Design of a program for the identification and correction of high emitting vehicles in Europe using remote sensing devices

J. Buhigas [1], M. Fleire [1], M. Pujadas [2]

[1] Opus Remote Sensing Europe, Madrid, 28015, Spain

[2] CIEMAT - Centro Investigaciones Energéticas, Medioambientales y Tecnológicas, Madrid, 28040, Spain

Keywords: remote, sensing, high-emitter, emissions

Presenting author email: javier.buhigas@opusrse.com

Abstract

The impact from High Emitting vehicles (HE) has been estimated in the past to be from 19% to 60% of the total on-road traffic emissions, depending on the pollutant[1]. Different studies have estimated that these vehicles represent between 3% to 5% of the circulating fleet [1]. Most of these HEs are faulty vehicles that could be detected, inspected and repaired. That action could reduce their emissions to normal vehicle emission levels and thus significantly decrease the total road transport emissions and consequently the health-related issues that air pollution causes. Remote sensing (RS) technology makes it possible to identify vehicles on public roads that emit high concentrations of pollutants in real-world driving conditions. This technology is used in the USA, China, Hong Kong and South Korea to identify HEs, but it has not been implemented in Europe yet for this purpose. To facilitate this application in Europe, this study explores how the identification of these vehicles on the road could be implemented.

- The first step is to conduct a remote sensing campaign using remote sensing devices (RSD) to screen and characterize the road transport emissions of the circulating fleet. The estimation of the minimum data needed for one of these campaigns consists in at least 100.000 valid measurements. This data should be collected in two different seasonal periods and with a mix of sites that guarantees a homogeneous vehicle specific power (VSP) distribution.
- By analyzing the data from the remote sensing campaign, a limit can be stablished to define what emission level is so high that a vehicle surpassing the limit is to be considered a HE.
- We propose a methodology that consists of establishing two different emission limits and that requires a minimum of two valid emission measurements per vehicle for a categorization. The first limit, called On-Road High-Emitter limit (ORHE), would represent the top 2% of emissions in the remote sensing campaign (P_{98}). The second limit would be the 20th upper percentile of the dataset (P_{80}). Taking into account these limits, there would be two options to label vehicles as HE: 1) Vehicles that exceed P_{98} once and at least P_{80} another time and 2) vehicles whose emissions are over P_{80} more than 70% of N, being N the number of times the vehicle is measured (with $N > 3$), should also be labeled as HE.
- If an on-road detection of a HE happens, the competent authority will demand the vehicle owner to perform an extraordinary test of the vehicle in a Periodical Inspection Station (PTI), to confirm the faulty function of the vehicle, with tests performed under a controlled environment. However, actual European PTIs lack of competent equipment to correctly assess some of the most harmful pollutants, as NOx. Our proposed methodology would require that at least a few stations on a given territory (i.e., only two stations per large city) should be equipped with new testing equipment to verify vehicles' emissions more correctly, as current procedures are not adequate.

To evaluate our proposed methodology, the Opus RSD has been compared to different modern vehicle emission testing equipment facilitated by different suppliers. The results indicate that using different measurement techniques (RSD and PTI tests) high NOx and CO emitting vehicles can be detected both on the road (by the RSD) and during in-situ inspections with new testing equipment. We have also studied the distribution of emissions of vehicles identified as HE by our methodology versus the rest of the vehicles. The results indicate that by applying this high emitter detection methodology, HE vehicles could reliably be identified without producing false positives, that is, without attributing high emitter characteristics to vehicles emitting normal pollution levels.

---

[1] According to CORETRA project (see ref. [1]), 19% for NO, 40% for HC, 39% for CO and 60% for $PM_{2.5}$.

1. Introduction

The harmful impact of transportation on the population is one of the most important health problems in the world, especially on cities, where most population concentrates and most vehicles circulate. Urban traffic is the main cause of air pollution. Exposure to air pollution causes direct health problems, such as asthma, hypertension, heart related diseases and cancer. More than 4 million people die each year from environmental pollution [2], resulting deadlier than AIDS, malaria and traffic accidents combined.

Cities main source of air pollution is road traffic. According to data from the inventory of polluting emissions to the atmosphere in the municipality of Madrid [3], road traffic is responsible, in average, of 55% $PM_{2.5}$ air pollution and 48% NOx pollution in all the region, while in some areas of the city the road traffic is responsible for more than 80% of all NOx pollution (especially in areas with heavy traffic). This is also a growing problem, since actual demographic trends suggest that by 2050 around 70% of the world's population will live in cities.

Part of this problem is caused by broken, misaligned or tampered vehicles. These vehicles circulate among us emitting very high amounts of polluting substances practically without any control. Various studies (CORETRA 2016, Barcelona 2017, GYSTRA 2018-2021) have identified that high-emitting vehicles (or simply High-Emitters, hereinafter HE) are only around 3 or 5% of the circulating fleet (depending on the study), while they are responsible for around 20% and 60% of the total emissions of NOx and $PM_{2.5}$, respectively. This means that it should be possible to decrease up to a 60% of the road transport pollution by identifying only 5% or the worst polluters and taking corrective measures on them. This would also be a minimal impact policy, as air quality could be improved with the least possible sanctioning policies.

The identification of HEs cannot currently be carried out by Periodical Technical Inspections (PTI) in Europe. This is because pollutant emissions from motor vehicles are mainly produced when the vehicle's engine is under load. In European PTIs, only CO emissions or opacity are measured, and they are tested with the engine at idle state, so its emissions in this state may not be realistic. On the other hand, NOx is one of the most worrying pollutants in cities, mainly produced by road transport, but it is not controlled in the PTI, as it can only be evaluated when the vehicle is under load. Moreover, PTI testing should be traceable to the rest of the vehicle controls, such as the one done in the Type-Approval process, that is with the vehicle loaded or even tested on the road in most recent Euro Standards (RDE test).

To measure remotely the real-driving emissions of circulating vehicles is perfectly possible through optical techniques - and deploying them on the public roads will allow to identify the HEs in an automated and cost-effective way. Although this technique has been used in numerous research projects in Europe there is currently no operational remote sensing program for the identification of high-emitting vehicles in Europe. This experience has been implemented successfully in other countries such as USA, China, Hong Kong and South Korea [4].

2. State of the art

The first remote technique applied to the vehicle exhaust emissions detection was developed at the University of Denver (USA) and patented in the 1980s. This technique has been verified and validated by numerous research papers, independent testing agencies and accreditation bodies, with extensive literature on the subject [5]. In this study, Opus RS technology has been used, specifically the RSD+ version of the Opus Remote Sensing Device (RSD). A single RSD can measure thousands of vehicles per day. Each measurement is carried out in half a second, through which the device quantifies the pollutant concentrations in the exhaust plume (it evaluates the following regulated pollutants according to the Euro Standard directives: HC, CO, NO, NO_2 and opacity). The RSD also measures the speed and acceleration of the vehicle, the environmental conditions at the time of the measurement (humidity, temperature and pressure) and it automatically takes a picture of the vehicle's license plate.

The Opus RSD has a practical application in the USA, which is the identification of the most polluting vehicles in real-world conditions. For decades, different programs in various states of the country (like Colorado, Indiana, Texas and Virginia) have used RSDs to monitor the circulating fleet on the road, thus identifying the high-emitters [6]. Once identified, their owners are officially notified to undergo a confirmation test at an emissions inspection facility, using ASM or IM240 cycles and dedicated inspection equipment. The results of the application of RS in the USA for this purpose have also been widely published. Moreover, the fact that these programs are still in operation in several territories is proof of their effectiveness in state control of the vehicles' emissions. The use of RS to identify high-emitters on the road has also been used in other Asian countries, such as China, but the available information on the effectiveness of these programs has not been found to be solid. However, this again indicates that this is an application that could be replicated in Europe.

The experience in the USA and Asia shows that the identification of HEs on the road through remote sensing techniques implies the establishment of certain emission limits for each pollutant that mark from which emission value a vehicle is identified as a High Emitter by the RSD. These limits are called ORHE limits: On-Road High-Emitters limits. However, these limits are not universal values. As the fleet circulating in each city or territory is different, as are the urban characteristics, driving behaviours, vehicle maintenance, etc., the distribution of the real-world emissions from road transport is different in every part of the world. In addition, in European regulation there is no specific emission limit for which a vehicle is or is not a HE, since there is no control on real-driving emissions after type-approval. While it is understood that limits should be set to identify extraordinarily high emissions, the specific values are not defined, and it is probably not possible to set single limits for the whole of Europe.

In Europe there have been some initiatives in the past to implement a high-emitter program. In Spain, the Spanish Center for Energy, Environmental and Technological Research (CIEMAT) led the CORETRA project in the years 2014 and 2015 [1], in which the circulating fleet in the Madrid region was extensively monitored for two years with Opus RSDs. As a result, CIEMAT proposed specific emission limits for detecting high emitters, but that proposal was not finally implemented in the Spanish traffic emissions legislation.

3. Proposed high-emitter control methodology for Europe

One of the regulatory barriers that are holding back in Europe the use of remote sensing for emission control purposes is lack of a legal support for sanctioning or regulating a vehicle solely on the basis of its remote emissions measurement. To solve this issue, a methodology combining an initial identification of a HE with remote techniques and a final verification of the vehicle in an official Technical Inspection centre is proposed. This strategy can be implemented under current European legislation. The high-emitter methodology we propose for Europe consists of the following steps:

- Set High-Emitter limits: In order to define the HE limits statistically representative for the circulating fleet of interest; the first step is to develop an extensive remote sensing campaign to get information about the current emitting behaviour of the fleet of interest that will be confronted with these limits. The measurements should be carried out in as many different locations as possible and in at least two different seasonal periods, in order to evaluate a significant sample of the fleet and guaranteeing a homogeneous VSP distribution (0-10, 10-20 and 20-30). It is very important to avoid measuring locations where the possibility of detecting engine cold emissions is not negligible. The number of remote sensing devices, measuring locations and sensors reallocation intervals should be customized for each territory to be screened, as the urban, fleet and socio-economic characteristics of each territory can be very different. The emission data collected should be analysed in order to define the representative HE limits according to the local fleet emissions distribution and the regulatory claims of the competent administration. Another important issue is whether the emission limits should be particularized for each type of vehicle according to fuel type, Euro standard and age, but this should be agreed with the competent authorities in each place.

  As predetermined ORHE limits values for the fleet of interest, the 98th (P_{98}) and 80th (P_{80}) percentiles obtained for each pollutant from the monitoring campaign database could be taken. Consequently, a vehicle could be considered HE if it at least exceeds the P_{98} and P_{80} once each or exceeds the P_{80} 70% of its measurements.

- On-road High-Emitter identification: The systematic control of traffic emissions by remote sensing monitoring in different places of a given territory will provide the information to identify continuously High Emitters on the road.

- Notification for verification: After a positive HE identification occurs, an instant notice can be sent to the vehicle owner by the traffic authority, to require the vehicle to be checked at a PTI in a short period of time. This notification procedure is already envisaged in current legislations in most of Europe. The shorter the time frame the vehicle is inspected, the better the chance of a correct vehicle verification. At the same time, a certain time margin may be considered necessary to provide legal certainty to the owner.

- Confirmation test at a technical inspection: The extraordinary inspection would be carried out in an inspection centre equipped with adequate instruments for a complete and dedicated test of polluting exhaust emissions. Some of these possible systems are evaluated in section 4.

- Correction: If the vehicle is confirmed as High-Emitter in the verification test, it could lose its circulating permit. To avoid this, the vehicle should be repaired in a workshop in a short period.

Obviously, this methodology of HE detection can be more sophisticated and, for instance, different criteria could be considered for each pollutant. Also, rules to combine two or more pollutants could be defined, but the protocol proposed here is considered to be sufficiently robust. This methodology has been designed to give the least possible number of false positives, ensuring that the vehicles called to extraordinary inspections (as identified as HE on the road) have extreme emissions in at least one of the monitored pollutants. Vehicles that do not exceed the ORHE limit but present frequent emissions between the two limits, strongly contribute also to increase the pollutant emission balance of the fleet and their correction is very important. National or regional authorities should determine the necessity for stablishing in each case a specific protocol to adapt the general procedure here proposed to the necessities of each HE control program and the region characteristics.

4. Example case: High emitter detection applied to Madrid circulating fleet

This section describes the studies, experiments and analyses that have been carried out in Madrid, Spain, to evaluate the suitability of the proposed high-emitter control methodology described before.

4.1. Madrid fleet emissions remote sensing screening

The first part of the study concerns the collection of measurements with the Opus RSD+ in real circulating conditions. We have compiled 758352 measurements collected at 22 different locations in the metropolitan area of Madrid between the years 2018 and 2021. These measurements have been carried out under the EU-funded project LIFE GySTRA, From the license plate number identified for each vehicle, the Spanish General Traffic Authority (DGT) provides technical characteristics of these vehicles. The data sample used for this study (see section 5.1) has only passenger cars with sufficient technical information for analysis. This data sample (n=382180) has a mean VSP of 10.20 kW/Ton (s=6.20), mean ambient temperature of 21.62 ºC (s=7.85), mean vehicle speed of 37.8 km/h (s=9.6 km/h) and mean road slope of 2.32 º (s=0.73). This data sample includes vehicles with an average age of 9.61 years (s=5.75). 68.3% of the vehicles analysed in this study are pure diesel-fuelled, 29.9% are pure petrol-fuelled and the rest have another type of propulsion system. The sample is formed by 25.2% Euro 3 and older cars, 25.1% Euro 4, 15.9% Euro 5, 30.3% Euro 6-b, 1.5% Euro 6-c and 1.8% Euro 6-dTemp.

4.2. HE identification protocol

The highest measurement values in a remote sensing monitoring campaign represent the highest emission cases of the entire fleet, but they do not necessarily represent the most polluting vehicles in all cases, as the emissions of a vehicle are variable. This means, a vehicle can have a one-time emission level within 2% of the highest values of an entire campaign but have other lower measurements as well. This variability, intrinsic to the vehicle emissions, makes identifying the most polluting vehicles quite complex. However, the pollutant emissions behavior of a High Emitter is typically highly variable too, but with high individual emissions throughout most of its operating cycle [10, 11]. In contrast, a perfectly good-maintained vehicle has relatively low emissions and it is extremely rare for it to have an extremely high emission episode.

Considering the general methodology proposed in section 3 for HE detection, in this study we have defined a procedure adapted to as best as possible to the characteristics of Madrid region. These conditions refer to the fact that a vehicle will be considered a HE on the road (and therefore will be sent for a verification test) if and only if:

- The VSP (kW/Ton) to consider a measurement as valid is between 0 to 30. This range has been stablished as a normal operating range in an urban environment.
- The minimum number of measurements of the same vehicle above the ORHE limit on a given pollutant is 1.
- The minimum number of measurements of the same vehicle above the 80th percentile (20% most polluting) on the same pollutant is 2.
- The 70% of N, being N the number of times a vehicle was measured (with $N > 3$), are in the 80th Percentile of all the values in a remote sensing monitoring campaign for a given pollutant.

With the above conditions a vehicle could be a HE in one pollutant or in several, but in this study it is proposed to start with a simple protocol that evaluates each pollutant individually with the same logic. It should be noted that the different ORHE limits (for each pollutant) do not depend on the type of fuel.

Once a confirmatory test is established at the PTI, equipped with enough tools to analyze these potentially defective vehicles, the proposed protocol could be tested and improved if necessary. Confirmation tests would show whether the protocol is too rigorous or too lax, based on the results of the confirmatory tests at the inspection station. Likewise, the result of the entire protocol depends on the final tests carried in the inspection stations and the results of these through tests to finally confirm that a vehicle is a HE.

4.3. Tests

To further evaluate the capabilities of the Opus RSD system to identify high-emitting vehicles, a series of specific experiments have been conducted in the year 2020. These experiments were carried out at the facilities of the PTI center: ITV Pinto Applus+ (Parcela M-1 3ª, Calle Carpinteros, 13, 28320 Pinto, Madrid, Spain). The study carried out is intended to cover two objectives:

1. To evaluate if a vehicle identified as a high-emitter on the road (in NOx or CO) with an RSD is also identified as a high-emitter with new testing equipment and new inspection methods at the PTI.
2. To evaluate if a high-emitter can be detected on the road consistently against vehicles that are not so much polluting, despite the variability of vehicles' emissions.

For objective 1, some vehicles measured with the RSD were also measured with new equipment from CAP-ASM and MAHA-MET, testing vehicles on a dynamometer, simulating different loads and measuring NOx and CO with a probe into the tailpipe. The measurements were done simulating the vehicle in two different regimes: (a) 50% of the vehicle power, speed at 15 mph and in 2nd gear; (b) 25% of the vehicle power at 25 mph and in 3rd gear.

For objective 2, we analyzed the data from the Madrid remote sensing campaign (LIFE GySTRA, see section 4.1).

Measurements with the RSD were done with the OPUS Accuscan™ RSD5000 (to remotely measure CO, NO, NO_2, HC and opacity at 230nm, hereinafter PM) with the vehicle in free circulation on the roadway, in the PTI parking facilities.

For this purpose, 35 different vehicles have been evaluated, which have been subjected to numerous measurements with the RSD at different driving conditions and to different tests carried out by the PTI equipment listed above. Most of these vehicles were provided by customers who voluntarily agreed to participate in the tests. Ten of the vehicles are petrol and the rest are diesel. Table 1 shows the tests that have been performed on each vehicle. The "✓" symbol indicates which tests have been successfully performed for each vehicle.

Figure 1. Pictures of the tests performed at the PTI. Left: tests with dynamometer; Middle and right: tests with the RSD.

Table 1: Tests performed on each vehicle.

Vehicle ID	Fuel type (P= petrol; D= diesel)	OPUS RSD (CO, NOx, PM)	CAP ASM. 50/15 - 2ª		MAHA. 50/15 - 2ª		CAP NOx. 50/15 - 2ª	CAP ASM. 25/25 - 3ª		MAHA. 25/25 - 3ª		CAP NOx. 25/25 - 3ª	
			CO	NOx	CO	NOx	NOx	CO	NOx	CO	NOx	CO	NOx
1	P	✓	✓	✓				✓	✓	✓	✓		
2	P	✓	✓	✓				✓	✓	✓	✓		
3	D	✓				✓							
4	D	✓				✓							
5	D	✓				✓							
6	D					✓							
7	D	✓				✓							
8	D	✓				✓							
9	P	✓	✓	✓	✓	✓		✓	✓				
10	P	✓		✓	✓			✓	✓				
11	D	✓		✓		✓			✓				
12	D	✓		✓		✓			✓				
13	P	✓	✓	✓	✓	✓		✓	✓	✓	✓		
14	D	✓	✓	✓	✓	✓		✓	✓	✓	✓		
15	D	✓		✓	✓	✓	✓		✓		✓		✓
16	D	✓	✓	✓	✓		✓		✓				✓
17	D	✓	✓	✓	✓	✓		✓	✓	✓	✓		
18	P	✓		✓	✓	✓		✓		✓			
19	P	✓			✓			✓		✓			
20	D	✓	✓	✓	✓	✓		✓	✓	✓	✓		
21	D			✓		✓	✓		✓		✓		✓
22	P	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
23	D	✓	✓	✓	✓	✓		✓	✓	✓	✓		
24	D	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
25	D	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
26	P		✓	✓	✓	✓				✓	✓		
27	D		✓	✓	✓	✓		✓	✓	✓	✓		

Vehicle ID	Fuel type (P= petrol; D= diesel)	OPUS RSD (CO, NOx, PM)	CAP ASM. 50/15 - 2ª		MAHA. 50/15 - 2ª		CAP NOx. 50/15 - 2ª	CAP ASM. 25/25 - 3ª		MAHA. 25/25 - 3ª		CAP NOx. 25/25 - 3ª	
			CO	NOx	CO	NOx	NOx	CO	NOx	CO	NOx	CO	NOx
28	D		✓	✓	✓	✓		✓	✓		✓		
29	D			✓		✓			✓		✓		
30	D	✓		✓		✓	✓		✓		✓		✓
31	D			✓		✓			✓		✓		
32	D			✓	✓	✓			✓		✓		
33	P	✓	✓	✓	✓	✓		✓	✓	✓	✓		
34	D	✓	✓	✓	✓	✓			✓	✓	✓		
35	D	✓		✓	✓	✓			✓	✓	✓		

5. Results

5.1. Remote sensing screening results and proposed on-road high-emitter limits for Madrid

From the remote sensing screening in Madrid (see section 4.1), the data is analysed. Considering that an RSD directly reports emission in ratios of pollutants with respect to CO_2 (in the case of particulate matter, it simply reports opacity at 230 nm), emission limits should be set at the same magnitudes that the system provides, in order not to introduce further transformations. Table 2 shows the results obtained in Madrid with the data sample explained in section 4.1 and the ORHE limit calculation procedure as defined in section 4.2. The methodology results in a share of high-emitters between 3.67% and 5.28% of the whole fleet, depending on the pollutant. The last column shows the estimated share of total emissions these vehicles are responsible for, assuming that their respective emitting behaviours are always similar in all conditions. As we are evaluating only passenger cars, this refers to the share of total emissions caused by this type of vehicles. For instance, the table shows that 5.28% of the most polluting cars in NO are responsible for 17.81% of all NO emissions emitted by all passenger cars.

Table 2: Average passenger cars emissions and ORHE limits for Madrid, Spain.

Pollutant	Magnitude (units)	Average fleet value	ORHE limit (P_{98})	Lower limit (P_{80})	Vehicles that are categorized as HE (number and percentage of the fleet)	Share of total cars emissions emitted by the HEs
Nitrogen oxide	NO/CO_2 (ppm/%)	19.7	101.2	42.3	n=4701; 5.28%	17.81%
Nitrogen dioxide	NO_2/CO_2 (ppm/%)	5.8	58.4	13.1	n=4203; 4.9%	26.29%
Particulate matter	Opacity in UV at 230nm (%)	0.16	2.6	0.3	n=3493; 4.01%	41.04%
Carbon monoxide	CO/CO_2 (%/%)	0.005	0.05	0.006	n=4117; 4.32%	23.04%
Hydrocarbons	HC/CO_2 (ppm/%)	2.0	15.1	5.0	n=3061; 3.67%	18.83%

Note that these limits would apply generically to any passenger car (and could possibly include vans and other light vehicles), regardless of the type of fuel used by the vehicle, its age, engine size or any other technical characteristics. Also, the percentages on the previous table refer to the vehicles that could potentially be considered as HE (in the range of VSP 0-30, with at least two correct measurements per pollutant and being passenger cars).

To evaluate if a common ORHE limit can be set to all vehicles, regardless of their technical characteristics, Figure 2 shows the average emissions of HE and non-HE vehicles per fuel and euro standard for nitrogen oxide. The graphs show that the mean emissions of the non-High Emitters differ abruptly from petrol to diesel cars, while the mean emissions of High Emitters are similar regardless of the fuel type. Also, even if there are differences by Euro Standard, the lowest mean emission of a HE group (8.2 g/kg) is higher than maximum mean value of any non-HE groups (7.0 g/kg), indicating that these limits can be established as common for all the fleet, independent to the fuel type and Euro Standard. This is further explored in section 5.3.

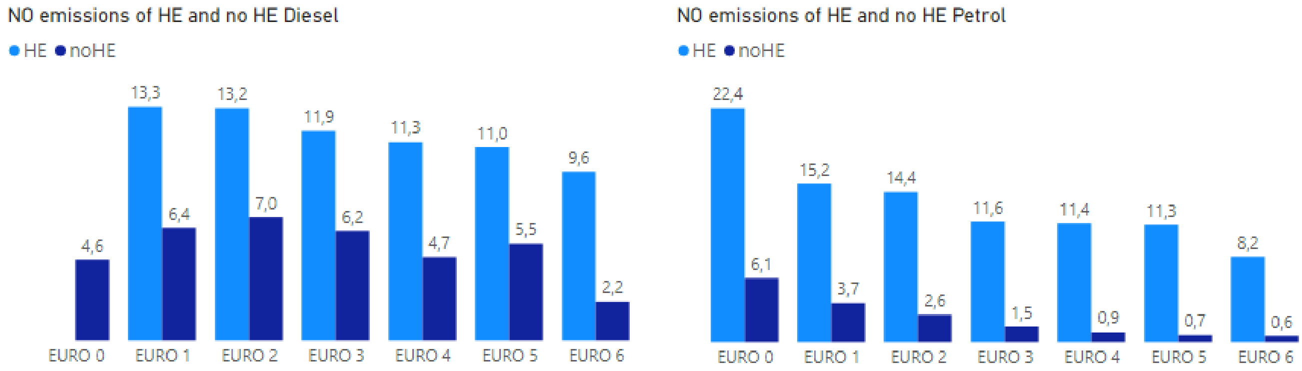

Figure 2. NO fuel-specific emissions (g per kg-fuel) of HE (light blue) and non-HE (dark blue) passenger cars by fuel and Euro Standard (x-axis). Left chart, diesel cars; right chart, petrol cars.

5.2. Comparison of remote sensing with new inspection testing equipment

From the experiments listed in Table 1 , comparative measurements of carbon monoxide (CO) and nitrogen oxides (NOx) are made (RSD vs CAP and RSD vs MAHA). The measuring methods and measurement magnitudes of each equipment are completely different, so a direct and quantitative comparison of the measurements provided by each system cannot be made. Furthermore, the measurements of each vehicle with the different methods and equipment have not been made at the same time (the vehicle was tested with one equipment and then moved to conduct a test with another equipment). As the emissions of a vehicle are variable, there may not necessarily be a relationship between the measurement of a vehicle with one method or another. However, the objective of these tests is to simply assess whether the qualitative identification of the emission status of a vehicle with one measurement method is similar to the qualitative identification of another method. In other words, it is of interest to know whether when one measurement method indicates that a vehicle has relatively high emissions, a different method shows a similar indication. Similarly, if an equipment shows a low level of emissions, the other equipment should indicate the same.

To make this qualitative comparison, the 35 vehicles on Table 1 have been taken as control fleet and the average values for all the measurements of each pollutant obtained with each method have been taken as reference values to analyze the behavior of the individual vehicles checked with the same measurement system. Afterwards, the individual values given by the correspondent equipment for a specific vehicle and the average reference values are calculated. This comparison is shown in Figure 3 and Figure 4. The results show that both measurement methods can identify when a vehicle has much higher emissions than other vehicles, for CO and NOx.

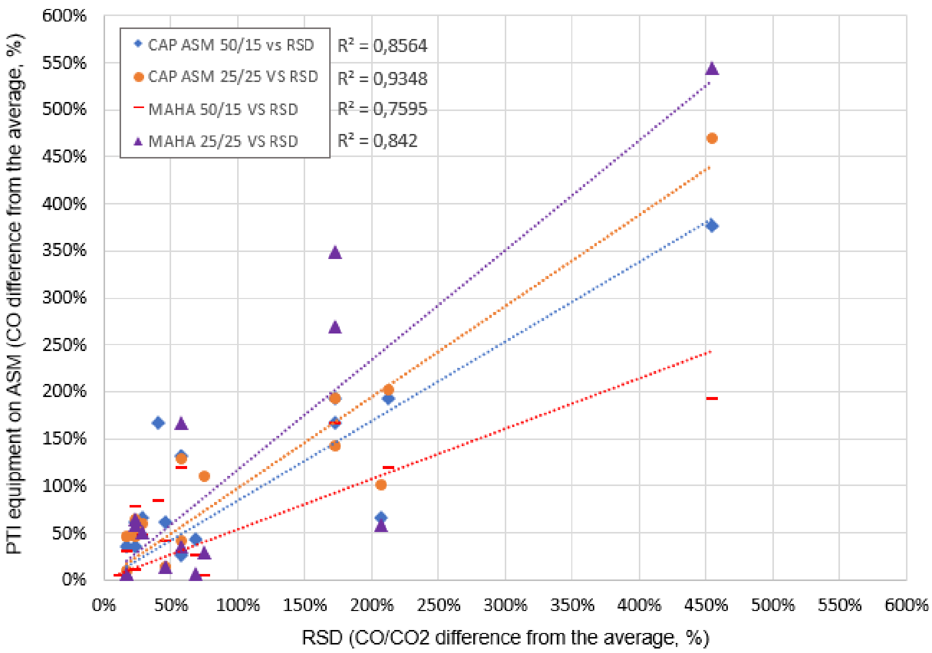

Figure 3: CO comparison between the RSD to CAP and MAHA systems. The X-axis shows the percentage difference of each vehicle's CO/CO_2 measurement done with the RSD compared to the average of all other RSD measurements. The Y-axis shows the percentage difference of each vehicle's CO measurement with the CAP and MAHA systems compared to the average of all CO measurements of these systems.

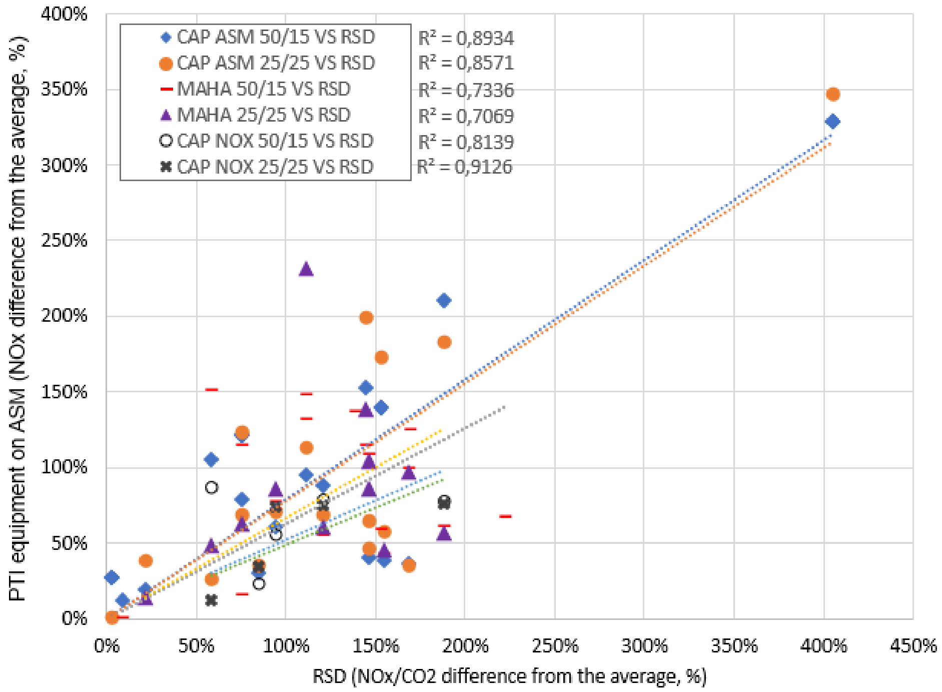

Figure 4: NOx comparison between the RSD to CAP and MAHA systems. The X-axis shows the percentage difference of each vehicle's NOx/CO_2 measurement done with the RSD compared to the average of all other RSD measurements. The Y-axis shows the percentage difference of each vehicle's NOx measurement with the CAP and MAHA systems compared to the average of all NOx measurements of these systems.

5.3. Emissions assessment of a high-emitting vehicle

To assess the effectivity of the proposed high-emitter methodology, we evaluate the real-world behavior of high-emitters and non-high-emitters. Five of the vehicles that were measured most times in the Madrid remote sensing campaign are selected and plotted on Figure 5. Three of these vehicles are classified by the high-emitter protocol as non-HE and two other vehicles are classified by the high-emitter protocol as HE in nitrogen monoxide (NO). As NO emissions are typically higher in diesel-fueled cars, only this fuel has been selected for a proper comparison. A summary of the main characteristics of these vehicles in shown in Table 3.

Table 3: Technical characteristics of five random vehicles measured more than 40 times by the RSD.

Vehicle ID	Fuel type	Euro Standard	Manufacturer	Model	Engine power (kW)	HE (Yes/No)
228700	Diesel	EURO 4	MERCEDES	CLASS E	140	No
246907	Diesel	EURO 6b	MERCEDES	CLASS E	143	No
257376	Diesel	EURO 5b	RENAULT	MEGANE	81	Yes
267939	Diesel	EURO 4	RENAULT	MEGANE	63	Yes
273741	Diesel	EURO 6b	RENAULT	CLIO	66	No

All these vehicles had more than 40 valid measurements with VSP between 0-30 kW/Ton. They are examples of typical vehicles that can be found in any European city. Each point in the graph represents an individual measurement of NO to CO_2 ratio. As it is known that NO emissions have an increasing tendency dependence on vehicle specific power, this analysis also allows to observe the sensitivity of finding a high emitter over a wide range of VSP.

The graph shows the higher variability of HEs and their tendency to high emission levels at any VSP. It can be seen that individual emission events of a high-emitter are most of the time above the lower limit (P_{80}) and even sometimes above the upper limit (ORHE, P_{98}). On the contrary, non-HEs have variable emissions, but consistently below the two limits, regardless of the VSP and other real-world factors. Even if the non-high emitting vehicles sometimes overpass the lower limit, this is a rare event, so it would be extremely unlikely that these vehicles could be classified as a HE with the proposed protocol. Also, if a vehicle does not overpass the ORHE limit but stays in the zone between both limits, it is safe to say that it can be classified as a high-emitter, as it would be showing the same behavior of a HE even without any individual emission was above the ORHE limit.

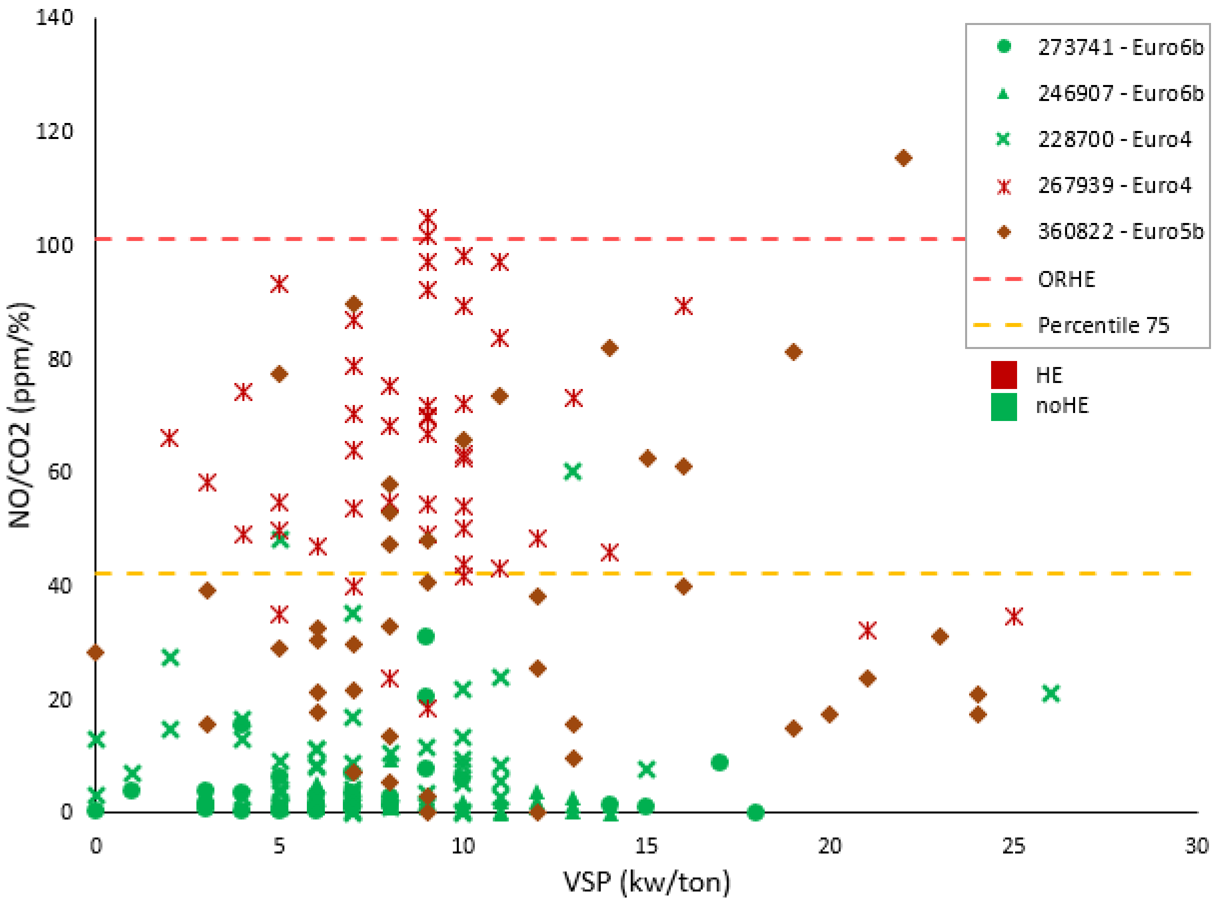

Figure 5: NO emission ratios (NO/CO_2) of five vehicles measured at least 40 times by the RSD in Madrid's roads. VSP is represented in the X axis. Red markers: individual measurements of vehicles classified as HE. Green markers: individual measurements of vehicles classified as non-HE. Upper horizontal dash line: ORHE limit of NO (101.2). Lower horizontal dash line: Lower limit of NO (42.3).

6. Conclusions

The results show that the Opus RSD can be used in Europe to identify high-emitting vehicles and that a methodology can be defined to identify high-emitters on the road by the RSD and be inspected for verification in a well-equipped inspection station, providing full traceability and legal safety on the driver. Other relevant conclusions of the study are:

- We estimate that the sample needed to define ORHE limits on a given territory should be at least 100.000 valid measurements of the vehicles to be subject to the program (i.e., passenger cars) measured with RSDs. To consider ambient and driving-style variability, this data should be collected in two different seasonal periods and with a site mix that guarantees a homogeneous and wide VSP distribution.
- The proposed methodology consists of defining two limits (for each pollutant) based on the collected remote sensing data. The first limit (ORHE) is the Percentile 98 of emissions from the remote sensing campaign. The second limit is the Percentile 80. Vehicles that exceed each limit at least once with at least two different observations or vehicles that have a continuous high-emitting behavior (70% of their measurements exceeding the top 20% of the fleet emission records) would be classified as HE. Our assessment indicates that this criterion clearly identifies in a safety way whether or not a vehicle is a HE despite the variability of its emissions. The results suggest that the emission performance of a HE has a distinguishable pattern on the road.
- The results indicate that it could be possible to set a single ORHE limit (per pollutant) irrespective of the type of vehicle measured by the RSD. Figure 5 shows that a HE can be an old or a modern vehicle (i.e. Euro 6b), of any fuel type and of any brand, model or engine power. This limit simplification would greatly facilitate the implementation of a HE program for two reasons. First, because otherwise individual limits would have to be designed for each vehicle type (which would require estimating and testing the suitability of dozens of different limits). Second, because otherwise the emissions of each vehicle would have to be checked against its technical characteristics, which would be too technically complex and would require a level of harmonization of technical data in traffic databases that does not exist today.

- The results indicate that there is a good correlation between the identification of a heavily polluting vehicle with the criteria established from the remote on-road measurements with RSD and the dynamometer measurements and direct exhaust measurements, In particular, CO and NOx measurements made with the Opus RSD adequately correlate with CAP and MAHA results.
- Our estimations show that a few high-emitting vehicles (between 4.3% and 5.6% of the circulating fleet) are responsible for a significant portion of the total emissions generated by all road urban traffic. Specifically: 18.9% of NO, 29.5% of NO_2, 44.4% of $PM_{2.5}$, 25.7% of CO and 22.2% of HC. These figures are consistent with other studies [1]. The large contribution of HEs on particulate matter emissions is noteworthy, possibly due to vehicles circulating without a particulate filter or with a broken particulate filter.
- High-emitters are most likely to be found by RSDs in cities, as this is where most vehicles circulate and where the air quality problem is severe. As the number of HEs found in cities will be very small (around 5%, as mentioned before), there would only need to be one or two properly equipped stations per every large European city to properly verify these vehicles. This will reduce the investments needed to improve vehicle monitoring in Europe, as not all stations would need to be modernized.
- As far as we know, there is currently no industry consensus or scientific clarity as to what new equipment or inspection methods should be implemented in Europe to improve the control of vehicles' emissions in the PTIs, especially for assessing NOx emissions. According to all the studies performed during our research, we believe it is feasible to consider that the RSD could become an inspection system to be installed inside the PTI. It is known that this system can assess with sufficient accuracy whether a vehicle is a high emitter on the road and that this categorization is in line with that of other sensors (CAP and MAHA). Since the RSD can evaluate all pollutants currently regulated by the EU (NOx, CO, PM and HC) at the same time, it could be a low-cost equipment to be installed permanently in the PTI to check vehicles previously identified on the road. This approach, in turn, would increase the traceability of the entire program, since a vehicle identified on the road as a HE would be verified with the same technology, but in a controlled environment, in an inspection center.

Acknowledgements

This project was funded by the European Commission within the LIFE programme in the GySTRA project: https://lifegystra.eu. The authors thank Applus+ for their excellent and professional collaboration and for facilitating a site and equipment to conduct the tests.

7. References

[1] Pujadas M. et al, Real-driving emissions of circulating Spanish car fleet in 2015 using RSD Technology, Science of The Total Environment 576, 2017.

[2] Jens Borken-Kleefeld and Tim Dallmann "Remote Sensing of motor vehicle exhaust emissions", ICCT 2018

[3] Landrigan P. J., Air pollution and health, The Lancet, 2017.

[4] Estudio para la cuantificación de la contribución de fuentes a los niveles de calidad del aire en el municipio de Madrid, Universidad Politécnica de Madrid, 2017.

[5] Carsten G. et al. Potential of Remote Sensing Devices (RSDs) to screen vehicle emissions, Publications Office of the European Union, 2019.

[6] McClintock, P., The Colorado Remote Sensing Program January–December 2011, Colorado Department of Public Health and Environment, 2012.

[7] Dallmann T. et al., Remote sensing of motor vehicle emissions in London, The ICCT, 2018.

[8] Feng A. et al. Development of Comprehensive Modal Emissions Model, Contractor's Final Report for NCHRP Project 25-11, 2000.

[9] Bernard Y. et al. Worldwide use of remote sensing to measure motor vehicle emissions, The ICCT, 2019.

[10] Yuhan H. et al. Remote sensing of on-road vehicle emissions: Mechanism, applications and a case study from Hong Kong. Atmospheric Environment, 2018.

[11] Bishop, G.A et al., Multispecies remote sensing measurements of vehicle emissions on Sherman Way in Van Nuys, California. Journal of the Air & Waste Management Association, 2012.