059	-0.0019	-0.0679	1.6793	-0.0428	-0.0891	-0.0796
PM Euro 6 Petrol PC	0.0728	-0.0093	0.0011	-0.0224	-0.0345	1.6262	-0.0545	-0.0862	-0.0542
NOx Euro 5 Diesel HGV	13.1091	**-0.7299**	**-0.1553**	-0.3469	-1.3835	**-3.9568**	**1.0731**	**7.2995**	**7.3600**
NOx Euro 6 Diesel HGV	2.7235	-0.4095	-0.0420	-0.2198	-0.2358	0.2101	0.1295	**6.6992**	**5.0465**
PM Euro 5 Diesel HGV	0.0280	-0.0030	-0.0012	0.0079	-0.0298	0.0006	0.0232	0.0171	-0.0158
PM Euro 6 Diesel HGV	0.0085	-0.0002	-0.0011	0.0020	-0.0100	-0.0067	0.0076	-0.0058	-0.0037

Table 4-17: The regression analysis results with ranges for the high-emitters

	NOx/ΔPM avg.	ΔNOx/ΔPM (AmbientTemp.)	ΔNOx/ΔPM (VSP.)	ΔNOx/ΔPM (SpeedKPH.)	ΔNOx/ΔPM (Aalst)	ΔNOx/ΔPM (Antwerp N186)	ΔNOx/ΔPM (Bruges)	ΔNOx/ΔPM (Ghent)	ΔNOx/ΔPM (Antwerp Exit Tunnel)
NOx Euro 4 Diesel PC	45.3324	-6.4862	-1.3417	-5.4851	-1.2373	-15.0923	4.4541	-12.8599	-1.3898
NOx Euro 5 Diesel PC	44.2821	-4.0192	-2.1230	-3.3639	-1.1352	-5.4352	2.7902	-8.3415	-2.7467
NOx Euro 6 Diesel PC	35.2356	-2.8853	-0.8525	-1.1754	-2.0245	-2.5833	5.3858	-5.0177	-2.3516
PM Euro 4 Diesel PC	1.8067	-0.0697	-0.1440	0.0335	-0.7484	8.7218	-0.0692	-0.4563	-0.6718
PM Euro 5 Diesel PC	0.6835	-0.0314	-0.0248	-0.0154	-0.4926	9.6407	-0.3068	-0.4762	-0.4894
PM Euro 6 Diesel PC	0.4311	-0.0233	0.0257	0.0532	-0.4492	5.9691	-0.0901	-0.2149	-0.2909
NOx Euro 5 Petrol PC	24.2819	-6.0216	-1.3350	1.5603	-13.8149	-6.7745	9.8120	-1.4937	-5.8961
NOx Euro 6 Petrol PC	21.3952	-3.4572	1.3625	-0.2657	-7.5911	-4.5455	6.6033	-0.4794	-4.3456
PM Euro 5 Petrol PC	0.4178	-0.0522	-0.0273	-0.0077	-0.2459	1.0614	0.0099	-0.2081	-0.1918
PM Euro 6 Petrol PC	0.3922	-0.0409	0.0263	-0.0802	-0.1815	2.5668	-0.0849	-0.2750	-0.2021
NOx Euro 5 Diesel HGV	48.6710	-3.7580	-0.4588	-0.9141	0.3395	-7.8106	-0.3334	-9.3655	50.8150
NOx Euro 6 Diesel HGV	18.5259	-2.5784	-0.6738	0.3601	-4.5605	5.4138	2.1467	-1.5137	-0.4930
PM Euro 5 Diesel HGV	0.3221	-0.0542	-0.0331	0.0287	-0.2613	-0.1665	0.0498	0.0915	-0.1973
PM Euro 6 Diesel HGV	0.0738	-0.0028	-0.0037	0.0013	-0.0516	-0.0734	0.0080	-0.0533	-0.0401

Based on the multi-regression analysis, a study of the combined effects, we must conclude that there are **no explicit arguments for showing a clear impact of the ambient temperature, vehicle-specific power, or velocity on the levels of NOx emissions**. What does stand out is the **dominant impact of the measurement location**. As such, the measurements performed in Ghent can generally be categorised as urban, allowing for a comparison with earlier remote sensing studies. For the Aalst measurements, typical motorway emissions occur, rather than what is seen for the Antwerp Kennedy tunnel exit where motorists need to accelerate after a deceleration before entering the tunnel. In Aalst, steady conditions allowed for cruise-control driving and thus more stable SCR efficiencies. Generally speaking, this kind of steady driving creates ideal circumstances for all types of emission control systems. Figure 4-71 shows the difference between Ghent (urban) and Aalst (motorway) NOx averages per fuel type and Euro class. Each location seems to have its unknown characteristics, affecting the emissions. But the Ghent results are nonetheless consistent with earlier urban remote sensing campaigns. This to stress that petrol technology remains a defendable choice in terms of keeping urban NOx emissions low, compared to diesel passenger car variants. Note the reduction of Euro 6d-Temp NOx emissions compared to the previous Euro classes, indicating that RDE requirements are taking effect. Note as well the elevated NOx emissions for petrol cars on motorways, which has been attributed to high-emitting events, skewing the averages for petrol cars. Such events might be explained by temporal high-power demands, offsetting the emission control system. Such conditions are more likely to occur on motorways than in moderate traffic.

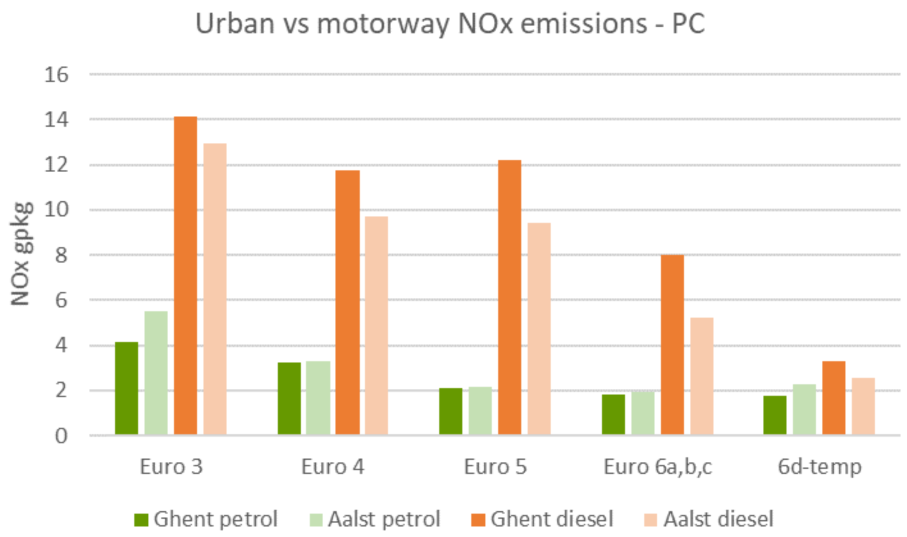


Figure 4-71: Comparison of Ghent (urban) and Aalst (motorway) NOx emissions per Euro class for passenger cars

Figure 4-72 shows the HGV NOx emissions for Ghent (urban) versus Aalst (motorway). Here, the lesser Euro V and VI NOx conversion efficiencies during slow start/stop driving in an urban context catches the eye, whereas motorway emissions are very low. This is probably due to the optimal SCR efficiency at high exhaust gas temperatures and more stable speeds on motorways. It has been known for some time that current heavy-duty legislation does not properly cover urban driving of trucks. The Step D and Step E parts of Euro-VI legislation are intended to remedy this. It is unclear if that will prove to be sufficient, as ISC tests of trucks have many other restrictions and limitations.

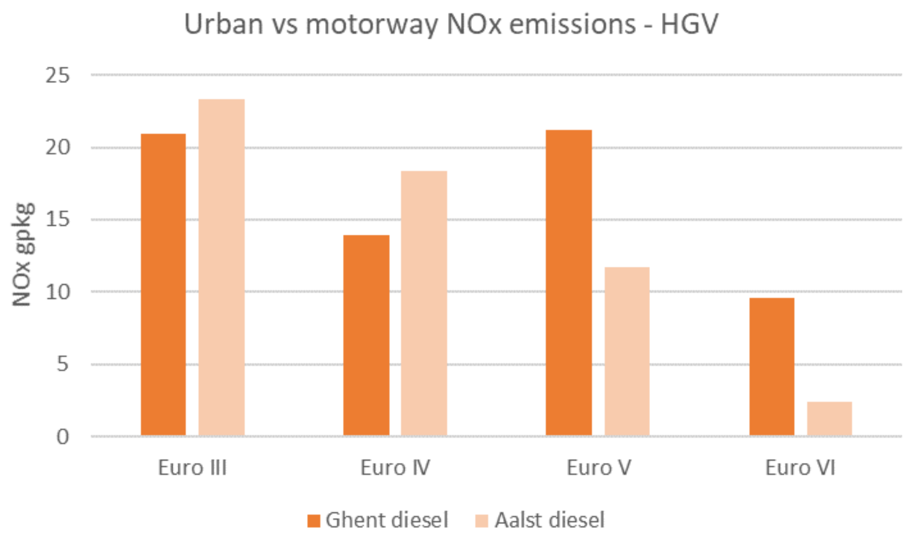


Figure 4-72: Comparison of Ghent (urban) and Aalst (motorway) NOx emissions per Euro class for heavy goods vehicles. Note that a much higher number of HG vehicles were measured in Aalst (9.266) as compared to Ghent (55).

4.5.5 Analysing the temperature impact on NOx for the Ghent measurements

In the multi-regression analysis, the ambient temperature effect was minimal for most vehicle categories, and below 20% for all categories. This is contrary to other earlier claims by other remote sensing studies. Therefore, this aspect is investigated further, to see why the effect is smaller than anticipated.

Looking only at the NOx emissions as a function of ambient temperature, and this specifically for the Ghent data, one may suspect an emission control optimisation around 25 degrees Celsius for the diesel vehicles (Figure 4-73). The temperature range for the type-approval tests is 20^o to 30^o Celsius, except for the latest Euro-6 vehicles, where a smaller range around 23^o C is required. There have been several claims in the past that data similar to this is an indication of a defeat device, i.e. an optimisation for the type-approval only.

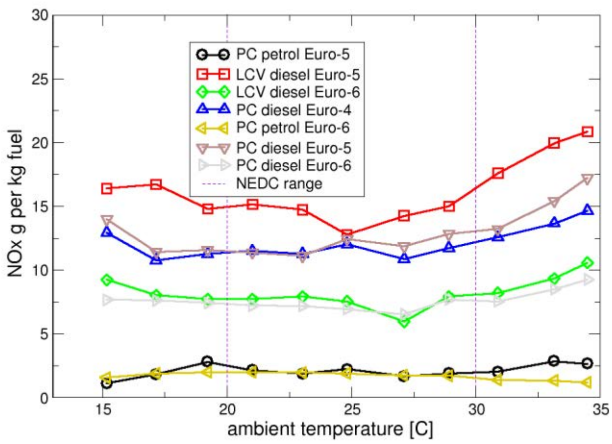


Figure 4-73: Distribution of Ghent NOx emissions as a function of the ambient temperature

Typically, warm weather occurs at the end of the afternoon, in specific traffic conditions, and drivers in a late-afternoon mood, possibly eager to go home during rush hour. If one would look at the average velocity for different ambient temperatures, a clear trend with decreasing velocity with ambient temperature is observed (Figure 4-74). The resolution is somewhat smaller, due to the larger variations. But all vehicle categories show a similar trend, indicating a general change in traffic with higher ambient temperature.

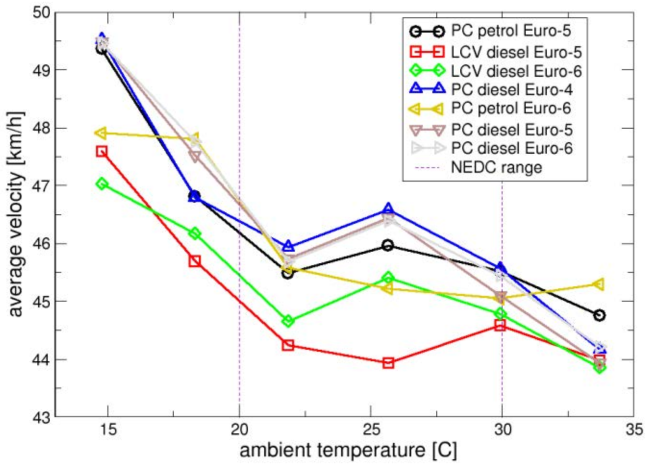


Figure 4-74: Distribution of the Ghent average velocity as a function of the ambient temperature

Moreover, the vehicle-specific power (VSP) also shows a trend with ambient temperature, with a dip at 30 km/h, and an increase above that temperature (Figure 4-75).

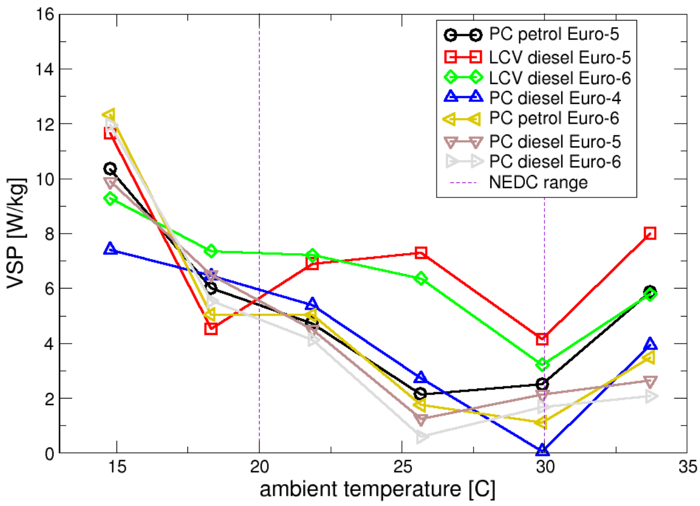


Figure 4-75: Distribution of the Ghent vehicle-specific power as a function of the ambient temperature

The ambient temperature changes throughout the day but so do the traffic conditions, and other aspects not known or understood. Hence, very likely, the **effects of ambient temperature cannot be trusted if not fully compensated for all the other changes during the day**, along with the temperature. To reach conclusive observations, measurements should be taken at different times of the year. Moreover, ambient temperature cannot be investigated separately but must be seen in combination with other aspects that may affect emissions. Currently, only VSP and velocity are included. Note that traffic intensity may be another aspect to include in the analyses. Furthermore, the correlation can be included in multi-regression analyses, as done above. Current, limited analyses explain why no ambient temperature effects were found to be significantly affecting the emissions. Previous remote sensing studies that claimed large temperature effects should be investigated for correlations with other aspects that vary over the day together with the ambient temperature. This analysis was done for a single location, therefore, many other variations seen in the full dataset with the change of location (road grade, speed limit, traffic dynamic, etc) were limited. Still, aspects of vehicle use, traffic, and driving behaviour that can vary with location, already show up being strongly correlated at a single location as traffic dynamics and other circumstances can vary throughout the day.

What can be concluded from this analysis is that the lowest temperatures in a given remote sensing campaign are to be reported in the early winter mornings when it is probably dark and heavy congestion occurs in the morning rush hours. The highest temperatures occur in summer in late afternoons, convening with the evening rush hours. More moderate temperatures occur during the day, with probably more moderate traffic conditions. Hence the findings for this study very likely apply more generally to remote sensing studies.

4.5.6 Anti-tampering campaign

During this Flemish test program, remote sensing partner HEAT contributed to an extraordinarily successful anti-tampering campaign, in which heavy goods vehicles were tested on-road in real-time by EDAR. During these tests, the system’s live interface identified high-emitting trucks that potentially utilised tamper devices based on the truck's real-time NOx emissions. Subsequently, suspicious trucks were pulled over for a roadside inspection by the federal police. This anti-tampering campaign **increased the** Government’s **tampering detection success rate from 9% to over 83%.**

During the campaign for heavy goods vehicles, the initial Euro V detection limit was set at 30 g NOx per kilogram fuel but in the course of the morning this was increased to 40 g NOx per kg fuel as a large number of trucks on that Monday morning had higher emissions than 30 g NOx per kilogram fuel, which made them suspicious. Even with the large group of police officers present, the steady flow of trucks with high emissions could not be handled.

One problem with the set-up was the lack of a real-time link with the vehicle registration data. Several trucks selected were older vehicles, e.g. Euro IV, and large vans, which did not have to comply with the same emission control legislation standards newer vehicles have to comply with. The focus was put on Euro V vehicles since the inspection teams involved were most experienced with this category. In the post-processing of the campaign, an attempt was made to extrapolate the reported share of defects and manipulations on the entire fleet’s emissions, based on the Euro V and VI measurements.

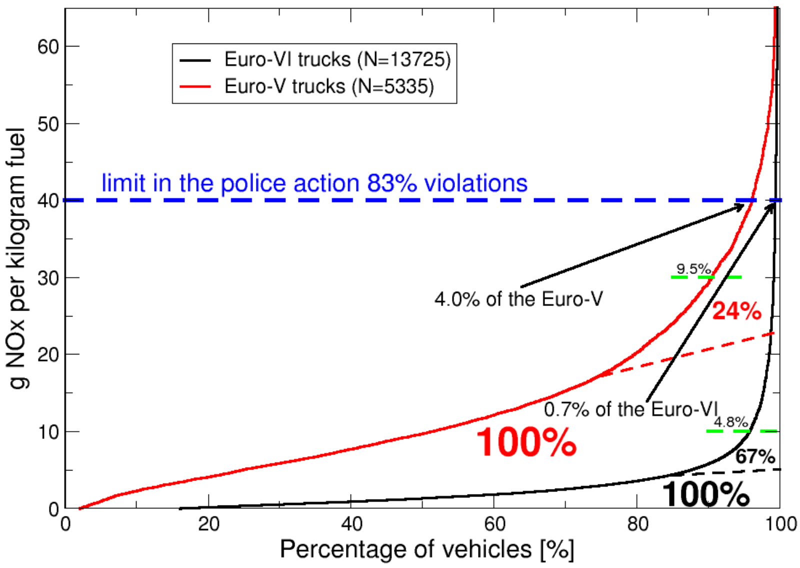


Figure 4-76: The results for the remote sensing test campaign against emission fraud by truck owners. Assuming emissions for vehicles without manipulations or defects would follow the dotted lines, the added impact due to defect emission control systems is estimated to amount to 24% and 67% of the total Euro V and VI NOx emission, respectively. Only the highest emitters were selected for roadside inspections, although manipulations can also occur without the trucks being targeted for the selected threshold limit. Realistic estimations are that 9.5% and 4.8% of the Euro V and VI truck fleet, respectively, are manipulated or in a state of poor maintenance.

Figure 4-76 shows the result of plotting the NOx measurement results of Euro V or Euro VI from low to high. To estimate the impact of SCR fraud and defects on NOx emissions, we look at the areas under the curves. The steep peaks on the right indicate that, for a limited proportion of vehicles, the emissions measured are much higher than for the rest of the fleet, which may indicate defects in or fraudulent use of the SCR. A linear fit based on the 10%-80% values, ending at the intersection with the full curve (i.e. the measured results), is used to estimate what would be the emissions of a fleet where such failures or fraud would not occur. This is shown in the figure in the dotted line. Its intersection with the 100% axis (i.e. the secondary y-axis) indicates the maximum NOx emission that would be expected for a regular fleet, i.e., 23 g/kg and 5.1 g/kg for Euro V and Euro VI, respectively. Considering a safety margin based on the dispersion of measurement results in the segment of the lowest measured emissions, these thresholds are increased to 30 g NOx/kg fuel for Euro V and 10 g NOx/kg fuel for Euro VI.

Assuming emissions would otherwise be distributed homogeneously, 9.5% Euro V and 4.8% Euro VI vehicles exceed these thresholds and are deemed to have been tampered with or to be circulating with a defective SCR. The share for Euro V may be higher because these vehicles are older, while the share for Euro VI will increase over time as the fleet ages and the more difficult to manipulate emission control systems are cracked/hacked. It follows from this analysis that, at the fleet level, emissions of Euro V and Euro VI trucks have increased by 24% and 67% compared with a fleet that would be compliant. Obviously, as the proportion of vehicles involved in fraud increases, so too will these percentages. At the level of individual vehicles, this means the following: **on average, a manipulated/defective Euro V truck emits as much as 3.5 regular Euro V lorries. However, an average manipulated Euro VI vehicle emits as much as 15 regular Euro VI vehicles**. These are very substantial increases in emissions so that a small group of vehicles can have a major effect on air quality.

In one day, 19 vehicles were investigated, of which 12 were found to be older vehicles. There were 6 fines distributed for tampering and a further 2 for defects. For one vehicle, nothing was found to explain the unauthorised emissions. Following the success of this campaign, a similar approach could be applied for detecting broken/removed diesel particulate filters on heavy-duty vehicles to get a realistic idea of the extent of this issue. A particle number counting test during a periodic technical inspection, however, may even be more successful. **For passenger cars, there is a lack of straightforward links between high-emitting events and tampering/wear as for many diesel vehicles, NOx emissions are already high without showing wear or tampering impacts**. As general NOx emissions in recent diesel vehicles seem to be improving due to better emission control systems being used in the fleet, the potential to distinguish tampered vehicles from regular ones by motorway roadside measurements increases. A suitable NOx threshold should be further investigated by combining emission readings with inspection results. For petrol cars, the analyses presented throughout this report indicate that high NOx emissions may occur during motorway driving. These high-emission events are no direct proof for tampering as these vehicles might perform normally during other trips. Given the very significant impact of tampering and malfunctioning vehicles on the emissions, we advise further investigations in preparation to include the passenger car fleet in similar campaigns as the one performed on trucks in the wake of this project.

5 CONCLUSIONS

The 2019 Flemish remote sensing campaign was the first in its kind covering motorway emissions, which has the consequence of providing new insights for both passenger cars (PC), light-commercial vehicles (LCV), and heavy goods vehicles (HGV). For the latter, results are based on the largest test population sampled so far. In this section, we'll concisely discuss the main findings.

General findings on fleet emissions and real-driving emissions (RDE) legislation:

1. Diesel vehicles remain the major cause for high NOx emissions, and this for every road type.
2. Concerning diesel Euro 6d-temp cars, lower NOx emissions are reported for the first time for a representative sample population, indicating the RDE legislation has a positive effect on pollutant emissions. However, the average emissions remain significantly higher than the NOx emission limit, even taking the temporary RDE-conformity factor of 2,1 into account. This indicates that the current RDE boundary conditions are insufficient to guarantee acceptable vehicle emissions in a variety of conditions that occur in real-world driving.
3. Petrol vehicles, known to be the cleanest vehicles with combustion engines for years in many respects, do show some increased nitrogen oxides (NO_x) emission correlated with motorway conditions. This is important when people live nearby and for the long-range background concentrations.
4. Robust three-way catalysts (TWC) keep petrol NOx averages stable, a situation that for the Flemish dataset seems to hold for the last 10 – 15 model years. High petrol NOx might be caused by manufacturers moving away from robust, properly dimensioned TWCs and a durable emission control system, although RDE is expected to bring them back on track.
5. LCVs have long been a blind spot in emission legislation, with more lenient limits, tests, and introduction dates. This is probably why very high NOx emissions are seen for each Euro class, with reductions taking place since 2017 as Euro 6 legislation got implemented for LCVs after the 2015 diesel scandal. This indicates the effect of public attention on NOx emissions by diesel vehicles. On the other hand, RDE legislation is lagging for LCVs, which is slowing down much-required gains in their emission performance. No RDE-compliant vans were reported in the Flemish campaign.
6. HGVs have generally become very clean since the introduction of Euro VI from 2014 onwards. The extensive sample of measured vehicles within this category confirms this statement. Nonetheless, HGV samples were mainly taken on motorways where selective catalytic reduction (SCR) technology is deemed to work optimally. The ability to measure on a multi-lane motorway at 120 km/h over a single lane has proven very useful for the purpose of assessing exhaust gas after-treatment system efficiencies A limited number of urban samples point out the known issue of poor NOx conversion in an urban context, characterised by lower velocities and frequent stop/go traffic.
7. Continued attention is needed on both petrol and diesel emissions, to keep manufacturers focused on reducing both urban and motorway emissions.
8. Remote sensing is found to be very suitable for showing trends in emissions. Single measurement results, however, cannot be compared to complete RDE test results as the test conditions are very different. Therefore, follow-up PEMS investigations are

required to check compliance with the RDE-requirements. Given the cost and limited scope of PEMS-testing, it is advisable to increase the efficiency of such PEMS (RDE-ISC) programs, building on the indications of a whole fleet monitoring scheme provided by remote sensing.

High-emitters and tampering:

Detecting tampering was the focus of this study. Remote sensing is found to be an important tool for detecting both fraud or design issues by manufacturers and vehicle tampering or poor maintenance by owners. Remote sensing can also help to identify vehicle segments and categories that significantly contribute to pollutant concentrations. The main findings are that:

1. Small groups of high-emitting vehicles can substantially affect average emissions and thus impact general fleet emissions. The cleaner the 'typical' vehicles of a category get, the higher the contribution of the high-emitters to the average emissions. A small fraction of vehicles, i.e. a few percent, may increase the average emissions from the typical vehicles of a category by 15% or more. This indicates the potential of policy strategies that focus on addressing high-emitters, and their causes.
2. Given very high diesel particulate filter (DPF) efficiencies, failures and/or illegal removals may have substantial impacts on the total PM emissions. As such, 10% of the diesel test population (Euro 5 – 6a,b,c) causes 80% of the cumulative PM emissions.
3. For NOx, diesel vehicles are in general a high-emitting group, which is why high-emitters only have a modest impact on the averages. Therefore, pre-Euro 6 diesel cars should be targeted as a whole group, rather than focussing on individual high-emitters. The cleaner recent diesel cars get, to more important it becomes to target high-emitters.
4. For petrol cars, 7% of the Euro 5 – 6a,b,c test population was categorised as being 'high-emitters'. They contribute about 41% of the cumulative petrol NOx emissions, indicating that petrol car results depend more on properly functioning TWC technology than diesel cars depend on SCR technology. High emissions of NOx tend to occur during motorway driving.
5. Based on probability distributions, the emission levels of high-emitters of typically cleaner and less clean vehicle categories seem to be similar. This is because if the emission control system fails, emissions are based on the physical characteristics of combustion, which lead to the same general maximal levels, e.g. 100 g NO_x per kg fuel.
6. Probability density functions are proposed as a suitable way to statistically assess the weight of high-emitters on the outside boundaries of the spread, as such:
    a. older diesel vehicles with high NO_x emissions have tails in their distribution that fall off rapidly, contributing little to the overall results, indicating that high-emitters have less impact on the averages compared to cleaner technologies;
    b. when more detailed insight into the emission behaviour of a specific group of vehicles (e.g. only the most recent petrol cars, or only cars belonging to a specific PEMS family) is required, larger experiments are needed. To ensure proper confidence in the results, RS campaigns covering longer periods are needed to effectively point out high-emitters, and;
    c. the difference between the median and the average, the latter based on the appropriate accounting of high values, is a good indication of the data in the tail.

Remote sensing's role in detecting tampering, in-service conformity testing, and market surveillance

When detecting specific emission issues with remote sensing, it is important to set the right thresholds. Different causes for emission issues (e.g. tampering, poor design, maintenance issues, etc) require different thresholds to be detected by remote sensing. An exceedance of three times the emission limit with a confidence level of 95% could be an initial limit for in-service conformity. An exceedance of five times the limit would suffice for tampering as emission levels are typically higher. The lowest limits are those related to technology effectiveness and durability, and refer only to the manufacturer's responsibility. For this issue, data of different vehicles, models, or even manufacturers can be combined to provide enough evidence and confidence to pursue further investigations. Remote sensing, and other information linked to emissions in normal use and air quality, can help to retain the sense of impact and relevance. It can also play a pivotal role to assess risks and urgency, and thus ensure an efficient organisation of market surveillance activities.

There are at least seven methods in which remote sensing can support emission mitigation policies. Each method has its requirements and characteristics.

1. Based on first principles, without underlying data, tampering and defects could be uncovered with a single passage with 5 times the exceedance of the emission limit. A location, like a stretch of motorway, should be selected as such that emission control technology, like SCR and DPF, should function properly. The false-positive results, i.e. an incidental high emission, will be limited in that case. This is linked to direct action, e.g. by the police, to catch the perpetrator in the act.
2. In the case of multiple passages of an individual vehicle with high emission readings, a subsequent request to visit a periodic technical inspection (PTI) test centre can be sent to the owner. For this application, multiple measurements and a lower average exceedance of a factor 3 will be more appropriate. Both methods 1 and 2, however, were not included in the scope of the original test campaign. Therefore, they should be investigated further.

Once an extensive set of remote sensing data is collected, alternative approaches using statistical methods are possible.

3. A tampering detection limit can be refined by using the typical spread (σ) in emissions for clean vehicles in a given vehicle category. Taking twice this spread is an appropriate detection limit for outliers like tampered and defective vehicles.
4. Likewise, the method for requesting a PTI can be refined using remote sensing data of a vehicle category. All the data from multiple passages provide an estimate of the typical spread in this data. This brings insight into the reliability of a single or very few measurements for the determination of the average emission behaviour. It will prevent an unwarranted request for a PTI test as emissions often vary for the same car. As such twice, or three times, a high emission can still be a coincidence. In the case of tampering, a vehicle can be restored to the original state before it is offered for PTI testing. Therefore, anti-tampering policies, particularly for SCR, should be generally based on direct enforcement, i.e. in a single passage.
    a. Applying remote sensing in a roadside inspection trial for HGVs and involving the federal police proved to be a very successful way of detecting high-emitters. The detection success rate was increased from 9% to 83%.
    b. 9.5% Euro V and 4.8% Euro VI heavy goods vehicles sampled are deemed to have been tampered with or to be circulating with a defective SCR. As Euro VI vehicles age, the risk of defects and by consequence tampering will increase.

c. At fleet level, emissions of Euro V and Euro VI trucks have increased by 24% and 67% compared with a fleet that would be compliant.

Three other uses of remote sensing data for mitigation policies involve high-emission events. For cleaner vehicles, it is observed that a small fraction of high-emission events substantially affects the average emissions of a vehicle category. Therefore, it is relevant to act upon this.

5. A detection limit like the one used for tampering detection (i.e. twice the average spread) can also be used as an indication of high-emission events. This can either be undetected deterioration or malfunctions, which would not lead to failure on the current PTI tests but require further investigation that may lead to an adaption of the PTI requirements or resolve issues related to in-service conformity.
6. A second issue with high emissions are certain vehicle makes and models that underperform compared to similar vehicles in the same category. This can indicate a compliance issue and can be a cause to perform follow-up ISC tests and to focus market surveillance initiatives on. Following an analysis presented on Euro 6b/c diesel vehicles, a specific Renault engine proves to be a clear candidate for mitigation actions, i.e. recalls and software updates.
7. Thirdly, observed high emissions in particular circumstances or conditions can bring to the surface relevant limitations of the procedures of RDE tests and heavy-duty PEMS-ISC tests.

In-service conformity testing can thus be based on remote sensing monitoring, however:

1. Crucial information is currently missing, namely to which PEMS family vehicles belong according to their emission certificate. With the WLTP transparency act and the information platform of the ISC-RDE testing, such information should become more easily available. Without such information, market surveillance cannot function properly. Using common classification and possibly even databases on vehicle emissions, surveillance is most effective.
2. For ISC, the most promising way to investigate issues with emissions and durability is to look at the engines as they are often shared between makes and models. A distinction on fuel type, engine size, and, if possible, engine power, should be made. Specific engine types are not distinguished in vehicle registration data and thus require expert insights.
3. It makes sense to set different thresholds for distinguishing durability issues (lowest threshold), repair issues that need further assessment during a periodic technical inspection (PTI, middle threshold), and illegal tampering (highest threshold). The latter limit refers to individual vehicles and requires a substantially higher threshold as tampering generally causes a very significant increase of emissions for the individual vehicles concerned. To spot and quantify these increases, one must determine the average emissions with sufficient confidence. This implies that remote sensing sampling is implemented over long periods to be able to determine reliable averages. The determination of such detection limits should be the focus of future roadside campaigns accompanied by the federal police.
4. Already on short-term, market surveillance and risk-based analysis of vehicles to test can be based on remote sensing if sufficient samples are taken. If conclusions on the level of engine types are to be drawn, at least 200 samples are needed per combination of engine type, vehicle model, and model year. Third-party indications of excessive emissions for a given model can be added as a source for RDE-ISC testing in the short-term as well.
5. Long-term market surveillance should include a systematic collection of emission data from both remote sensing, periodic technical inspection (PTI), and roadside inspection (RSI), besides the short-term measures described above. Such a structured emission database, to which all sources contribute, and an effective legal framework to support such a scheme are yet to be developed.

Scientific contributions to post-processing remote sensing data

Multi-regression analyses are proposed to disentangle different dependencies and to prevent conclusions without underlying causal relation. Additionally, these analyses are proposed to look for strong correlations between parameters as these are typically seen in emission testing campaigns on dynamometers or using portable/smart emissions measurement systems (PEMS/SEMS). The main findings are that:

1. no explicit arguments were found for showing a clear impact of the ambient temperature, vehicle-specific power, or velocity on the levels of NOx emissions. What does stand out is the dominant impact of the specific measurement location;
2. dominant differences between locations make comparisons between results difficult. With a variety of locations, however, results allow for broader conclusions and more realistic averages on the condition that sampling took place in a representative way, i.e. including different representative locations, and;
3. Ghent's results are consistent with earlier urban remote sensing campaigns, and Aalst's results are the most representative for typical motorway driving.

Conversions of measurements expressed in grams pollutant/kg fuel to a mg/km unit should be based on realistic CO_2 data, a novel approach has been proposed based on MILE21 data, starting from the measured CO_2 emission per vehicle. Key insights are that:

4. vehicle weight and age are found to be the best estimators for real-world CO_2;
5. generic fuel consumption data for a category of vehicles, like Euro 5 petrol vehicles, do not have sufficient differentiation to limit the bias based on weight, while 2/3rd of the fuel consumption is related to it, and;
6. variation of fuel consumption and CO_2 emissions across the passenger car fleet can easily be 80%.

PM thresholds for roadside controls or used to collect data relevant for market surveillance can be used more effectively when filter regenerations can be spotted. To this aim, PM analyses should include spatial distributions of the PM and CO_2 plumes. Only PM measurements that spatially coincide with the CO_2 measurements are counted to avoid interference with non-exhaust PM sources. Temperature and multiple passage analysis of the vehicle are used to exclude regeneration events.

Temperature windows require more in-depth research

7. There is no direct and straight-forward way to demonstrate ambient temperature dependencies of vehicle emissions using remote sensing data.
8. Likely, effects attributed to ambient temperature cannot be trusted if not fully compensated for all the other changes during the day, along with the temperature.

Concluding remarks

The 2019 Flemish remote sensing campaign was a success in many aspects. Nearly 190,000 valid samples were obtained for which the required technical vehicle information could be fetched. These results cover a wide array of driving situations (urban, rural, and motorway). Also, new methodologies to post-process remote sensing data in a transparent way are proposed. When applied over longer periods and covering different sampling locations, remote sensing data becomes a strong means on which in-service conformity, market surveillance, and local emission legislation can be built. To assist future research in the field of remote sensing and future remote sensing applications, several guidelines are formulated in the following and final chapter 6 ‘Recommendations‘.

6 RECOMMENDATIONS

1. Remote emission sensing on motorways is essential for SCR anti-tampering campaigns as in these circumstances SCR systems should work optimally. As such, the impact of tampering is distinguishable, unlike in urban situations. Moreover, motorway monitoring allows for high sampling rates and a large fraction of heavy goods vehicles, especially when compared to urban and rural monitoring.
2. Since emissions are strongly correlated with locations and less so with velocity and dynamics, it is essential to have different locations in a remote sensing campaign if average emissions, covering multiple aspects of normal use, are to be determined. Different vehicle categories and vehicle technologies have distinct differences in emissions associated with the location of measurements.
3. To investigate a particular group of vehicles like a fuel-Euro class combination, a brand, a particular vehicle model, or a PEMS family for in-service conformity testing, it is necessary to start with a sufficiently large remote sensing campaign to retain a sufficient number of vehicles in a specific group. Often more than 100,000 measurements are needed to allow for more detailed investigations. To have enough confidence in the measurements of a specific group with high emissions, at least 30 measurements are needed. The current measurement campaign was performed slightly too early to cover the Euro-6d-temp diesel vehicles in-depth since they entered the market in significant numbers less than half a year before.
4. In case typical emission measurement results are low, a small number of high-emitters can have a significant contribution to the average result. Thus, sufficient measurements are required to have a reliable estimate of the average. As a rule of thumb, the cumulative 20% of the highest emissions should be based on at least 20 measurements to draw any conclusion, for which many more low polluting measurements, i.e., hundreds, are needed, to sample enough high emissions.
5. Follow-up investigations should be based on impact. The impact is represented by the level of exceedance of typical, or accepted, emission levels and the fraction of vehicles with these high emissions. This may be a complete group of vehicles, like Euro 5 diesel cars, a manufacturer with make and model, like the Renault Euro-6b 1461 cc diesel engine, or intermittent occurrences of high NOx emissions in Euro-4 to Euro-6 petrol cars. Investigations should include root cause analyses, addressing the responsible party, and establishing mitigation actions. Depending on the vehicle model, some of which may be eligible for RDE-ISC testing, a different course of action can be taken. In the past, the responsibility of the manufacturer of vehicles on the road was limited. Since this situation has changed with new legislation for the newest and longest-lasting vehicles currently on the road, this must be the first course of action with the future in mind. Other problems that disqualify these vehicles from ISC testing, such as tampering and sub-standard maintenance, can be followed up separately and may eventually result in the need to improve legislation (improvements to type-approval testing procedures, better PTI-tests, etc). To allow for such effective surveillance in Flanders and Belgium, legal initiatives that facilitate these operations are feasible. This includes extending the scope of roadside controls, referring suspicious vehicles to PTI based on multiple passage analyses, integrating information from fleet monitoring techniques such as remote sensing with findings from PTI and roadside controls with external (3rd party) input to better direct market surveillance efforts, etc. Insights on emissions originating from the before-mentioned sources should be brought together in a structured emission database.
6. Any remote sensing campaign should be linked with a real-world fuel consumption study to translate the gram-per-kg-fuel results to gram-per-kilometre results for impact and

comparison with the existing limits. Average fuel consumption does not suffice if specific groups of vehicles are investigated as fuel consumption may vary greatly.

7. Vehicle emissions present a holistic problem that requires a comprehensive approach. It may not be initially clear what causes high emissions and who is responsible for it. Nonetheless, it can no longer be that nobody is held responsible and that problems persist to exist, like what happened with Euro 5 diesel cars from 2009 until 2015. Therefore, any investigation into the cause of high emissions of a particular group of vehicles, for example starting with RDE-ISC testing, should leave its options open, and establish the connection to bring problems forward to other responsible parties, including periodic inspection authorities, police, and legislators. Not in all cases, high emissions will lead to a non-compliance issue, but it may raise suspicions regarding defeat devices, improper application of AES (Auxiliary Emission Strategy), improper use of OBD to be excluded from RDE testing, and many other emissions problems not yet covered explicitly in type-approval legislation.
8. Concerning vehicle information, the vehicle category, fuel type, emission class, and sub-class should be readily made available to roadside inspectors that pull over vehicles with high emissions for inspection. PEMS family data should also be available and should be recorded along with inspection results for subsequent analyses (if a PEMS family is found to cause many problems, this may point to a design or durability issue that should be addressed by the manufacturer). For this, PEMS family data should be included in the technical information managed by the national vehicle registry (*Dienst Inschrijving Voertuigen*). Privacy issues that might occur to obtain this required technical vehicle data based on the license plate should be addressed with a correct legal framework to facilitate inspection schemes and subsequent analyses. Moreover, both the vehicle owner and the manufacturer have responsibilities when it comes to vehicle emissions. Separately, the owner should ensure the vehicle is in a proper state and necessary software updates are implemented. This can be read out from the OBD system. The link between the type-approval and the actual state of the vehicle should be made in the roadworthiness documentation updated during PTI. In that case, durability problems, observed in the periodic inspection can also lead to RDE-ISC testing. This nevertheless requires structured feedback from PTI to market surveillance authorities, hence the need for an emission database.
9. Any analyses of vehicle emissions should start at the larger group. If within such a group a specific sub-group has substantial and significantly higher emissions, they should be investigated further. ‘High emission’ should be defined as emissions substantially higher than the spread in the group, e.g. twice or thrice the average upward spread, as expressed in terms of percentiles. Enough confidence is needed to warrant pursuing a further investigation. Standard methods, for example designed for normal probability distributions or quality control, cannot be applied with sufficient confidence because of the observed variations in emissions. If certain vehicles, however small in numbers, are observed to have twice the emissions than the average of that group, it warrants an investigation. Moreover, if a larger group of more than 3% of the total fleet on the road, for example a specific brand, has more than 50% higher emissions than the average of the legislative category, an investigation is warranted too. With such large numbers in the fleet, the statistics are likely sufficient to establish this difference of 50% with confidence. In this case, the largest impact on the total emissions receives the most attention, but smaller groups are not ignored by looking at the deviations from the average independent from the size of the group.