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TNO report

TNO 2022 R10798

Analysis of the emission performance of the vehicles tested for the Green Vehicle Index (GVI) project

Date 3 May 2022

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Copy no 2022-STL-REP-100344584
Number of pages 32 (incl. appendices)
Sponsor Dutch Ministry of Infrastructure and Water Management
Project name Programmasubsidie Meetprogramma voertuigemissies 2022
Project number 060.51098

Summary

The Green NCAP consortium is working on the development and implementation of a methodology to rate the sustainability performance of relatively new vehicles. The Horizon 2020 ‘Green Vehicle Index’ (GVI)[1,2] project has been set up to accelerate and improve the Green NCAP consumer programme [3]. Within the GVI project, that started in June 2019 (and ended in January 2021), the testing and rating methodology was further developed, covering all types of available propulsion systems. In total 49 modern vehicles (Euro 6d, and Euro 6d-T) were tested and rated. TNO was one of the GVI consortium partners.

Comprehensive testing programmes, both on-road and in the laboratory, give insight into emission behaviour in different potential high-emission situations. In general, the emission performance of the tested vehicles is very good, and this is a major improvement over the previous generations Euro-6 vehicles. The introduction of RDE legislation clearly shows an effect, successfully reducing a large part of the gap between type approval emissions and emissions during real-world driving. Under some circumstances though, elevated pollutant emissions may still occur. This is for example the case during a cold engine start, high driving dynamics, prolonged idling and DPF regenerations. The GVI programme provided insights in the emission levels during these circumstances. Moreover, in the measurement programme non-regulated emissions were considered as well, like NH_3, N_2O and particle number down to 10 nm (PN10).

On behalf of the Dutch Ministry of Infrastructure and Water Management, TNO briefly summarized the emission performance of the vehicles tested within GVI. There is a specific focus on the non-regulated pollutants and the situations with elevated emissions. Moreover, the potential impact on TNO’s VERSIT+ emission factors based on these insights are described in the relevant chapters.

In this report, more than 40 vehicles were analysed that had been subjected to the broad testing programme devised within GVI. This included a range of Euro 6d-Temp and Euro 6d diesel, petrol, plug-in petrol, petrol hybrid, and CNG vehicles. The vehicles were tested both in the laboratory on the chassis dynamometer as well as on the road with PEMS (Portable Emissions Measurement System).

The current analysis results in the following main conclusions:

- **Non-regulated pollutants NH_3 and N_2O deserve continued monitoring**
  Across all performed tests, petrol vehicles emit an average of 13 mg/km NH_3, while diesel vehicles emit 1.6 mg/km NH_3. Note that the test performed at cold ambient temperature (-7 °C) as well as the high-speed BAB tests show a wider range of average NH_3 emissions.

  With regard to N_2O, diesel vehicles emit an average of 14 mg/km (3.7 g CO_2

[1] The GVI project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 814794
[2] https://www.gvi-project.eu/
[3] https://www.greenncap.com/

eq.), while petrol vehicles emit on average 1.1 mg/km. Furthermore, no clear correlation was observed between low NO_x and N_2O emissions.

- **Most vehicles perform within the GVI thresholds for regulated pollutants**
  Within GVI and Green NCAP performance thresholds (vehicle and engine technology neutral) are established for each relevant emission constituent. Trip-averaged regulated pollutants show that most vehicles perform better than the GVI threshold (i.e., an 'upper limit'). Nevertheless, several vehicles have average emissions above the GVI threshold. This mainly occurred during the high-speed (BAB) and low ambient temperature (-7 °C) lab tests and the heavy on-road test.

- **Cold engine starts are a localised effect**
  There is a large variation in both the total amount of pollutants emitted during a cold engine start, as well as the distance within these emissions occur. However, the average distance with elevated emissions due to the cold engine start is often two kilometres or less. Moreover, the emissions associated to the cold engine start are often dominant in the total trip emissions.

- **Idling NO_x emissions increase significantly after around five minutes**
  There is a large variation in how the diesel cars' NO_x emissions increase over time. Some vehicles show that idling emissions can be kept low. As idling is most likely to occur in urban situations, these elevated emissions should always be taken into account in normal use to not underestimate urban emissions.

- **DPF regenerations lead to a significant increase in emissions, and can occur in urban settings**
  If the expected average DPF regeneration interval is 450 km, this would lead to an average increase of 5.2 mg/km NO_x, 5.1 mg/km CO and 3.4 x 10^{10} [#/km] on the respective emission factors if the emission factors are based on measurements that do not include DPF regenerations. However, DPF regenerations can lead to a *local* additional 4 g of NO_x or CO, or 5 x 10^{13} PN.

- **For most trips, expanding PN23 measurements down to PN10 still resulted in average emissions below 6 x 10^{11}**
  For multiple vehicles, particle number size down to 10 nm (PN10) was measured alongside the usual PN23 measurements for selected tests. In this report the results of four vehicles were analysed (including petrol, HEV petrol, and PHEV petrol vehicles). These tests and vehicles revealed an average increase of 87% when measuring particle number down to 10 nm instead of to 23 nm. For PEMS trips specifically, this was 40%, while for the high-speed BAB test there was an average increase of 190%. Despite this increase, these vehicles remained below the current limit of 6 x 10^{11} during most of the trips.

Contents

1 Introduction

1.1 Background

The Green NCAP consortium is working on the development and implementation of a methodology to rate the sustainability of a vehicle, currently limited to passenger cars in a proper condition with relatively low mileages. This Green NCAP rating provides consumers with an objective and clear view on how clean their car, or a car that they consider to purchase, is. This enables the consumer to make an informed choice, considering the cars real-world fuel consumption, CO_2 emissions and impact on air quality. The idea is that this will decrease the emissions of new cars, not by penalizing manufacturers for producing polluting cars, but instead by creating a demand from the consumer to car manufacturers to produce clean cars.

Green NCAP was initiated by Euro NCAP with the aim to develop a tool on the environmental performance of passenger cars with similar impact as the Euro NCAP safety labelling. In this respect Green NCAP should go beyond current emission legislation. A critical success factor for Green NCAP is the testing methodology: which kind of tests must be performed, which pollutants should be included, under which conditions and how it is made sure that tests give a reliable and objective view of the environmental vehicle performance.

The Horizon 2020 ‘Green Vehicle Index’ (GVI)[4,5] project has been set up to accelerate and improve the Green NCAP consumer programme [6]. Most of the partners of the GVI project are also partner in the Green NCAP initiative. Within the GVI project, that started in June 2019 and ended in January 2021, the testing and rating methodology was further developed, covering all types of available propulsion systems. In total 49 modern vehicles (Euro 6d, and Euro 6d-Temp) were tested and rated, based on these latest test procedures, contributing to the Green NCAP database of consumer information.

The project resulted in many interesting outcomes. One part of the outcomes is related to the emission performance of these modern vehicles. In general, the emission performance of these vehicles is very good, a major improvement over the previous generations Euro-6 vehicles. This is the result of the introduction of Real Driving Emissions (RDE) legislation, which successfully reduced a large part of the gap between type approval emissions and emissions during real-world driving. Nevertheless, there are still circumstances where elevated pollutant emissions may occur. For example, during a cold engine start, high driving dynamics, prolonged idling and DPF regenerations. The GVI programme provided insights in the emission levels during these circumstances. Moreover, in the measurement programme also non-regulated emissions were considered, like NH_3, N_2O and sub 23 nm particles. These insights can, for example, serve as input for calculating emission factors for air quality models. Emission factors are distinct for categories with distinct emission performance, technology, or vehicle type or usage.

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[4] The GVI project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 814794

[5] https://www.gvi-project.eu/

[6] https://www.greenncap.com/

Partners
The GVI programme is executed by a consortium where TNO was part of. The other consortium members within GVI were: IDIADA, FIA, ADAC, UTAC, TCS, OAMTC, ICRT, IFA, ACI, CSI-SPA, EMPA, BASt and Horiba MIRA Ltd.

1.2 Aim of this report

On behalf of the Dutch Ministry of Infrastructure and Water Management, TNO briefly summarized the highlights of the emission performance of the vehicles tested within GVI. There is a specific focus on the non-regulated pollutants and the situations with elevated emissions. Moreover, the report describes the potential impact on TNO's VERSIT+[7] emission factors based on these insights.

1.3 Structure of this report

In Chapter 2 the test program is described. In Chapter 3 the additional insights with regard to the non-regulated pollutants are shown, while Chapter 4 focuses on the average regulated pollutants. In Chapter 5 the observations regarding circumstances with elevated emissions, like cold start emissions and high engine load are shown. Chapter 6 describes the impact of broadening the scope from PN23 to PN10 on particle emissions. Chapter 7 zooms in on the correlation between measurements with PEMS compared to laboratory equipment, followed by the conclusions of the report results in Chapter 8.

[7] TNO's emission factor model. This model is used for the Dutch Emission Inventory for road traffic:
http://www.emissieregistratie.nl/erpubliek/documenten/Lucht%20(Air)/Verkeer%20en%20Vervoer%20(Transport)/Methoderapporten%20Taakgroep%20Verkeer%20en%20Vervoer/Geilenkirchen%20et%20al.%20(2020)%20Methods%20for%20calculating%20the%20emissions%20of%20transport%20in%20NL_def.pdf

2 Test program

2.1 Test cycles

The vehicles were tested both in the laboratory on the chassis dynamometer as well as on the road with PEMS (Portable Emissions Measurement System). Figure 1 shows an overview of the test matrix.

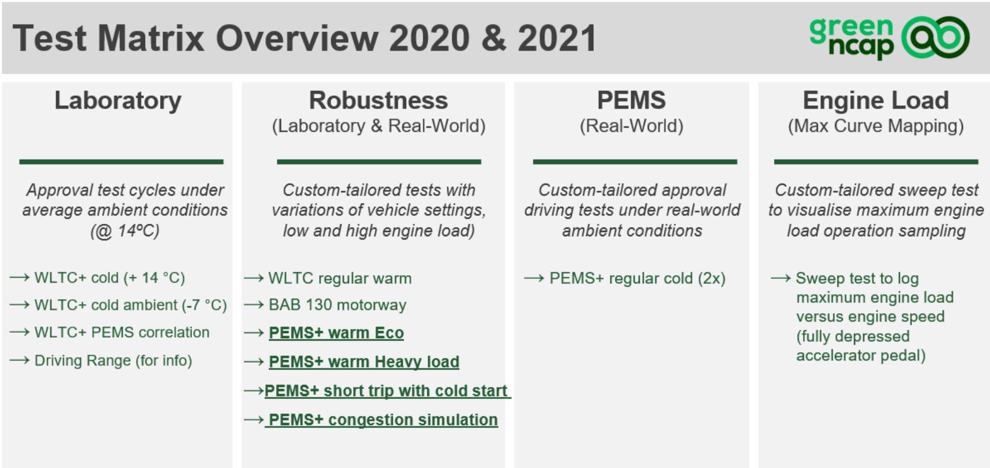

Figure 1: Test Matrix overview

On the chassis dynamometer the following tests are driven:

1. WLTC+ (Worldwide harmonized Light vehicles Test Cycle) with cold engine start: This test is based on the type approval test conditions from the WLTP[8], however, a lower ambient air temperature is used, i.e., 14 degrees Celsius instead of 23 degrees Celsius. Moreover, the air-conditioning is switched on. This test is performed to verify if the state of the vehicle by relating the results to the type approval limits and values. This test is also repeated, but then with the PEMS installed to check the correlation between PEMS and the laboratory equipment. Moreover, the WLTC+ is also driven in cold ambient conditions (-7 degrees Celsius). Finally, the WLTC+ is driven with a warm engine start.
2. BAB 130 (ADAC[9] Highway Cycle) with warm engine start: This cycle is developed by ADAC and simulates dynamic highway driving. The maximum speed is 130 km/h and includes accelerations with wide open throttle. With this test the impact on the emission performance of dynamic highway driving at high speeds is assessed.

With the real-world tests by using PEMS the same principle is maintained as for chassis dynamometer tests, i.e., starting with tests based on the RDE (Real-Driving-Emissions) test, followed by tests with conditions which are not necessarily limited to the conditions covered in the official RDE procedure. However, the applied conditions are realistic.

[8] Worldwide Harmonised Light Vehicle Test Procedure
[9] Allgemeiner Deutscher Automobil-Club

The following tests are driven:

3. PEMS+ regular: a test which is comparable to the RDE procedure with 'standard' conditions: The maintained driving style is 'normal', i.e., following the Gear Shift Indicator (GSI), normal anticipation and normal accelerations. The test is started with a cold engine. The weight of the vehicle includes the PEMS, the driver and the test engineer. This test is performed to check whether the results are compliant with the type approval limits.
    a. The PEMS+ short trip with cold start is based on the PEMS+ regular, with only the first 8 kilometers of the trip considered in the data processing. This is relevant to evaluate the impact of a cold engine start during short urban trips.
4. PEMS+ warm eco: On road test with 'light' conditions: For this test the same trip is used as during the 'standard' test. However, there are some deviations with regard to the test conditions:
    a. Maximum speed of 110 km/h on the highway
    b. Economy driving style; better anticipation, i.e., more coasting gear and less braking
    c. Air-conditioning: off
    d. 15 minutes of idling in the urban phase of the trip (start/stop system deactivated)

    This test is meant to assess whether or not the emission control devices also work with lower engine loads and lower exhaust temperatures.
5. PEMS+ warm heavy load: On road test with 'heavy' conditions: For this test the same trip is used as during the 'standard' test. However, there are some deviations with regard to the test conditions:
    a. Start with warm engine, but with 15 minutes of idling before the start of the trip
    b. Sportive driving style: minimum coasting in gear, more aggressive braking, more aggressive shifting
    c. Maximum payload
    d. Air-conditioning and other auxiliary devices at maximum

    This heavy test is meant to include a sufficient amount of demanding events with high engine loads. With this test the vehicle's emission performance can be assessed under these heavy conditions.
6. PEMS+ congestion simulation: 15 minutes of idling | 5 minutes stop and go: 10-meter driving (first gear, max 10 km/h) → 10 seconds stop → 10 meter driving etc. Start/stop system deactivated.

A detailed description of the test procedures can be found on the Green NCAP website[10].

2.2 Emissions measured

The following regulated emissions were measured on the chassis dynamometer: CO (carbon monoxide), HC (hydrocarbons) and NO_x (nitrogen oxides). Additionally, CO_2 (carbon dioxide), PM (particulate matter) and PN (particle number) were measured.

[10] https://www.greenncap.com/test-procedures/

Furthermore, the following emission were measured: NH_3 (ammonia), CH_4 (methane), and N_2O (nitrous oxide) were measured. Some of the partners also measured PN10 (particle number size above 10 nm). With PEMS, all vehicle measurements included CO, NO_x, PN and CO_2.

2.3 More than 40 vehicles were included in this analysis

In total 49 vehicles were measured in the GVI programme, the following type of vehicles are included:

- Petrol, Diesel, HEV and CNG;
- Mainly Euro 6d-Temp and 6 Euro 6d vehicles (see explanation below);
- Acceptance range: 3000 – 30 000 km;
- Average distance at intake: 7000 km;
- Common rail, direct and multi-port injection;
- DPF and GPF equipped vehicles, as well as petrol without particulate filter;
- Manual transmission, robotised manual, automatic, CVT.

From September 2017 the Euro 6d-Temp emission standard was introduced for new light-duty passenger vehicles (M1) and light commercial vehicles (N1 class 1, ≤1305 kg). The major difference between Euro 6d-Temp and the first generation Euro 6, is the introduction of on-road emissions testing with PEMS. Furthermore, Euro 6d-Temp vehicles are evaluated by the WLTP (including a low ambient test). From 2020 onwards Euro 6d (final) is in force for these vehicle types. With Euro 6d, additional requirements were implemented, including a lower conformity factor (i.e., lower average emission values accepted as measured with PEMS) and In-Service-Conformity Real-Driving Emissions (ISC-RDE).

3 Additional insights into non-regulated pollutants

Although NH_3 and N_2O can have large environmental impacts, neither of these are as of yet addressed within current emission legislation for light-duty vehicles. Within GVI testing, both of these pollutants were measured during laboratory testing. This provides essential insights into the emissions of newer vehicles, which can be directly translated to new emission factors for these pollutants. Note that as these pollutants are non-regulated, it is unlikely that their emission behaviour has been tailored to laboratory testing. Therefore, these emissions may be considered indicative of on-road emissions.

3.1 Most vehicles emit less than 13 mg/km NH_3

NH_3 emissions are a by-product of emission management systems. In the case of petrol and CNG vehicles, NH_3 is a by-product of the catalytic conversion in the three-way catalyst. In diesel vehicles NH_3 is injected to reduce NO_x, so-called 'ammonia slip' can lead to NH_3 emissions.

On average, diesel vehicles have lower NH_3 emissions than those with other fuel types (Figure 3.1), though for most tests average emissions are below 13 mg/km. Across all performed tests, petrol vehicles emit an average of 13 mg/km, while diesel vehicles emit 1.6 mg/km. Note that both the test performed at cold ambient temperature (-7 °C) as well as the high-speed BAB tests show a wider range of average NH_3 emissions. Furthermore, no clear correlation between NO_x and NH_3 emissions is observed (Figure 3.2).

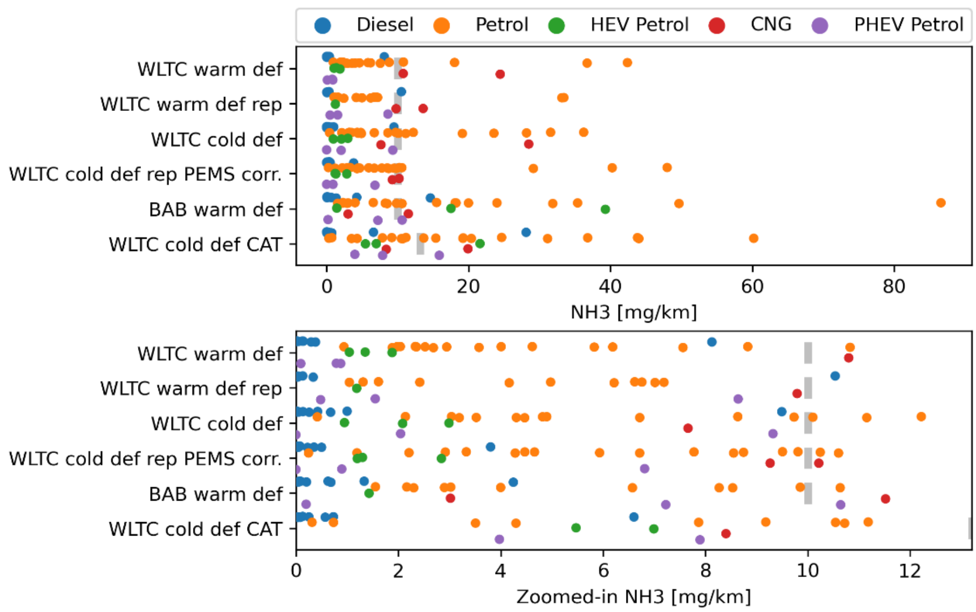

Figure 3.1: NH_3 emissions as averaged over the entire trip. The top panel shows all data measured on the chassis dyno including the thresholds (upper limit, as described in chapter 4) proposed by GVI in grey. The bottom panel shows a zoomed-in version of the top one.

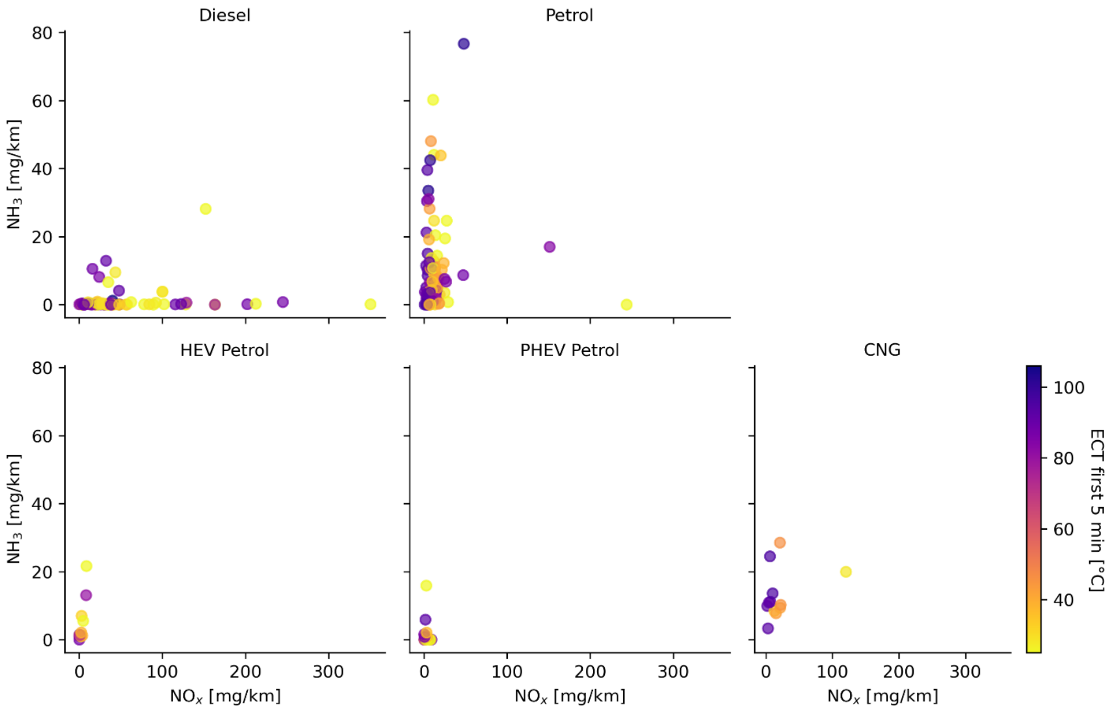

Figure 3.2: NH_3 compared to NO_x trip averages. The colour of the points indicates the average engine coolant temperature over the five minutes of the trip (colour gradient applies to all panels).

3.2 High N_2O emissions are measured for diesel vehicles

As mentioned in previous study (de Ruiter et al., 2020), up until recently, little was known about N_2O emissions. The measurements performed within GVI have contributed significantly to our knowledge in this field. N_2O is a greenhouse gas with a significant environmental impact: 1 g of N_2O is equivalent to 265 g of CO_2.[11] Diesel vehicles show consistently high N_2O emissions compared to other fuels, though some vehicles do have lower average N_2O emissions for the high-speed BAB test (Figure 3.3). On average, diesel vehicles emit 14 mg/km N_2O (3.7 g CO_2 eq.), while petrol vehicles emit 1.1 mg/km. Most of the N_2O emissions are below 25 mg/km.

These measurements highlight the need for continued measuring of N_2O emissions and have led to an increase in the VERSIT+ (TNO's) emission factors.

[11] The value of 265 applied in this report is derived from the IPCC's Fifth Assessment Report. However, other values have also been published, such as 298 g of CO_2 eq. in the Official Journal of the European Union (volume 61), L 328, 21 December 2018, p 152.

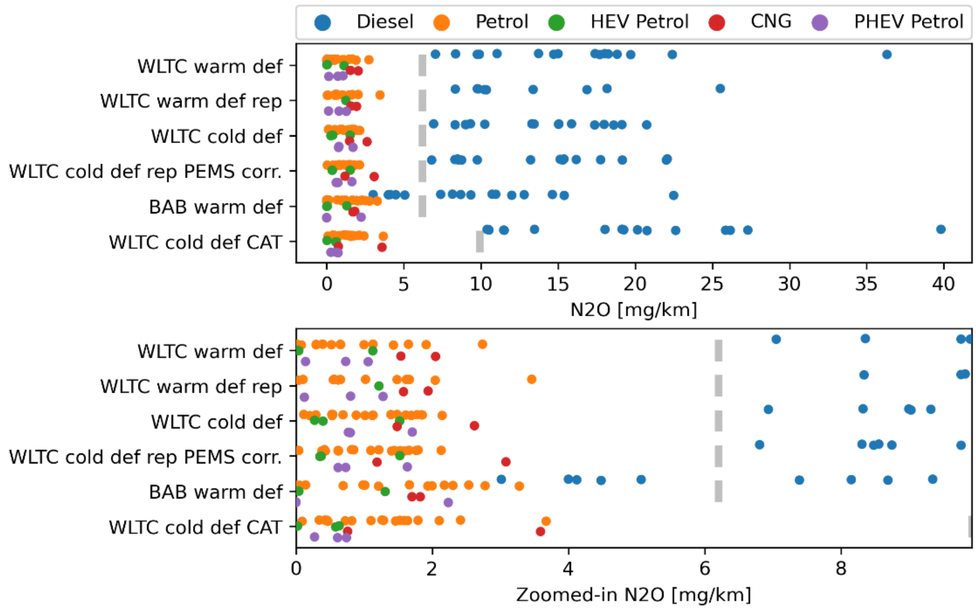

Figure 3.3: N_2O emissions as averaged over the entire trip. The top panel shows all data measured on the chassis dyno including the thresholds proposed by GVI in grey. The bottom panel shows the zoomed-in version of the top panel.

4 Trip-averaged regulated pollutants show most vehicles performing better than GVI threshold

Within GVI and Green NCAP performance thresholds are established for each relevant emission constituent. The thresholds are technology neutral and are independent of vehicle size, body style, maximal vehicle mass (capped to 3,500 kg). The pollutant thresholds for the PEMS+ tests are higher than those of the chassis dynamometer tests by a conformity factor of 1,32, based on the PEMS uncertainty margin. Where possible, the thresholds are based on the emission legislation. However, the most stringent limit is chosen. For example, the GVI threshold for NO_x emissions during chassis dynamometer tests is 60 mg/km (based on the limit for petrol vehicles) for all vehicle types, while emission legislation for diesel vehicles is less stringent (80 mg/km). Since not all emission constituents are regulated, plausible thresholds are determined in the technical working group of GVI/Green NCAP. Within GVI, these thresholds are also referred to as ‘upper limits’, which are used for rating the vehicles. For this purpose, ‘lower limit’ values were established as well. The ‘lower limit’ values were assumed to be 0 in GVI. In other words, only zero tailpipe emissions are given the maximum score for the pollutant emissions.

4.1 Pollutants measured during on-road measurements

For the pollutants CO, NO_x and PN, measurements are made both on-road with PEMS equipment and on the chassis dyno using laboratory equipment.
The trip-averaged emissions show wide ranges per fuel type.

4.1.1 CO

For CO, most trips fall within the GVI threshold (Figure 4.1), although outliers are observed especially for the high-speed BAB and cold ambient temperature (-7 °C) laboratory tests, as well as the ‘heavy’ on-road test. On average, the petrol vehicles emit 470 mg/km, which is an order of magnitude smaller than the current VERSIT+ emission factors (the current urban emission factor is 4.5 g/km).

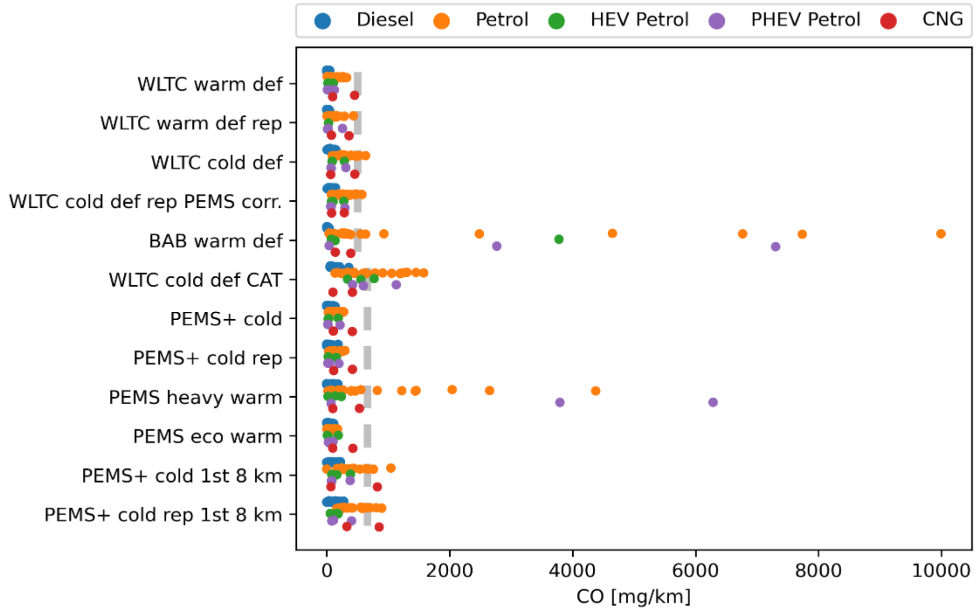

Figure 4.1: CO emissions as averaged over the entire trip. The thresholds proposed by GVI are shown in grey.

4.1.2 NO_x

Several diesel vehicles have average emissions above the GVI threshold, again for the high-speed and low temperature lab tests and the heavy on-road test. Note that the average emissions were also determined for the first eight kilometres of the cold start on-road tests (PEMS+ cold 1st 8 km in Figure 4.2); most vehicles also meet the threshold when the emissions are averaged only over the first eight kilometres.
On average, diesel NO_x emissions are 49 mg/km, which corroborates current VERSIT+ emission factors for Euro 6d-Temp. Note that for urban and rural driving there is almost a 50% difference between averages determined for Euro 6d-Temp and Euro 6d. This difference has been observed in other measurement programmes (De Ruiter et al., 2020 & Van Mensch et al., 2022), and was confirmed by the GVI data.

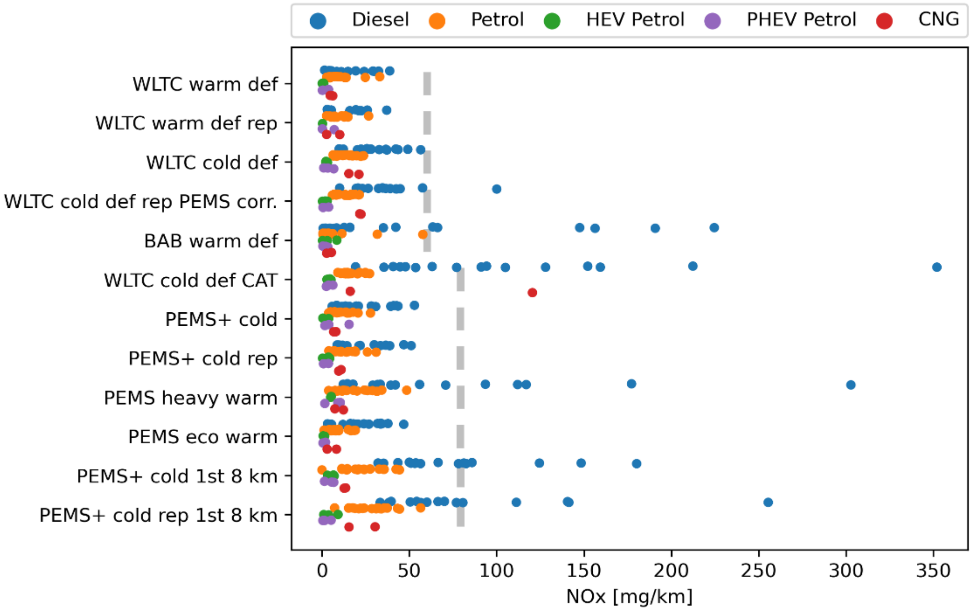

Figure 4.2: NO_x emissions as averaged over the entire trip. The thresholds proposed by GVI are shown in grey.

4.1.3 PN

For PN, the trips that lead to average emissions above the posed threshold are those with cold starts, though there are very few (Figure 4.3). The average of the first eight kilometres is compared with the average over the entire corresponding on-road test in Figure 4.4. The tested vehicles include a variety of vehicles with DPF, GPF and without particulate filter. There is a general clustering of the three categories, though there are a number of petrol vehicles without particulate filters that perform better than those with GPF. Typically, all petrol vehicles with direct injection are equipped with GPF. For port-fuel injection petrol vehicle there is no particle emission standard and GPF technologies are not applied in this case.
A more in-depth study would be needed to establish potential consequences for PM.

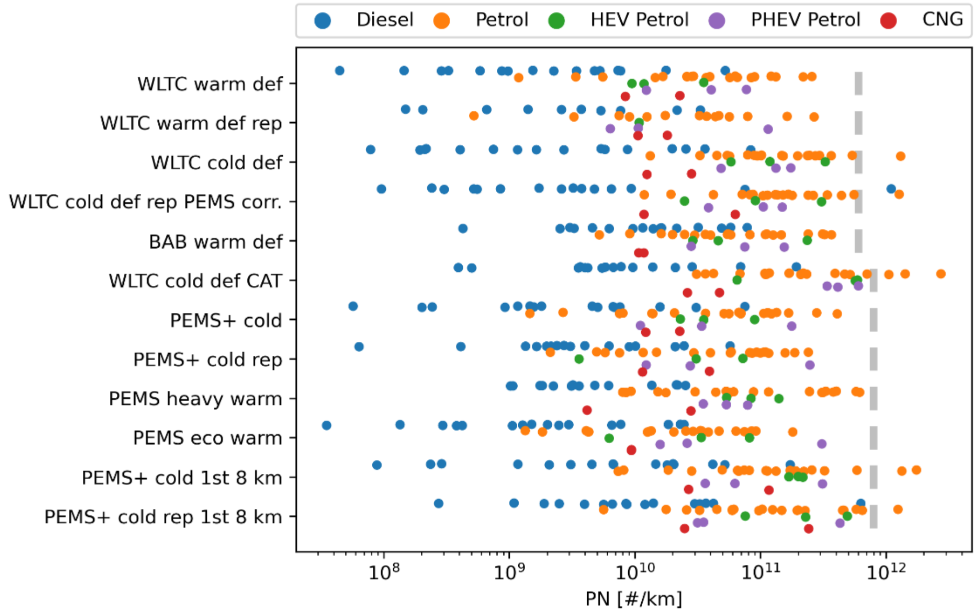

Figure 4.3: PN emissions as averaged over the entire trip. The thresholds proposed by GVI are shown in grey.

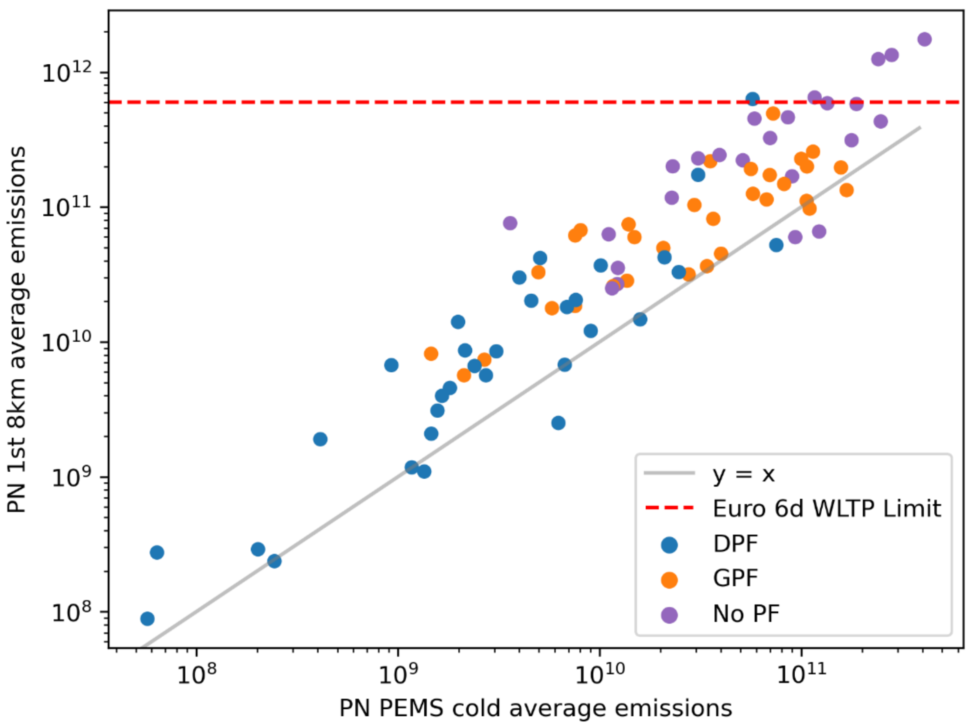

Figure 4.4: PN emissions as averaged over the first 8 km of a trip, as compared to the average over the entire trip. Blue points indicate diesel vehicles with DPF, orange petrol vehicles with GPF, and purple vehicles without a particulate filter. The dashed red line indicates the Euro 6d WLTP limit for PN.

4.2 CH_4 and THC are measured only in the laboratory

CH_4 and THC emissions are measured in the laboratory on a chassis dyno.[12] Most tests fall within the proposed thresholds, though there are again a number of outliers.

4.2.1 CH_4

There is a substantial difference between the average CH_4 measured for the two different CNG vehicles for the cold ambient temperature test and the high-speed BAB test, which is not evident during the different WLTC tests. This would suggest that further testing would be useful to determine the likely emissions during on-road driving. Measured average emissions for diesel vehicles are slightly higher than what is currently in VERSIT+ (e.g., 5 mg/km vs 2 mg/km). In contrast, for petrol vehicles, the average measured emissions are more than an order of magnitude lower than currently in VERSIT+ for urban and rural areas (e.g., 41 mg/km vs 1.7 mg/km for urban areas).

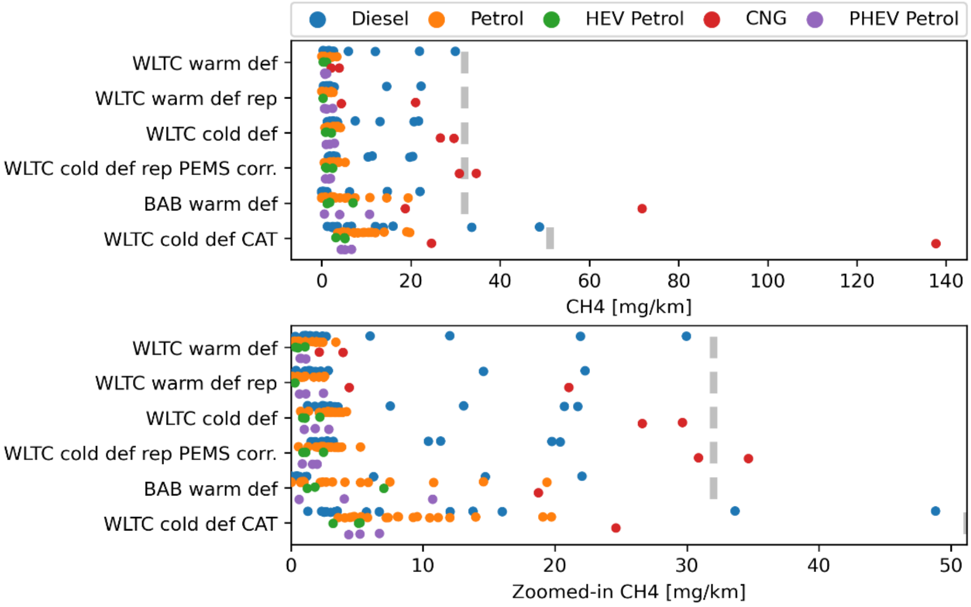

Figure 4.5: CH_4 emissions as averaged over the entire trip. The top panel shows all data measured on the chassis dyno including the thresholds proposed by GVI in grey. The bottom panel shows the zoomed-in version of the top panel.:

4.2.2 THC

When considering Figure 4.6, the average emissions during the cold ambient temperature are obviously higher than the other tests performed. As mentioned above there is a large discrepancy with regards to the difference in average THC as measured for the two CNG vehicles during WLTC tests vs. the high-speed and cold ambient temperature tests.

[12] Note that GNCAP considers CH_4 as a Greenhouse Gas (GHG) instead of a pollutant.

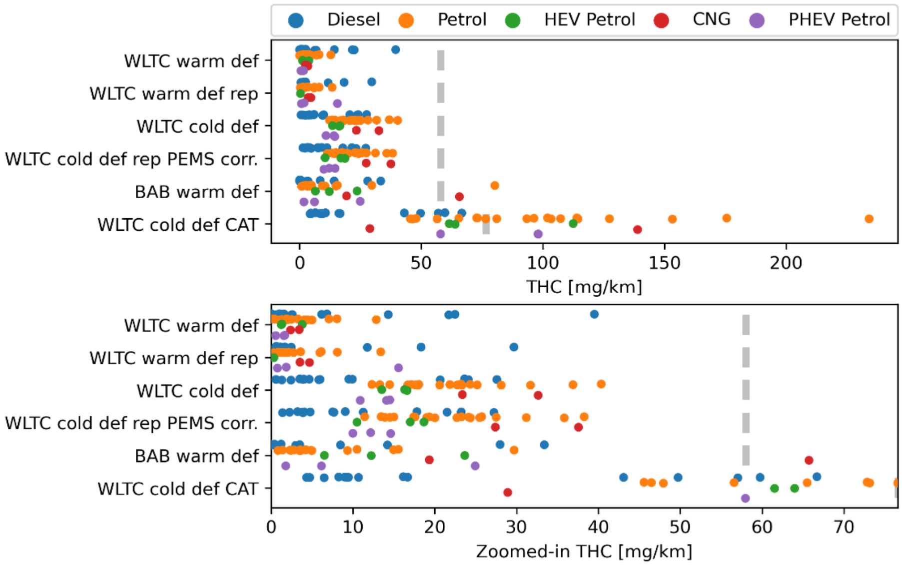

Figure 4.6: THC emissions as averaged over the entire trip. The top panel shows all data measured on the chassis dyno including the thresholds proposed by GVI in grey. The bottom panel shows the zoomed-in version of the top panel. This graph includes THC results, however, in the current GNCAP evaluation the threshold is applicable to NMHC, as CH_4 has been shifted to GHG.

5 Specific testing for potential high-emission situations highlights differences in emission behaviour

A number of different tests are used to investigate the emissions of vehicles during situations which could lead to high emissions. Here five different situations are highlighted: cold starts, cold starts at low temperature, idling emissions, dynamic driving, and DPF regenerations. These test results reinforce that there is a large variation in how different vehicles perform under these conditions.

5.1 On average, cold engine starts are often complete within the first two kilometres

To determine the magnitude of cold start emissions, the end of cold start period should be defined. Therefore, in this study, the end of a cold start is investigated by looking at plateaus in emissions. Figure 5.1 shows an example of how the impact of a cold start is determined. The vehicle represents a modern diesel vehicle. Figure 5.1 displays that after 2.2 kilometres a plateau in emissions occur, in these 2.2 km, 238 milligrams (mg) of NO_x are emitted. After this 2.2 km, there is hardly any increase of emitted NO_x. This 238 mg of NO_x can be seen as an offset due to cold start. This offset is often a large part of the total emissions. Clearly, these effects depend on the type of pollutant, and the type of vehicle.

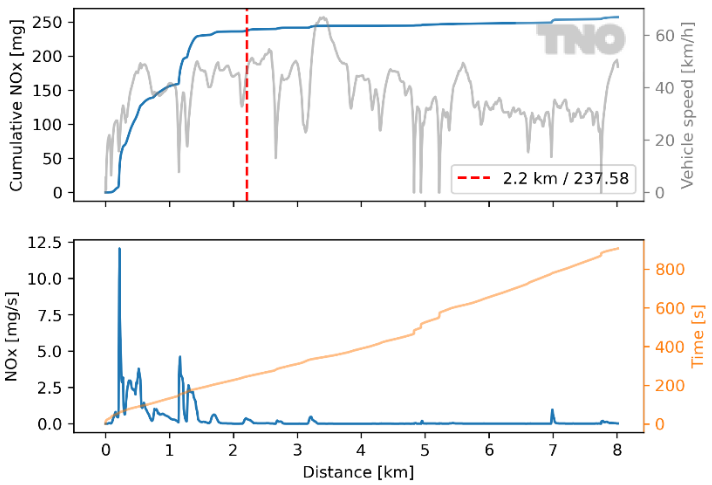

Figure 5.1: End of cold start can be investigated by looking at plateaus in emissions

With regards to emission factors, the effects of these emissions are often delocalised over all urban and rural roads. However, it is becoming clear that the high emissions associated with cold engine starts are confined to increasingly shorter distances. There is a large variation in both the total amount of pollutants emitted during a cold start (Figure 5.2), as well as the distance within these emissions occur, but the average distance is often within two kilometres. This suggests that cold-start emissions could perhaps be better considered as a more localised emission source, localised where vehicles start driving with cold engines.

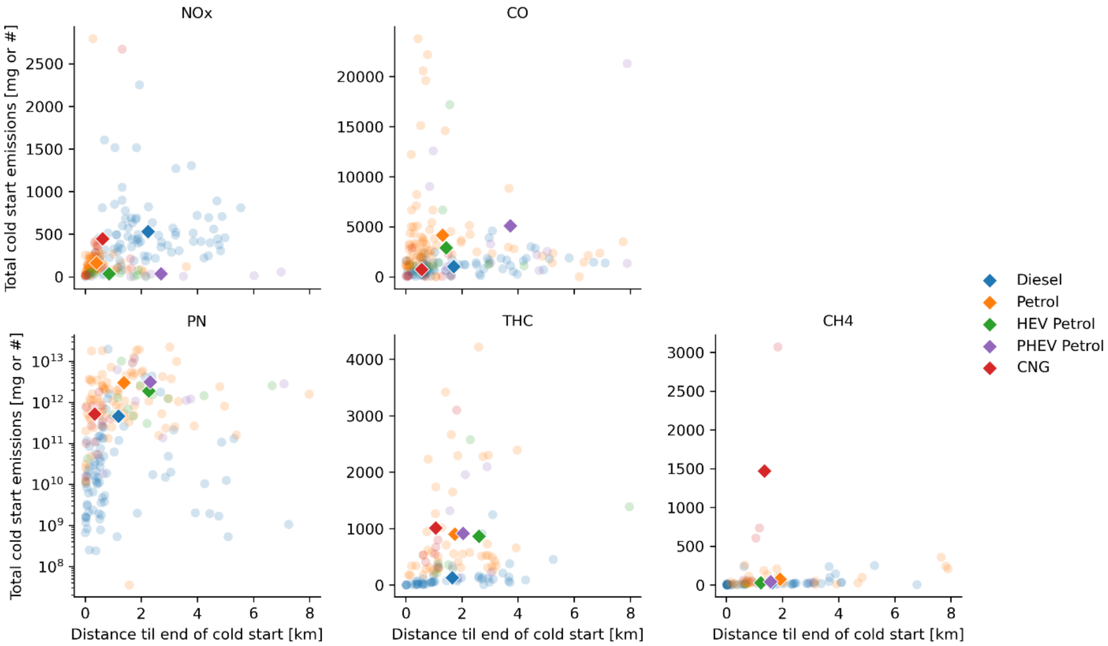

Figure 5.2: Total emissions and the distance until the end of the cold start. Each round point indicates a trip (coloured by fuel type), while the diamonds indicate the average per fuel type.

5.2 Comparing total cold start emissions during laboratory tests at two different temperatures highlights the need for more testing at low temperatures

For each vehicle, a low temperature laboratory test was performed on the chassis dyno. In

Figure 5.3 the total emissions per cold start are compared to the relevant ambient temperature, for both PEMS and laboratory measurements. Note that no marked difference was observed for PN at low temperature. The increase in emissions at low temperature varies (as shown by the light blue and orange lines Figure 5.3). Furthermore, interpolation or extrapolation of this increase is likely invalid as the two tests with the lowest temperatures are mostly a) WLTC tests (measured at 14 °C) and b) separated by more than 20 °C. I.e., most of the other tests, including PEMS, were tested at temperatures higher than 14 °C. For example, extrapolating the emissions from measurements above 0 °C down to low temperatures would suggest a very different low temperature behaviour. For this reason, we suggest that more low temperature tests are needed before more definitive conclusions can be reached.

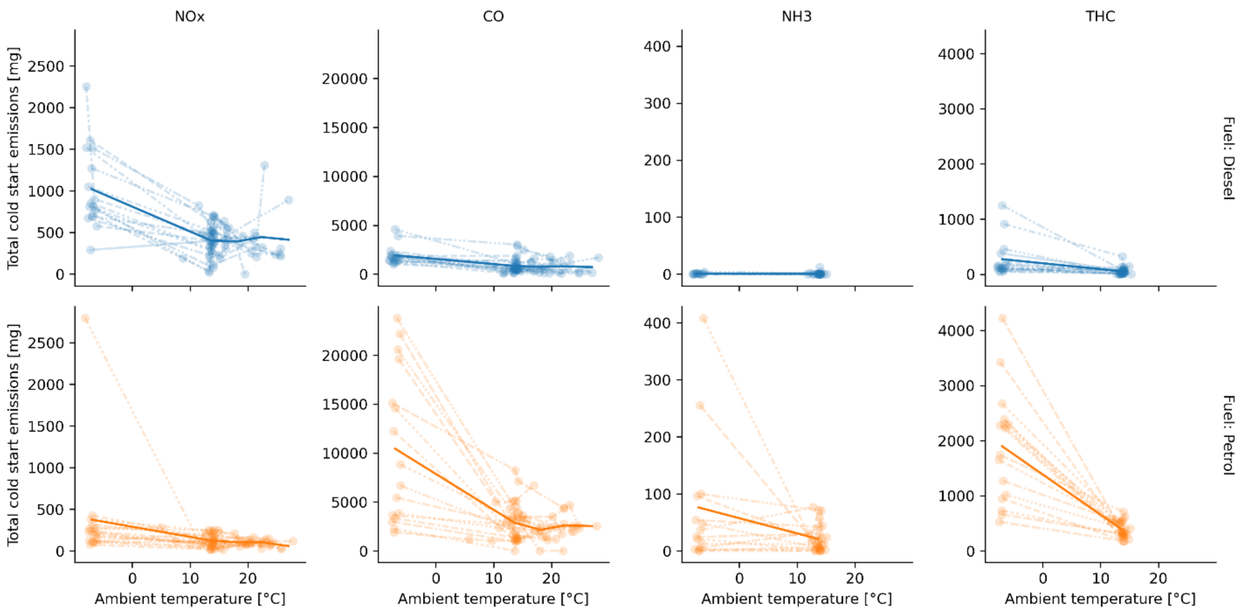

Figure 5.3: Total emissions per cold start compared to the relevant ambient temperature, for both PEMS and laboratory measurements. Each point indicates a measurement, and measurements per vehicle are connected with lines. The bold lines indicate the average emissions for all tests measured at that temperature. Diesel (blue) and petrol (orange) results are shown on different rows, while each column corresponds to a pollutant.

5.3 Idling NO_x emissions increase significantly after around five minutes

Idling is a common occurrence during normal vehicle use but is not accounted for during type approval testing. However, as shown in Figure 5.4, idling NO_x emissions for diesel cars can increase dramatically after the first few minutes. Although the petrol vehicles tested did show an initial peak, most remained low with very slight increases. Notably, there is a large variation in how the diesel cars' NO_x emissions increase over time, highlighting that some vehicles demonstrate that idling emissions can be kept low. However, considering that most idling is likely to occur in urban situations, not taking the elevated emissions into account could lead to a significant underestimation of urban emissions.

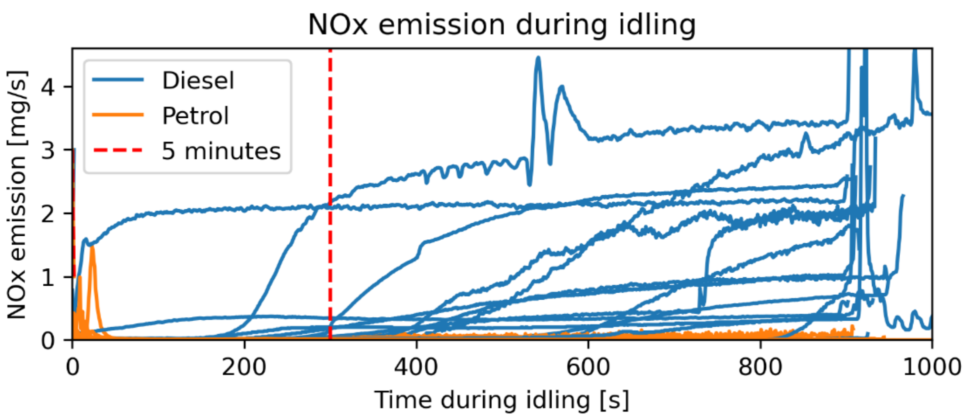

Figure 5.4: Instantaneous NO_x emissions during a period of extended idling for a number of different petrol and diesel vehicles. The red line indicates five minutes, which is the maximum duration of idling allowed during an RDE test.

5.4 Dynamic driving leads to significantly higher emissions

Dynamic driving is often described using $v \cdot a_{pos}$, with a the acceleration and v the positive velocities, where the product is positive. The high values of $v \cdot a_{pos}$ can be considered aggressive driving at lower speeds. However, high values of $v \cdot a_{pos}$ can also occur during passing manoeuvres or accelerating onto the highway. Emissions during four different on-road tests are compared for different $v \cdot a_{pos}$ for both a petrol and diesel vehicle, as shown in Figure 5.5 and Figure 5.6 respectively. In the case of the petrol vehicle, the 'PEMS heavy warm' test has significantly higher CO emissions, though both the cold tests do show higher emissions at higher $v \cdot a_{pos}$ (Figure 5.5, left panel).

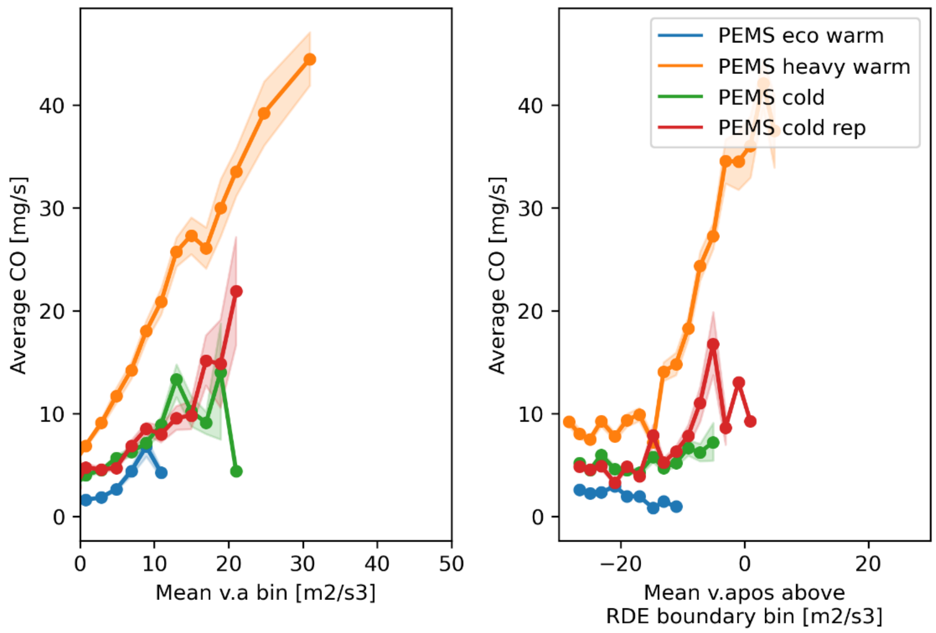

Figure 5.5: CO emissions of a petrol Euro 6d-Temp vehicle (left) as a function of $v \cdot a_{pos}$ and (right) as compared to the boundary to $v \cdot a_{pos}$ that would apply during an RDE test.

Although NO_x emissions for the diesel vehicle are consistently lower at lower $v \cdot a_{pos}$ for all four trips (Figure 5.6, left), a sharp increase is observed at higher $v \cdot a_{pos}$. This becomes especially evident when compared to the $v \cdot a_{pos}$ boundary (Figure 5.6, right), where increased emissions are observed above zero.
Note that when compared to the petrol vehicle above, this diesel vehicle was driven in more situations with $v \cdot a_{pos}$ above the RDE boundary (right panel in Figure 5.5 and Figure 5.6). These measurements highlight the need for broad testing to determine emission levels which do occur during normal on-road driving, but are not included in type-approval testing.

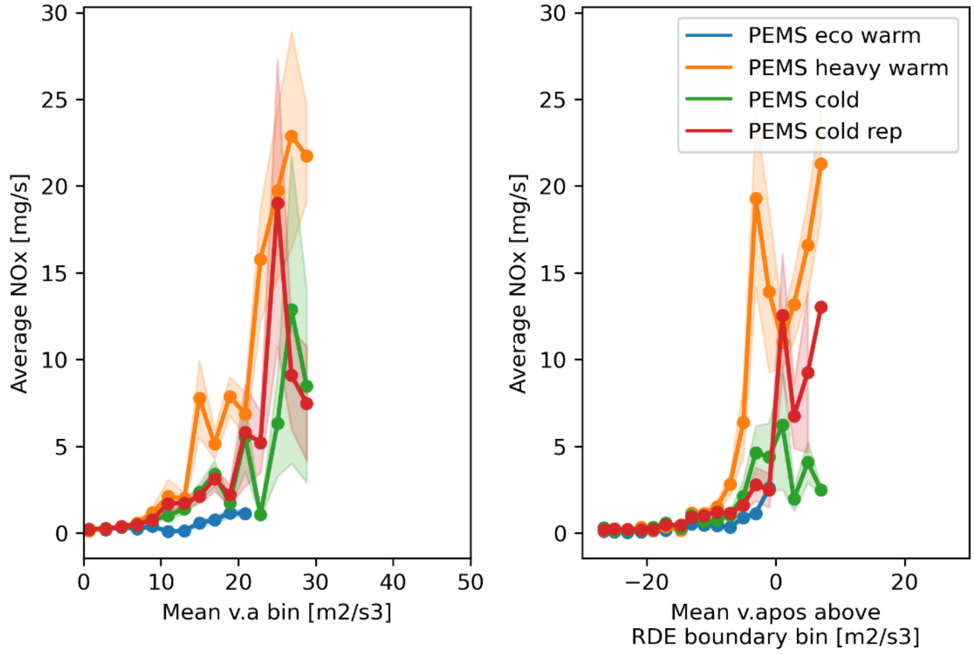

Figure 5.6: NO_x emissions of a diesel Euro 6d-Temp vehicle (left) as a function of $v \cdot a_{pos}$ and (right) as compared to the boundary to $v \cdot a_{pos}$ that would apply during an RDE test.

5.5 DPF regenerations lead to a significant increase in emissions

Diesel particulate filters (DPFs) are used in diesel vehicles to filter particulate matter and thereby decrease PN emissions. The built-up particulate matter is regularly oxidised via very hot exhaust gas temperatures in a regeneration event. During DPF regenerations significantly higher NO_x, CO and PN emissions are detected than during normal driving (Figure 5.7). However, it is difficult to ascertain how often these events occur, as they are often separated by hundreds of kilometres which is often longer than an average testing programme. Because it is often difficult to determine the interval between DPF regenerations, it is difficult to quantify exactly how much of an effect these elevated emissions would have on average emissions.

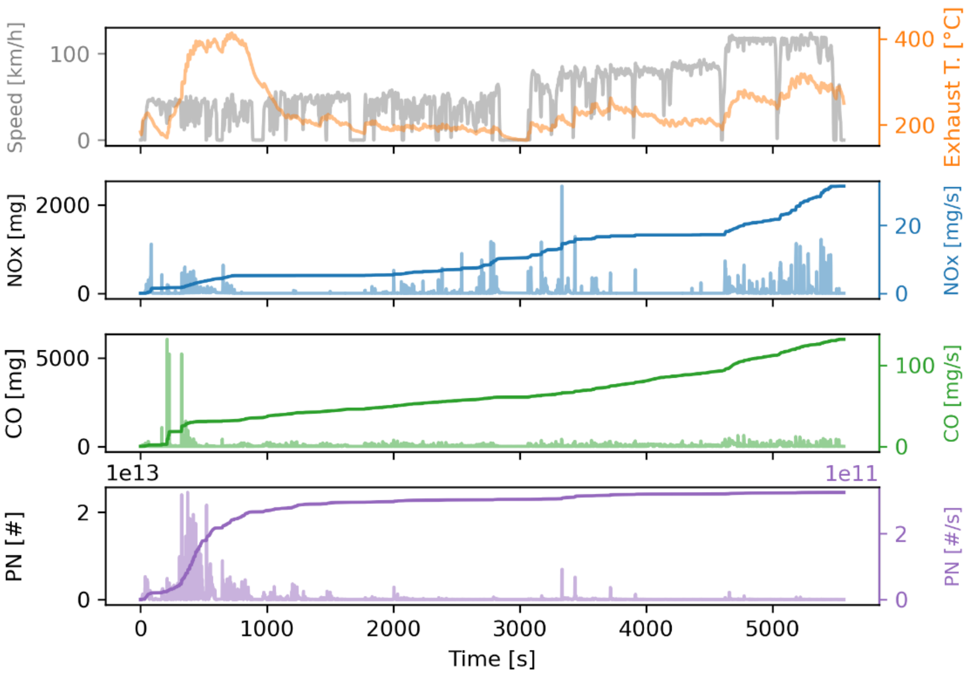

Figure 5.7: Relevant details for a trip containing a DPF regeneration, shown over time. The top panel shows the instantaneous speed in grey, and the exhaust gas temperature in orange. The lower three panels show both the cumulative (darker line) and instantaneous (lighter line) emissions for NO_x, CO, and PN respectively. The regeneration takes place between approx. 250 and 1000 s.

In (de Ruiter *et al.*, 2020), 5 Euro 6d-Temp vehicles were found to have an average DPF interval of 208 – 628 km. If the expected average DPF interval is 450 km, this would lead to an average increase of 5.2 mg/km NO_x, 5.1 mg/km CO and 3.4 x 10^{10} [#/km] on the respective emission factors if the emission factors are based on measurements that do not include DPF regenerations. However, as shown in Figure 5.8, DPF regenerations can lead to a *local* additional 4 g of NO_x or CO, or 5 x 10^{13} PN. Although it has been supposed in the past that DPF regenerations occur primarily at high speeds (Indrajuana et al., 2020), Figure 5.7 shows that there are also incidences where regenerations occur at low speeds, and therefore likely in urban areas. In urban areas, DPF regenerations can therefore have a large impact on local emissions.

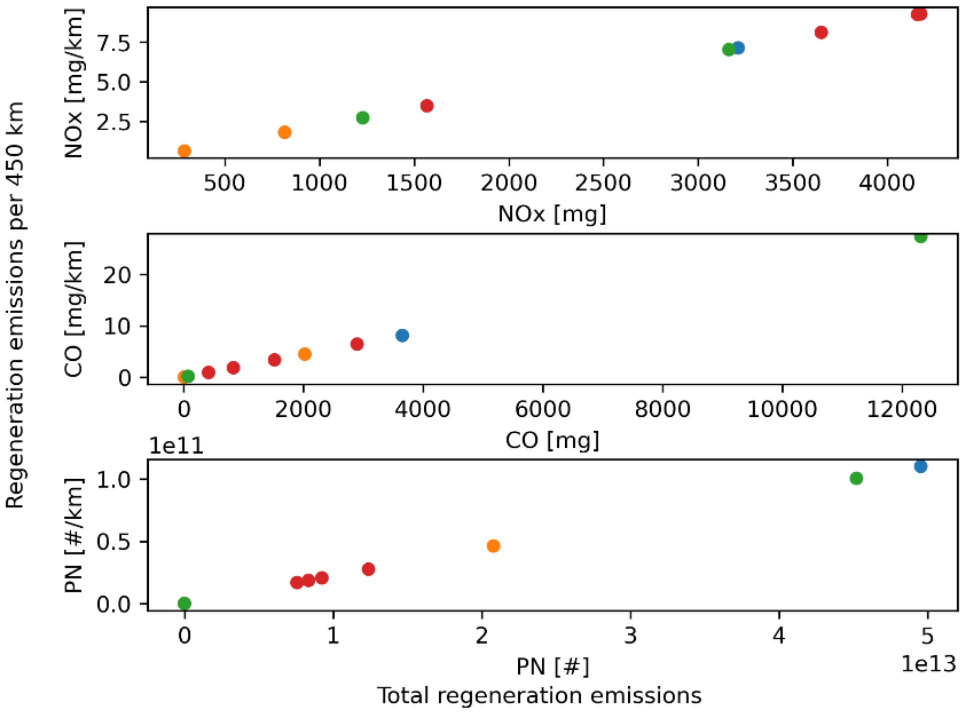

Figure 5.8: Total pollutant emissions during regeneration, colour indicates the specific vehicle.

6 Broadening the scope of PN emissions down to 10 nm leads to an average increase of 87 percent

For multiple vehicles, particle number size down to 10 nm (PN10) was measured alongside the usual PN23 measurements for selected tests. In this report the results of four vehicles were analysed (including petrol, HEV petrol, and PHEV petrol vehicles). The comparison between these is shown in Figure 6.1. For all tests and vehicles, there is an average increase of 87% when measuring particle number down to 10 nm. Therefore, almost half of the PN emissions above 10 nm occur between 10 nm and 23 nm, with more smaller particles at higher velocities and more aggressive driving. For PEMS trips specifically, this was 40%, while for the high-speed BAB test there was an average increase of 190%. However, with the exception of two trips, average emissions remained well below the Euro 6d WLTP limit.

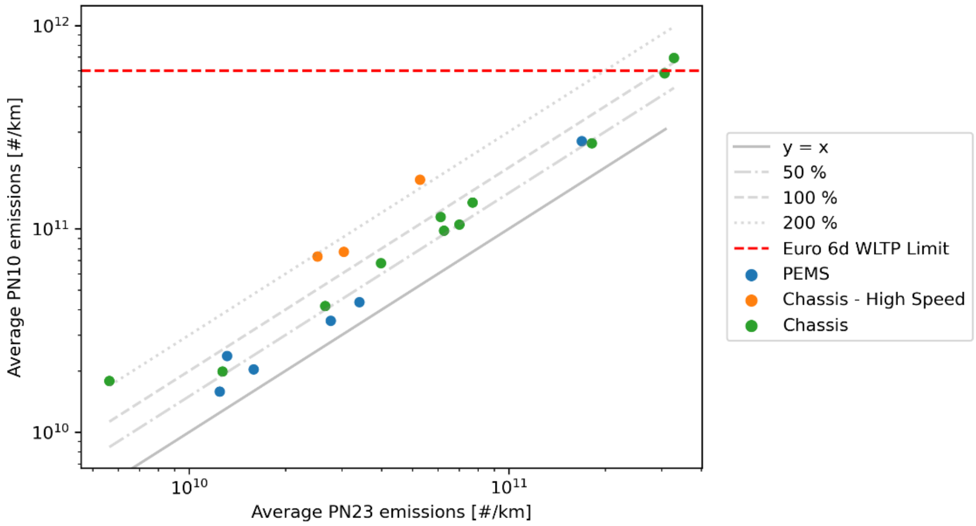

Figure 6.1: Average PN10 emissions as compared to the average PN23 emissions per trip. Points are coloured to indicate whether the trip was measured by PEMS or on the chassis dyno (Chassis). The high-speed BAB tests are coloured separately (Chassis – High Speed). Grey lines give an indication of PN10 relative to PN23, where the solid line indicates y = x and the dashed lines indicate an increase of 50, 100 or 200%.

7 Strong correlation between laboratory and PEMS measurement equipment

WLTC tests were performed on the chassis dyno while PEMS equipment was also installed. The average emissions as determined via laboratory equipment and PEMS are shown in Figure 7.1, while the absolute and percentage errors for petrol and diesel are shown in Table 7.1. There is a strong correlation for the three pollutants NO_x, CO and PN, though there are some interesting observations. In the case of NO_x, there is a maximum absolute error of 12 mg/km (for a petrol car with average emissions of 25 mg/km), though the average across all fuels is only 2.2 mg/km. The largest percentage errors are observed for diesel measurements of PN, where an absolute error of 1.6×10^9 #/km corresponds to a percentage error of over 100 %. However, related to the emission limit of 6 x 10^{11} #km, the deviation is less than 1%. In the case of CO there is a general underestimation by PEMS for petrol vehicles, on average by 27 mg/km. Considering the order of magnitude of the measured emissions, as well as the fluctuations of emissions over the length of a trip, we consider the deviations between laboratory and PEMS equipment very small.

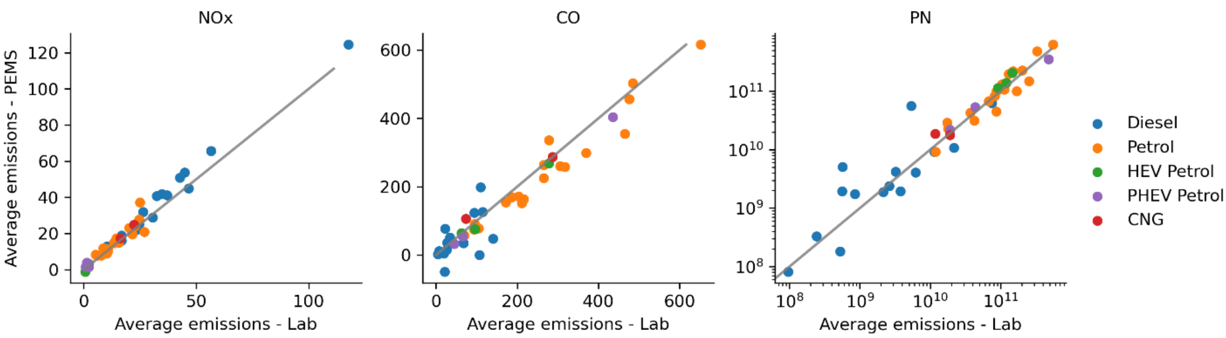

Figure 7.1: Average emissions per trip as determined via laboratory equipment compared to the average emissions as measured on the PEMS system.

Table 7.1: Average absolute and percentage error of PEMS with respect to measurements on the chassis dyno for diesel and petrol vehicles.

Pollutant	**Fuel**	**Average absolute error**	**Average percentage error [%]**
NOx [mg/km]	Diesel	4.2	11.0
	Petrol	1.3	10.8
CO [mg/km]	Diesel	-9.9	-17.7
	Petrol	-27.3	-11.6
PN [#/km]	Diesel	1.6E+09	117.9
	Petrol	1.1E+10	7.0

8 Conclusion

Comprehensive testing programmes, both on-road and in the laboratory, give insight into emission behaviour in different potential high-emission situations. In this report, more than 40 vehicles were analysed that had been subjected to the broad testing programme devised within GVI. This included a range of Euro 6d-Temp and Euro 6d diesel, petrol, plug-in petrol, petrol hybrid, and CNG vehicles. The current analysis results in the following main conclusions:

- **Non-regulated pollutants NH_3 and N_2O deserve continued monitoring**
  Across all performed tests, petrol vehicles emit an average of 13 mg/km NH_3, while diesel vehicles emit 1.6 mg/km NH_3. Note that the test performed at cold ambient temperature (-7 °C) as well as the high-speed BAB tests show a wider range of average NH_3 emissions.

  With regard to N_2O, diesel vehicles emit an average of 14 mg/km (3.7 g CO_2 eq.), while petrol vehicles emit on average 1.1 mg/km. Furthermore, no clear correlation was observed between low NO_x and N_2O emissions.

- **Most vehicles perform within the GVI thresholds for regulated pollutants**
  Within GVI and Green NCAP performance thresholds (vehicle and engine technology neutral) are established for each relevant emission constituent. Trip-averaged regulated pollutants show that most vehicles perform better than the GVI threshold (upper limit). Nevertheless, several vehicles have average emissions above the GVI threshold. This mainly occurred during the high-speed (BAB) and low ambient temperature (-7 °C) lab tests and the heavy on-road test.

- **Cold engine starts are a localised effect**
  There is a large variation in both the total amount of pollutants emitted during a cold engine start, as well as the distance within these emissions occur. However, the average distance with elevated emissions due to the cold engine start is often two kilometres or less. Moreover, the emissions associated to the cold engine start are often dominant in the total trip emissions.

- **Idling NO_x emissions increase significantly after around five minutes**
  There is a large variation in how the diesel cars' NO_x emissions increase over time. Some vehicles show that idling emissions can be kept low. As idling is most likely to occur in urban situations, these elevated emissions should always be taken into account in normal use to not underestimate urban emissions.

- **DPF regenerations lead to a significant increase in emissions, and can occur in urban settings**
  If the expected average DPF regeneration interval is 450 km, this would lead to an average increase of 5.2 mg/km NO_x, 5.1 mg/km CO and 3.4×10^{10} [#/km] on the respective emission factors if the emission factors are based on measurements that do not include DPF regenerations. However, DPF regenerations can lead to a *local* additional 4 g of NO_x or CO, or 5×10^{13} PN.

- **For most trips, expanding PN23 measurements down to PN10 still resulted in average emissions below 6 x 10^{11}**
  For multiple vehicles, particle number size down to 10 nm (PN10) was measured alongside the usual PN23 measurements for selected tests. In this report the results of four vehicles were analysed (including petrol, HEV petrol, and PHEV petrol vehicles). These tests and vehicles revealed an average increase of 87% when measuring particle number down to 10 nm instead of to 23 nm. For PEMS trips specifically, this was 40%, while for the high-speed BAB test there was an average increase of 190%. Despite this increase, these vehicles remained below the current limit of 6 x 10^{11} during most of the trips.

9 References

de Ruiter, J. M. *et al.* (2020). *Emissions of five Euro 6d-Temp Light Duty diesel vehicles* - TNO 2020 R12024.

Indrajuana, A. P. *et al.* (2020). *Monitoring-based assessment of the NOx-emissions of a Renault Talisman and a Volkswagen Caddy* - TNO 2020 R10438

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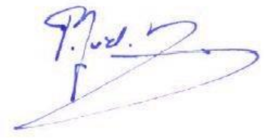
10 Abbreviations

ACI	Automobile Club d’Italia
ADAC	Allgemeiner Deutscher Automobil-Club
BAB130	Bundesautobahn test
BASt	Bundesanstalt für Straßenwesen
CAT	Cold Ambient Temperature
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CNG	Compressed Natural Gas
CVT	Continuously Variable Transmission
DPF	Diesel Particulate Filter
Empa	Eidgenössische Materialprüfungs- und Forschungsanstalt
FIA	International Automobile Federation
GHG	Greenhouse Gas emissions
GPF	Gasoline Particulate Filter
GVI	Green Vehicle Index
HEV	Hybrid Electric Vehicle
ICRT	International Consumer Research & Testing
IDIADA	Institut d'Investigació Aplicada de l'Automòbil
IFA	Institut für Fahrzeugantriebe & Automobiltechnik
N_2O	Nitrous Oxide
NCAP	New Car Assessment Programme
NH_3	Ammonia
NO_x	Nitrogen Oxides
NMHC	Non-Methane Hydrocarbons
ÖAMTC	Österreichische Automobil-, Motorrad- und Touring Club
PEMS	Portable Emissions Measurement System
PHEV	Plug-In Hybrid Electric Vehicle
PM	Particle Matter
PN	Particle Number
PN10	Number of Particles with a size down to 10 nm
PN23	Number of Particles with a size down to 23 nm
RDE	Real Driving Emissions
THC	Total Hydrocarbons
TCS	Touring Club Schweiz
TNO	Netherlands Organisation for Applied Scientific Research
UTAC	Union Technique de l'Automobile, du motocycle et du Cycle
WLTC	Worldwide harmonized Light vehicles Test Cycle
WLTP	Worldwide harmonized Light vehicles Test Procedure

11 Signature

The Hague, 3 May 2022

TNO



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