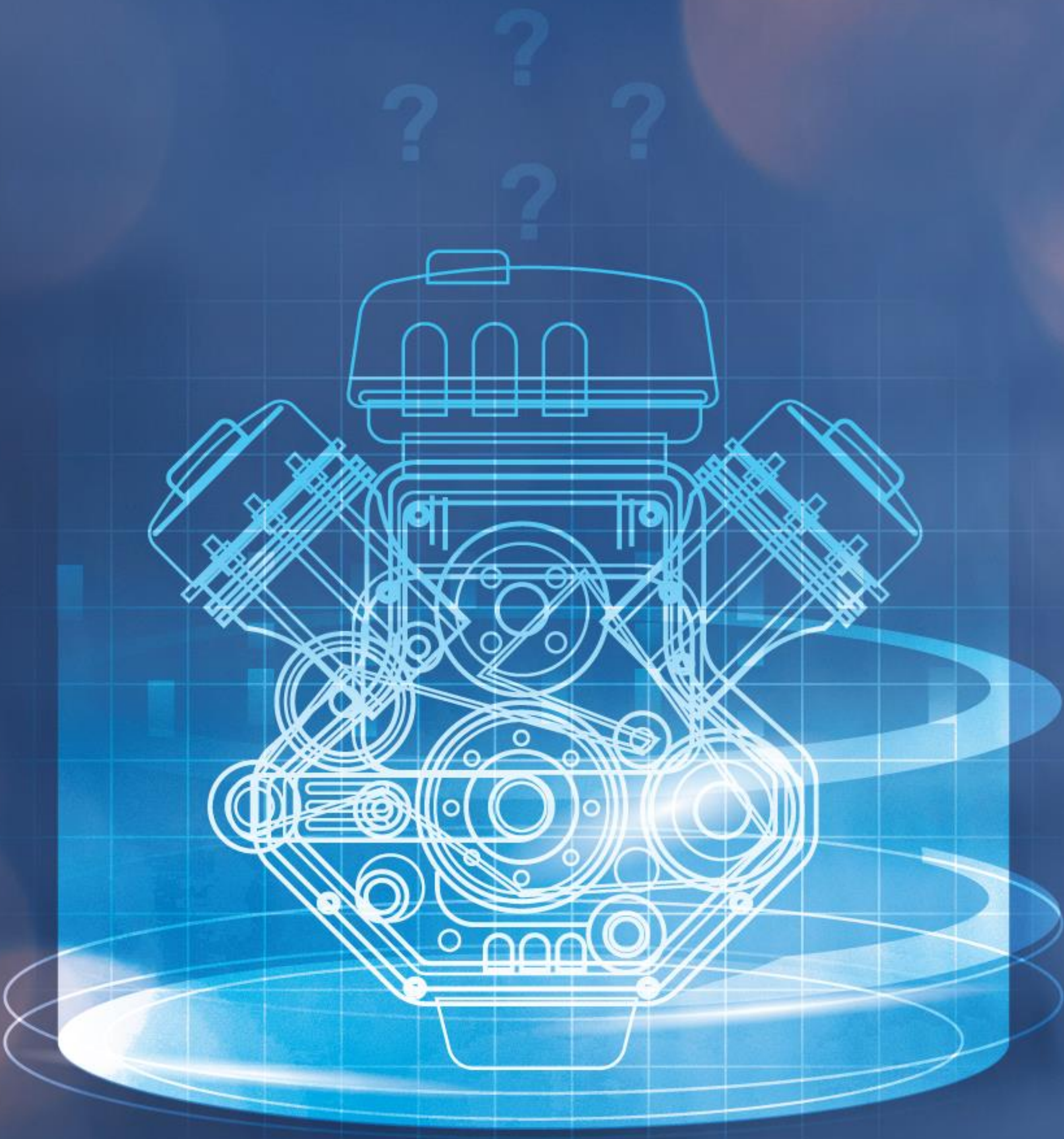

New diesels, new problems

TRANSPORT & ENVIRONMENT

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Executive summary

Diesel car sales are in free fall. The Dieselgate scandal caused a collapse in customer confidence exacerbated by increasing restrictions on diesel car use in cities. In an attempt to ensure past investments in diesel technology can provide a return, the car industry claim new diesel cars are now "clean". This report demonstrates that the strictest EU car pollution controls are failing to stop large amounts of dangerous particle pollution from diesel cars. It presents the results of independent lab tests which reveal that even the latest diesel models are a serious health hazard.

This is mainly because the best available pollution control technology, diesel particle filters (DPFs), have to be cleaned ('regenerated') regularly which causes diesel vehicles to 'spill out' large amounts of pollution roughly every 480km[1]. Tests show these spikes can occur in urban areas and last as long as 15km, during which emissions of **dangerous particle pollution surge to over 1,000 times their normal rate**. This flaw was written out of EU emissions tests: when the extreme particle emission peaks occur, emission limits are ignored and tests reinitiated although more stringent regulation was discussed as early as 2007.[2] T&E estimates that **more than 45 million cars** carry the technology in Europe, producing pollution spikes which occur once a fortnight on average. The findings disprove automotive industry claims that the newest Euro 6d-temp diesel models are clean,[3,4,5,6] which should be acknowledged when designing clean air policies, and especially the future post-Euro 6 standard.

Particle pollution is increasingly seen as 'pollution enemy number one'. Ambient particulate matter is ranked as the 6th highest risk factor for total deaths globally[7]. Particle pollution affects more people than any other pollutant, according to the World Health Organisation (WHO)[8], with 77% of the inhabitants of European cities exposed to levels above WHO guidelines.[9] Progress to reduce the pollution problem across Europe has come to a near complete stop, according to the latest data from the European Environment Agency (EEA).[10] It is also the type of air pollution that is 'most closely associated with increased cancer incidence, especially **lung cancer**'.[11] Chronic exposure to particulate matter is linked to **cardiovascular and respiratory diseases**.[12] In particular, the number of particles in the air is increasingly seen as a strong determinant of adverse health effects. Exposure to high numbers of particles **can even have immediate negative effects on the heart**[13]. **Ultrafine particles** (smaller than the size of a typical virus) could be the **most dangerous form**, as they can penetrate deep into the body[14] and have just been linked to brain cancer.[15] Ultrafine particles are emitted in large amounts by internal combustion engines.

Particle pollution was considered solved after **DPFs** became a mandatory part of the exhaust systems for all new diesel cars in 2013.[16] However, in order to work they **must be cleared periodically** in an automatic on-road process known as regeneration. This process causes pollution spikes, particularly of the number of particles, and is poorly regulated under the latest Euro 6 regulations although more stringent regulation of regenerations was discussed as early as 2007.[17] As emission limits don't have to be met on regenerating tests, the current type-approval method of taking regeneration into account involves dividing the large spike in emissions by several hundred kilometres, effectively diluting the large pollution peaks. However, even this does not apply to the number of particles emitted[18].

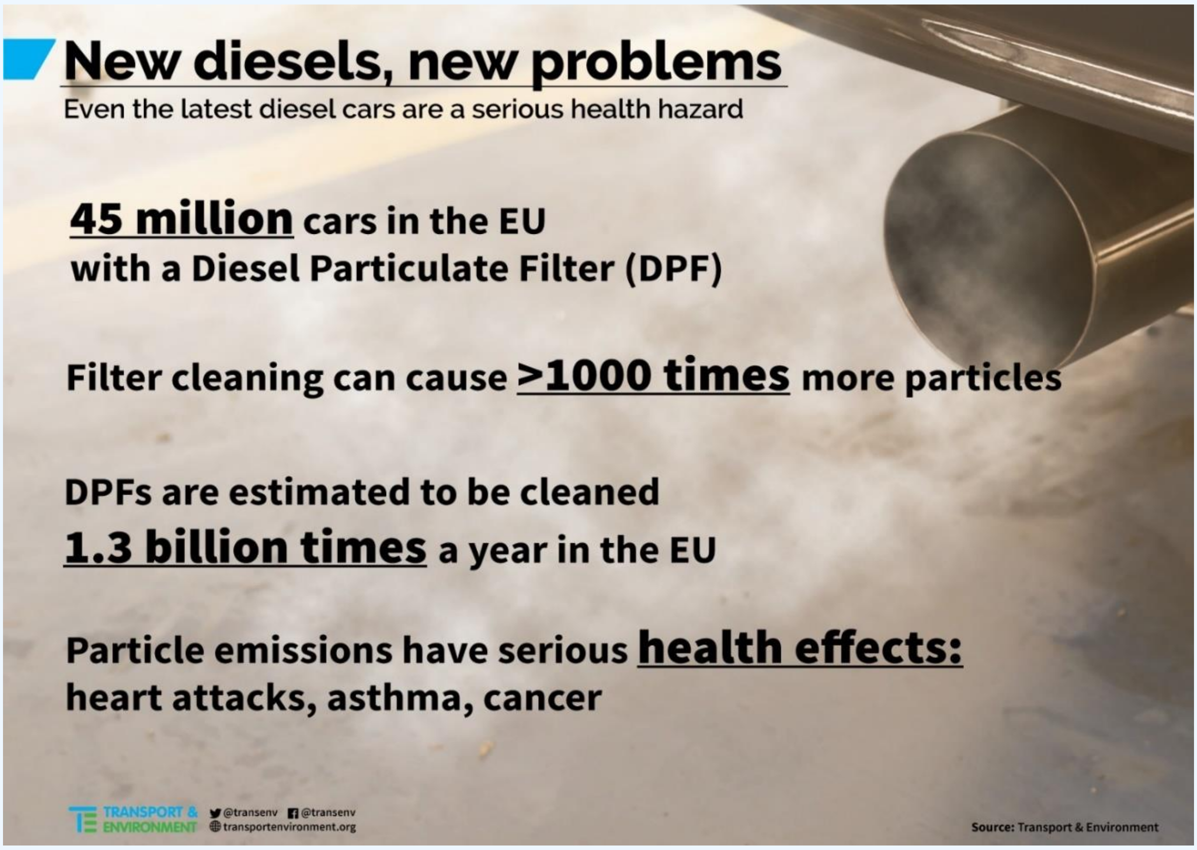
To understand how polluting the latest diesel vehicles are, Transport & Environment asked **a world leading and independent laboratory (Ricardo)** to test **two of Europe's most popular diesel cars** approved under the latest Euro 6d-temp standard that carmakers argue delivers 'clean diesel'. The vehicles tested are a **Nissan Qashqai** and an **Opel/Vauxhall Astra**. The Nissan was the 2nd best-selling car in the class C SUV segment, and the Opel/Vauxhall was the 4th best-selling in

the C segment in Europe in 2018[19]. The laboratory tests simulated real-world driving and measured a range of pollutants including those **which are currently unregulated** and difficult to measure on the road, such as ultrafine particles, volatile and semi-volatile particles and ammonia. The results were compared to official type-approval data where available.
The main findings are:

- **On laboratory test cycles based on the EU's new 'Real Driving Emissions' tests, more than 1,000 times more particles were emitted during DPF regeneration.** The cars would have exceeded the legal limits for the number of particles emitted if these emissions were not ignored by the EU emissions standard. All tests during which a regeneration occurred witnessed a steep increase in the number of regulated particles compared to tests in which a regeneration did not occur. The particle number emissions limit of $6x10^{11}$/km for solid particles larger than 23nm was exceeded by between 32-115% on all tests where a full regeneration occurred.[20] But current regulations do not apply the legal limit to regenerating tests.
- **However, both models respected legal limits for gaseous pollutants and particulate matter** (nitrogen oxides, carbon monoxide, total hydrocarbons, total hydrocarbons and nitrogen oxides, particulate matter). This is positive although it comes a full 12 years after the definition of these limits in EU law. However, during regeneration, emissions of all of these pollutants increased significantly.
- The regeneration blind spot in regulations mean that between **60-99% of emissions of all regulated particles is ignored for the two test cars**.
- **A large proportion of particles are not even measured today but constitute a serious health risk.** Currently only solid particles which are larger than 23nm in diameter are regulated. However, when solid particles as small as 10nm were measured the total PN emissions increased by between 11-184% compared to when only regulatory particles were measured. This means that large amounts of particle pollution are completely neglected from a regulatory point of view, despite potentially being the most harmful to human health.
- **Regeneration events for the Astra occurred almost twice as often as during type-approval.** The distance between two DPF regenerations was 419km for the Astra; this is almost half of the distance determined at type-approval. A similar distance of 423km was determined for the Qashqai.
- **Approximately 45 million diesel cars cause a total of 1.3 billion regenerations per year in the EU.** T&E estimates that there are approximately 45 million diesel cars fitted with a DPF in the EU[21]. Given that the average EU diesel mileage is estimated to be between 13,600 to 23,200 km[22], a DPF regeneration is estimated to occur, on average, every other week for most diesel cars[23], or 1.3 billion times each year in the EU.[24]
- **DPF regeneration can occur in all driving conditions, including in and around urban areas.** While regeneration is more likely to occur during higher speed driving, Emissions Analytics reported as early as 2013 that DPF regeneration occurs during urban driving also. This is necessary to prevent filter clogging, especially when cars are driven exclusively in urban areas.[25] Moreover, during the tests particle number emissions continued to be higher during urban driving for 30 minutes after the end of regeneration.

These results suggest that DPFs are not the definitive solution to the diesel particle problem many had suggested, and instead can cause substantial peaks of air pollution during real-world driving conditions.

For public health, **what matters is the actual emissions from the vehicle**, not only whether an emissions limit measured using a specific test is met. The results of this test programme suggest that the **newest Euro 6d-temp diesel cars respect legal limits within the boundary conditions of regulatory tests** but that there are **still serious gaps** in the new regulatory tests that fail to capture all driving conditions and **spikes in particle number emissions**. There are also a **number of harmful pollutants** that are **entirely unregulated**. That means it is incorrect to say that diesel is now 'clean'.



These findings should prompt regulators to:

- Acknowledge that even the latest **Euro 6d(-temp) diesel cars** are highly polluting and design clean air policies accordingly, including access rights to Zero/Low-Emission Zones, purchase incentives and similar policies.
- **Emission limits need to set a pathway towards zero pollutant emissions and must be reduced downwards as soon as possible.** T&E recommends that the European Commission be ambitious and aim for the post-Euro-6 emission limits to be the most stringent emissions limits globally.
- Design the future post-Euro 6 standard in a way that requires emission limits for all pollutants, including particle number, to be met under all driving conditions, and also during DPF regeneration. Currently unregulated pollutants, such as ammonia and ultrafine particles smaller than 23 nanometres, must also be included.
- The new Commission should use the new EU type approval framework to **monitor on-road compliance** and take corrective measures where necessary. This will require allocating significant additional resources to agencies and services dealing with emissions testing as well as the creation of an EU-level agency or authority to oversee tests, enforcement and possible fines and recalls.

Endnotes Executive Summary

[1] AA, 'DPFs can be problematic' accessed 16/10/2019

[2] Jon Andersson, Barouch Giechaskiel, Rafael Muñoz-Bueno, Emma Sandbach, Panagiota Dilara, ' Particle Measurement Programme (PMP) Light-duty Inter-laboratory correlation exercise final report' June 2007

[3] CNN Business, Ivana Kottasová, 'Volkswagen nearly killed diesel cars. Now it says they're back', 30th of January 2019

[4] www.peugeot.co.uk/bluehdi accessed 18/11/2019

[5] https://www.spokanemercedes.com/mercedes-benz-clean-diesel/ accessed 18/11/2019

[6] https://www.vauxhall.co.uk/fleet/range/ecotec/diesel-engines.html accessed 18/11/2019

[7] Health Effects Institute, 'State of Global Air', Boston, 2018

[8] WHO, Air Pollution - Key Facts, 2 May 2018

[9] European Environment Agency: Air Quality in Europe - 2019 Report, October 2019

[10] European Environment Agency: Air Quality in Europe - 2019 Report, October 2019

[11] WHO, Air Pollution - Key Facts, 2 May 2018

[12] WHO, Air Pollution - Key Facts, 2 May 2018

[13] Peters, A., Hampel, R., Cyrys, J. et al, ' Elevated particle number concentrations induce immediate changes in heart rate variability: a panel study in individuals with impaired glucose metabolism or diabetes', Particle and Fibre Toxicology, 2015

[14] Health Effects Institute, 'Understanding the Health Effects of Ambient Ultrafine Particles, 2013

[15] Weichenthal et al., 'Within-City Spatial Variations in Ambient Ultrafine Particle Concentrations and Incident Brain Tumors in Adults', Epidemiology, 2019

[16] https://www.acea.be/industry-topics/tag/category/air-quality accessed 11/11/2019

[17] Jon Andersson, Barouch Giechaskiel, Rafael Muñoz-Bueno, Emma Sandbach, Panagiota Dilara,' Particle Measurement Programme (PMP) Light-duty Inter-laboratory correlation exercise final report', 2007

[18] Unless a regeneration occurs on two consecutive tests. In this case emission limits apply to the second test only.

[19] JATO Dynamics, Data for Automotive News Europe, Volume 10, Issue 2, February 2019

[20] The Conformity factor (CF) for PN was not taken into account during this testing programme as the CF exists to account for any measurement error in the portable emissions measurement system (PEMS) compared to regulatory laboratory equipment. Regulatory lab-based equipment was used to measure emissions during this testing programme, therefore a CF shouldn't be applicable.

[21] Estimated number of Euro 5b and Euro 6 diesel cars sold between 2011 and the first half of 2019 in the EU based on combined data from ICCT's Pocketbook, Element Energy and ACEA, taking into account that some older models may have been scrapped. Some manufacturers implemented DPFs on diesel vehicles before the Euro 5b legislation came into force, however these were not included in the total DPF fleet figure due to the difficulty associated with obtaining data for which vehicles were and were not fitted with a DPF and detailed enough EU-wide registration data per model.

[22] Belgium data: Belgian Federal Ministry of Mobility, England: UK Department of Transport, France: French Ministry of Environment & L'Argus.fr, Germany: KBA, Italy: Atmospheric Pollution Research, The Netherlands: BOVAG-RAI

[23] Based on a regeneration distance of 480 km from the British Motoring Association

[24] Based on 28 regenerations per year

[25] The Telegraph, David Motton, 'Emission tests 'substantially underestimate' pollution pumped out by diesels', 29th May 2014

Table of Contents

List of acronyms

CLOVE Consortium tasked by the European Commission to work on post-Euro 6 emission standards

CO_2 Carbon dioxide

CO Carbon monoxide

DOC Diesel Oxidation Catalyst

DPF Diesel particulate filter

EGR Exhaust gas recirculation

EGT Exhaust gas temperature

HC Hydrocarbons

ISC In-service conformity

NH_3 Ammonia

NO_2 Nitrogen dioxide

NOx Nitrogen oxides

OBD On-board diagnostics

PEMS Portable emissions measurement system

PM Particulate matter

$PM_{2.5}$ Particulate matter with a diameter up to 2.5 microns

PMP Particle Measurement Programme

PN Particulate number

PNA Passive NOx Absorber

RDE Real Driving Emissions

RPA Relative positive acceleration

SCR Selective catalytic reduction

THC Total Hydrocarbon

WHO World Health Organization

WLTP Worldwide Harmonized Light Vehicle Test Procedure

1. Objectives & context: The need to investigate all driving conditions in order to capture pollutant emission peaks

Since the beginning of the Dieselgate scandal in 2015, the emissions of diesel cars have moved to the centre of attention in debates on air quality. Several auto manufacturers, including most notably Volkswagen, were implicated in cheating on emissions tests and it was revealed that many diesel passenger cars emit much more nitrogen oxides (NOx), during real world driving, than allowed by regulations. In part to combat emissions cheating, new on-road emissions (RDE) testing has been introduced in the European Union (EU) and since September 2019, all new cars sold in the EU have to pass the RDE tests as part of the type approval process under the Euro 6d(-temp) standard. The results of these tests suggest that progress has been made in reducing nitrogen oxide emissions[1] and carmakers claim that the new diesel models are clean.[2,3,4,5] But there remain serious doubts about whether this is actually true under all driving conditions and for all pollutants. The RDE testing procedure has narrow boundary conditions, outside of which cars do not have to meet emission limits. T&E's earlier work already highlighted in 2018 that emissions of even the newest diesel cars can be much higher if they are driven on roads with hills, with faster accelerations, and at higher speeds that are more representative of how cars are typically driven.[6]

Particle pollution moving to the centre of attention

With the focus on NOx emissions as a result of the Dieselgate scandal, particle pollution has received less attention over the past years. However, due to its serious health effects, it is increasingly recognised as 'pollution enemy number one'. Ambient particulate matter is ranked as the 6th highest risk factor for total deaths globally[7] and particle pollution affects more people than any other pollutant, according to the World Health Organisation (WHO). It is also the component of air pollution that is 'most closely associated with increased cancer incidence, especially lung cancer' and chronic exposure to particulate matter is linked to cardiovascular and respiratory diseases. At present 77% of inhabitants of European cities are exposed to particulate matter levels above WHO guidelines[8] and even in areas where limits are met, the air is not necessarily safe to breathe as according to the WHO, 'small particulate pollution have health impacts even at very low concentrations – indeed no threshold has been identified below which no damage to health is observed'.[9] Progress to reduce the problem across Europe is at a near complete stop, according to the latest data from the European Environment Agency (EEA).[10] Cars and trucks are one of the main contributors to poor air quality due to particle pollution; in Brussels alone they account for 29% of $PM_{2.5}$ emissions.[11]

Reasons for the focus shifting from particle mass to particle number

In recent years, the focus on particles has shifted away from particle mass to particle number due to the emerging body of evidence which suggests that the number of particles inhaled, especially of ultrafine particles (smaller than 100nm), may have a greater negative health impact than their mass. These particles are deposited in the lungs and airways with high efficiency[12] and after inhalation, they can spread throughout the entire respiratory system. The smaller the pollutant is, the further into the tissue of the lungs

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1 T&E, 'EU must withdraw carmakers' 'license to pollute' as data shows new cars meet limits', 2019
2 CNN Business, Ivana Kottasová, 'Volkswagen nearly killed diesel cars. Now it says they're back', 30th of January 2019
3 www.peugeot.co.uk/bluehdi accessed 18/11/2019
4 https://www.spokanemercedes.com/mercedes-benz-clean-diesel/ accessed 18/11/2019
5 https://www.vauxhall.co.uk/fleet/range/ecotec/diesel-engines.html accessed 18/11/2019
6 T&E, 'Cars with engines: can they ever be clean?', 2018
7 Health Effects Institute, 'State of Global Air', Boston, 2018
8 European Environment Agency: Air Quality in Europe - 2019 Report, October 2019
9 WHO, 'Air Pollution Key Facts', 2nd of May 2018
10 European Environment Agency: Air Quality in Europe - 2019 Report, October 2019
11 City of Brussels, ' Expected effects from the low emission zone on air quality in the Brussels region', 2019
12 ICRP respiratory deposition model as presented in DownToTen, 'Particle emissions measurements on CNG vehicle focusing on, sub-23nm', TAP Conference 2019

it can travel.[13] These particles have also been shown to translocate to other organs such as the brain.[14] The severity of the harm caused by these particles is dependent on many factors but several studies have made the link between ultrafine particle exposure and negative health effects. Worryingly these particles are emitted in large amounts from internal combustion engines.

Recent research has linked the exposure of children to ultrafine particles with the onset of asthma.[15] For adults, an increase in the number of ultrafine particles in the air by 10,000/cm^3 was found to increase the risk in adults of developing hypertension/diabetes by 3-4%, heart failure by 2-5% and brain tumours by 10-13%.[16] This is equivalent to one new brain tumour case per 100,000 people for every 10,000/cm^3 increase in the number of ultrafine particles.

In comparison the current diesel particle number emission standard is 600,000,000,000/km. Finally, research suggests that exposure to high numbers of particles can even have immediate negative effects on the health of vulnerable groups, with data indicating that freshly emitted ultrafine particles and aged fine particulate matter are both associated with changes in cardiac function in individuals with type 2 diabetes and impaired glucose tolerance in urban areas.[17] These studies indicate that the emissions of large numbers of particles and in particular ultrafine particles are of serious concern to public health.

Particle pollution was considered solved after diesel particulate filters (DPFs) effectively became a mandatory part of the exhaust systems after the introduction of a particle number emissions limit for all new diesel cars in 2013, with some cars already required to meet the limit in 2011.[18] DPFs work by reducing particle emissions from diesel cars by trapping particles made in the engine inside the filter thereby reducing the amount of particle pollution emitted from diesel cars.

Diesel Particulate Filters regularly need to regenerate. What does this mean for emissions?

However, there is reason to believe that DPF filters do not effectively reduce particle number emissions under all possible conditions. As soot from the engine accumulates on the filter over time, the car has to go through periodic DPF regeneration events to prevent the exhaust from clogging. The regeneration itself involves an increase in the temperature of DPF up to a minimum of 550°C; the temperature threshold at which soot begins to burn when excess oxygen is present. Once the DPF reaches this minimum temperature, the soot accumulated in the DPF is burnt and the DPF is 'cleaned'. Worryingly, several studies have indicated that this DPF 'cleaning' is associated with a large increase in the emission of regulated pollutants and especially of particle number (PN) emissions[19]. Given that the UK's AA (British Motoring Association) estimates that a regeneration occurs on average every 480 km[20] and the serious health effects of particle pollution, these episodes of high pollutant emissions are of serious concern for air quality and public health.

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[13] CE Delft, 'Health Impacts and costs of diesel emissions in the EU', 2018

[14] Oberdorster, G., Sharp, Z., Atudorei, V., Elder, A., Gelein, R.Kreyling, W., and Cox, C., 'Translocation of inhaled ultrafine particles to the Brain', Inhalation Toxicology, 2004

[15] Lavigne E., Donelle J., et. al., ' Spatiotemporal Variations in Ambient Ultrafine Particles and the Incidence of Childhood Asthma', American Journal of Respiratory and Critical Care, 2019

[16] Dr. Scott Weichenthal, ' Emerging health impacts of ambient ultrafine particles and deep learning for air pollution exposure science', ETH-Nanoparticle Conference, Zurich, 2019

[17] Peters, A., Hampel, R., Cyrys, J. et al, ' Elevated particle number concentrations induce immediate changes in heart rate variability: a panel study in individuals with impaired glucose metabolism or diabetes', Particle and Fibre Toxicology, 2015

[18] https://www.acea.be/industry-topics/tag/category/air-quality accessed 10/11/19

[19] M.Leblanc, L. Nöel, B.R'Mili, A. Boréave, B.D'Anna, S.Raux, 'Impact of engine warm-up and DPF active regeneration on regulated & unregulated emissions of a Euro 6 Diesel SCR equipped vehicle, 'Journal of Earth Sciences and Geotechnical Engineering, 2016

[20] AA, 'DPFs can be problematic' accessed 16/10/2019 https://www.theaa.com/driving-advice/fuels-environment/diesel-particulate-filters

Emission standards don't have to be respected during DPF regeneration tests

This is especially the case given that, at the present time, pollutant emissions are poorly regulated on tests during which a DPF regeneration occurs as emission limits are allowed to be exceeded on WLTP and RDE tests during which a regeneration occurs. This is allowed by the regulation on the Worldwide Harmonised Light Vehicle Test Procedure (WLTP 2nd act) which clearly states that '*during cycles where a regeneration occurs, emission standard need not apply*'[21]. Only so-called additive or multiplicative k_i factors, are currently used to account for the increase in regulated gaseous and particle mass emissions due to DPF regeneration[22].

These k_i factors essentially average the (usually) higher emissions measured on tests during which a DPF regeneration occurs by the distance between two consecutive regenerations. This factor is then used to scale the results of WLTP or RDE tests during which a regeneration does not occur. However, the use of k_i factors effectively allows large amounts of pollution to be emitted on these tests and on the road when a regeneration occurs, as the potentially high emissions due to DPF regeneration are averaged over a large number of tests. However, most importantly k_i factors do not need to be determined for particle number emissions, only for the total mass of particles emitted. This is despite the Particle Measurement Programme (PMP) coming to the conclusion as far back as 2007 that 'in principle, there is no reason why regeneration particle number emissions should not be accounted for at type approval'.[23] This loophole in regulation essentially allows vehicles to emit an unlimited number of particles on tests and on the road when a regeneration occurs[24]. This is despite a particle number emission limit being in place since 2013 for all diesel vehicles.

Test work with a focus on DPF regeneration and unregulated pollutants

Due to the lax emissions regulation surrounding DPF regeneration and previous studies which suggest pollutant emissions increase markedly during DPF regeneration on WLTP tests, T&E have undertaken this testing project to investigate the emissions of both regulated and unregulated pollutant emissions during DPF regeneration from the latest diesel cars. This report presents the results of an investigation into the emissions of two Euro 6d-temp diesel cars tested in 2019. The cars were tested using a real-world driving (RDE) test cycle reproduced on the chassis dynamometer in order to measure a range of currently unregulated pollutants. The particular focus of this report is the emissions of currently unregulated volatile, semi-volatile and smaller than 23nm particle emissions. Ammonia emissions, which are currently unregulated for passenger cars but contribute to the formation of secondary particles in the air, is also discussed for both vehicles. In order to understand the make-up of particles emitted from the car during regeneration, a chemical analysis of the particulate matter has also been undertaken. The current regulatory approach to regenerations is discussed and the effect on total emissions during all kilometres driven and how this is reflected in current regulations is analysed.

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[21] European Commission Regulation (EU) No 2018/1832

[22] Unless a regeneration occurs on two consecutive tests, in this case emission limits only apply to the second test.

[23] Jon Andersson, Barouch Giechaskiel, Rafael Muñoz-Bueno, Emma Sandbach, Panagiota Dilara, ' Particle Measurement Programme (PMP) Light-duty Inter-laboratory correlation exercise final report', 2007

[24] Unless a regeneration occurs on two consecutive tests, in this case emission limits only apply to the second test.

2. Methodology: RDE based testing of two Euro 6d-temp vehicles with one of Europe's leading vehicle test laboratories

Two Euro 6d-temp diesel vehicles were selected for the testing programme. The vehicles were chosen based on EU market penetration as well as the availability of Euro 6d-temp vehicles at the time of testing. The testing programme was conducted by Ricardo at their Shoreham Technical Centre in the UK during July and August 2019. The cars used in the testing programme were rented from ProRent, Germany, by Ricardo.

Two Euro 6d-temp vehicles tested: Nissan Qashqai and Opel/Vauxhall Astra
Both of the vehicles tested were C-segment Euro 6d-temp vehicles. The first vehicle tested was a Nissan Qashqai two wheel drive with a diesel 1.5 litre, 4 cylinder, 115 PS engine with maximum rated power of 85 kW with a manual 6 speed transmission. The odometer reading at delivery was 6,400 km. The after-treatment system (used to reduce emissions and located in the tailpipe) was not known but Ricardo proposed this may contain[25] both low pressure and high pressure exhaust gas recirculation (EGR), a close coupled diesel oxidation catalyst (DOC), followed by a selective catalytic reduction coated diesel particulate filter (SCRF),[26] selective catalytic reduction (SCR) and an ammonia slip catalyst (ASC) as shown in Figure 1. The SCRF is a special type of Diesel Particle Filter which has a selective catalytic reduction (SCR) coating capable of not just filtering particles but also reducing NOx emissions.

The second vehicle tested was an Opel/Vauxhall Astra two wheel drive vehicle with a 1.6 litre, 4 cylinder, 110 PS engine, with max rated power of 81 kW with a manual 6 speed transmission. The odometer reading at delivery was slightly higher than the Nissan Qashqai at 20,072 km. The after-treatment configuration was not known, but Ricardo proposed[27] this may comprise low pressure EGR, close coupled DOC/passive NOx absorber (PNA) followed by an SCR and SCRF as shown in Figure 1. Unfortunately, neither the certificate of conformity nor the documentation obtained from the type-approval authority states the exact exhaust layout therefore the exhaust configuration presented is a best guess only.

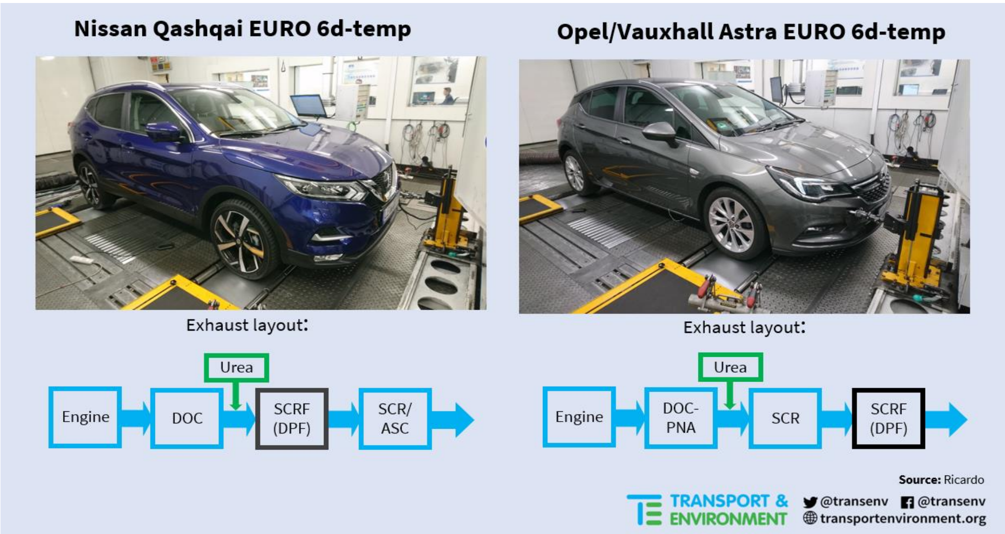

Figure 1. Picture of the Nissan Qashqai and the Opel/Vauxhall Astra on the chassis dynamometer at Ricardo's Shoreham Technical Centre with the potential exhaust layout pictured below

[25] Based on the emission results of this test testing programme and the presentation at the SIA Powertrain conference 2018; Renault, C Bergeris, J. Thobonnet, L. Ouhayoun, A. Hollemaert, E. Aguado 'The New Renault 200HP 2.0litre Diesel engine evolution'
[26] In this report the SCRF is referred to as the DPF.

Prior to the start of testing, each vehicle underwent a comprehensive safety check to ensure that both vehicles were suitable to take part in the testing programme. This included tyre checking, an on- board diagnostics (OBD) scan to determine that no faults were present, and a mechanical fitness check. Each vehicle was flushed and filled with UK pump-grade EN590 fuel from a dedicated isolated batch.

Experimental set-up

All vehicle testing was performed at the Ricardo's Shoreham Technical Centre (STC) on a 4-WD chassis dyno in a climatically controlled chamber. The temperature for this testing programme was kept constant for all tests at 23°C. Each vehicle was fitted with a surface thermocouple in the exhaust to aid with the identification of regeneration events. Relevant OBD channels were monitored using a DiagRAD tool. Continuous raw emissions of currently regulated pollutants (NO, NO_2, CO, THC, CH_4, NMHC) were measured directly at the tailpipe using the Horiba MEXA-ONE system. Diluted emissions were analysed after the constant volume sampling (CVS) system continuously by another Horiba MEXA-ONE. Bagged diluted emissions were also analysed. Due to the length of the RDE cycle 4 bags were used; 2 in the urban phase, 1 in the rural and 1 on the motorway section. The bag split data is presented in Annex 1.

Particle size and concentration of volatile, semi-volatile and solid particles in the 5-1,000nm size range were measured directly at the tailpipe using a differential mobility spectrometer (DMS500). Post-CVS sampling of solid particle number was conducted by the Horiba MEXA 2000 SPCS for particles larger than 23nm (current regulatory size threshold). Solid PN emissions below the current regulatory size threshold were measured continuously using the DownToTen (DTT)[28] system with size cut-off thresholds of 4, 10 and 23nm. Both the SPCS and DTT systems were preceded by a catalytic stripper to remove volatile and semi-volatile particles. PM filter analysis was conducted in order to determine the composition of particles emitted and included the composition analysis of fuel, oil, anions, sulphates and black carbon. Emissions of currently unregulated ammonia (NH_3) was continuously measured directly at the tailpipe, with a frequency of 1Hz, using the Quantum Cascade Laser (QCL). The location of all analysers is shown in figure 2.

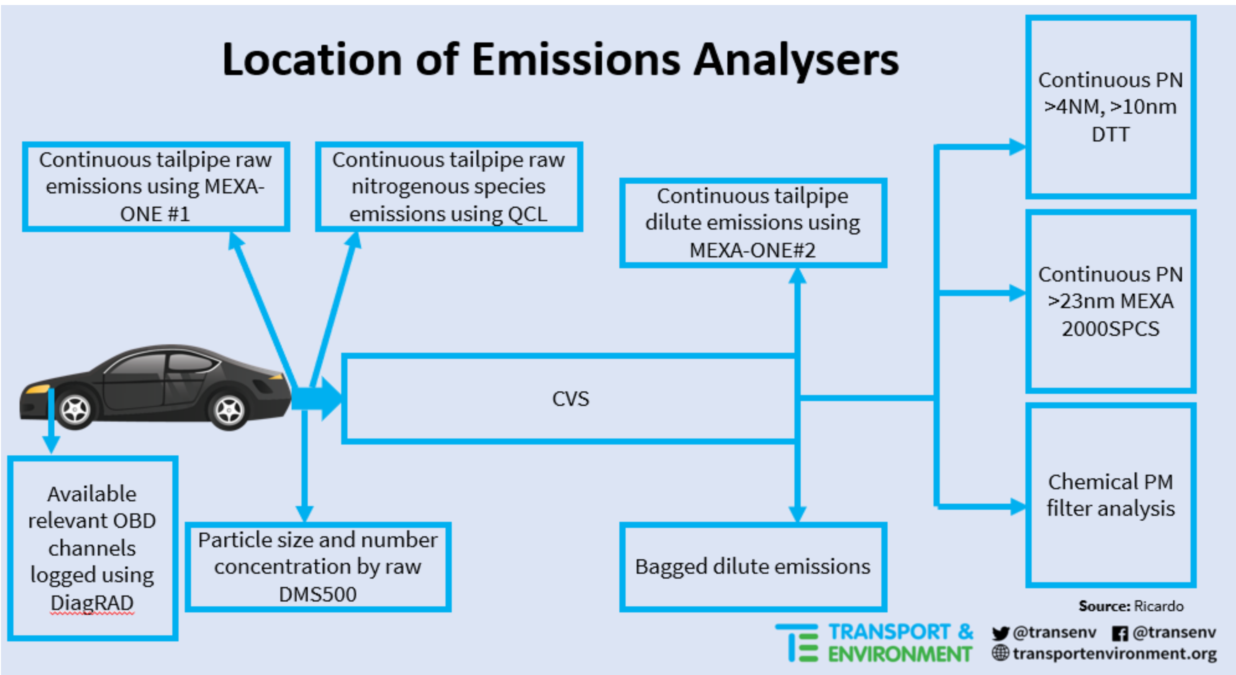

Figure 2. Set-up of emissions analysers on the four-wheel chassis dynamometer at Ricardo's Shoreham Technical Centre

[28] www.downtoten.com

Laboratory based RDE Testing

Both vehicles were tested on the same real-world driving (RDE) cycle conducted on Ricardo's four wheel-drive chassis dynamometer. The testing was conducted in the laboratory in order to enable the measurement of pollutants which are difficult to measure on the road at present, such as particles smaller than 10nm. The RDE cycle used in the testing program was previously developed by Ricardo from PEMS data collected on Ricardo's Eastbound RDE drive[29] using a D-class vehicle. The RDE cycle is presented in figure 3.

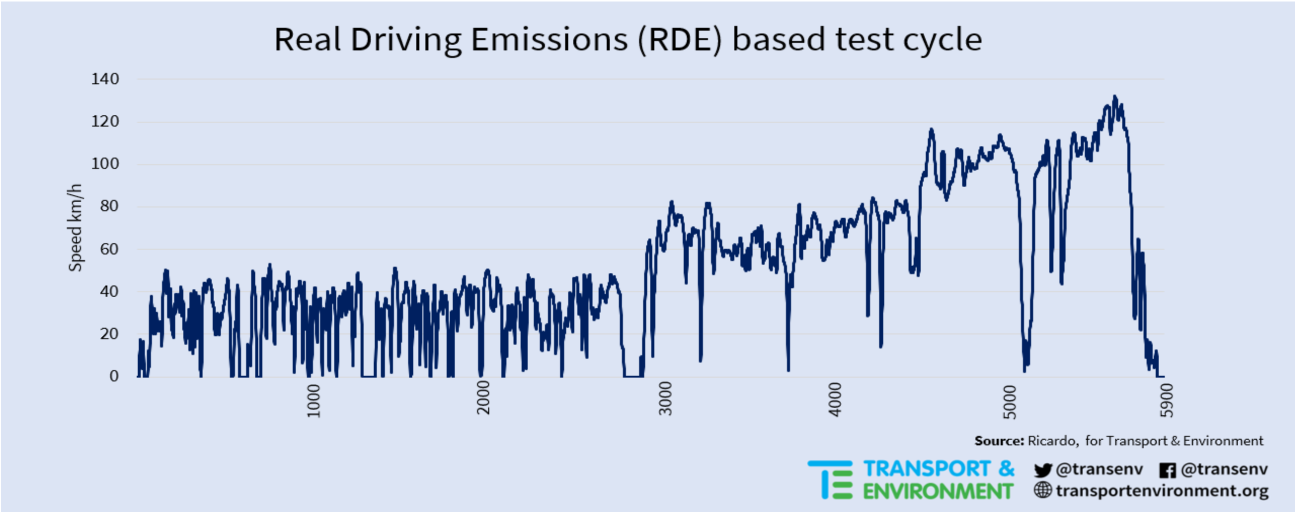

Figure 3. RDE- based test cycle used on the chassis dyno during this testing programme

Prior to start of testing, each vehicle's 12V battery was fully charged and each vehicle was subject to a WLTC pre-conditioning cycle. No further battery charging took place after the WLTP pre-conditioning in order to more closely reflect the typical driving conditions of these vehicles.[30] No auxiliaries (such as air-con, radio, etc.) were used during the testing programme due to the potentially large variability in engine demand and emissions due to auxiliary use.

Road load and vehicle test mass data was derived from each car's certificate of conformity (CoC) and is available in Annex 2. Comparison of the repeatability of the vehicle speed (from OBD) and facility gradient confirmed very good repeatability between tests for both vehicles. V*a_pos and RPA, the metrics used in the EU RDE regulation to assess upper and lower driving dynamics respectively, were also very similar and valid for all tests, an example of which is available in Annex 3.

This is also supported by the good repeatability of CO_2 between tests varying between 117-121 mg/km for the Qashqai and 122-125 mg/km for the Astra on non-regenerating tests, slightly lower than the type-approval WLTP CO_2 value. The v*a_pos and CO_2 results are indicative of a moderate test cycle. All data presented in this report is raw emission data from the test facility, emissions have not been processed through the EMROAD or CLEAR tool as T&E is of the belief that it is the actual pollution emitted from the tailpipe which matters for air quality[31]. This is also the approach taken by the European Commission's Joint Research Centre in their recent RDE testing programme[32].

[29] The data used for the development of the cycle was validated using RDE package 4

[30] Apart from the first RDE test on the Qashqai

[31] T&E, Letter to TCMV members, European Commission's proposal regarding the RDE 4th package & WLTP 2nd act, 27th of April 2018

[32] Ricardo Suarez-Bertoa, Victor Valverde, Michael Clairotte, Jelica Pavlovic, Barouch Giechaskiel, Vicente Franco, Zlatko Kregar, Covadonga Astorga, 'On-road emissions of passenger cars beyond the boundary conditions of the real-driving emissions test', Environmental Research, 2019

The RDE tests were ran in pairs of two beginning with a cold start RDE test after overnight soaking of the vehicles at 23°C followed by a hot RDE test later that day. The test programme is summarised in table 1. In order to make this report easier to follow, each test has been assigned a code with A/Q indicating whether the test was performed on the Opel/Vauxhall Astra or the Nissan Qashqai, c/h indicates whether the test was a cold or hot start, R denotes the presence of a full regeneration and "R" denotes the presence of a potential partial regeneration[33].

Car	Test number	Cold/hot start	Regeneration	Test code
Nissan Qashqai	Q1	Cold	Yes	Q1cR
Nissan Qashqai	Q2	Hot		Q2h
Nissan Qashqai	Q3	Cold		Q3c
Nissan Qashqai	Q4	Hot		Q4h
Nissan Qashqai	Q5	Cold		Q5c
Nissan Qashqai	Q6	Hot	Yes	Q6hR
Opel/Vauxhall Astra	A1	Cold	Yes partial	A1cR
Opel/Vauxhall Astra	A2	Hot		A2h"R"
Opel/Vauxhall Astra	A3	Cold		A3c
Opel/Vauxhall Astra	A4	Hot		A4h
Opel/Vauxhall Astra	A5	Cold		A5c
Opel/Vauxhall Astra	A6	Hot	Yes	A6h

Source: Transport & Environment

TRANSPORT & ENVIRONMENT @transenv @transenv transportenvironment.org

Table 1. Summary of car testing schedule

[33] The different types of regeneration are explained further in chapter 3a.

3. Understanding and identifying the regeneration of diesel particulate filters (DPFs)

As described in chapter I, diesel cars have to go through periodic DPF regeneration events in order to prevent the exhaust from clogging up with soot which accumulates on the filter over time. An active regeneration itself involves an increase in the temperature of the DPF to a minimum of 550°C; the temperature threshold at which soot begins to burn in excess oxygen. This is usually achieved by excess fuel, not burnt in the engine, oxidising on the DOC and creating an exotherm which increases the temperature of the exhaust gas. Once the DPF reaches 550⁰C, soot (and any adsorbed HC) accumulated in the DPF react with excess oxygen present in the diesel exhaust to produce CO_2 and H_2O. However, several research papers suggest that the DPF regeneration also results in an increase in the emissions of other pollutants and especially of particles. In order to assess the effect of DPF regeneration on pollutant emissions, it is first necessary to identify when regeneration events occur and for how long they last.

3.1 Identification of regeneration

Firstly, in order to study the impact of regeneration on emissions, it is necessary to identify the regeneration event itself. The DPF regeneration event was identifiable through the use of instantaneous emissions of THCs and PN which increased markedly during regeneration. Furthermore, the availability of on-board diagnostic (OBD) channels via the DiagRAD tool on the Qashqai, allowed the identification of regeneration through exhaust gas temperatures (EGT) and the OBD binary regeneration indicator. Due to the lack of relevant OBD channels on the Astra, a surface thermocouple mounted on the exhaust aided with the identification of the regeneration.

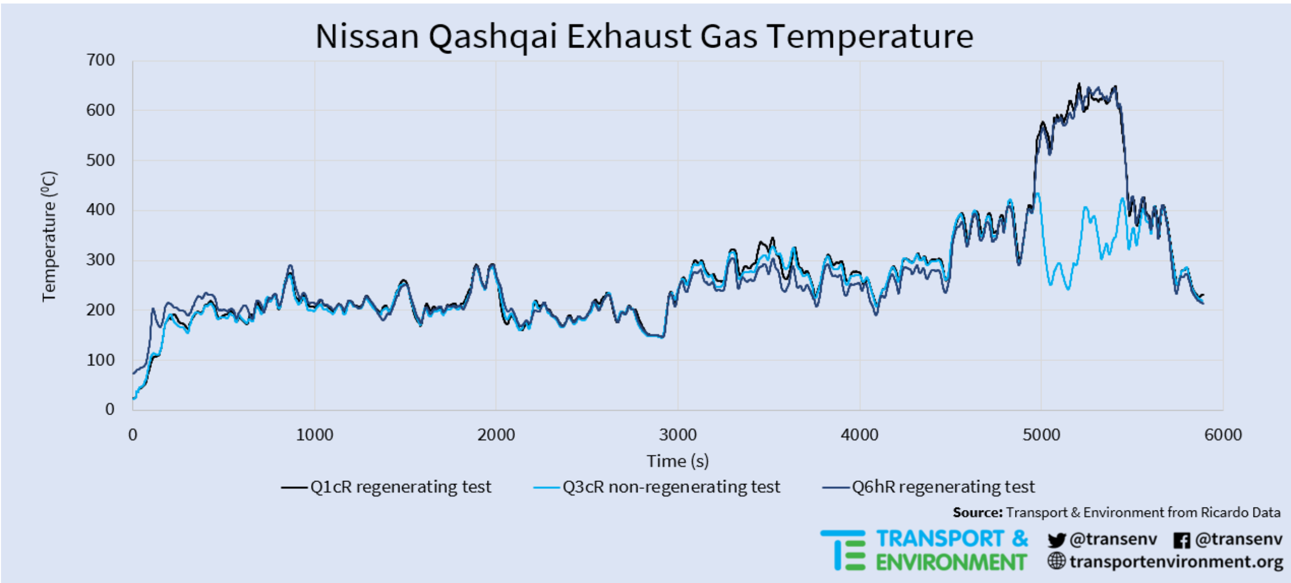

Figure 4. Example of Data used to confirm the presence of a regeneration event, in this case using OBD exhaust gas temperature data from the Nissan Qashqai which indicates a substantial increase in exhaust gas temperature during the first and 6th test.

For the Qashqai, a substantial increase in the OBD exhaust gas temperatures (EGT) after 4,960s during the motorway phase of the 1st and 6th test, compared to test Q3c (non-regenerating test) indicates the start of regeneration. The EGT increased substantially during regeneration with maximum recorded temperatures reaching 723°C (Q1cR) and 713°C (Q6hR). The binary regeneration indicator on the Qashqai triggered slightly earlier and at almost the exact same point on both cycles, 4,954s (Q1cR) and 4,951s (Q6hR) suggesting that this indicates the switch in engine calibration strategy associated with regeneration.

A substantial increase in instantaneous HC emissions from both cars indicates the start and end of post-injection[34] due to DPF regeneration. Late fuel post-injection is the common engine operating strategy used for an active DPF regeneration, usually accompanied by some exhaust throttling. For the Astra, a significant increase in the production of HC emissions during the motorway phase of A1hR and A6hR confirms the presence of a regeneration event during these tests. The subsequent rise in EGT, measured by the thermocouple on test A1cR and the subsequent rise in PN emissions are additional indicators of a regeneration taking place (graphs available in Annex 4). Unfortunately, due to a technical issue, the EGT was not recorded by the thermocouple during test A6hR but the concurrent increase in HC and PN emissions, which mirrors the increase observed during the first regeneration, confirms the presence of a DPF regeneration during this test.

The first Astra regeneration (A1cR) did not complete by the end of the test, resulting in an incomplete regeneration. This was confirmed by HC data showing the start of post-injection (5,594s) starting significantly later in this test compared to A6hR (5,538s) and EGT[35] remaining elevated by approximately 150°C at test end compared to non-regenerating tests. The subsequent hot RDE test (A2h'R') began after 77 minutes. The exhaust temperature during the first ~1,000s of this test remained elevated compared to a hot non-regenerating RDE test (A4h). This was coupled with significantly higher THC emissions in the first 250s, which suggest significant enrichment or post-injection. The difference in temperature between the two tests did not exceed 50°C, and did not come close to the temperatures recorded during the active regeneration in the previous cycle. However, much higher NO_2 emissions, which started 350s after test starts, as well as very high PN emissions during the first 1,000s compared to test A4h (graphs available in Annex 5), suggest that the car may have created an opportunity for passive NO_2 mediated regeneration in order to get rid of the remaining soot in the filter after the first incomplete regeneration.

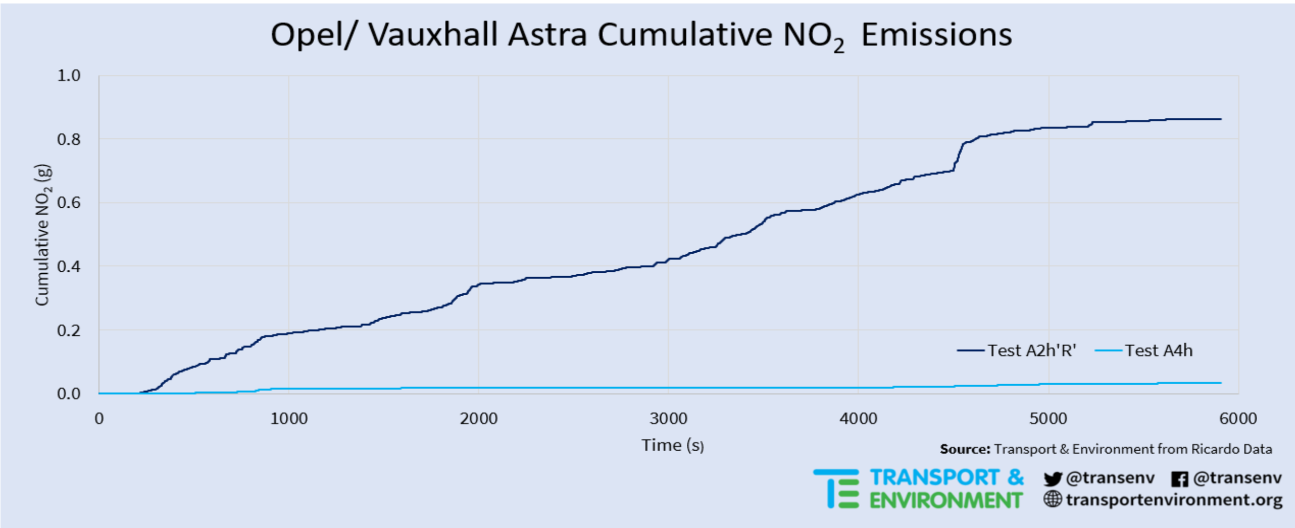

Figure 5. Cumulative NO_2 emissions, measured by Quantum Cascade Laser (QCL), from the Opel/Vauxhall Astra during test A2h"R" and A4h, showing a significant increase in the production of NO_2 during the second Astra test.

A passive regeneration is different to an active regeneration as the passive regeneration relies on the production of high levels of NO_2 by the engine for use in the oxidation of soot. NO_2 is able to oxide soot at a lower temperature of between 250°C and 400°C[36] compared to 550°C needed for soot oxidation by oxygen. However, if this is the case, the high levels of NO_2 produced in order for the passive regeneration to occur

[34] Post injection is the process of injecting fuel into the cylinder after the combustion event. This means that unburnt fuel is released from the engine directly onto the DOC. Here the fuel is oxidised rapidly resulting in a large exotherm, which increases the exhaust temperature.
[35] Measured by the exhaust surface mounted thermocouple
[36] J.-O. Müller, B. Frank, R. E. Jentoft, R.Schlögl, D. S. Su, 'The oxidation of soot particles in the presence of NO_2' Catalysis Today, 2012

were not all used for soot oxidation resulting in large amounts of the toxic gas slipping out of the tailpipe. During the entire test almost 0.9g of NO_2 was emitted from the tailpipe compared to 0.03g during A4h. The high NO_2 emissions continued until ~5,220 seconds into the test which can be seen in figure 5. Emissions of PN reduced after the first 1,000s but remained significantly elevated compared to A4h until the motorway phase. This is likely due to the loss of filtration efficiency of the DPF associated with the loss of the 'soot cake'[37]. CO emissions were lower than during A4h and did not appear to increase, as was the case for both the partial and full regeneration on the Astra, this could be due to efficient oxidation of CO by NO_2[38]. The continuation of high NO_2 production for most of this cycle potentially suggests an extended period of modified engine operation to enhance passive regeneration.

In summary, for both vehicles, every active regeneration took place in the motorway section of the test. The Qashqai underwent two complete regenerations during the 1st and 6th test. The Astra underwent one incomplete regeneration during the 1st test and a complete regeneration during the 6th test. A potential passive regeneration may have taken place during the second RDE test (A2h'R') on the Astra.

3.2 Duration of the regeneration event

A significant amount of time was necessary for the full DPF regeneration to take place. The amount of time that each regeneration took to complete depended on the vehicle, as well as the method used to determine the length of regeneration. Instantaneous THC emissions were used for this purpose as these were easily comparable between the two vehicles. Using THC emissions was considered a better approach than using CO and PN as elevated THC emissions indicate the process of regeneration via post-injection, whereas the associated increase in CO and PN emissions are the effects of the regeneration event.

The time taken for the Astra to fully regenerate on test A6h'R', as determined through analysis of instantaneous THC emissions, was around 7 minutes and was quicker than the DPF regeneration event on the Qashqai which took 8-9 minutes to complete. During the regeneration event up 12 km were driven on the Astra and up to 15 km on the Qashqai.

3.3 Distance between consecutive regenerations

The distance between consecutive regenerations, from the start of the first active regeneration to the start of the second consecutive active regeneration, was also determined through the analysis of instantaneous THC emissions for both vehicles. For the Qashqai, the distance between consecutive regenerations was 423km and for the Astra the distance was virtually the same at 419 km.

[37] The 'soot cake' is a layer of soot deposited on the filter walls which increases the filtration efficiency of the DPF. When this is removed the filtration efficiency of the filter decreases and much more PN is emitted by the vehicle.

[38] David C. Carslaw, Naomi J. Farren, Adam R. Vaughan, William S. Drysdale, Stuart Young, James D. Lee, 'The diminishing importance of nitrogen dioxide emissions from road vehicle exhaust', Atmospheric Environment: X, 2019

4. Test Results: DPF regenerations increase emissions of regulated pollutants

4.1 Legal limits for regulated pollutants and PM are respected but emissions still increase during regeneration

While the main focus of this report is on the emissions of particles, particularly currently unregulated particles from DPF regeneration; it is important to also look at the effect of regeneration on the emissions of other currently regulated pollutants[39]. T&E's tests show that finally, 12 years after the Euro 6 emission limits were defined[40], both cars respected the emission limits for gaseous pollutants and particulate matter during one type of RDE based laboratory tests.

NOx emissions stay under legal limits but increase significantly during regeneration

The nitrogen oxides (NOx) limit of 80mg/km for Euro 6 diesel passenger cars was respected for both cars on all tests including tests during which a regeneration took place. Whole test emissions did not exceed 41 mg/km for the Qashqai and 33 mg/km for the Astra. However, there was still a significant increase in emissions due to regeneration during motorway driving up to approximately 75% of the NOx emission limit[41]. For the Qashqai motorway emissions increased from 20-28 mg/km on non-regenerating tests up to 52-58 mg/km on regenerating tests. Astra motorway emissions were of the same magnitude of 59 mg/km during test A6hR, this is surprising given that the Astra's emissions performance was better than the Qashqai's during motorway driving on non-regenerating tests with emissions not exceeding 8 mg/km. While NOx emission stayed below legal limits on regenerating tests for the two cars tested, it is possible that more demanding driving conditions during regeneration may result in higher NOx emissions or that NOx emission limits may not be met by other diesel cars on tests that include DPF regeneration.

Carbon monoxide and hydrocarbon emissions both increase during regeneration but stay below legal limits

The current diesel emission limit for carbon Monoxide is 500 mg/km. This was respected by both cars on all tests, staying below 17 mg/km for the Qashqai and 67 mg/km on the Astra on all tests. The total hydrocarbon (THC) and NOx (HC+NOx) limit for diesel passenger cars is 170 mg/km. This was also respected by both vehicles, staying below 50 mg/km, on all tests. Specifically, on regenerating tests, the emissions of both hydrocarbon and carbon monoxide increased during the motorway phase of the test compared to non-regenerating tests but still respected the legal limits.

Particulate Matter emissions saw a large increase during regeneration

Regeneration events lead to a large increase in Particulate Matter (PM) emissions of both vehicles[42] however the PM emission limit of 4.5 mg/km was not exceeded. On non-regenerating tests PM emissions for the Qashqai vehicle stayed below 0.07 mg/km. However, regeneration lead to a significant increase in PM production up to 1.63 mg/km (Q1cR) and 1.19 mg/km (Q6hR). While this is still below the legal limit of 4.5mg/km, it represents an increase in PM emissions of 30 fold for a cold start RDE and 17 times for a warm start RDE test. The PM emissions of the Qashqai, during the motorway phase reach 3.61 mg/km (A1cR) and 2.65 mg/km (A6hR). The increase in PM emissions was smaller for the Astra, reaching 1.09 mg/km over the whole test (A6hr), compared to less than 0.15 mg/km on all other tests, with 2.65 mg/km emitted during motorway driving.

[39] The emissions results presented in this section are from the analysis of bagged dilute emissions, apart from PM.

[40] European Commission Regulation (EC) No 715/2007

[41] No specific emission limit applies to the motorway phase of the RDE test as is the case for urban phase emissions. For motorway emission only the test average emission limit applies

[42] As measured by the regulatory gravimetric filter method.

A chemical analysis was conducted on filters from the motorway of regenerating and non-regenerating tests as well as on a blank filter[43] for each vehicle. Filters from non-regenerating tests were indistinguishable from blank filters due to the small amount of PM captured on the filter.[44] PM emissions from the Qashqai were higher than from the Astra largely due to much higher emissions of soluble sulphates. This could be either due to higher Platinum Group Metals (PGM) loading in the aftertreatment of the Qashqai, allowing for greater storage of sulphates and subsequent release during the high exhaust temperatures present during regeneration, or due to the use of a higher sulphated ash, phosphorus and sulphur (SAPS) oil compared to the Astra. Black carbon emissions, of around 0.5 mg/km during regeneration were similar from both vehicles.

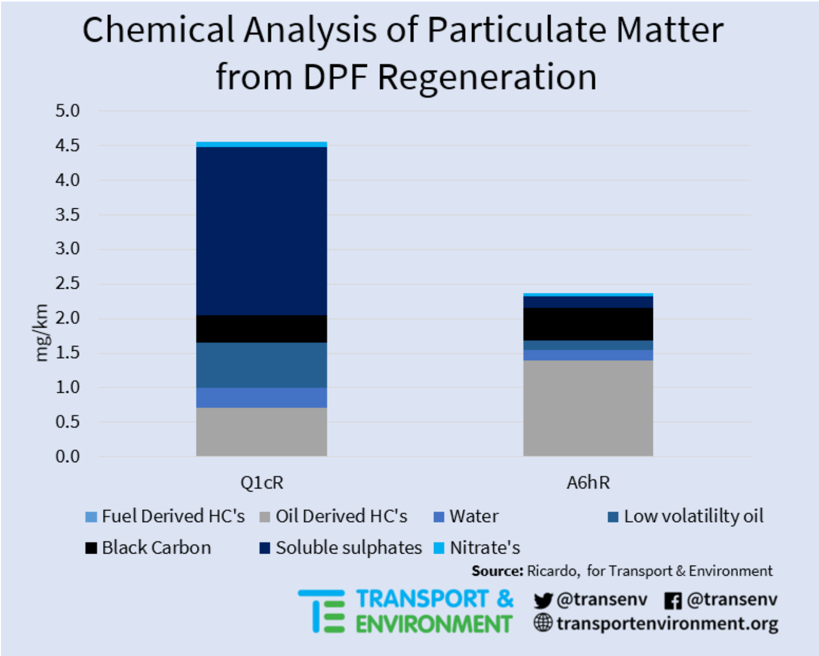

Figure 6. Results of the chemical analysis of PM from regeneration, showing markedly higher levels of soluble sulphate emissions from the Qashqai than the Astra during regeneration

4.2 The limit for particle number emissions is exceeded during DPF regeneration but this is ignored by regulation

The following section discusses the emissions of currently regulated larger than 23nm solid particles.

Particle number emission limit exceeded by between 32 % and 115 % due to DPF regeneration

As can be expected from the large increase in PM emissions due to DPF regeneration, particle number (PN) emissions also increased by a large amount on all tests during which an active DPF regeneration took place. However, unlike for PM, the particle number (PN) emissions limit of $6x10^{11}$/km[45] was exceeded by between 32-115 % on all tests during which a full, active regeneration took place. Unfortunately, this is allowed by the current emissions regulation[46] which allows emission limits to be exceeded on both WLTP and RDE tests, if a DPF regeneration occurs during the test[47].

[43] The blank filter contained high levels of oil-derived HC's, which could lead to these results to be overstated.
[44] Typical filter masses were <20µg
[45] No conformity factor (CF) of 0.5 is used for PN emissions as the CF exists only to account for the potential increased measurement error of the PEMS equipment compared to laboratory based PN measurement equipment. As emissions were measured using laboratory equipment no CF should be applied.
[46] European Commission, Regulation (EU) 2017/1151
[47] Unless a regeneration occurs on two consecutive tests, in this case emission limits apply to the second test

The largest amount of PN was emitted by the Astra on test A6hR, during which a full active regeneration took place, with emissions of 1.3 $x10^{12}$/km. This is more than double the current particle number emissions limit. PN emissions from the Qashqai on regenerating tests were slightly lower at 7.9 $x10^{11}$ /km (Q1cR) and 8.5 $x10^{11}$ /km (Q6hR) but this still resulted in an exceedance of the PN limit by 32 and 41%.The emission limit was not exceeded during test A1cR, however the DPF regeneration did not complete during this test, most likely resulting in lower PN emissions compared to A6hR. On tests during which regeneration did not occur PN emissions stayed within the legal limit and did not exceed $1.06x10^{11}$/km for the Qashqai and $2.98x10^{10}$/km for the Astra, indicating that for these two vehicles DPF regeneration is responsible for the exceedance of the PN emissions limit on tests during which a full active regeneration takes place.

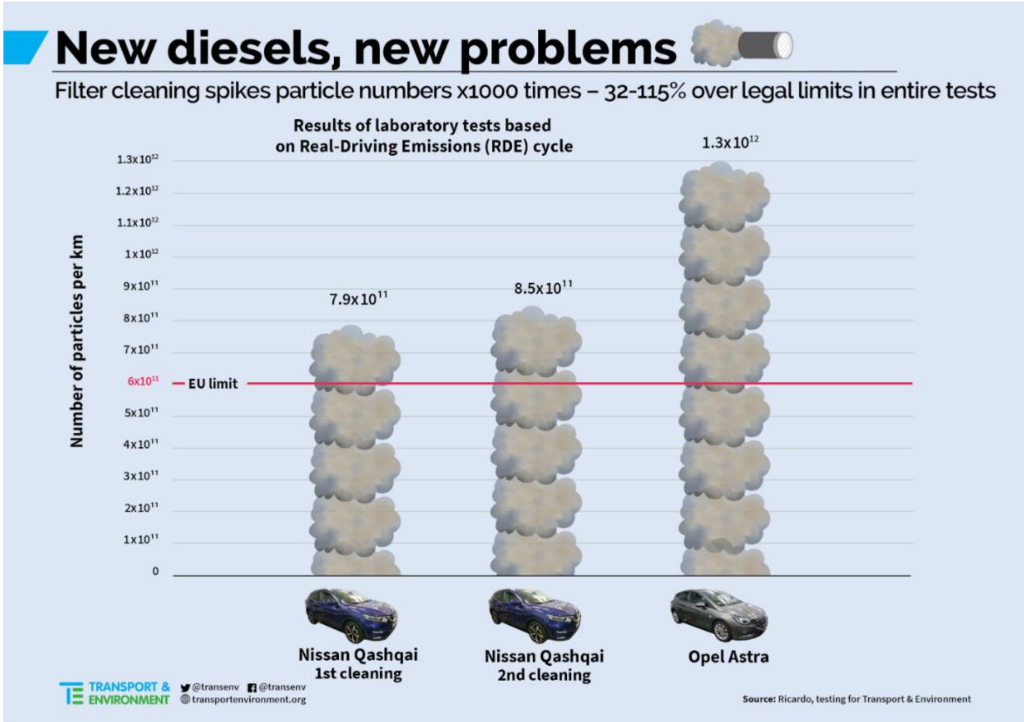

Figure 7. Number of particles emitted (solid, >23 nm) per km on test cycles with a full, active regeneration

DPF Regeneration causes a large spike in particle number pollution

It should be noted that emissions limits were exceeded over the entire test which is 85 km long, however the active DPF regenerations were confined to the motorway phase of the test (37 km). This resulted in a large spike in motorway phase PN emissions, compared to the full test, of $1.9x10^{12}$/km (Q1cR), $2.1x10^{12}$/km (Q6hR) for Qashqai and $3.5x10^{12}$ /km (A6hR) for the Astra, exceeding the particle emission limit by between 3-5 times.[48] Motorway emission during test A1cR, during which a partial regeneration took place, were smaller than during the other full regeneration on the Astra but the PN emission limit was still exceeded by 13% with emissions of $6.8x10^{11}$/km. While the PN emission limit in this case was not exceeded over the whole test, this result is significant as it indicates that even a partial regeneration can result in a large spike PN emissions.

However, while a large number of particles are emitted during the motorway phase of regenerating tests, the spike in particle pollution, specifically during the DPF regeneration event itself, is still underestimated by the motorway phase emissions. This is because no DPF regeneration took longer than 15km to complete

[48] There is currently no legally binding particle emission limit during the motorway phase of the RDE as is the case for the urban phase or the whole cycle. However, in order to limit cars' impact on air quality emissions standards should be met during all parts of the RDE cycle.

while the distance of the motorway phase of the test was 37km. The PN missions during the DPF regeneration itself are discussed in Chapter 7.1.

The tested cars emitted up to 1848 times more particles during regeneration compared to non-regenerating tests

Nonetheless, focusing only on the absolute number of particles emitted in comparison to the legal limit does not tell the full story of the impact of regeneration on the emission of particles. This is because both vehicles emit significantly less PN than the legal limit on non-generating tests. The Qashqai emitted on average 6.0×10^9/km during cold start tests and 5.6×10^{10}/km on hot start tests, average cold start PN emissions from the Astra were slightly higher at 1.6×10^{10}/km and hot start PN emissions lower at 1.5×10^9/km[49]. This means that the actual increase in the emission of particles between regenerating and non-regenerating tests is much larger than the exceedance of the particle emission limit.

The Qashqai vehicle actually emitted 1848 times more particles during the motorway phase of the first test and 1536 times more during the motorway phase of the 6th test, compared to non-regenerating tests. This large increase in the number of particles emitted during the motorway phase resulted in emissions during the whole RDE test increasing by 133 and 15 times respectively. The increasing in the PN emissions of the Astra during test A6hR was of the same magnitude, resulting in an increase during the full regeneration (A6hR) of 1154 times during the motorway phase and 851 times over the entire test.

The results presented above indicate that the regeneration event results in a large spike in the number of currently regulated particles emitted from these two vehicles. The increase in the production of particles during the regeneration event, which lasted up to 15km during this testing programme, is so large that when averaged over the entire 85km of the test it still results in an exceedance of the particle emission limit for all tests during which a full regeneration occurred.

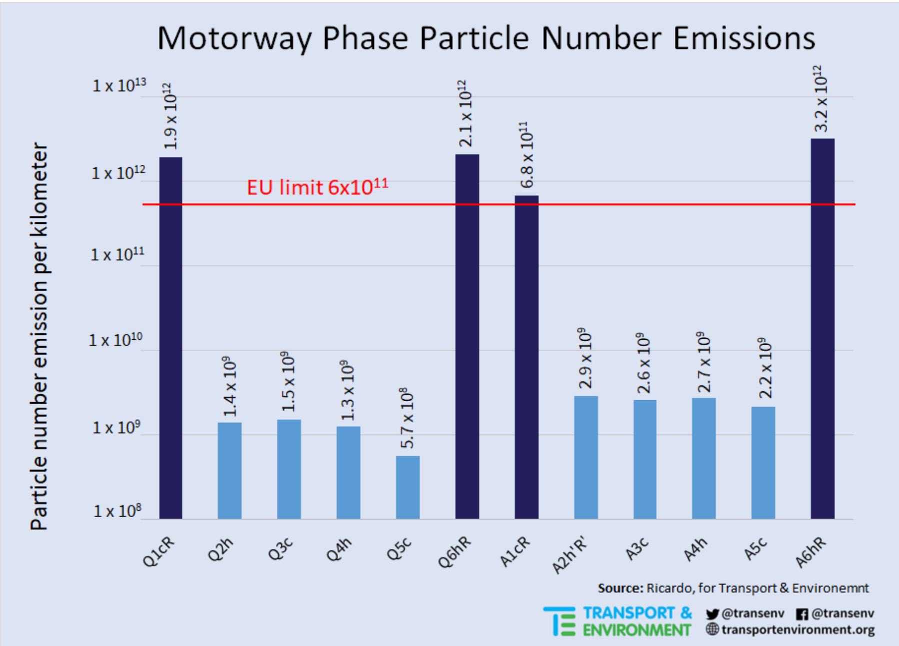

Figure 8. Qashqai and Astra, larger than 23nm particle number motorway phase emissions, showing a very large increase in emissions due to DPF regeneration

[49] A2h'R' was not used to calculate average hot emissions due to the potential regeneration taking place at the start of the test

4.3 The impact of DPF regenerations lasts much longer than just the regeneration event, spilling over into urban driving

After the completion of the regeneration event, the particle emissions did not immediately decrease to the same levels as measured prior to regeneration. PN emissions continued to be significantly higher during the urban phase of the subsequent test following a regeneration event, indicating that the impact of regeneration on emissions last longer than just the regeneration event itself. After the first regeneration on the Qashqai, PN emissions during the following RDE test (Q2h) continued to be impacted by the effects of regeneration for the first 30 minutes of the test. This resulted in large emissions of PN during the first 10 km of urban driving[50],During this time, PN emissions averaged 8.6 $x10^{11}$ / km, an increase of 42 times compared to the average hot emissions measured on non-regenerating tests[51].

The large increase in Qashqai PN emissions following the regeneration is most likely due to the burn off of the ‘soot cake’ during the regeneration event. The ‘soot cake’ is a layer of soot stored on the DPF which helps trap particles and increases the filtration performance of the filter. The loss of the ‘soot cake’, in this case, results in emissions above the limit of 6 $x10^{11}$ /km during the first half of the urban drive. Post regeneration, the filtration performance of the filter recovers as soot is deposited onto the filter. In the case of the Qashqai, filtration efficiency largely recovered during the second half of the urban phase, resulting in total urban emissions being compliant with the legal limit. A similar increase in PN emissions occurred following the incomplete regeneration on the Astra during A1cR, however for this car the emissions stayed below the PN limit. From the vehicle and emissions data available, it is not absolutely clear if the increase in PN emissions during the first 1,000s of the following RDE cycle (A2h’R’) is due to a passive regeneration occurring or due to the loss of filtration efficiency of the DPF, or both.

The increase in particle number emissions following a regeneration event clearly indicates that the impact of regeneration on particle number emissions is not just confined to the regeneration event itself. Particle emissions continue to be elevated even after the regeneration event has finished, until the soot cake is rebuilt inside the filter and the DPF filtration efficiency recovers.

[50] Equal to the first half of the urban phase or the emissions from the first regulatory bag
[51] Compared to the average emissions of the urban phase of Q4h and Q6h

5. Test Results: DPF regenerations also increase emissions of harmful but currently unregulated pollutants

The tests results presented in the last chapter only covered the emissions of currently regulated pollutants. However, many other harmful pollutants are also emitted out of the tailpipe of diesel cars.

5.1 Sub-23nm particles: large amounts of small, dangerous and unregulated particles are emitted on all tests

The PN emissions results discussed previously only include particles which are currently regulated. At present, this is only solid particles which are larger than 23nm in diameter. However, particles as small as 2.5nm in diameter are emitted out of the tailpipe of vehicles with an internal combustion engine. The DownToTen (DTT) EU-funded project specialising in the measurement of particles smaller than 23nm (which includes Ricardo) have demonstrated that the measurement of particles down to 10nm can increase the total amount of particles emitted from diesel vehicles by a large amount. On a diesel vehicle equipped with a DPF, this increase has been shown to be up to threefold. The same group has also demonstrated that particles smaller than 10nm are also emitted from diesel vehicles albeit in smaller amounts than particles in the 10-23nm size range[52]. It is for these reasons, coupled with the negative health effects of small particles, that T&E decided to investigate the impact of regeneration on the emission of solid particles as small as 4nm during this testing programme. The DownToTen system was used to measure instantaneous emissions of particles with size intervals of >4nm, >10nm and >23nm, the data obtained is discussed in the following sections.

Large numbers of 10-23nm particles are emitted on all tests

Large numbers of particles of between 10-23nm in size were emitted from both vehicles during all tests. This resulted in total particle number emissions increasing by between 11-184 %, over the whole test, compared to when only regulatory particles were measured. The number of 10-23nm particles emitted varied significantly between the Astra and Qashqai vehicles, as well as between different tests. Hereinafter, particles in the 10-23 nm size range will be referred to as $PN_{10\text{-}23}$.

The largest number of 10-23nm particles are emitted on regenerating test

For the Qashqai, the regeneration event lead to a large increase in the emission of $PN_{10\text{-}23}$, with emissions 174 higher during test Q1cR and 52 times higher during Q6hR, compared to non-regenerating tests[53]. The emissions of these very small particles were so large that total test emissions of $PN_{10\text{-}23}$ alone came very close to the PN emission limit, averaging 4.7×10^{11}/km during Q1cR and 5.3×10^{11}/km during Q6hR. This means that emissions of $PN_{10\text{-}23}$ alone accounted for 78% (Q1cR) and 88% (Q6hR) of the emission limit. Emissions from the Astra were lower during regenerating tests, however a large amount of these particles were still emitted. $PN_{10\text{-}23}$ emissions during the full regeneration (A6hR) were just over 50% of the PN emission limit at 3.1×10^{11}/km, increasing 136 times compared to emissions during A4h.This data shows that the largest number of currently unregulated 10-23nm particles are emitted during DPF regeneration events and that the number of 10-23nm particles emitted on these tests alone contributes between 50-88 % of the PN limit. DPF regenerations substantially increase the emissions of small particles and not just of currently regulated particles larger than 23nm.

[52] Ricardo, Jon Andersson, 'Update on sub-23nm exhaust particle number emissions using the DownToTen sampling and measurement systems, 23rd ETH-conference on Combustion Generated Nanoparticles, 2019, Zurich, Switzerland.

[53] Cold non-regenerating emissions are the average of Q3c and Q5c, hot non-regenerating emissions are the average of Q2h and Q4H.

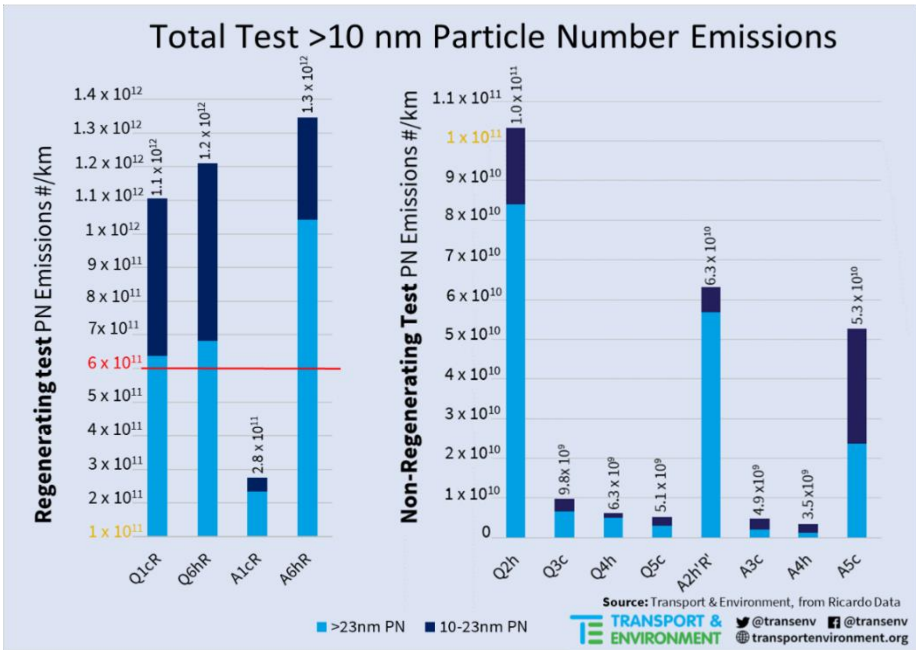

Figure 9. Particle number emissions of regulated (>23nm) particles and non-regulated (10-23nm) particles. Particularly large amounts of unregulated particles are emitted on regenerating tests.

The number of 10-23nm particles emitted on regenerating tests exceeds the emissions of regulated particles on non-regenerating tests

For both vehicles, the number of 10-23nm solid particles emitted on regenerating tests ($3.05x10^{11}$ - $5.28x10^{11}$/km) were significantly higher than the emission of regulatory 23nm particles on non-regenerating tests ($1.6x10^{9}$ - $1.1x10^{11}$/km). This clearly shows that the magnitude of emission of these very small 10-23nm particles, due to DPF regeneration, from both vehicles is so large that it surpasses the emission of regulated PN on non-regenerating tests.

Inclusion of 10-23 nm particles more than doubles total PN emissions on some tests

While per km emissions of PN_{10-23} were highest on regenerating tests, emissions of PN_{10} made a significant contribution to the total number of larger than 10nm particles emitted on all tests. In fact, emissions of PN_{10-23} were larger than emissions of >23nm PN on three Astra non-regenerating tests, contributing 58% (A3c), 65% (A4h) and 55% (A5h) to >10nm PN emissions. On-non-regenerating tests the contribution of PN_{10-23} to >10nm PN emissions varied between 19-44% for the Qashqai and between 10-65% for the Astra.

Thereby, inclusion of PN_{10-23} emissions resulted in a large increase in the total amount of particles measured compared to when only regulated particles larger than 23nm were measured. For the Qashqai, on average, PN emissions on non-regenerating tests increased by 42% and on regenerating tests by between 73 and 77%. This resulted in emissions of larger than 10nm PN over the whole test of $1.11x10^{12}$/km (A1cR) and $1.21x10^{12}$/km (A6hR) exceeding the PN limit of $6x10^{11}$/km by 84% and 102%.

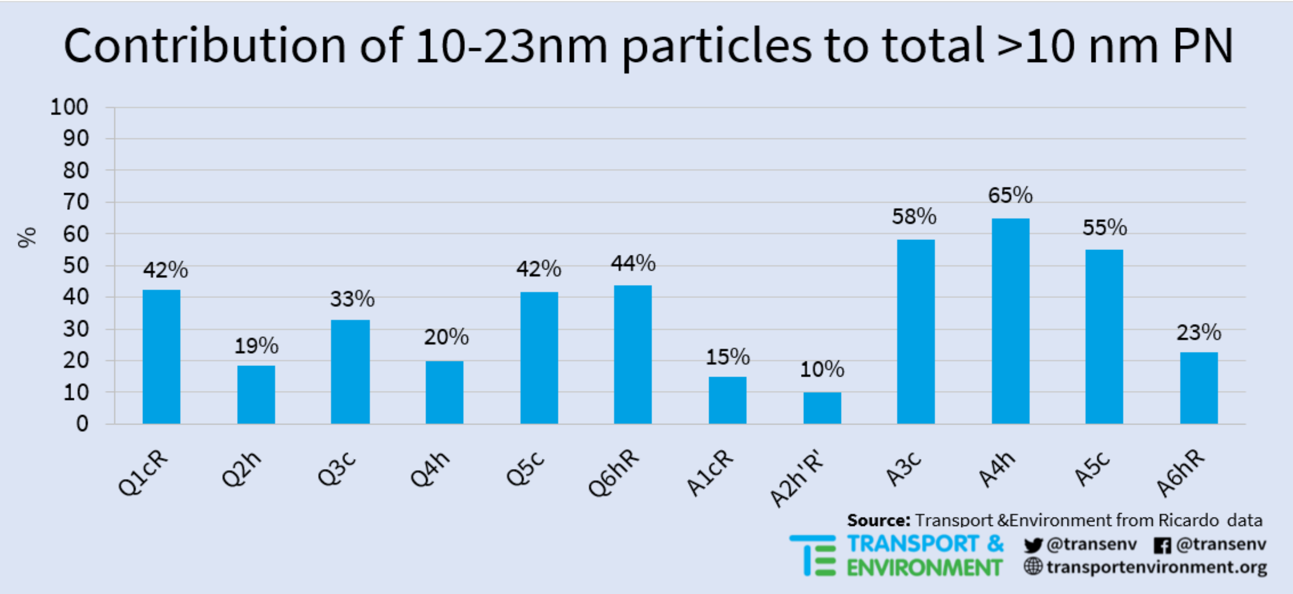

Figure 10. Contribution of 10-23nm particles to total larger than 10nm emissions. 10-23nm constitute a large percentage of total solid particle emissions on all tests in some cases exceeding the emissions of regulated particles.

The increase in PN emissions, due to the inclusion of PN_{10-23}, was smaller for the Astra on regenerating tests increasing by 18 % on test A1cR and by 29 % on test A6hR. This resulted in measured emissions of >10nm PN during A6hR of 1.35 $x10^{12}$, exceeding the PN emission limit by 124%. Emissions during A1cR were lower at 2.75 $x10^{11}$ /km, most likely due to the regeneration no finishing before the end of the test. The inclusion of PN_{10-23} in total PN emissions generally resulted in a larger increase in total PN emissions on the Astra non-regenerating tests, increasing by between 11-184%. However, none of the non-regenerating tests exceeded the PN emission limit when PN_{10-23} emissions were included, this was also the case for the Qashqai.

The large contribution of 10-23nm particles to total PN emissions on all tests indicates that the current regulatory measurement of particles only as small as 23nm underestimates a large number of solid particles emitted from these vehicles. No sampling losses were accounted for these particles during this testing programme, due to a lack of standardized methodology. However, the number of 10-23nm particles measured would likely be increased further if sampling losses, of particles within this size range, were accounted for in future regulation. The differences in particle emissions between the Qashqai and the Astra, both in terms of size and during different operating conditions, suggests that there is a large difference in the size distribution of particles emitted from diesel cars depending on the engine and aftertreatment technology employed, even between diesel vehicles of the same emission standard. This suggests that there is likely to be large variability within the diesel car market.

Particles of between 4 to 10nm in size are also emitted during regeneration

Particles of between 4 and 10nm (PN_{4-10}) in size were likely to be emitted on all tests during which a full regeneration took place. The increase in measured particles, over the whole test, between the 4 and 10 nm PN analysers was 9% (Q1cR), 11% (Q6hR), 16% (A6hR), with an increase in particle measurement between the 4nm and 10nm particle counters only detectable during the motorway phase of regenerating tests. On non-regenerating tests, emissions of PN_{4-10} were below the detectable threshold. This does not necessarily mean that no particles of between 4 and 10 nm in size were emitted on these tests but due to the very small size of these particles, the sampling losses within this size range may be as high as 90%. However, the collection efficiency of DPFs under non-regenerating conditions is higher for PN_{4-10} than for >10nm particles, and therefore low particle emissions might be expected. Furthermore, the difference in PN emission between the 4nm and 10nm PN analysers may be over or underestimated by up to 10%, due to analyser variability. No correction was applied to sub-23nm PN data to account for losses, due to a lack of standardised methodology. The Particle Measurement Programme (PMP) working group is currently finalizing the approach for corrections at 10nm, but not considering a lower size threshold.

Despite the uncertainty regarding the absolute number of 4-10nm particles measured, the data suggests that for these two vehicles DPF regeneration is likely the most significant source of 4-10nm particles. Furthermore, what is clear is that in order to fully capture all of the particles emitted by the vehicle, particularly within the 4-10nm size range, a robust standardized methodology must be developed to account for sampling losses, dilution factors and to ensure traceable absolute particle number calibrations for all particle counters. This is particularly important, given that the DTT particle measurement equipment is likely to be used for regulatory sub-23 nm particle measurement in the future.

5.2 Volatile & Semi-volatile particles: when measured, the total particle count increase by between 1-77 times

Emissions of volatile and semi-volatile particles are not currently regulated as part of the vehicle emission standards. During this testing programme, total emissions of volatile, semi-volatile and solid particles of between 5 and 1,000nm in size were measured using the DMS500. The size distribution of the particles measured is split into two discrete particle sizes the nucleation mode which includes particles of between 5-50 nm in size and includes volatile, semi-volatile and solid particles and the accumulation mode which includes solid particles of between 50-100 nm in size.

The particle emissions measured by the DMS, both within the nucleation and accumulation size modes, were highest on regenerating tests, due to a large increase in both nucleation (largely volatile) and accumulation (soot) mode particles. Particle emissions were much higher than those measured by the DTT >4nm, which has a catalytic stripper to remove volatile particles,, reaching 7.96×10^{13}/km (Q1cR), 1.04×10^{14}/km (Q6hR), 4.15×10^{12}/km (A1cR) and 4.02×10^{13}/km (A6hR) increasing the total amount of particles measured by between 15 and 77 times during these regenerating tests compared to the DTT >4nm measurement indicating that a large amount of volatile and semi-volatile particles is produced as the DTT equipment does not measure these particles. The increase in total particle emissions was much smaller on non-regenerating tests of between 1 and 5 times. The large difference between the number of particles measured by the DTT>4nm (which only measures the emission of solid particles) and DMS shows that a large amount of volatile and semi-volatile particles are emitted on all tests. The much larger increase in the total particles emitted during regenerating tests indicates that the regeneration event is responsible for a large increase in the production of condensable species compared to non-regenerating tests.

From the size distribution of total particles measured during each test, shown in figure 15, it is clear that emissions increase by a large amount for all particle sizes up to 200nm during the partial (A1cR) as well as the full (A6hR) regeneration on the Astra. This is particularly pronounced within the nucleation mode indicating that the largest increase in emissions occurs for volatiles particles. This is also the case for both regenerating tests on the Qashqai. The size distribution of particles emitted during Q1cR and Q6hR tests is almost identical for particles of up to 200nm in size suggesting that the size and number of particles produced during regeneration is highly repeatable between tests. The size distribution for particles of up to 200nm is also very similar between tests A1cR and A6hR on the Astra. However, the number of particles produced during A1cR test is markedly lower, most likely due to the regeneration not running to completion during this test. This is in contrast to significant differences in the size distribution between non-regenerating tests for both vehicles. The high repeatability of the particle size distribution on regenerating tests suggests that the particles emitted during regeneration originate from the engine and are not compacted particles stored on the DPF being re-released as compacted particles would be expected to have a less repeatable particle size distribution.

There is a large difference in the particle size distribution between regenerating and non-regenerating tests, with a particularly large increase in particles within the nucleation mode, particularly of between 5 and 25nm in size. The distribution of nucleation mode particles changes from a bimodal distribution with a mode around 5-6nm and 10-20nm for the Qashqai and 5-7nm and 10nm for the Astra during most tests to a unimodal distribution. Both the Qashqai and Astra nucleation modes from regenerating tests are skewed towards sub-10nm particles. This is more pronounced for the Astra vehicle, with the mode of the distribution at 8-9nm for the Qashqai and 7-8nm for the Astra. The mode of accumulation mode particles on regenerating tests occurs at 170nm for the Astra and 170-190nm for the Qashqai. However, the increase in accumulation mode particles due to regeneration is smaller than nucleation mode particles.

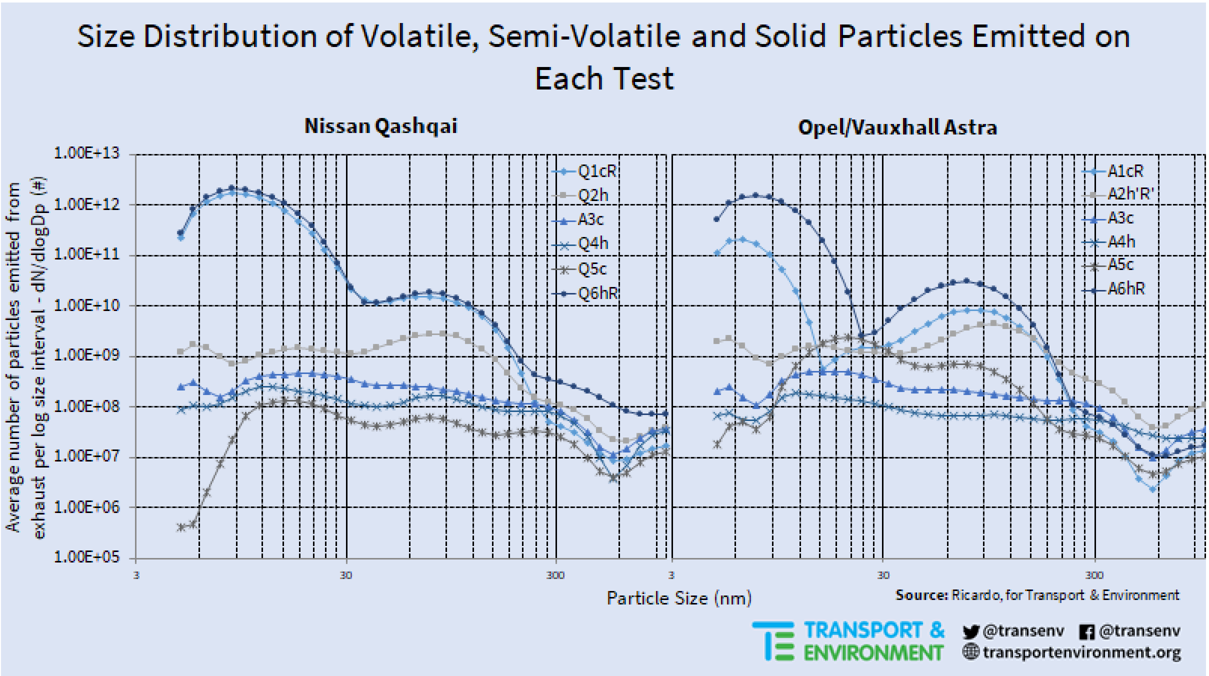

Figure 11. Particle size distribution of all the volatile, semi-volatile and solid particles emitted on each RDE test. There is a particularly large increase in emissions of nucleation mode particles <50 nm on regenerating tests.

The number of volatile particles measured is highly dependent on dilution and environmental conditions so will not necessarily be representative of real world volatile PN production. However, from these results it is clear that large amounts of condensable species, within the nucleation mode, are emitted during regeneration. As such future regulation should look for look to include the measurement and regulation of volatile and semi-volatile species.

5.3 Ammonia: one of the tested cars emits large amounts of ammonia, contributing to secondary particle pollution

Ammonia is a toxic pollutant which contributes to the formation of secondary particles and therefore contributes to $PM_{2.5}$[54]. Ammonia has been shown to be emitted from the tailpipe of diesel vehicles, usually due to overdosing of urea used for NOx control. Ammonia Slip Catalysts (ASC) can be used to reduce ammonia emissions, however the use of this technology on passenger cars in the EU is not widespread due to a lack of an ammonia emission limit for passenger cars in the EU. Due to this and evidence that some diesel vehicles emit large amounts of ammonia[55], T&E decided to include the measurement of ammonia emissions to this testing programme.

[54] JRC, R. Suarez-Bertoa, 'Current non-regulated emissions in EU', Integer Emissions Summit & AdBlue Conference, Munich, 2019
[55] Ricardo Energy and Environment, Rebecca Rose, 'Real world measurement of ammonia emissions from vehicles' presentation, Routes to Clean Air, 30th October 2018

Out of the two vehicles that T&E tested only the Qashqai was likely[56] to be fitted with an ASC. This combined with most likely a mature urea dosing strategy resulted in very low emissions of ammonia from the Qashqai. Emissions of ammonia from this vehicle remained below 1mg/km during all phases of all tests, including tests during which a regeneration took place. In contrast, the emissions of ammonia from the Astra were significantly higher on non-regenerating tests varying between 0.5- 6.4 mg/km, with some higher emissions of up to 14.5 mg/km during motorway driving.

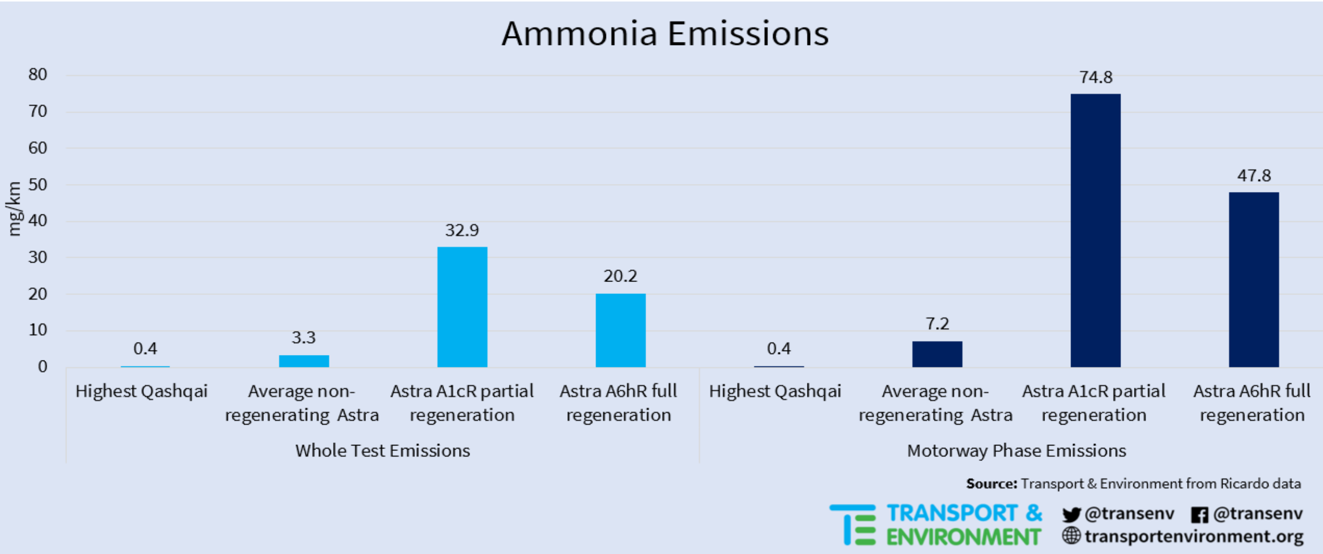

Figure 12. Whole test and motorway phase ammonia emissions. Large emissions of ammonia from the Astra during regeneration result in whole test emissions of up to 32.9 mg/km

The Astra's ammonia emissions increased by large amounts during both the partial (A1cR) and full regeneration (A6hR) with test emissions averaging 32.9 mg/km and 20.2 mg/km. The emissions of ammonia measured during A1cR were over 90 times higher than the highest test result of the Qashqai (0.35 mg/km), showing the much poorer ammonia emissions performance of the Astra. As expected, the main contribution to these very high ammonia emissions was the motorway phase of the test; 74.9mg/km during A1cR and 47.8 mg/km on the full regeneration (A6hR).

The much higher ammonia emissions during normal driving of the Astra compared to the Qashqai suggest much poorer urea dosing control on this vehicle, particularly during the regeneration. High temperatures in the SCR coated DPF (SDPF) at the time of regeneration could lead to ammonia desorption from the filter, which as well as increasing ammonia emissions substantially could also result in poor NOx conversion efficiency. Unlike the Qashqai, there is probably no additional SCR or ASC fitted after the SDPF which could trap the excess ammonia resulting in high emissions during DPF regeneration.

[56] Suggested as likely by Ricardo based on the emission results of this test testing programme and the presentation at the SIA Powertrain conference 2018; Renault, C Bergeris, J. Thobonnet, L. Ouhayoun, A. Hollemaert, E. Aguado 'The New Renault 200HP 2.0litre Diesel engine evolution'

6. DPF Regeneration Analysis & Current Policy: regeneration events add significant amounts of pollution but this is not properly reflected in regulation

6.1 Regenerations are poorly regulated

At the present time, emissions during DPF regeneration are almost completely unregulated during the type-approval process, essentially allowing large amounts of pollution to be emitted on the road or in the laboratory when a regeneration takes place. This is allowed by the WLTP regulation which clearly states that *'during cycles where a regeneration occurs, emission standard need not apply'*.[57] The only exception is if a regeneration occurs on two consecutive tests. In this case limits only apply to the second test.

However, in order to account for the potentially large increase in regulated gaseous and PM emissions during regeneration events, the current regulation stipulates that either additive or multiplicative k_i factors must be determined. This essentially involves the division of the high emissions measured on a WLTP test during which a regeneration occurs by the distance in between two consecutive WLTP tests during which a regeneration occurs. These factors are then used to scale the results of WLTP and RDE tests (during which a regeneration does not occur) to give the final emissions result; if this value is below the limit for each pollutant the car passes the test[58]. The use of k_i factors essentially dilutes the high emissions which occur during regeneration events, thereby allowing these diesel vehicles to easily meet the emission standards, despite emissions of some pollutants potentially exceeding emission limits on tests which include a DPF regeneration event.

At present, the determination of a k_i factor for particle number is completely omitted by the regulation. This is particularly worrying given the large number of particles measured on regenerating tests during this testing programme. As stated in Annex XXII, Sub-Annex 6, Appendix 1 of Commission Regulation 2017/1151, which describes the methodology for determining k_i factors, '*the provisions of this Appendix shall apply for the purposes of PM measurement only and not PN measurement'.* This is reiterated yet again in the latest act of the WLTP regulation. In T&E's opinion, this is a loophole in the regulation that should have been closed a long time ago considering that a particle number limit has been in place for all diesel vehicles since 2013 and the Particle Measurement Programme (PMP)in 2007 (around the time of the development of the Euro 6 emissions standard) came to the conclusion that 'in principle, there is no reason why regeneration particle number emissions should not be accounted for at type approval using the distance weighted average procedure [k_i factor] currently applied for particulate mass'[59].

To add to the undemanding nature of the regulation surround DPF regeneration, car manufacturers are able to choose from two different methods of determining k_i factors for the limited amounts of pollutants which are actually regulated through k_i factors. Firstly, the manufacturer can demonstrate to the type-approval authority that a regeneration does not increase emissions of regulated pollutants to above the legal limits on the WLTP test. In this case, no k_i has to be determined for gaseous pollutants or PM.[60] If this is not the case, the manufacturer must follow the following method: Emissions of regulated pollutants[61] are measured during a WLTP test during which a regeneration occurs, this is done either on the chassis dyno or an engine test bench. Consecutive WLTP cycles are ran until a regeneration occurs. K_i factors are then

[57] European Commission, Regulation (EU) 2017/1151
[58] Before the application of deterioration factors
[59]Jon Andersson, Barouch Giechaskiel, Rafael Muñoz-Bueno, Emma Sandbach, Panagiota Dilara, 'Particle Measurement Programme (PMP) Light-duty Inter-laboratory correlation exercise final report', 2007
[60] In this case, a fixed k_i of 1.05 will be applied to CO_2 and fuel consumption only.
[61] Excluding PN

calculated based on formulas outlined in the regulation. The non-regenerating WLTP emissions are calculated from the average of at least two non-regenerating tests between consecutive regenerations, which the manufacturer is free to choose, unless emissions on WLTP tests between regenerations do not vary more than 15%. In that case, emission results from the type-approval WLTP emissions test can simply be used. Additionally, the legislation allows the use of k_i factor families. This essentially allows the same k_i factors to be used for all vehicles within a family if the following criteria are met: identical fuel type, combustion process, filter (construction, type and working principle, volume +/- 10%, temperature +/- 100°C at the second highest reference speed), the test mass of each vehicle should be less than or equal to the mass of the vehicle used for k_i determination plus 250 kg. This is likely to introduce a significant margin of error to the use of k_i factors.

6.2 On the Astra, regeneration occurred more often than indicated by Type-approval data

One of the key determinants of the size of the k_i factor is the distance between consecutive DPF regenerations. In this section the distance between consecutive regenerations during T&E's testing programme is discussed, and the Astra result is compared to that determined at type-approval which was obtained from the Czech Type-approval authorities.

The distance between two consecutive regenerations based on T&E's tests were determined from the instantaneous THC emissions (see chapter II). The distance between consecutive regeneration for the Qashqai was 423 km. The distance for Astra was slightly shorter at 419 km. This is broadly in line with the regeneration interval of 480 km estimated for diesel cars by the UK's AA (British Motoring Association)[62]. In comparison, the type-approval data for the Astra obtained from the Czech type-approval authority states that the amount of WLTP tests between consecutive regenerations is 33, equal to 767 km. This is 348 km more than determined during this testing programme. This essentially means that DPF regeneration events during which large amounts of particle pollution are produced and emission limits don't have to be met for any of the regulated pollutants occur almost twice as frequently as suggested by the type-approval data, for this car.

There are several potential reasons for the large discrepancy in the distance between consecutive regenerations based on the use of WLTP rather than RDE cycle during type-approvals:

1. WLTP cycles are usually less demanding than RDE tests,[63] potentially resulting in less soot production and subsequently slower soot accumulation on the filter equating to a longer distance between consecutive regenerations compared to RDE based driving.
2. Running consecutive hot WLTP cycles compared to alternating cold and hot start test is not representative of real-world driving. Cold start emissions usually contribute a large amount to total test soot emissions. If only consecutive hot WLTP's take place during type-approval this is likely to artificially reduce the regeneration distance, due to slower soot accumulation in the filter. This testing programme involved alternative cold and host start test which is more representative of real-world driving.
3. An additional margin of error could potentially be attributed to the use of k_i families; a vehicle with the lowest engine out soot within the k_i family could have been used by the manufacturer to determine the distance between regeneration for the whole k_i family, potentially resulting in a longer regeneration interval. However, it is unlikely that this alone accounts for such a large difference.

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62 AA, 'DPFs can be problematic' accessed 16/10/2019 https://www.theaa.com/driving-advice/fuels-environment/diesel-particulate-filters
63 T&E, 'Cars with engines: can they ever be clean?', September 2018

4. The first Astra regeneration or the potential passive regeneration during the second test may have not fully emptied the filter, compared to type approval, resulting in a shorter distance between consecutive regenerations measured during this testing programme. However, even if was the case it is possible that this could also occur during real world driving and the emissions limits would apply to the second test.
5. The Astra used may have a higher accumulated mileage than the car used for determining k_i factors during type-approval resulting in a larger amount of ash in the DPF and therefore a smaller soot storage capacity. This could result in a shorter regeneration distance. However, the Astra had only driven just over 20,000 kilometres before the start of testing so this is unlikely to have contributed to such a large difference in the regeneration distance and if this was the case than the impact of ash in decreasing the regeneration distance will only increase with vehicle age.

What is clear from the large difference in the distance between consecutive regenerations determined using the regulatory WLTP approach and the independent RDE-based approach is that the type-approval procedure appears to significantly underestimate the distance between consecutive regenerations during real world driving for the Astra. This may also be the case for other vehicles on the road today. As the distance between consecutive regenerations is a critical component of k_i determination, the large discrepancy between the laboratory and real world based testing suggests that a laboratory based k_i factor is unlikely to represent the full impact of DPF regeneration on real world pollutant emissions. In this case, the emissions from regeneration are averaged over almost twice as many kilometres during type-approval, meaning that the emissions contribution from DPF regeneration is almost half of what it should be, thereby significantly underestimating the impact of DPF regeneration on real world emissions.

The CLOVE consortium (tasked by the European Commission, with assessing future regulation) have stated that RDE testing may be proposed for the determination of k_i factors in the future post EURO-6 regulation[64]. In order for type-approval data to accurately reflect the frequency with which regenerations occurs during real world driving, it is necessary to move away from a WLTP to an RDE based methodology for determining the distance between consecutive regenerations at type-approval.

6.3 Pollution from regeneration significantly increases total pollutant emissions for every km that the cars drive

T&E have used the pollutant emissions measured during regenerating tests and the distance in between consecutive regenerations to determine the real-world impact of the DPF regeneration event on the emissions of each car for every kilometre that the vehicle drives on the road. This essentially averages the high emission from regenerating tests over the distance between two consecutive regenerations. The methodology used for the calculations is described in Annex 6 and is based on the methodology used for the determination of the k_i factor during type approval except that RDE, not WLTP, tests are used in order to allow the evaluation of the real-world impact of the DPF regeneration.

[64] CLOVE, 'Study on post-EURO 6/VI emission standards in Europe, Progress in task 2.2: Development of a new array of tests', Presentation to the Advisory Group on Vehicle Emission Standards (AGVES), Brussels, October

The impact of regeneration on total particle number emissions for every km driven

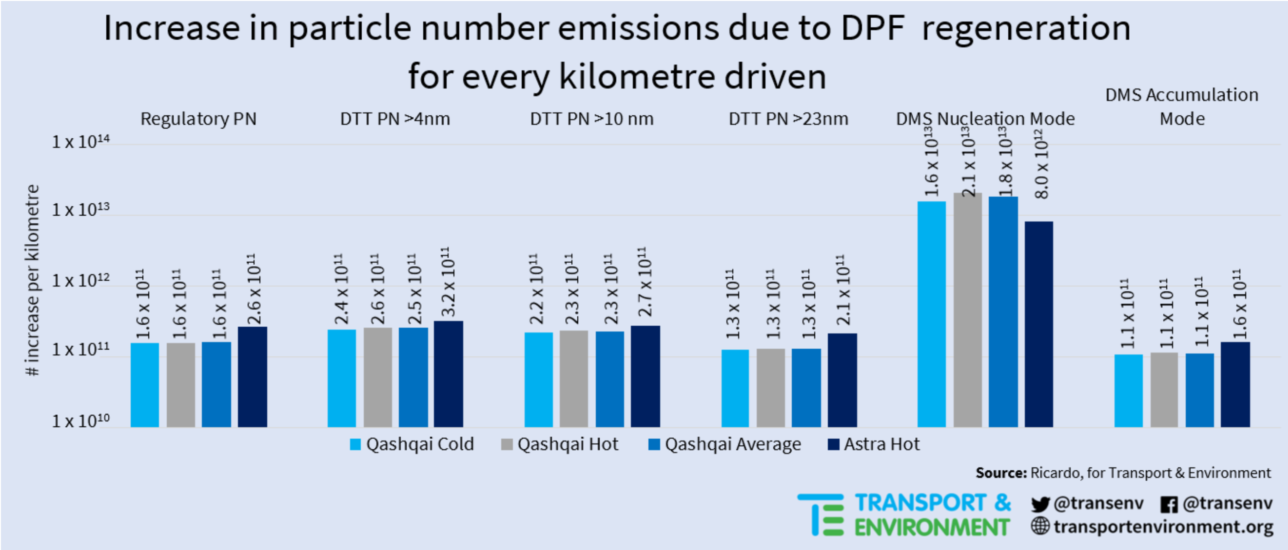

Figure 13. Increase in per km particle number emissions due to regeneration, averaged over the distance between two consecutive full regenerations.

The impact of the regeneration event on real world particle number emission for every kilometre that the car drives is presented in Figure 13. Both the cold and hot real-world impact of the regeneration could be calculated for the Qashqai as a full regeneration took place on both a cold and a hot test. For the Astra only the hot impact of regeneration could be calculated as the cold regeneration did not complete before the end of the test.

The real-world impact of the regeneration for every kilometre that the car drives is large for particle emissions and broadly similar for the two vehicles tested. The impact of the regeneration on regulated >23nm PN emissions was largest for the Astra with only a small difference between the cold and hot regeneration impact for the Qashqai. For solid particles, the regeneration alone accounts for about 25-50% of the Euro 6 PN limit, depending on the size of solid particles measured.

The increase in emissions due to regeneration, despite being averaged over 400 km for each vehicle, is the dominant determinant of total PN emissions for the two diesel cars when the impact of regeneration on regulatory particles is added to the regulatory PN emissions measured on non-regenerating tests (figure 12). When the >23nm PN emissions results from non- regenerating tests are added to the per km impact of regeneration, the total PN emissions increase substantially by between 2-43 times for the Qashqai and 5-173 times for the Astra[65]. This means that by not regulating PN emissions on regenerating tests between 60-98% of particle pollution is completely not regulated on the Qashqai and between 78-99% on the Astra. This is likely to also be the case for other diesel vehicles on the market with a similar filter and regeneration strategy.

[65] As the cold impact of regeneration could not be determined for the Astra the impact of regeneration on only hot tests has been calculated. The relatively large variability in the impact of including the effect of regeneration in total PN emissions is due to differences in the base PN emissions measured on non-regenerating tests.

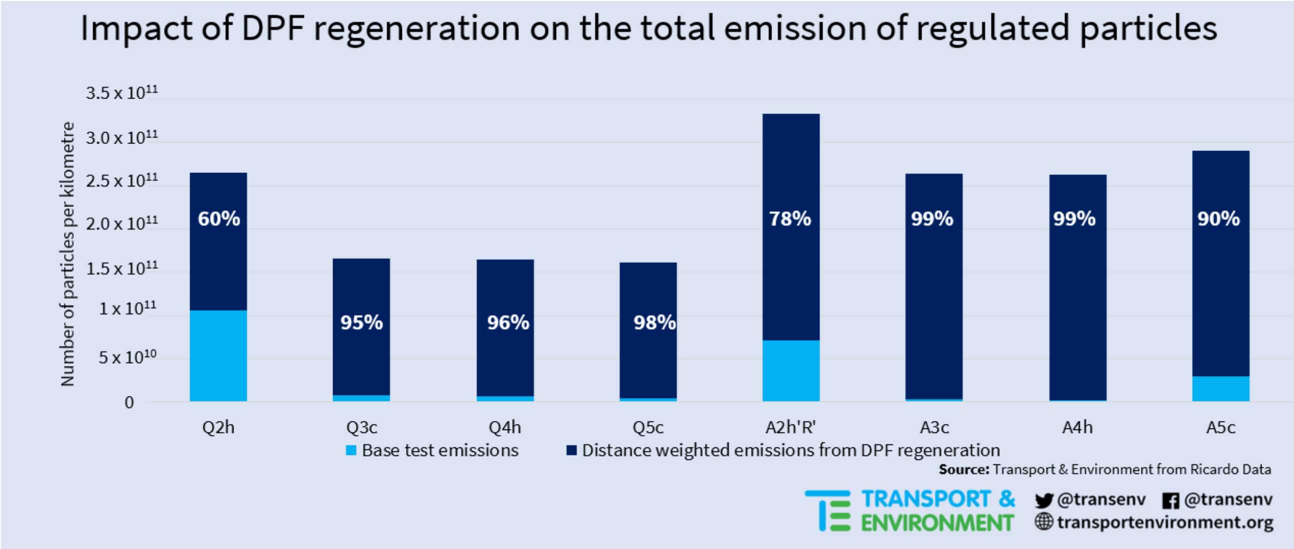

Figure 14. Total test PN emissions of non-regenerating test when the impact of regeneration is included. Despite the PN emissions from regeneration being averaged over more than 400km, emissions from regeneration are still larger than the PN emissions measured on all non-regenerating tests[66].

However, the determination of k_i factors for PN pollution, even during real world driving, would not be effective in limiting the large amounts of PN emitted on regenerating tests and ensuring that cars meet the PN emission limits on regenerating tests. Combining the per km impact of regeneration on regulatory PN emissions with regulatory PN results on non-regenerating tests did not result in an exceedance of the 6 $x10^{11}$/km PN limit. This is also the case when the same calculation is performed for particles larger than 10 and 4nm. Therefore, the only way to ensure that PN emissions are respected by diesel cars when a regeneration occurs during real-world driving is to ensure that PN emission limits have to be met on tests and real-world driving when a regeneration occurs.

Impact of gaseous emissions from regeneration on total emissions from every km driven

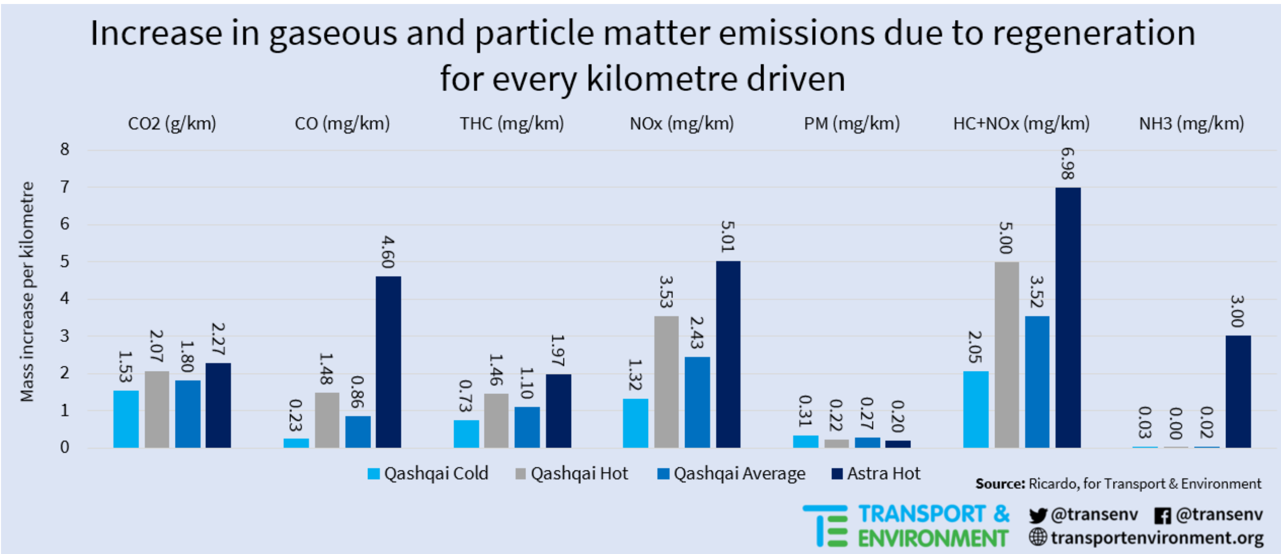

Figure 15. Increase in per km regulated gaseous emissions and PM due to regeneration

The per km impact of regeneration on gaseous pollutants and PM is presented in figure 13. The per km impact of regeneration is smaller than for particle number but still significant, especially for the emissions

[66] A2h'R' was included in the analysis as despite potentially including a passive regeneration the emission limits would apply to this test, due to regeneration taking place on two consecutive tests.

of NOx for both vehicles, which witnessed the largest increase of between 1.3-5.0 mg/km. The increase in the emissions of PM is particularly interesting because, as it is the case for PN, the per km increase due to regeneration is larger than the base emissions measured on non-regenerating tests for both cars; 0.07mg/km (Qashqai) and 0.08-0.15mg/km (Astra). The inclusion of regeneration PM emissions increases the PM emissions measured on non-regenerating test by up to 4 times. However, this increase is not as large as seen for PN emissions, confirming that PM is not a good indicator of the increase in particle number emissions due to regeneration. Addition of the per km regeneration impact for regulatory gaseous and PM emissions to emissions measured on non-regenerating tests, does not result in an exceedance of the emission limit of any of the regulated pollutants or PM on any of the tests.

While emissions limits of regulated gaseous and PM emissions were respected on regenerating tests for both vehicles, this may not necessarily be the case for all diesel cars sold within the EU. The use of k_i factors to regulate emissions from regeneration still allows diesel cars to emit more than the emission limits during laboratory or road based tests when a regeneration occurs. This would likely be the case, even if the determination of k_i factors would be based on RDE testing. This would occur as long as emissions on non-regenerating tests are low enough to offset the increase in emissions due to regeneration. This is highly likely given that the emission measured on regenerating tests are already decreased by averaging of the emissions by the distance between two consecutive regenerations. As such, the only way to ensure that emissions limits are respected on tests and on the road when a regeneration occurs is to ensure that emission limits apply to these driving conditions.

6.4 Comparison of WLTP based type-approval data compared to RDE based independent testing

The impact of regeneration on emissions of CO, THC, NOx, THC+NOx and PM determined during this testing programme can be compared to the impact calculated from the k_i factors determined during type-approval. Unfortunately, type approval k_i data could not be obtained for the Qashqai, although requests were submitted. Type-approval k_i data for the Astra, obtained from the Czech type-approval authority (TAA), only includes k_i factors for CO, THC, NOx, THC+NOx and PM no k_i factors were provided for PN[67]. The lack of PN k_i factor provided is disappointing on the part of Opel, considering that on the type-approval paperwork, there is a column available for the manufacturer to supply the PN k_i factor and given that some manufacturers such as Volkswagen choose to disclose their PN k_i's publicly. Nevertheless, the TA k_i factors allow for comparison of the impact of regeneration on emissions of CO, THC, NOx, THC+NOx and PM.

The increase in emissions due to regeneration is severely underestimated during WLTP-based testing
The difference between the type-approval- and RDE-determined per km increase in emissions due to regeneration for CO, THC, NOX, THC+NOx and PM is presented in figure 14. The procedure for calculating these values from the Astra's certificate of conformity is described in Annex 7, the values calculated are presented in figure 16.

As can be seen from the values calculated, the increase in emissions due to regeneration is underestimated during WLTP-based type-approval procedure for all pollutants, compared to independent RDE-based testing. For CO and THC, the difference is 1.6 and 3.7 times respectively, but the difference is much larger for NOx and PM. The type approval procedure underestimates the increase in emissions due to regeneration by 17 times for NOx and by 42 times for PM. The large difference suggests that the WLTP-based procedure for accounting of regeneration emissions is highly unrepresentative of the increase experienced during real-world driving.

The difference in the size of the impact of regeneration on per km emissions between WLTP and RDE testing can arise due to two reasons. Firstly, from the difference in the distance between consecutive regenerations

[67] Data from the Czech Type-approval authority used in this report is available in Annex 8.

determined by the two procedures and secondly due to the difference in the magnitude of the increase in emissions, due to regeneration, between the two procedures. The difference in the magnitude of the discrepancy between RDE and WLTP testing varies across pollutants suggesting that the cause is not just the difference in the distance between consecutive regenerations but also in the absolute increase in emissions measured.

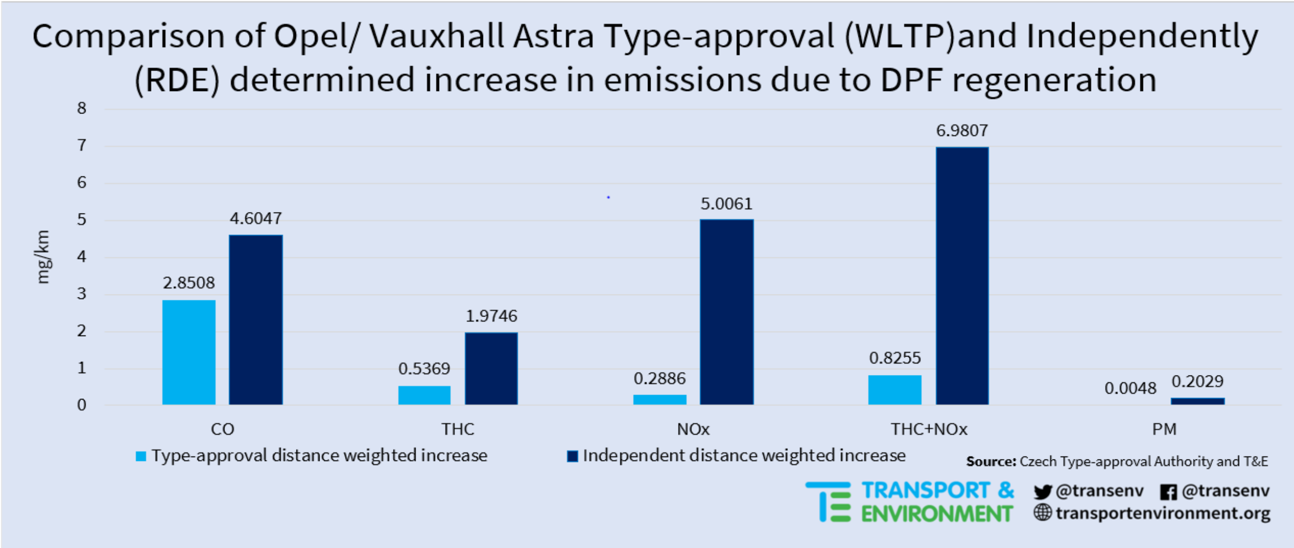

Figure 16. Comparison of the increase in emissions due to regeneration between the Astra type-approval data and the independent RDE based data. Type-approval data underestimates the increase in all regulated pollutants due to regeneration.

Due to the WLTP procedure not being representative of most real-world driving conditions[68] this difference is likely to continue as long as the impact of regeneration on cars' emissions is determined during laboratory and not real world RDE testing. As such, it is imperative that as part of the future post-Euro 6 regulation the impact of the regeneration event on pollutant emissions is determined based on RDE on-road tests and not the laboratory based WLTP procedure.

6.5 Regenerations also increase CO_2 emissions

The impact of a regeneration on CO_2 emissions should not be underestimated. The extra fuel required to increase the exhaust temperature to a level where soot burning can occur significantly increases CO_2 emissions as does the burning of the soot trapped in the filter.

The increase in CO_2 emissions due to regeneration during the motorway phase on the Qashqai were 16.7 g/km, 12.5% (Q1cR) and 17.2 g/km, 12.8% (QhR6), resulting in a total increase in CO2 emissions over the whole 85km of the total RDE cycle of 7.6 g/km, 6.3% and 10.3 g/km, 8.7%, respectively. The increase in CO_2 emissions during the motorway phase of A6hR was larger for the Astra at 21.2 g/km, 16.3% resulting in an increase of 11.2 g/km, 9.2% during the entire test. The impact of the regeneration event for both vehicles, when the distance between consecutive regenerations is taken into account, results in an increase in CO_2 emissions of between 1.5-2.7g for every kilometre that the vehicle drives.

The larger CO_2 emissions on the Astra due to regeneration may be to a larger amount of soot stored in the filter and subsequently burnt or due to the difference in the position of the filter in the exhaust of the Astra. The filter in the Qashqai is positioned directly after the DOC and mixer plate, resulting in heat generated on the DOC reaching the filter first. In the Astra, the DPF is positioned post-SCR, further away from the engine and DOC, in a colder position. This means that the heat generated on the DOC during regeneration will be

[68] T&E, 'Cars with engines: can they ever be clean?', September 2018

lost across the SCR so a greater increase in temperature and therefore a larger amount of fuel is likely necessary to ensure that the temperature within this filter is at a level which enables soot burn to occur.
At present k_i factors, at type-approval, for CO_2 and fuel economy are determined based on WLTP testing, in order to ensure that this is representative of real-world driving, these k_i factors should be determined on the road.

6.6 Summary of the shortcomings of the current regulatory approach identified in this testing programme

Based on the regulatory procedure described in the previous section and the results of this testing programme, 4 main issues have been identified regarding the regulation of emissions from DPF regeneration:

1. **Emissions limits, for any of the regulated pollutants, do not apply during laboratory or RDE tests if a DPF regeneration occurs**[69] This allows cars to exceed the emission limits for regulated pollutants on tests during which a regeneration occurs. This is unacceptable as emission limits should be respected by all cars, at all times.
2. **The use of k_i factors to account for high emissions due to DPF regeneration allows emissions limits to be exceeded** Averaging high emissions over several hundred kilometres does not account for the impact on local air quality due to the high concentrations of pollutants emitted during the actual regeneration event itself. The use of k_i factors to account for the increase in emission due to DPF regeneration allows pollutant emission limits to be exceeded during these tests and ignores the impact that this can have on air quality.
3. **PN emissions from regeneration are not even regulated by k_i factors** PN emissions limits don't apply on regenerating tests[70] as is the case for other pollutants, however for PN k_i factors don't even need to be determined meaning that an essentially unlimited number of particles can be emitted on regenerating tests, which can be seen from the high PN emissions from regenerating cars measured during this testing programme. These high emissions are currently allowed despite a PN limit being in place for diesel passenger cars since 2011 and the wealth of evidence linking particle number emissions to negative health effects.
4. **The WLTP based procedure for determining k_i factors is unrepresentative of real-world driving** K_i factors are determined based on WLTP testing which is not representative of most real-world driving conditions.[71] This means that the distance between consecutive regenerations is likely to be smaller in the real world than at type approval, and the increase in pollutants emissions due to regeneration is likely to be larger as was the case for the Astra during this testing programme.

The CLOVE consortium (tasked by the European Commission to investigate future emissions regulation) have stated that future regulation should address Specific Operation RDE testing (SORDE)[72]. This would include RDE testing during aftertreatment regeneration, which would be considered as a valid trip. It has also been indicated that SORDE based testing may be proposed for the determination of k_i factors. Furthermore, the consortium will investigate emissions from regeneration during RDE testing further as well as investigating the impact of temperature on DPF regeneration emission by chassis dyno testing at -10 and 35 ^{0}C. This investigation will not just be restricted to diesel particle filter but will also include gasoline particle filters on a range of cars including hybrid and alternative fuel vehicles. This indicates that the high

[69] Unless a regeneration occurs on two consecutive tests, in this case the emission limits have to be met on the second test.
[70] Unless a regeneration occurs on two consecutive tests, in this case the emission limits have to be met on the second test.
[71] Get Real Project, 'Why new laboratory tests will do little to improve real-world fuel economy', 2019
[72] CLOVE, 'Study on post-EURO 6/VI emission standards in Europe, Progress in task 2.2: Development of a new array of tests', Presentation to the Advisory Group on Vehicle Emission Standards (AGVES), Brussels, October 18th 2019

emissions associated with aftertreatment regeneration have been identified by the Consortium as a serious issue that warrants further investigation.

The issues highlighted above coupled with the large emissions of PN on regenerating tests during this testing programme indicate that a different approach must be taken to effectively regulate regenerative emissions of gaseous pollutants and PN. Cars must respect the legal emission limits for all pollutants under all driving conditions including on tests/drives during which a regeneration occurs. As such, future regulation must ensure that cars have to meet the emission limits for all pollutants, including currently unregulated pollutants on tests and on the road when a DPF regeneration occurs. In order to ensure on-road compliance RDE testing during which a regeneration occurs should be included in the type-approval procedure. Furthermore, in order to accurately account for the increase in fuel consumption and CO_2 due to regeneration during real world driving k_i factors for CO_2 and fuel consumption should be determined based on RDE and not WLTP tests.

7. Many pollutants emitted today are not regulated but pose a serious health risk and must be regulated in the future

Many pollutants which were measured during this testing programme are either not properly regulated on tests during which a DPF regeneration occurs, such as NOx, or are completely absent from regulation such as ammonia. In this section of the report the emissions, health effects and the future potential of regulating these pollutants is discussed.

Requirements to meet emission standards for regulated gaseous pollutants and PM on regenerating tests must be introduced in future emissions regulation

While, for the two diesel cars tested, the diesel emissions standards for gaseous pollutants (CO, NOx, THC+NOx) and particulate matter (PM) were respected on all regenerating tests, this may not necessarily be the case for all diesel vehicles that are equipped with a DPF. The current emissions regulation does not require emission standards for these pollutants to be met on tests during which a regeneration occurs and emissions of these pollutants from DPF regeneration are only regulated through largely ineffective k_i factors. Which, even if determined on RDE tests during are unlikely to result in a substantial decrease in pollutant emissions during regeneration. As such, in order to ensure that emission limits for these pollutants are respected on all vehicles during all driving conditions, including during DPF regeneration, the future post-EURO 6 emission standards must require cars to meet the emission limits for all regulated pollutants on tests during which a regeneration occurs, regardless of whether the test occurs on the road or in the laboratory.

Particle number emission from regeneration must be robustly regulated in the future

At present, particle number emissions from diesel vehicles on tests during which a regeneration occurs are almost completely unregulated. The current regulation does not require Ki factors to be determined for PN, and PN emission standards only apply if two consecutive regenerations occur in a row but only on the second test. This loophole in the regulation of PN emissions during regenerating tests has led to a situation where, as shown during this testing programme, large amounts of PN are emitted due to DPF regeneration and PN emissions limits are exceeded on regenerating tests. During this testing programme the PN emission limit was exceeded by between 32-115% on tests during which a full regeneration occurred.

In recent years, the focus on particles has shifted away from particle mass to particle number due to the emerging body of evidence which suggests that the number of particles inhaled, especially of ultrafine particles (smaller than 100nm), may have a greater negative health impact than their mass. Ultrafine particles are deposited in the lungs and airways with high efficiency and after inhalation, they can spread throughout the entire respiratory system, – where they will finally end up depends mainly on their size. The smaller the pollutant is, the further into the tissue of the lungs it can travel. These particles have also been shown to translocate to other organs such as the brain. The severity of the harm caused by these particles is dependent on many factors but several studies have made the link between ultrafine particle exposure and negative health effects. Recent research has linked the exposure of children to ultrafine particles with the onset of asthma. For adults, an increase in the number of ultrafine particles in the air by 10,000/cm^3 was found to increase the risk in adults of developing hypertension/diabetes by 3-4%, heart failure by 2-5% and brain tumours by 10-13%. This is equivalent to one new brain tumour case per 100,000 people for every 10,000/cm3 increase in the number of ultrafine particles. In comparison the current diesel particle number emission standard is 600,000,000,000/km. Finally, research suggests that exposure to high numbers of particles can even have immediate negative effects on the health of vulnerable groups, with data indicating that freshly emitted ultrafine particles and aged fine particulate matter are both associated with changes in cardiac function in individuals with type 2 diabetes and impaired glucose tolerance in urban areas.

Given the serious health effects of particle number pollution and the large number of particles emitted due to DPF regeneration, it is necessary for public health that these emissions are robustly measured, regulated and reduced in line with the European Commission's 'zero-pollution ambition'. As a first step, the future post-Euro 6 emission standards must measure and regulate particle number emissions from regeneration.

Smaller than 23nm particles must be regulated

However, it is not just the emission of currently regulated particles that are of concern for public health. During this testing programme, large emissions of solid particles smaller than 23nm were measured on all tests, but at present these particles are completely absent from EU emissions regulations at as current emissions limits only apply to particles larger than 23nm in size. This is despite evidence to suggest that these very small particles could also be the most harmful to human health. The adverse health effects of the particles are due to a wide variety of chemical and physical properties, which cause oxidative stress and inflammatory reactions throughout the body. As well as the high efficiency with which these particles are deposited within the lungs and airways as well as their ability to translocate to other areas of the body such as the brain and blood.

The large increase of between 11-184% in the amount of PN emitted from the two cars tested when particles as small as 10 nm in size were measured (compared to the measurement of only regulated >23nm particles) indicates that a large proportion of particle pollution from diesel cars is currently completely 'invisible' from a regulatory point of view. This is not only the case for tests during which a DPF regeneration occurred; emissions of 10-23 nm particles accounted for between 10-65 % of >10 nm PN emissions on all tests. For the Astra, on 3 non-regenerating tests the emissions of 10-23 nm particles exceed the emissions of regulated particles. These results clearly show that the current method of measuring particles only down to 23nm significantly underestimates the total amount of solid particles emitted from diesel cars. In the case of the two cars tested, this could result in particle emissions being underestimated by up to 65%.

Therefore, in order to fully capture all of the solid particles emitted from diesel engines under all driving conditions it is necessary, to measure particles which are smaller than 23nm in size. There are already several EU funded projects (DownToTen, PEMs4Nano, SUREAL-23, as well as the PMP working group) looking into the accurate measurement of particles down to 10nm both on the road and in the laboratory. Successful on-road measurement of particles down to 10nm has already been demonstrated and the CLOVE consortium, tasked by the European Commission, with assessing future emissions regulations, have already stated that the technology is mature enough for the measurement 10nm particles to be included in post Euro- 6 emissions regulations. In fact, Horiba, a provider of emissions measurement equipment, is almost ready to start the sale/upgrade of lab based PN measurement equipment down to 10nm, with PEMS based systems set to follow in the near future.

However, including the measuring of particles only down to 10nm will not capture all of the particles emitted from the exhaust pipe of diesel cars. During this testing programme, a difference of up to 15% was measured between the 4nm and 10nm PN emissions analysers on DPF regenerating tests. This suggests that DPF regeneration also results in the emission of solid particles smaller than 10nm and therefore extending the measurement of particle number emissions down to 10nm will not be enough to fully capture all solid particles emitted from diesel cars. Due to the larger variability in measurement conditions during RDE testing it may not be possible, in the near future, to measure particles between 2.5-10 nm in size on the road. However, these particles can be measured in the laboratory and should be included in future regulation. As mentioned previously in this report, in order to facilitate the inclusion of 2.5-10nm particles in future regulation a robust standardized methodology must be developed to account for sampling losses, dilution factors and to ensure traceable absolute particle number calibrations for all particle counters.

Given the large amount of currently unregulated sub-23nm solid particles emitted from both diesel cars tests and the negative health effects associated with the inhalation of these particles, it is imperative that the future post-Euro 6 emissions standard includes the regulation of all solid particles as small as 2.5nm in size in order to regulate the emissions of all particles from cars. On-road RDE testing must involve the measurement of particles down to 10nm and with further investigation the measurement of particles down to 2.5nm should be included. Moreover, the European Commission's 'zero-pollution ambition' must also apply to these ultrafine particles.

Volatile and semi-volatile particles must be regulated

Volatile and semi-volatile particles are currently completely unregulated in EU emissions regulations. However, they are precursors for the formation of secondary particles which contribute to the total PM2.5. The results of this testing programme have shown that a large amount of condensable species are emitted on all tests, with particularly high emissions during regenerating tests. By excluding the measurement of volatile and semi-volatile particles from regulation, the total amount of all particles emitted from diesel engines is currently underestimated, this pollution must be regulated as part of the future post-Euro 6 emission standards. The CLOVE consortium, has acknowledged that volatile and semi-volatile particles constitute a significant and possibly hazardous fraction of exhaust aerosol. The consortium has also suggested that volatile and semi-volatile particles could be regulated in the future through a total particle number emission limit.

No repeatable and robust method currently exists for the measurement of volatile and semi-volatile particles, but should be developed in order to allow for their inclusion in future emissions regulation.

An ammonia emission standard for light duty vehicles must be introduced

Emissions of ammonia from car exhausts are also of significant concern for air quality and the environment. Ammonia is a considered a precursor for the formation of secondary particles, negatively impacting air quality, as well as causing environmental damage through acidification, nitrification and eutrophication. Every 1mg of ammonia emitted from the exhaust is estimated to lead to the formation of 1mg of $PM_{2.5}$[73] and the World Health Organisation recognises that ammonia is a major component of PM air pollution. Ammonia emissions from road-transport can have a significant impact on air quality, this is especially the case in urban areas where vehicle emissions are considered to be the main source of ammonia pollution.

Ammonia emissions from diesel vehicles mostly originate from the SCR system used for NOx emissions control. AdBlue (urea) is dosed into the exhaust and decomposes to form ammonia which is then stored on the SCR/SDPF and used for the conversion of NOx. However, if the AdBlue dosing and aftertreatment system is not designed properly excess ammonia can slip out of the exhaust in large amounts. A study by Ricardo has shown that emissions of ammonia from diesel cars have been increasing in recent years due to the increased use of SCR systems on newer diesel cars. Despite ammonia's negative impact on air quality and high emissions from some diesel passenger cars, ammonia emissions from passenger vehicles are, at present, completely unregulated. This is despite an emission limit of 10ppm being in place for heavy duty vehicles since 2013. Furthermore, ammonia slip catalysts, which are effective at reducing ammonia emissions from diesel cars, are already available on the market today and are already being used by some manufacturers such as Nissan and VW. ASC's are placed downstream of all other emission control components in the exhaust and are designed to trap any excess ammonia that slips past the SCR which is then catalytically oxidised to form nitrogen gas.

The high levels of ammonia emitted from the Astra, particularly on regenerating tests (up to 33 mg/km) are completely unacceptable and unnecessary. During test A1cR, the total amount of ammonia emitted from the exhaust was equal to 2.79g, potentially resulting in the formation of up to 2.79g of secondary particles. As the legal particle mass emission limit is 4.5mg /km or 0.38g for the entire cycle, the mass of secondary particles formed from the ammonia emissions alone could exceed this limit by over 7 times. This is even

[73] JRC, R. Suarez-Bertoa, 'Current non-regulated emissions in EU', Integer Emissions Summit & AdBlue Conference, Munich, 2019

before the mass of primary particles emitted by the vehicle is taken into consideration. Primary PM emissions for this test were 0.33mg/km or 0.03g in total, equal to less than 10% of the legal PM limit and significantly less than the potential secondary particles formed from ammonia.

As data from the Qashqai has shown, the technology is already available to control the amount of ammonia emitted from diesel vehicles to below 1mg/ km at all times, even on regenerating tests. There is absolutely no excuse for any vehicle to be emitting as much ammonia as the Astra, at any time. With almost universal use of SCR systems on diesel cars in recent years, there is a risk that a significant amount of the diesel passenger car fleet currently emits large amount of ammonia when driven on the road posing a large and unnecessary risk to air quality. The CLOVE consortium has already indicated that emissions of ammonia should be regulated for passenger cars as part of the future, post EURO-6 emissions regulations, with a particular focus on real- world driving.

Given the negative effects that ammonia emissions can have on air quality and readily available technology to reduce ammonia emissions from diesel cars it is imperative that as part of the future post-Euro 6 emissions legislation, ammonia emission limits are introduced for passenger vehicles. These should be applicable for both laboratory and RDE based testing with ammonia emission measurement included in the RDE testing procedure in order to ensure on road compliance.

8. Polluted air and serious negative health effects, the consequences of DPF regeneration?

T&E estimates that there are approximately 45 million diesel cars fitted with a DPF in the EU[74]. Given that the average EU diesel mileage is estimated to be between 13,600 to 23,200km per year[75], a DPF regeneration is estimated to occur on average every other week for most diesel cars[76]. This means that every year 1.3 billion of these polluting DPF regeneration events take place in the EU[77]. Despite the large emissions of particles from diesel cars during regeneration and the large amount of diesel cars fitted with a DPF on the road today, it is sometimes argued that regeneration events occur far away from where people live, breathe and work and that therefore these high particle emissions do not matter. As this testing programme and other investigations show, there are several reasons why this is not true.

8.1 DPF regenerations cause large spikes in particle pollution that can negatively affect public health

Firstly, the concern with particle pollution from DPF regeneration is not just that particle number emission limits are exceeded on tests during which DPF a regeneration occurs because it is clear that this releases large amounts of particle pollution into the air. However, what total test PN emissions don't show is the large spike in particle pollution during the actual regeneration event itself. For the two cars tested, emissions of regulated PN during the regeneration event (averaged over a 15 km regeneration distance) were very high; between $6.2\text{x}10^{12}$ to $7.6\text{x}10^{12}$/km for the Qashqai and $6.78\text{x}10^{12}$ to $8.83\text{x}10^{12}$/km[78] for the Astra, far above the $6\text{x}10^{11}$ /km PN emission limit. Emissions during DPF regeneration can be so high that Opel/Vauxhall themselves state that '*You may also notice an emission of odours and smoke and an increase in heat, which is a normal part of the [DPF regeneration] process',*[79] thereby indirectly acknowledging that an increase in pollution is a normal part of the DPF regeneration process. During this testing programme emissions of regulated particles were found to increase by over 1000 times due to DPF regeneration, compared to non-regenerating tests.

Furthermore, the large spike in emissions due to DPF regeneration can last for a significant amount of time. A regeneration during this testing programme has been shown to last up to 9 minutes and 15 km, while data from an on-going on-road testing programme between PSA and T&E indicates that the average PSA customer's journey is about 9min and 10km long, [80] Together, this suggests that the large spike in particle emissions due to regeneration can occur for the equivalent of an entire average car journey, or more. Also, Opel/Vauxhall themselves claim that a regeneration event can take up to 25 minutes to complete[81],

[74] Estimated number of Euro 5b and Euro 6 diesel cars sold between 2011 and the first half of 2019 in the EU based on combined data from ICCT's Pocketbook, Element Energy and ACEA, taking into account that some older models may have been scrapped. Some manufacturers implemented DPFs on diesel vehicles before the Euro 5b legislation came into force, however these were not included in the total DPF fleet figure due to the difficulty associated with obtaining data for which vehicles were and were not fitted with a DPF and detailed enough EU-wide registration data per model.

[75] Belgium data: Belgian Federal Ministry of Mobility, England: UK Department of Transport, France: French Ministry of Environment & L'Argus.fr, Germany: KBA, Italy: Atmospheric Pollution Research, The Netherlands: BOVAG-RAI

[76] Based on a regeneration distance of 480 km from the British Motoring Association

[77] Based on 28 regenerations per year

[78] Calculated based on a regeneration distance of 15 km, (Regeneration RDE emissions minus non-regenerating emissions)* (85*15). 85 being the km distance of the tests. 15km was the maximum distance driven during any of the regeneration events measured during this testing programme and was used to calculate the per/km PN emissions during regeneration for all vehicles.

[79] Vauxhall, 'How do I clean my diesel particulate filter?' Accessed 16/10/2019 https://www.vauxhall.co.uk/help-centre/owners/cleaning-my-diesel-particulate-filter.html

[80] PSA Group, T&E, FNE & Bureau Veritas, Real world fuel economy measurements: Technical insights from 400 tests of Peugeot, Citroën and DS cars, Table 2, September 2017

[81] Vauxhall, 'How do I clean my diesel particulate filter?' Accessed 16/10/2019 https://www.vauxhall.co.uk/help-centre/owners/cleaning-my-diesel-particulate-filter.html

suggesting that the spike in particle pollution due to regeneration can even last significantly longer than measured during this testing programme.

The large spikes in particle emissions due to DPF regeneration are of concern because they can potentially have serious negative effects on public health. Exposure to particle emissions has been linked to a number of serious health consequences. For adults, an increase in the number of ultrafine particles in the air by 10,000/cm^3 was found to increase the risk in adults of developing hypertension/diabetes by 3-4%, heart failure by 2-5% and brain tumours by 10-13%. This is equivalent to one new brain tumour case per 100,000 people for every 10,000/cm^3 increase in the number of ultrafine particles.[82] In comparison the current diesel particle number emission standard is 600,000,000,000/km. Research also suggests that exposure to high numbers of particles can even have immediate negative effects on the health of vulnerable groups, with the data indicating that freshly emitted ultrafine particles and aged fine particulate matter are both associated with changes in cardiac function in individuals with type 2 diabetes and impaired glucose tolerance in urban areas.[83]. Children, elderly, pregnant women and people who already suffer from diseases such as asthma and chronic obstructive pulmonary disease (COPD), will be more sensitive to air pollutants and experience more health effects than others.[84, 85]

All this suggests that locally higher concentrations of air pollution from traffic, such as from high numbers of particles emitted from diesel cars due to DPF regeneration events, are of serious concern to public health. As such, the emissions of all pollutants, but in particular the number of particles emitted during DPF regeneration, must be more stringently regulated and reduced in the future. Moreover, as the World Health Organisation states, 'small particulate pollution have health impacts even at very low concentrations – indeed no threshold has been identified below which no damage to health is observed'[86]. This casts serious doubts about whether diesel cars can ever be clean enough from a public health point of view. Specifically, the high amounts of pollution emitted during the regeneration event should not be averaged over several hundred kilometres through the use of k_i factors as this essentially works to conceal the large spikes in the emission of particles and other pollutants from the DPF regeneration event. For the protection of public health, it is imperative that in the future post-Euro-6 emissions regulation diesel cars are required to meet the emission standards during all driving conditions and this must include tests and real world driving during which a DPF regeneration event occurs.

8.2 DPF Regenerations can and do occur in cities

One of the current arguments against more rigorously regulating DPF regeneration is that DPF regenerations occur mainly on high speed roads away from where people breathe. While it is true that it is more favourable for a regeneration to occur during higher speed driving, due to a lower fuel penalty and fuel in oil issues, DPF regeneration events can and do occur in cities, towns and urban areas.

For car owners who only drive in cities it is highly likely that the regeneration will also occur in the city as otherwise the DPF filter will become clogged. For most cars it is likely that the temperatures required for a DPF regeneration to occur are possible to achieve during urban driving unless the typical driving profile of the car's owner includes very low speed, short journeys, start/stop conditions or cold weather, in which case some vehicles may struggle to reach the required temperature for a regeneration to occur. If a regeneration is unable to occur under normal driving conditions, the vehicle may instruct the driver to continue driving until a regeneration occurs and completes or the filter may become clogged. If the filter becomes clogged,

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[82] Dr. Scott Weichenthal, 'Emerging health impacts of ambient ultrafine particles and deep learning for air pollution exposure science', ETH- Nanoparticle Conference, Zurich, 2019

[83] Peters, A., Hampel, R., Cyrys, J. et al, ' Elevated particle number concentrations induce immediate changes in heart rate variability: a panel study in individuals with impaired glucose metabolism or diabetes', Particle and Fiber Toxicology, 2015

[84] WHO, 'More than 90% of the world's children breathe toxic air every day', October 2018

[85] Simoni, Marzia et al., 'Adverse effects of outdoor pollution in the elderly' Journal of thoracic disease, 2015

[86] WHO, Ambient (outdoor) air quality and health, 2018

the car is likely to enter limp only mode and an urgent service regeneration is necessary. This means the only option is to go to the car dealer for the vehicle to undergo a service regeneration. This can impose significant cost to the car owner usually in excess of 100 Euro[87] or potentially a warranty cost to the manufacturer. Given that this outcome is likely to result in poor customer satisfaction, it is highly likely that most diesel vehicles are able to undergo DPF regeneration during urban conditions.

Furthermore, despite all of the active regenerations measured during this testing programme taking place during motorway driving, other testing programmes have reported regenerations during urban driving. In 2013, Emissions Analytics (EA) reported that regenerations often take place during the urban driving portion of their tests. This happens even after the car has been driven outside of urban conditions just before the regeneration occurs,[88] thereby indicating that DPF regenerations occur during urban driving, even when the vehicles have been given the opportunity to regenerate outside of urban conditions.

When approached for comment regarding urban regeneration, Nick Molden, CEO at Emissions Analytics commented that based on his observation of vehicles tested since 2013 'the frequency of regenerations during urban driving has reduced' however, the frequency with which DPF regenerations occur during EA's testing programme is increasing[89]. Emissions Analytics found that between 2011-2015, on average, DPF regenerations occurred on 17.2% of EA's tests, between 2016-2019 that figure had risen to 38%[90]. From the data available it is unclear whether the amount of regenerations that currently take place in cities has actually reduced, given that for newer vehicles the frequency with which regenerations take place appears to have increased. However, the increased frequency of DPF regeneration is concerning given the high emissions of PN associated occur during the DPF regeneration event.

Furthermore, during T&E's testing programme conducted for this report, it is possible that the Astra underwent a passive regeneration during the urban driving part of the test directly following the first regeneration, which also resulted in a significant increase in the number of particles and other pollutants emitted from the car, compared to other tests. This regeneration could have been initiated due to the regeneration (started in the previous test) not completing before the end of the test which could have resulted in an insufficient amount of soot removal from the filter. Depending on the DPF regeneration strategy employed by different car manufacturers, this kind of regeneration during urban driving could potentially also occur on other car models.

Since DPF regenerations result in a large increase in dangerous particle emissions and DPF regenerations can and do occur in cities and towns next to where people live, work and breathe it is imperative that cars are required to meet the emission standards for all pollutants on tests and on the road when a regeneration occurs. Moreover, diesel vehicles should not be classified as 'clean' given the high amount of particle pollution emitted from diesel cars during DPF regeneration.

8.3 DPF regeneration on high speed roads does not mean pollution occurs away from people

Even if DPF regeneration events occur more frequently during higher speed driving on rural or motorway roads compared to urban driving, this does not necessarily mean that pollution from DPF regeneration is emitted away from where people breathe. High speed expressways and motorways do not just exist in the middle of the countryside. Most cities in Europe have motorways or expressways near where people work, live and breathe. Notable examples are the North and South circular roads in London, Brussels' Ring, Paris' "Boulevard Périphérique" and A86 motorway, Madrid's M-30 motorway, Rome's "Grande Raccordo Anulare" and the Berliner Ring (Bundesautobahn 10). In some cases, these roads are adjacent to houses,

[87] RAC, 'Diesel particulate filters: what you need to know', March 2018
[88] Emissions Analytics, 'DPF Regeneration Mysteries', Newsletter, November 2013
[89] The figures quotes are from a direct discussion between T&E and Nick Molden, CEO of Emissions Analytics
[90] The figures quotes are from a direct discussion between T&E and Nick Molden, CEO of Emissions Analytics

offices and pavements meaning that DPF regenerations which occur on these roads will negatively impact the air quality for many people.

Furthermore, research conducted by Emissions Analytics on particle pollution inside cars suggests that car drivers and passengers are also affected by outside particle pollution, with car air filters unable to remove all of the particle pollution from the air before it enters the passenger cabin. The research indicates that the concentration of particles larger than 15nm is at a similar level inside of cars as on the outside, when air circulation is turned off.[91] This suggests that people inside cars could also be negatively affected from high numbers of particle pollution emitted from diesel cars during DPF regeneration.

8.4 Particle pollution can travel over long distances

Besides it cannot be assumed that particle pollution stays at the place where it is emitted. Research by the World Health Organisation concluded: "PM in the size between 0.1 µm and 1 µm [100 - 1000 nm] can stay in the atmosphere for days or weeks and thus can be transported over long distances in the atmosphere (up to thousands of kilometres)"[92], the WHO study even found that pollutants emitted in one European country can affect PM concentrations in neighbouring countries and even countries far distant from the source. The Particle size distribution (as measured by the DMS500 during this testing programme) has shown that a large number of particles within this size range were emitted from both cars on regenerating tests, indicating that DPF regeneration events can contribute to transportable particle pollution.

Given that particle pollution from diesel cars and in particular the large amounts of particle pollution which are generated during DPF regeneration events are capable of travelling long distances, it is not correct to assume that particle pollution from DPF regeneration is irrelevant for public health if it is not generated in close proximity to where people breathe. Particle emissions from DPF regeneration can clearly contribute to background levels of particle pollution and the evidence discussed above clearly demonstrates that it is crucial that particle number emissions are reduced in line with the EU's 'zero-pollution ambition'. As such, it is vital that as part of the future post-Euro 6 emission standard, the requirement is introduced that all pollutant emission limits must be respected on all tests during which a regeneration occurs and that a pathway towards zero pollutant emissions is defined.

8.5 The effects of regeneration last longer than just the regeneration event

Furthermore, high emissions of particles are not just confined to the DPF regeneration event itself. The results of this testing programme have shown that even after the regenerations completes the filtration of the DPF continues[93] to be impacted by the effects of regeneration. For the Qashqai this resulted in 42 times higher particle number emissions during the first 10km of urban driving after the first regeneration event, compared to other non-regenerating tests[94]; resulting in emissions of PN during the first 10km exceeding the PN emission limit. The PN emissions gradually reduced, returning to levels comparable to other tests after about 30 minutes of urban driving which meant that when emissions were averaged over the whole of the urban journey, PN emissions were compliant with the limit.

The increase in PN emissions, after regeneration, is most likely due to loss of DPF filtration due to loss of the 'soot cake' which aids in particle filtration. This indicates that urban air quality could potentially be negatively affected for several kilometres of driving following a regeneration event. While this is technically captured by the current regulation, compliance with the legal limit is highly dependent on the length of the

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[91] CLOVE, 'Study on post-EURO 6/VI emission standards in Europe, Progress in task 2.2: Development of a new array of tests', Presentation to the Advisory Group on Vehicle Emission Standards (AGVES), Brussels, October 18th 2019

[92] WHO Regional Office for Europe, 'Health risks of particulate matter from long-range transboundary air pollution', 2006

[93] Todd J. Toops, Josh A. Pihl, Charles E. A. Finney, Jens Gregor, Hassina Bilheux., 'Progression of Soot Cake layer Properties During the systematic Regeneration of Diesel Particulate Filters Measured with Neutron Tomography', Emission Control Science and Technology, 2015

[94] Compared to the average PN emissions of the first half of the urban phase of A4h and A6hR.

urban journey post regeneration. The CLOVE consortium, that currently carries out testing work for the European Commission, has already highlighted that compliance with emission limits on short urban journeys may be an issue for some vehicles and could potentially be captured in the post EURO-6 regulation as part of SORDE testing.[95] T&E believes that all cars should meet all emission limits at all times, regardless of the length of the journey as such T&E supports the inclusion of shorter urban RDE testing in post-EURO 6 regulation.

[95] CLOVE, 'Study on post-EURO 6/VI emission standards in Europe, Progress in task 2.2: Development of a new array of tests', Presentation to the Advisory Group on Vehicle Emission Standards (AGVES), Brussels, October 18th 2019

9. Conclusions and policy recommendations: diesel cars are still not clean and future regulations must set course towards zero emissions

9.1 Conclusions

This investigation by T&E into the emissions of new diesel vehicles during laboratory testing based on RDE-tests has shown that the two latest EURO 6d-temp vehicles tested meet the emission standards for regulated pollutants on tests during which a DPF regeneration did not occur. However, the latest diesels Euro 6d-temp diesel cars tested, despite being labelled as clean by the car industry[96] still produce large amounts of dangerous particle pollution during the cleaning (regeneration) of the diesel particulate filter. PN emissions of regulated particles increased by over 1000 times during DPF regeneration, resulting in the particle number (PN) emission limit being exceeded on every test during which a full DPF regeneration took place by between 32-115 %. At present, this is allowed by the regulation which states that '*during cycles where a regeneration occurs, emission standard need not apply*'[97], essentially allowing vehicles to emit a large amount of pollution on RDE and WLTP tests during which a DPF regeneration takes place.

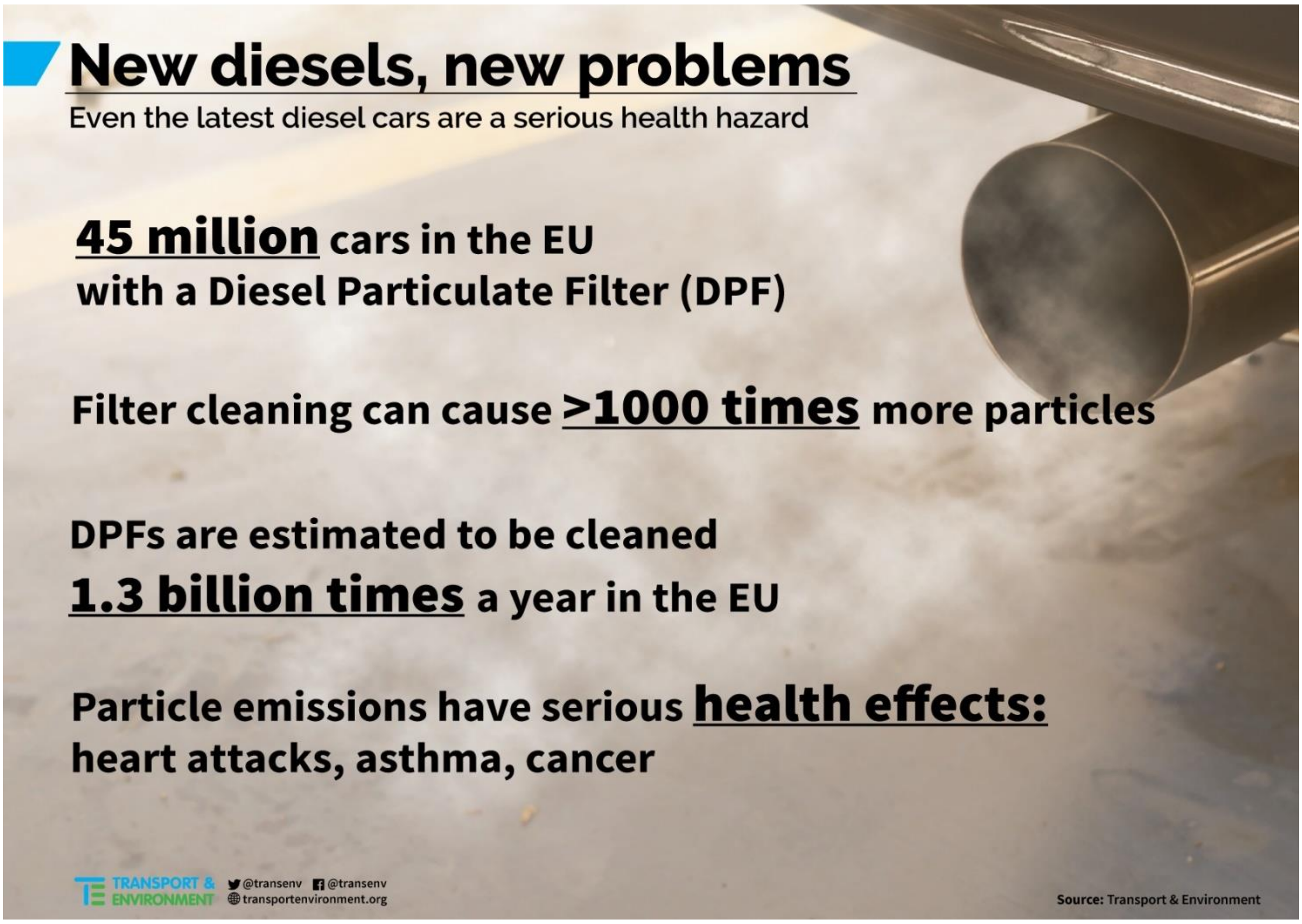

Figure 17. Summary of findings

K_i factors used to regulate emission of regulated gaseous and PM emissions from regeneration, essentially average the spikes in emissions from DPF regeneration over several hundred kilometres and do not apply particle number emissions. For regulated gaseous pollutants and PM the results of this testing programme

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[96] www.vauxhall.co.uk/fleet/range/ecotec/diesel-engines.html accessed 25/11/2019
[97] Unless a regeneration occurs on two consecutive tests, in this case the emission limits apply to the second test only

indicate that the WLTP based procedure for determining k_i factors underestimates the real-world increase in emissions due to regeneration compared to RDE based testing for the Astra casting doubt on how representative these factors are of real-world emissions.

The current lack of a particle number emission limit on DPF regenerating tests means that between 60-99% of regulated particles emitted from the two cars tested are completely unregulated at present. This is particularly worrying given the serious health effects that have been linked to particle pollution, which include the risk of developing cardiovascular and respiratory diseases, as well as of lung cancer.[98] However, it is not only the emissions of regulated particles above 23nm which increased due to DPF regeneration. A large amount of currently unregulated smaller than 23nm particles were emitted on regenerating tests, with emissions of 10-23nm particles of up to 5.28 $x10^{11}$ km on regenerating tests. The emissions of these particles were so large that these particles alone almost exceeded the PN emissions limit on regenerating tests. Furthermore, on tests during which a regeneration occurred particles within the 4-10nm range were also detected.

Nevertheless, a large number of 10-23nm particles were emitted on non-regenerating tests as well. The measurement of solid particles as small as 10 nm increased the total amount of particles measured by between 11-184% on all tests, compared to when only regulated particles were measured, demonstrating that measurement of particles only down to 23nm can significantly underestimate the total amount of particles. Measurement of currently unregulated volatile and semi-volatile particles, which contribute to $PM_{2.5}$ pollution, increased the total amount of particles measured by between 1-77 times, indicating that a significant amount of condensable species are also emitted on all tests, with particularly large emissions due to DPF regeneration.

In addition to particles, large amounts of currently unregulated ammonia (NH_3) were emitted from one of the vehicles tested, especially on regenerating tests. Emissions on tests during which an active regeneration took place were between 20-33mg/km. Unlike for heavy duty where an emissions limit for NH_3 is already in place, no such limit exists for light duty vehicles despite ammonia being a precursor for the formation of secondary particles, with every 1mg of ammonia estimated to contribute to 1mg to $PM_{2.5}$.

From the results of this testing programme it is clear that DPF regeneration results in a large increase of both regulated and currently unregulated pollutants. Most seriously, emission limits for particle number are currently exceeded on such tests for both of the vehicles tested, exposing that despite the industry's claims diesel cars are still not 'clean'. Considering that there are an estimated 45 million diesel vehicles on the road today fitted with a DPF, with an estimated 1.35 billion regenerations taking place every year in the EU, the potential impacts on air quality are serious and cannot be ignored.

9.2 Policy recommendations

These findings should in T&E's view prompt policy makers and authorities to take the following decisions, namely in view of the ongoing work at the European level on the future post-Euro 6 emissions standard:

Policy recommendation 1: Take into account actual pollution from Euro 6 diesel cars and not classify them as 'clean' when it comes to fiscal incentives, access rights to Low-Emission Zones, purchase incentives and similar policies.

The results of this test programme strongly suggest that even the newest Euro 6d(-temp) diesel cars cannot be considered as 'clean' and therefore exempt from taxes, road charges or local access restrictions. This important finding should be reflected in policies at all levels.

[98] WHO, Air Pollution - Key Facts, 2 May 2018

- **Taxes:** Many Member States apply differentiated tax rates based on carbon dioxide emissions and, sometimes, pollutant emissions of cars. Given the full extent of pollution from diesel cars, no diesels (including the latest Euro 6d-temp and 6d) may be put on equal footing with zero-emission vehicles. Real-world pollutant emissions from all driving conditions, including DPF regeneration, should be taken into account and an air quality increment added accordingly to current CO_2 taxation to incorporate their full exhaust emissions impact.
- **Zero- and Low-Emission Zones:** There should not be any blanket exemptions for any diesels (including Euro 6d-temp and 6d) in pollution hotspots that have introduced Zero-/Low-Emission Zones. Vehicles should be treated based on their real-world emissions[99] and only zero-emission vehicles should eventually be granted unlimited access to areas accessible to cars. Modern technologies, such as remote sensing, should be used by local authorities for screening vehicle emissions. The Commission should work with member states to provide a framework for such technology to eventually be used for enforcement as part of the review of the EU Periodic Technical Inspections directive.
- **Purchase incentives:** Consumers, companies or fleet owners should not be incentivised to purchase Euro 6d-temp or 6d diesels based on the inaccurate assumption that these cars are clean. Public support such as tax rebates or purchase subsidies should only be given to zero-emission technologies and mobility options as only these are truly able to solve the air pollution crisis, not fossil fuels.

Policy recommendation 2: Legal limits need to set a pathway towards zero pollutant emissions and must be reduced downwards as soon as possible.

The new President of the European Commission, Ursula von der Leyen, has made reducing emissions and improving the health of citizens one of her cross-cutting priorities.[100] She has asked the relevant Commissioners to pursue a "zero-pollution ambition"[101] which also covers air pollution. If the EU is to achieve this ambition, a far-reaching overhaul of current vehicle emission limits is indispensable. This is also strongly supported by the work of the World Health Organisation (WHO) that states that "small particulate pollution have health impacts even at very low concentrations – indeed no threshold has been identified below which no damage to health is observed."[102]The results from this test programme strongly suggest that even the newest diesel engines are not clean once a more comprehensive approach to measuring particle emissions is chosen. In order to truly deliver clean air in Europe the following policy changes need to happen:

- **Firstly, emission limits need to set a pathway towards zero pollutant emissions and must be reduced downwards in the meantime**. T&E recommends for the European Commission's to be ambitious and to aim for the post-Euro-6 emission limits to be the most stringent emissions limits globally.
- **Phase out the sales of new vehicles with internal combustion engines by 2035 at the latest.** The EU needs a coherent emission reduction roadmap which sets the course towards 100% sales of zero-emission vehicles by the early 2030's because eventually, only the transition towards zero-emission vehicles will reduce air pollution from transport to the strict minimum necessary to protect human health. The transition away from CO_2-emitting internal combustion engines is also

[99] Emissions Analytics, Nick Molden, 'The impact of RDE and WLTP legislation based upon EQUA Index real-world test data' presentation, 27th February 2019

[100] European Commission: Mission Letter - Virginijus Sinkevičius, Commissioner-designate for Environment and Oceans, 10th September 2019

[101] European Commission: Mission Letter - Virginijus Sinkevičius, Commissioner-designate for Environment and Oceans, 10th September 2019

[102] WHO, Ambient (outdoor) air quality and health, 2018

necessary to reduce greenhouse gas emissions from road transport and to limit global warming in line with the Paris Climate Agreement, as well as to achieve net zero CO_2 emissions by 2050.

- **Phase out all vehicles with internal combustion engines on EU roads by 2050**. In order to ensure that cars with internal combustion engines do not continue to pollute and emit CO_2 emissions indefinitely it is necessary to move towards a time limited type-approval system for these vehicles. Type-approvals for cars with internal combustion engines must expire by 2050 at the latest, in order to achieve the ambition of net zero CO_2 emissions by 2050.

Policy recommendation 3: Design the future post-Euro 6 standard in a way that ensures emission limits for all pollutants, including particle number, must be met under all driving conditions, also during DPF regeneration.

As the results of this testing programme have shown, a large amount of harmful pollutants are emitted from diesel cars which are completely unregulated at the present time. The future post-Euro 6 emission standard provides the opportunity to ensure that all pollutants harmful to health and the environment are properly regulated.

If vehicles respect the emission limits for all pollutants during regeneration, k_i factors will only be necessary for the determination of the fuel economy and CO_2 impact of the DPF regeneration event as these are not subject to vehicle-specific limits. However, unlike the current WLTP based procedure, the k_i factors for CO_2 and fuel economy should be determined based on RDE testing. This should ensure that the increase due to DPF regeneration determined at type-approval is more representative of the increase experienced during real-world driving.

- **Fundamentally, emission limits need to be respected during all driving conditions, including on tests during which a DPF regeneration occurs** especially given that all new diesel vehicles must be fitted with a DPF. In order to ensure this, k_i factors for pollutants should be removed in the post-Euro 6 regulation. As this report has shown, even if determined based on RDE testing, k_i factors will be ineffective at limiting emissions from DPF regeneration.
- **The RDE and WLTP testing procedure should include on-road emissions from regeneration:** In order to ensure that vehicles meet the emissions standards when a regeneration occurs during on-road driving, RDE type approval procedure must be updated to include at least one on-road test during which a full regeneration occurs, i.e. the real-world particle number and gaseous emissions during regeneration are taken into account. During this test, all applicable emission standards need to be respected. At least one WLTP test during type-approval must include a regeneration in order to measure the emissions of 2.5-10 nm particles as well as other pollutants which cannot be currently measured during real-world driving.
- **Measure and regulate particles <23 nm:** In order to ensure that all particles emitted from cars with internal combustion engines are effectively regulated, on-road particle measurement needs to include, at a minimum, the measurement of particles down to 10nm. Laboratory based testing needs to measure particles down to 2.5 nm, to ensure that all particles that are emitted from the engine are measured and regulated.
- **Measure and regulate volatile and semi-volatile particles:** A robust and repeatable method of measuring volatile and semi-volatile particles needs to be developed to allow for inclusion of these particles in the future emissions regulations.
- **Introduce an ammonia emission limit:** To ensure car manufacturers design vehicles emission control systems in a way which limits harmful ammonia emissions, an effective ammonia emission limit should be introduced along with an RDE based testing method for ensuring compliance.

Policy recommendation 4: Use the new EU type-approval framework to monitor on-road compliance and take corrective measures where necessary

Improving vehicle emissions standards is indispensable but will not alone suffice to reduce pollutant emissions on the road. It is critical to also monitor and enforce these standards during the whole lifetime of the vehicle.[103] The new laws[104] adopted in the wake of the Dieselgate scandal provide the European Commission and third parties with the power to do so. The obligations of Member States are also more clearly defined.

- **The European Commission must use this opportunity to set up a rigorous market surveillance programme.** The European Commission must use the powers granted in the legislation to thoroughly test vehicles sold on the EU market in order to ensure that all emission limits are met on the road, during real world driving, and not just in the laboratory. Vehicles also need to be checked throughout their lifetime to ensure that the emissions performance of these vehicles does not degrade over time.
- **If necessary, the Commission must issue EU wide recalls.** If any emissions issues are uncovered either by the Commission, the Member States or third parties the Commission must issue EU wide recalls of the affected vehicles and oversee that the measures taken result in emissions compliance and are not just a fix on paper. This is necessary to ensure that illegal vehicles are taken off the road swiftly and not allowed to continue polluting as is the case today. T&E lately estimated that about 51 million dirty diesel cars and vans are being driven in Europe.[105] However, only about 8 million cars have been effectively recalled to date and the effectiveness of the required software updates has often been limited.
- **The European Commission must critically oversee and audit the work of Member State Type Approval Authorities.** This is necessary to ensure that Member States undertake the necessary market surveillance programmes and to ensure that the type-approval and market surveillance rules are applied stringently across all Member States. This will require allocating significant additional resources to agencies and services dealing with emissions testing as well as the creation of an EU-level agency or authority to oversee tests, enforcement and possible fines and recalls.

To conclude, this report has shown that the strictest EU car pollution controls are failing to stop large amounts of dangerous particle pollution from diesel cars. The findings shatter automotive industry claims that new diesel models are clean and therefore **call into question the future of diesel vehicles altogether**. Diesel cars cannot be considered truly 'clean' and therefore cannot be compared to zero-emission technology.

[103] Currently only up to 5 years or 100,000 km
[104] European Commission Regulations, (EU) 2018/858 & (EU) 2018/1832
[105] T&E, 'Dirty diesels grow to 51 million across the EU, as carmakers still put profit before clean air', 2019

Annexes

Annex 1: Split of Dilute Emissions Bags

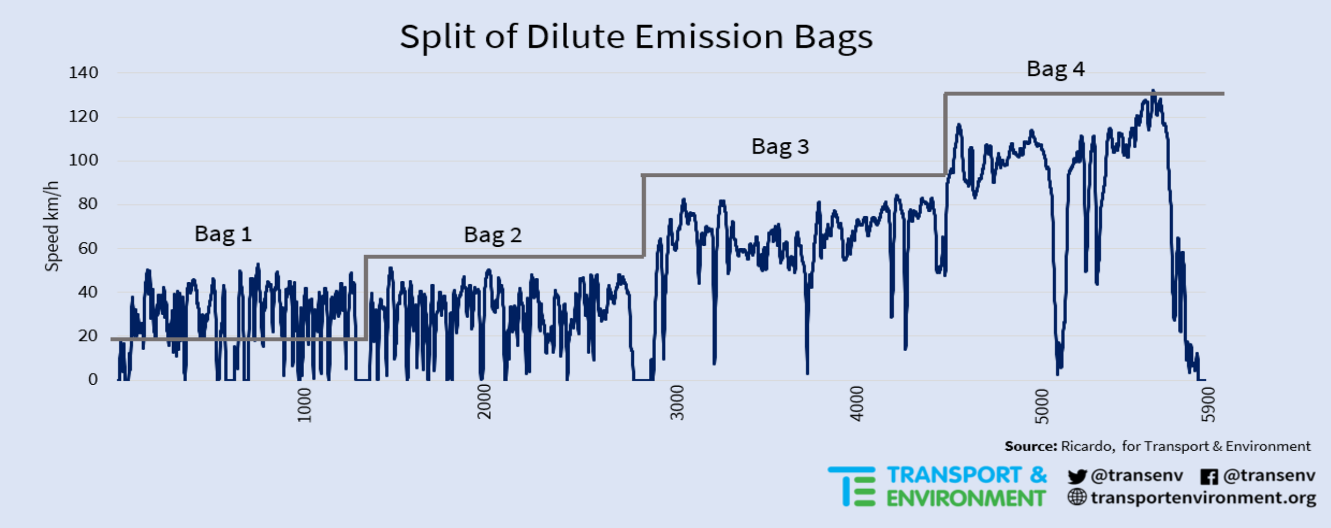

Figure A1: Split of Dilute Emissions Bags

Annex 2: Road load and test mass data

	Qashqai	Astra
Test Mass (kg)	1574.1	1490
F0 (N)	117.35	80.9
F1 (N/(km/h)	0.7386	1.134
F2 (N/(km/h)^2	0.03482	0.02895

Source: Vehicles' Certificate of Conformity

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Table A1: Road load and test mass data

Annex 3: Example V*a_pos and RPA

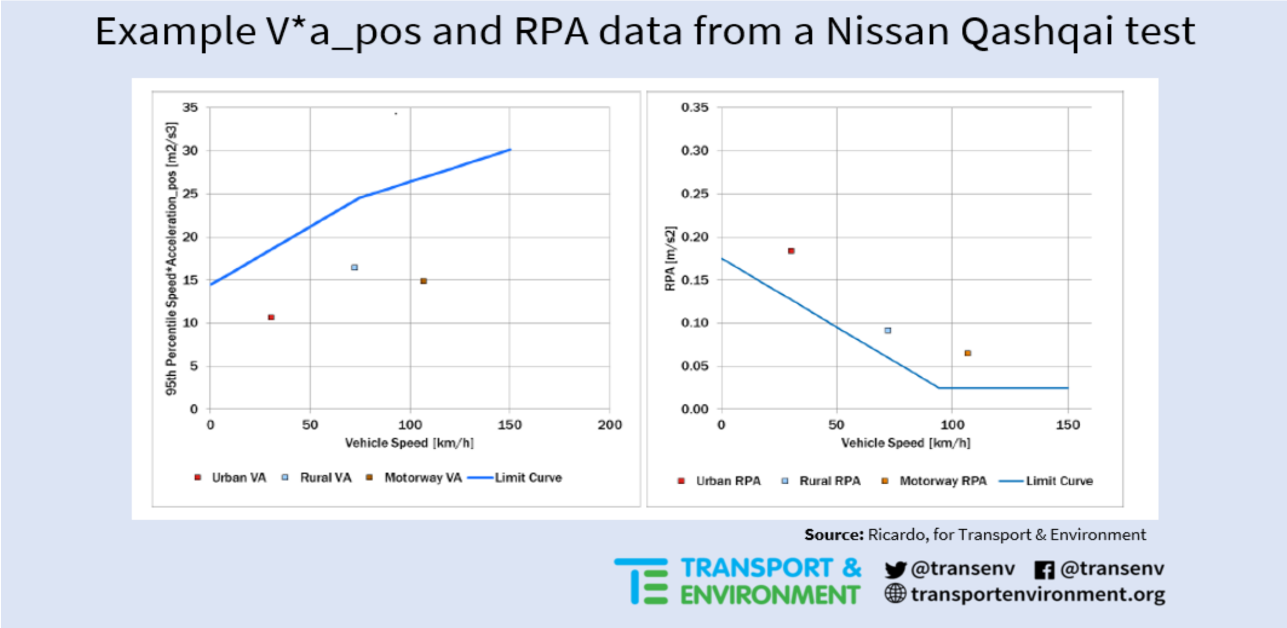

Figure A2: Example test V*a_pos and RPA data from a Nissan Qashqai test

Annex 4: Astra DPF Regeneration indicators

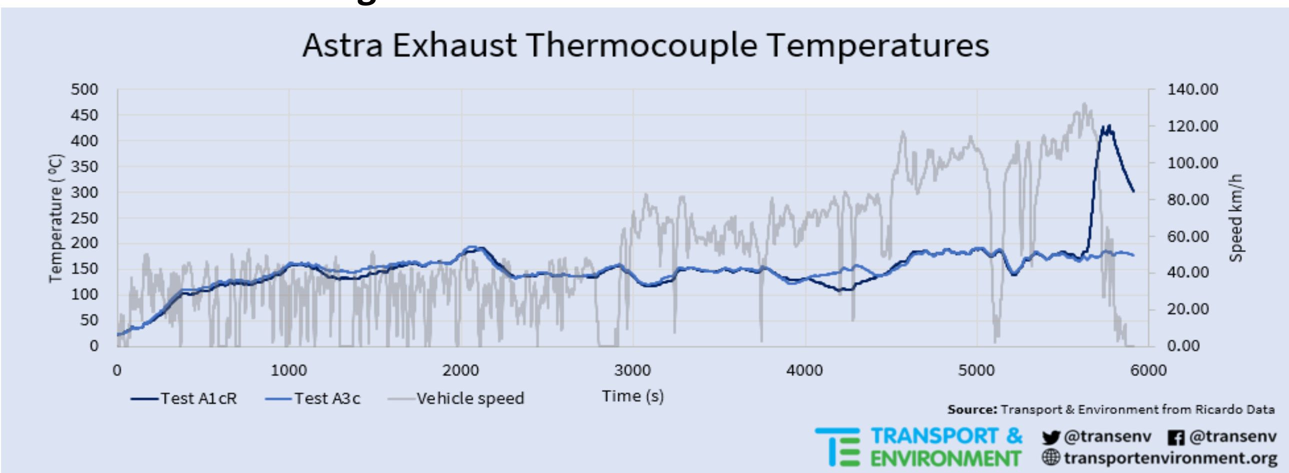

Figure A3: Astra Exhaust thermocouple temperatures; There is a clear large increase in exhaust temperatures towards the end of the first test on the Astra (compared to test A3c, a non-regenerating tests), temperatures remain significantly elevated towards the end of the test indicating an incomplete regeneration

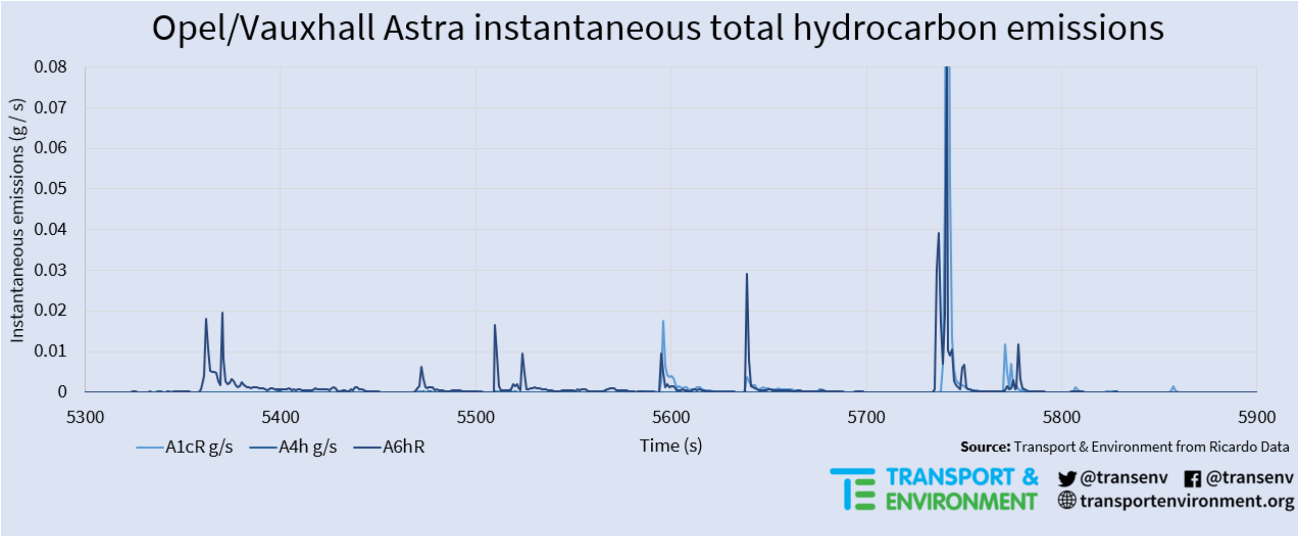

Figure A4. Hydrocarbon (HC) production increases significantly (due to post-injection) during both the 1st and 6th Astra test (during the motorway phase) indicating the presence of a DPF regeneration. Increased HC production starts earlier during the 6th test and finished before the end of the test, indicating a complete DPF regeneration.

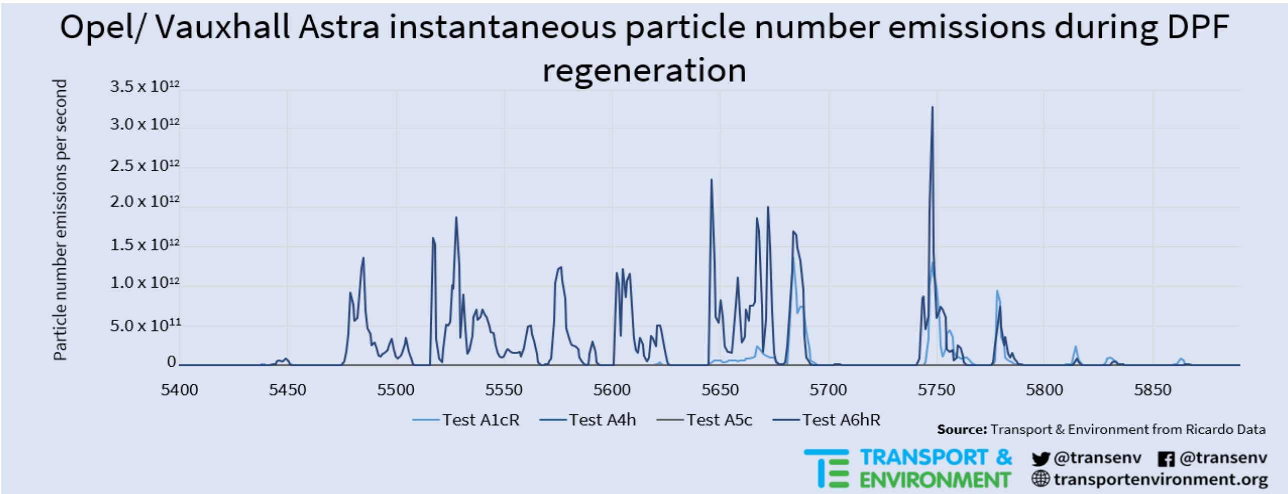

Figure A5: There is a significant increase in the production of particles during both the 1st and 6th Astra test, following the increase in exhaust temperature and hydrocarbon production, this starts earlier on the 6th Astra tests compared to the 1st.

Annex 5: Indicators of a potential passive regeneration during the 2nd Astra test

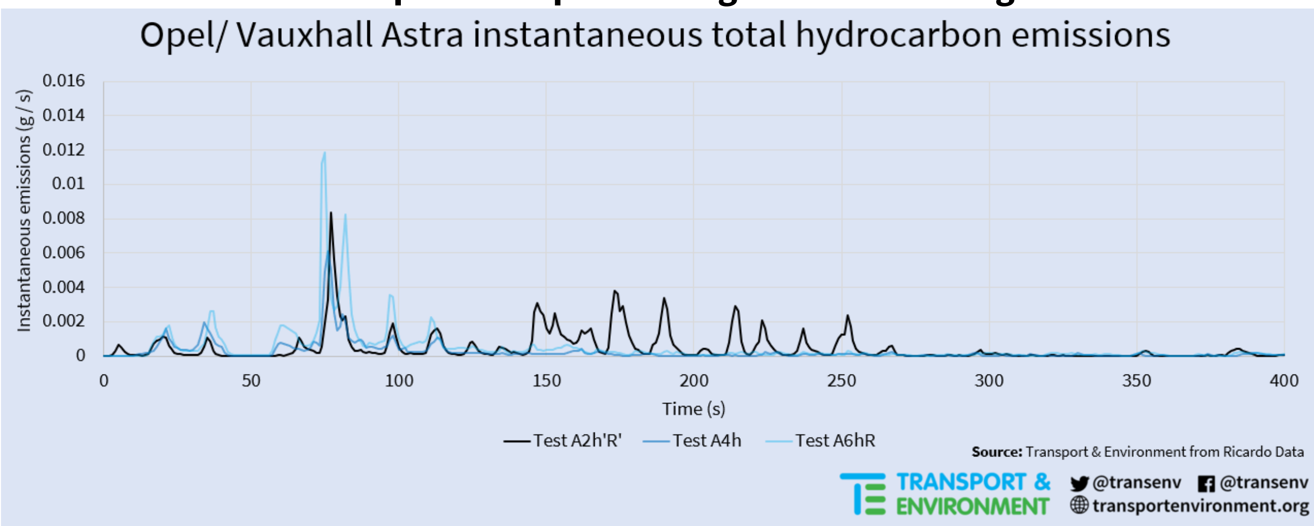

Figure A6: Increased production of hydrocarbons during the first ~250 second of test A2h'R', compared to two other hot start tests.

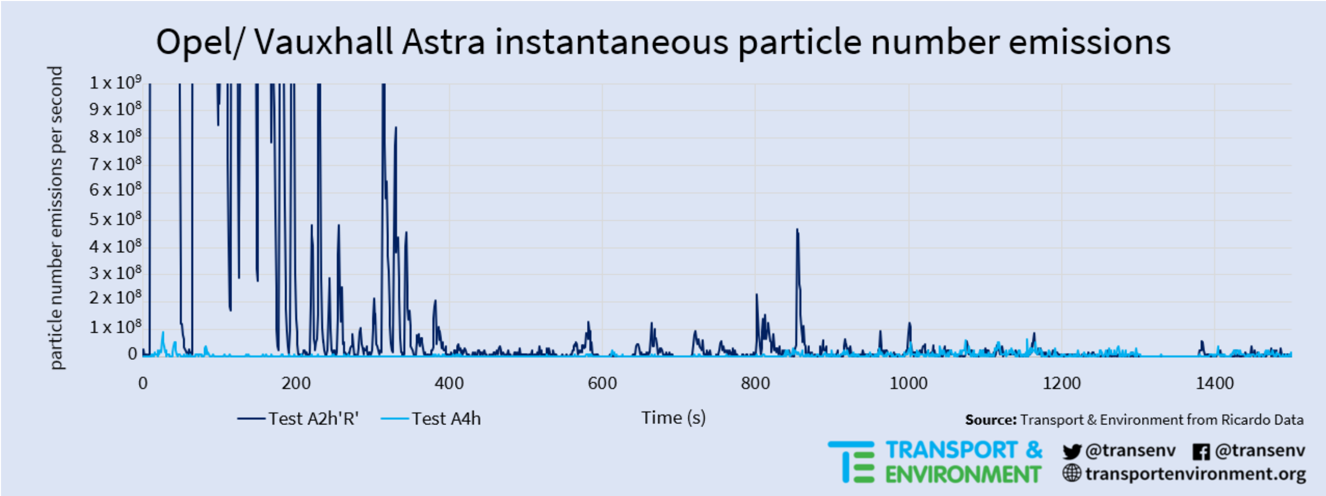

Figure A7: Significantly increased PN production for the first ~1000 seconds of test A2h'R' compared to test A4h.

Annex 6: The methodology for calculating the per km impact of regeneration on emissions based on data obtained from this testing programme

The impact of the regeneration on every kilometre driven was calculated as follows: First, the mean mass non-regenerating RDE emissions were calculated (M'sij) for each pollutant and for each vehicle. For the Qashqai, the average of Q3c and Q5c cold RDE tests were used to calculate the cold (M'sij) and Q4h for the hot (M'sij). For the Astra, hot (M'sij) test A4h was used. For the regenerating RDE emissions (M'rij), the following tests were used for the Qashqai: Qc1R (cold M'rij), Q6hR (hot M'rij) and for the Astra: A6hR (hot M'rij). Next, the mean mass emissions Mpi for each pollutant were determined using the formula outlined in the WLTP 2nd act[106] as shown below. The amount of cycles between consecutive regenerations (D) was 4 for the Qashqai and 3.94 for the Astra.

$$M_{pi} = \frac{M'_{sij} \times D + M'_{rij} \times d}{D+d}$$

Please note that when referring to the regulatory approach in this case: Msi = M'sij and Mri = M'rij because the number of cycles required to complete the regeneration for each vehicle (d) = 1.
In order to determine the absolute increase in emissions due to regeneration for every kilometre the car drives, the non-regenerating emissions (M'sij) were subtracted from the mean mass emissions (Mpi) for every pollutant.

Annex 7: The methodology for obtaining the per km increase in emissions due to regeneration from data from the Certificate of Conformity and Type-Approval information obtained from the Czech type-approval authorities

The per km increase in emissions, due to regeneration, determined during type approval for the Astra were calculated from the WLTP emissions results detailed in the vehicles certificate of conformity and the k_i and deterioration factors obtained from the Czech type-approval authorities.

Firstly, the deterioration factors for each pollutant must be subtracted from the WLTP emissions values. This gives the WLTP emissions measured during type approval with k_i factors applied. This value must then be divided by the multiplicative k_i factors for each pollutant to give the base emissions measured during

[106] Commission Regulation (EU) 2018/1832

type-approval. The difference between the two WLTP values (with and without k_i factors applied) is the increase in emissions due to regeneration, for every km driven, as determined by the type-approval procedure. The increase in THC+NOx was calculated by combing the increase of THC and NOx.

Annex 8: Ki and DF data from Czech Type-approval authority

Data from Czech Type-approval authority

Astra	CO	THC	NOx	PM
Units	mg/km	mg/km	mg/km	mg/km
Multiplicative Ki	1.0351	1.0860	1.0140	1.0245
Additive DF	4.13	3.62	0.00	0.04

Source: Czech Type-approval authority

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Table A2: Opel/Vauxhall Astra data obtained from the Czech Type-approval authority

Annex 9: Opel/Vauxhall Astra Certificate of Conformity emissions data (WLTP)

Data from the Opel/ Vauxhall Astra's Certificate of Conformity

Astra	CO	THC+ NOx	NOx	PM
Units	mg/km	mg/km	mg/km	mg/km
WLTP	88.2	31.3	20.9	0.24

Source: Certificate of Conformity

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Table A3: Data from the Opel/Vauxhall Astra's Certificate of Conformity