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Analysis of the emission performance of vehicles tested within the Green NCAP programme

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Summary

In 2022 an initial investigation was performed on data made available as part of the Horizon 2020 'Green Vehicle Index' (GVI) project which highlighted the emission performance of Euro 6d and Euro 6d-Temp vehicles [TNO 2022a]. This analysis is continued with additional data from the Green NCAP consortium. [1] On behalf of the Dutch Ministry of Infrastructure and Water Management, TNO has summarised the highlights of the emission performance of the vehicles tested within Green NCAP and compared this to the GVI dataset.

Comprehensive testing programmes, both on-road and in the laboratory, give insight into emission behaviour in different potential high-emission situations. In this report, 101 vehicles were analysed, including a range of Euro 6d-Temp and Euro 6d diesel, petrol, plug-in petrol, petrol hybrid, CNG and BEV vehicles.

The data collected for Green NCAP has a number of interesting outcomes. One part of the outcomes is related to the emission performance of 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 occur. For example, during a cold engine start, high driving dynamics, prolonged idling and DPF regenerations. The Green NCAP programme provides insights in the emission levels for a number of these circumstances. Moreover, in the measurement programme non-regulated emissions such as NH_3 and N_2O are also considered. These insights can, for example, serve as input for determining emission factors for air quality models. Emission factors are distinct for categories with distinct emission performance, technology, or vehicle type or usage.

In this report there is a specific focus on the non-regulated pollutants and the potential impact on TNO's VERSIT+ [2] emission factors based on these insights.
Moreover, the performance of electric vehicles are included.

The current analysis results in the following main conclusions:

- *High trip-averaged emissions for regulated pollutants are primarily observed during the high speed (BAB) and cold ambient temperature (-7 °C) laboratory tests, and heavy on-road tests*
  Even though most of the vehicles tested performed well within the thresholds for the RDE-like on-road tests, these three tests especially demonstrated high average emissions for regulated pollutants. This re-emphasises the need for comprehensive testing.

- *Non-regulated pollutants N_2O and NH_3 deserve continued monitoring*
  Diesel vehicles show consistently high N_2O emissions compared to other fuels; petrol vehicles emit a trip-averaged 0.96 mg/km N_2O, while diesel vehicles emit around 14 mg/km (3.7 g CO_2 eq.).

[1] https://www.greenncap.com/
[2] TNO's emission factor model. This model is used for the Dutch Emission Inventory for road traffic: https://www.tno.nl/nl/duurzaam/duurzaam-verkeer-vervoer/emissiefactoren-luchtkwaliteit-stikstof/

However, several vehicles showed VERSIT+ road-type emissions of over 40 mg/km (11 g CO_2 eq.). This reduces the benefits of the typical lower CO_2-emissions of diesel vehicles. Across all performed tests, petrol vehicles emit an average of 11 mg/km NH_3, while diesel vehicles emit 2.6 mg/km. There are several petrol vehicles with VERSIT+ road-type emissions higher than 20 mg/km, though one diesel 6d-Temp has emissions in excess of 80 mg/km.

- *Cold starts are now considered best represented by a point source*
  Extended testing has shown that high emissions due to a cold engine occur over increasingly short distances. A technology-neutral approach has been taken where cold start extra emissions are determined using the difference between the average emissions during the first kilometre and the average over an entire trip. This has been implemented within VERSIT+ as the road-type 'WKS' (Wegtype Koude Start).

- *PN emissions vary significantly depending on engines and how they're used*
  When considering PN emissions as a function of both CO_2 and velocity, the localisation of high emissions varies between vehicles as well as technologies. PN emission factors have been reintroduced to VERSIT+ using the emission factors calculated here, for petrol cars this is an order of magnitude higher than previously used emission factors.

- *Several of the tested vehicles likely have an insufficiently large catalyst*
  Relatively high pollutant emissions as a function of CO_2 can indicate the inability of the after-treatment system to effectively treat the exhaust gas flow due to its size. Several diesel vehicles have been observed which demonstrate this.

- *Energy consumption of BEVs, caused by propulsion or auxiliaries, can be substantial*
  The charging losses of the 16 tested BEVs are substantial and vary from about 8 to 21%. Also during stationary moments (speed < 0.5 km/h), the power use can be substantial. Averaged over all stationary moments per single test the mean power use is roughly between 0.5 and 2.5 kW. For urban use with an average speed of 30 km/h that means that, of the total energy consumption, 17-80 Wh/km is not related to propulsion, which can be up to half of the total consumption.

Samenvatting

In 2022 is een eerste analyse uitgevoerd op meetdata welke beschikbaar kwam in het Horizon 2020 ''Green Vehicle Index' (GVI) project dat de emissieprestaties van Euro 6d en Euro 6d-Temp voertuigen onder de aandacht bracht [TNO 2022a] . Deze analyse is voortgezet met aanvullende meetdata van het Green NCAP consortium[3]. In opdracht van het Nederlandse Ministerie van Infrastructuur en Waterstaat, heeft TNO de in het oog springende emissieprestaties van de in Green NCAP geteste voertuigen samengevat en vergeleken met de GVI dataset.

Uitgebreide testprogramma's, zowel op de weg als in het laboratorium, geven inzicht in het emissiegedrag in verschillende situaties die mogelijk tot hoge emissies kunnen leiden. In dit rapport zijn 101 voertuigen geanalyseerd, deze omvatten een scala aan Euro 6d-Temp en Euro 6d diesel, benzine, plug-in benzine, hybride benzine, CNG en batterij-elektrische voertuigen (BEVs).

De analyse van de data welke verzameld is voor Green NCAP heeft een aantal interessante uitkomsten. Een deel van de uitkomsten is gerelateerd aan de generieke emissieprestaties van moderne voertuigen. In het algemeen zijn de emissieprestaties van deze voertuigen goed, een forse verbetering ten opzichte van vorige generaties Euro 6 voertuigen, dit geldt in het bijzonder voor dieselvoertuigen. Dit is het resultaat van de introductie van Real Driving Emissions (RDE) wetgeving Hiermee is met succes het grote gat (grotendeels) gedicht tussen emissies tijdens de typekeuring en emissies gedurende alledaags rijden op de weg. Desalniettemin zijn er nog altijd omstandigheden, waaronder verhoogde vervuilende emissies kunnen plaatsvinden. Bijvoorbeeld tijdens een koude start van de motor, tijdens rijden met hoge dynamiek (frequent hard optrekken en afremmen), langdurig stationair draaien en regeneraties van het roetfilter. Het Green NCAP programma verschaft specifieke inzichten in de emissieniveaus gedurende een aantal van deze omstandigheden. Daarnaast biedt het meetprogramma ook inzicht in ongereguleerde vervuilende emissies zoals ammoniak (NH_3) en lachgas (N_2O). Deze inzichten kunnen, bijvoorbeeld, dienen als invoer voor het bepalen van emissiefactoren voor luchtkwaliteitsmodellen. Emissiefactoren zijn verschillend voor categorieën met verschillende emissieprestaties, technologie, voertuigtype of gebruik.

In dit rapport ligt de nadruk specifiek op de ongereguleerde vervuilende emissies en de mogelijke invloed op TNO's VERSIT+[4] emissiefactoren gebaseerd op deze inzichten. Daarnaast zijn de prestaties van elektrische voertuigen onderzocht.

[3] https://www.greenncap.com/
[4] TNO's emissiefactor model. Dit model wordt gebruikt voor de Nederlandse registratie van verkeersemissies: https://www.tno.nl/nl/duurzaam/duurzaam-verkeer-vervoer/emissiefactoren-luchtkwaliteit-stikstof/

De huidig analyse leidt tot de volgende hoofdconclusies:

- *Hoge ritgemiddelde emissies van gereguleerde luchtverontreinigende stoffen worden hoofdzakelijk waargenomen gedurende tests met hoge snelheid (BAB) en koude (-7 °C) omgevingstemperatuur tests en gedurende testen op de weg met uitdagende omstandigheden.*
  Ook al presteerden de meeste geteste voertuigen binnen de limieten van de RDE-achtige op-de-weg tests, voor deze drie (typen) tests waren de gemiddelde emissies voor gereguleerde *luchtverontreinigende* stoffen hoog. Dit benadrukt het belang van uitgebreide test programma's.

- *Niet-gereguleerde vervuilende stoffen als lachgas (N_2O) en ammoniak (NH_3) vereisen continue monitoring*
  Dieselvoertuigen vertonen consistent hoge lachgas emissies vergeleken met ander brandstoffen; benzinevoertuigen stoten ritgemiddeld 0.96 mg/km N_2O uit, terwijl dieselvoertuigen rond 14 mg/km uitstoten (3.7 g CO_2 eq.). Daarnaast vertoonden verscheidene voertuigen VERSIT+ wegtype emissies van meer dan 40 mg/km (11 g CO_2 eq.). Dit vermindert het voordeel van typisch laag CO_2 uitstotende dieselvoertuigen. In alle uitgevoerde tests, emitteerden de benzinevoertuigen gemiddeld 11 mg/km ammoniak (NH_3) en de dieselvoertuigen gemiddeld 2.6 mg/km NH_3. Er zijn verscheidene benzine voertuigen met VERSIT+ wegtype NH_3 emissies hoger dan 20 mg/km, alhoewel één diesel 6d-Temp voertuig NH_3 emissies hoger dan 80 mg/km had.

- *Koude start emissies kunnen tegenwoordig het best gerepresenteerd worden als een emissiepuntbron*
  Uitgebreid testen heeft aangetoond dat de hoge emissies als gevolg van een koude (motor) start optreden over steeds korter wordende afstanden. Een techniek neutrale benadering is (daarom) gekozen, waarin extra emissies als gevolg van een koude start bepaald worden door het verschil te bepalen tussen de emissie gedurende de eerste kilometer en het (km-) gemiddelde over de gehele rit. Dit is geïmplementeerd in VERSIT+ als wegtype 'WKS' (Wegtype Koude Start).

- *PN emissies variëren aanzienlijk afhankelijk van het type motor en het gebruik daarvan*
  Als PN emissies beschouwd worden als een functie van de CO_2-emissie en de voertuigsnelheid, dan blijken hoge PN-emissies afhankelijk van voertuig én technologie. PN emissiefactoren zijn in VERSIT+ opnieuw geïntroduceerd op basis van de in dit rapport berekende emissiefactoren. Voor benzinevoertuigen blijken deze PN-emissiefactoren een orde van grootte hoger dan de tot dusver gebruikte PN-emissiefactoren.

- *Verscheidene van de geteste voertuigen hebben waarschijnlijk een te kleine katalysator*
  Relatief hoge vervuilende emissies als functie van de CO_2-emissie kunnen wijzen op het onvermogen van het nabehandelingssysteem om de uitlaatgassen effectief te reinigen als gevolg van te kleine afmetingen (capaciteit) er van. Dit is bij verscheidene dieselvoertuigen waargenomen.

- *Het energieverbruik van BEVs, veroorzaakt door de voertuigaandrijving dan wel de hulpsystemen (airco, verwarming, verlichting etc.), kan aanzienlijk zijn*
  De laadverliezen van de 16 getest BEVs zijn aanzienlijk en variërend van ongeveer 8 tot 21%. Zelfs tijdens stationaire momenten (snelheid < 0.5 km/h), kan het gebruikte vermogen aanzienlijk zijn. Gemiddeld over alle stationaire momenten per test ligt het gemiddeld gebruikte vermogen tussen 0.5 en 2.5 kW. Voor stadsgebruik met een gemiddelde snelheid van 30 km/uur betekent dit dat, van het totale energieverbruik, 17 tot 80 Wh/km niet gerelateerd is aan aandrijving, wat tot ongeveer de helft van het totale energieverbruik kan zijn.

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Abbreviations

Abbreviation	Meaning
ACI	Automobile Club d'Italia
ADAC	Allgemeiner Deutscher Automobil-Club
BAB130	Bundesautobahn test
BASt	Bundesanstalt für Straßenwesen
CAT	Cold Ambient Temperature
CH4	Methane
CO	Carbon monoxide
CO2	Carbon dioxide
CNG	Compressed Natural Gas
CVT	Continuously Variable Transmission
DPF	Diesel Particulate Filter
Empa	Eidgenössische Materialprüfungs- und Forschungsanstalt
EFs	Emission Factors
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
LPABEUR6	VERSIT+ class: Euro 6 petrol car, taxonomy prefix P_6
LPACEUR6	VERSIT+ class: Euro 6 CNG car, taxonomy prefix C_6
LPADEDT6	VERSIT+ class: Euro 6d-Temp diesel car, taxonomy prefix D_6dT
LPADEUD6	VERSIT+ class: Euro 6d diesel car, taxonomy prefix D_6d
LPEBEUR6	VERSIT+ class: Euro 6 petrol plug-in car, taxonomy prefix E--P_6
N2O	Nitrous Oxide
NCAP	New Car Assessment Programme
NH3	Ammonia
NOx	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
TCSE	Total Cold Start Emissions
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
WKS	VERSIT+ point source representation of the cold start extra emissions
WT1	VERSIT+ urban road type
WT2	VERSIT+ rural road type
WT3	VERSIT+ motorway road type

1 Introduction

In 2022 an initial investigation was performed on data made available as part of the Horizon 2020 'Green Vehicle Index' (GVI) project which highlighted the emission performance of Euro 6d and Euro 6d-Temp vehicles [TNO 2022a]. In this report this analysis is continued with additional data from the Green NCAP consortium.[5]
Note that significant parts of Chapters 1 and 2 will therefore be familiar to prior readers of *Analysis of the Emission Performance of the Vehicles Tested for the Green Vehicle Index (GVI) Project* [TNO 2022a].

1.1 Background

The Green NCAP consortium aims to rate the sustainability of a vehicle in a comprehensive way. The scope is limited to passenger cars in good condition with relatively low mileages. The Green NCAP rating provides consumers with an objective and clear view on how sustainable their car, or car they're considering purchasing, is. The rating enables the consumer to make an informed choice, and considers both a car's real-world fuel/energy consumption and greenhouse gases (GHG), as well as its impact on air quality. The intention is that this will lead to new cars with a lower environmental impact, by creating a demand for clean cars by consumers, instead of penalising manufacturers for producing polluting cars.

Green NCAP was initiated by Euro NCAP with the aim of developing a labelling methodology on the environmental performance of passenger cars with an impact comparable to the Euro NCAP safety labelling. In this respect Green NCAP goes beyond current emission legislation. A critical success factor for Green NCAP is the testing methodology: the tests performed, the pollutants included, the conditions under which this occurs, and the assurance that tests give a reliable and objective view of the environmental vehicle performance.

The Horizon 2020 'Green Vehicle Index' (GVI)[6][7] project was set up to accelerate and improve the Green NCAP consumer programme. Most of the partners in GVI project are also partners within the current Green NCAP initiative. Within the GVI project a testing and rating methodology was developed, covering all types of available propulsion systems, which has been further streamlined within the Green NCAP programme. In the current analysis, a total of 101 modern (Euro 6d and Euro 6d-Temp) vehicles were considered.

The data collected for Green NCAP has a number of interesting outcomes. One part of the outcomes is related to the emission performance of 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.

[5] https://www.greenncap.com/
[6] https://www.gvi-project.eu/
[7] The GVI project received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 814794

Nevertheless, there are still circumstances where elevated pollutant emissions occur. For example, during a cold engine start, high driving dynamics, prolonged idling and DPF regenerations. The Green NCAP programme provides insights in the emission levels for a number of these circumstances. Moreover, in the measurement programme non-regulated emissions such as NH_3 and N_2O are also considered. These insights can, for example, serve as input for determining emission factors for air quality models. Emission factors are distinct for categories with distinct emission performance, technology, or vehicle type or usage.

Partners

The current Green NCAP consortium consists of IDIADA, FIA, ADAC, UTAC, TCS, OAMTC, ICRT, IFA, ACI, CSI-SPA, EMPA, BASt, Horiba MIRA Ltd, BMVI, DEKRA, DFT, gencat, KBA, ecologique-solidaire, and TNO. The GVI consortium members within GVI were: IDIADA, FIA, ADAC, UTAC, TCS, OAMTC, ICRT, IFA, ACI, CSI-SPA, EMPA, BASt, Horiba MIRA Ltd and TNO.

1.2 Aim of this report

On behalf of the Dutch Ministry of Infrastructure and Water Management, TNO has briefly summarised the highlights of the emission performance of the vehicles tested within Green NCAP and compared this to the GVI dataset. There is a specific focus on the non-regulated pollutants and the potential impact on TNO's VERSIT+[8] emission factors based on these insights [Emissiefactoren voor luchtkwaliteit en stikstofdepositie 2023]. Moreover, the performance of electric vehicles are included.

1.3 Report outline

In Chapter 2 the test program is described. In Chapter 3 the average results of the laboratory and on-road test are described, including the insights from the non-regulated pollutants. Chapter 4 focuses on the impact of these results on the emission factors. In Chapter 5 a detailed analysis is shown on PN emissions, CO_2 emissions, catalyst size and extensive idling. Chapter 6 describes insights for battery electric vehicles with regard to energy consumption and charging losses. Chapter 7 provides the main conclusions of this report.

[8] TNO's emission factor model. This model is used for the Dutch Emission Inventory for road traffic: https://www.tno.nl/nl/duurzaam/duurzaam-verkeer-vervoer/emissiefactoren-luchtkwaliteit-stikstof/

2 Test programme

2.1 Test cycles

Vehicles were tested both on-road with PEMS (PEMS (Portable Emissions Measurement System), and in the laboratory on a chassis dynamometer. Within the GVI project an expansive test procedure was performed for each vehicle, while the current Green NCAP programme has become more streamlined with a two-stage testing approach. This means that not every test is driven for each vehicle. An overview of the test programme can be found on the GNCAP website.[9] For completeness, we summarise all the tests contained in the current analysis.

Laboratory

On the chassis dynamometer the following tests can be 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[10], 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[11] 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.

On-road

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.
The following can be 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.

[9] https://www.greenncap.com/two-stage-test-process/
[10] Worldwide Harmonised Light Vehicle Test Procedure
[11] Allgemeiner Deutscher Automobil-Club

a. **The PEMS+ short trip with cold start** is based on the PEMS+ regular, with only the first 8 kilometres 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[12].

2.2 More than 100 vehicles were included in this analysis

The current analysis more than doubles the number of vehicles measured within the GVI programme: 101 vehicles have been measured within Green NCAP. Of these, 16 were BEV.

As noted in our earlier analysis, these include:

- Petrol, Diesel, HEV and CNG
- Mainly Euro 6d-Temp and Euro 6d vehicles
- Acceptance mileage range: 3000 – 30 000 km
- Average intake accumulated distance : 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

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

2.3 Emissions measured

On the chassis dynamometer CO (carbon monoxide), HC (hydrocarbons) and NO_x (nitrogen oxides) were measured, as well as CO_2 (carbon dioxide), PM (particulate matter), PN (particle number) and CH_4 (methane). Furthermore, NH_3 (ammonia) and N_2O (nitrous oxide) were also measured. With PEMS, all vehicle measurements included CO, NO_x, PN and CO_2. Additional signals from the measurements, such as vehicle speed and engine speed, were used in support of the analyses. For electric vehicles, no (wear) emissions were measured. The additional signals energy consumption, vehicle speed and altitude were used for the analysis in Chapter 6.

3 Most vehicles are usually clean according to their trip averages

Within Green NCAP performance thresholds have been established for each relevant pollutant. These thresholds are technology independent, and are used to rate the tested vehicles. A conformity factor of 1.32 is applied to the thresholds for on-road (PEMS) tests and the WLTC test at cold ambient air temperatures (WLTC cold CAT). In some cases these thresholds are more stringent than current legislation (for NO_x the threshold is 60 mg/km for both diesel and petrol while the current diesel limit is 80 mg/km), while for NH_3 and N_2O thresholds have been devised even though no limits for these exist within current legislation. As may be expected, high average emissions are most often seen during the PEMS heavy warm, BAB warm, and WLTC cold CAT tests.

3.1 Pollutants measured on-road

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

3.1.1 CO

Most trip-averaged CO emissions fall within the Green NCAP thresholds (Figure 3.1), with exception of the aforementioned PEMS heavy, BAB, and WLTC CAT tests. Especially high CO emissions are observed for petrol cars during the BAB tests. On average, the emissions during this test are 1.7 g/km compared to 132 mg/km for the RDE-like PEMS+ test (compared to a median of 360 and 110 mg/km respectively). This suggests that emissions on the highway may be underestimated in the current VERSIT+ WT3 emission factors (113 mg/km compared to the 350 mg/km calculated for this data set, see also Section 4.2).

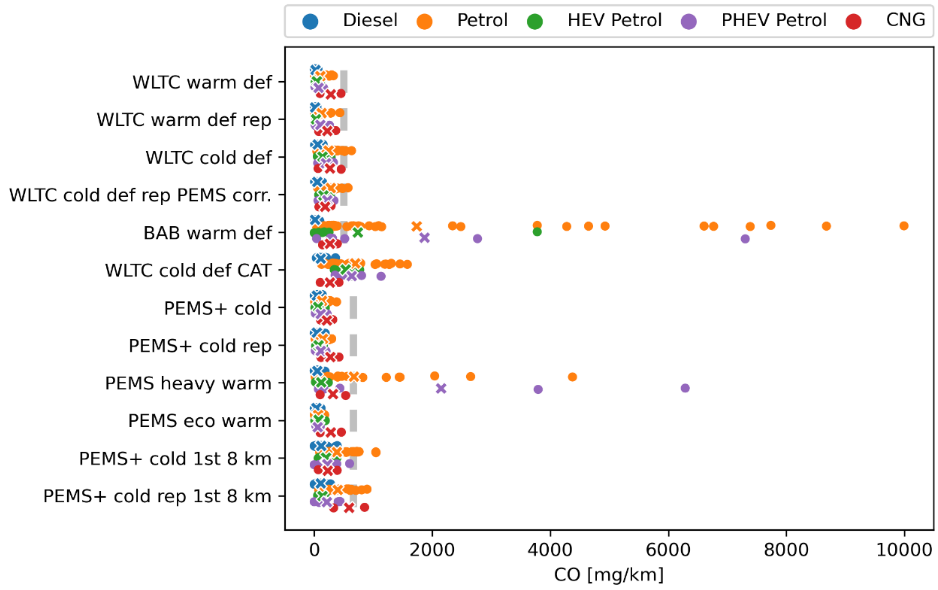


Figure 3.1: CO emissions as averaged over the entire trip. The Green NCAP thresholds are shown in grey. Averages per fuel type per test type are shown by crosses.

3.1.2 NO_x

Most trip-averaged NO_x emissions are below the Green NCAP thresholds (Figure 3.2). However, the average emissions over all diesel vehicles for both the BAB and WLTC CAT test are higher than the thresholds, though the PEMS heavy average is only slightly below. The number of vehicles tested with higher emissions than the threshold during the BAB and WLTC CAT test has increased compared to the previous study. The average emissions for most of the diesel vehicles during the 1st 8 km of the PEMS+ cold tests fall below the Green NCAP threshold, which confirms that tests of this length can be sufficient for cold start testing.

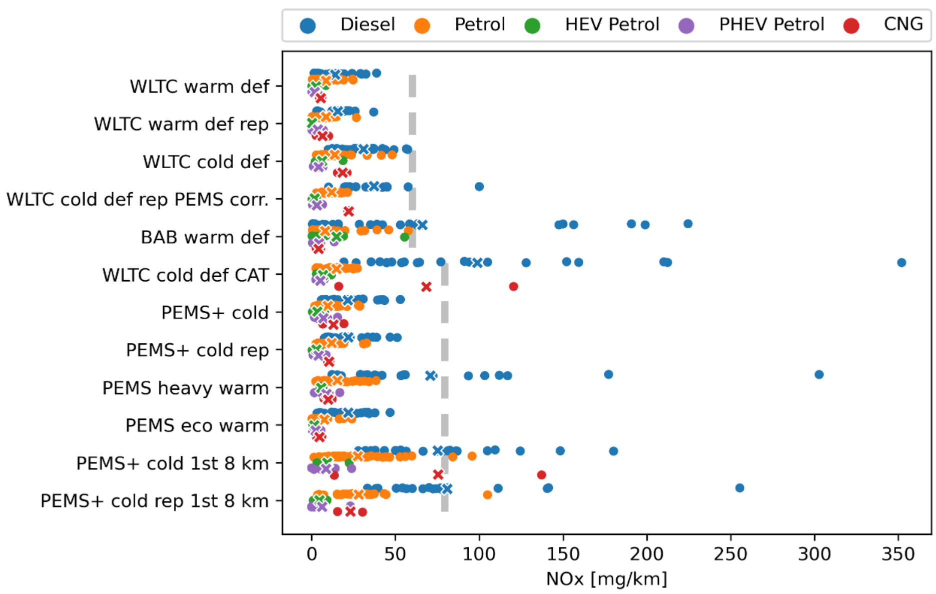


Figure 3.2: NO_x emissions as averaged over the entire trip. The Green NCAP thresholds are shown in grey. Averages per fuel type per test type are shown by crosses.

3.1.3 PN

Very few tests have average PN emissions above the threshold (Figure 3.3), though there are three cold WLTC tests that do. There are also only a few PEMS+ cold tests where the emissions over the first 8 km are above the threshold.

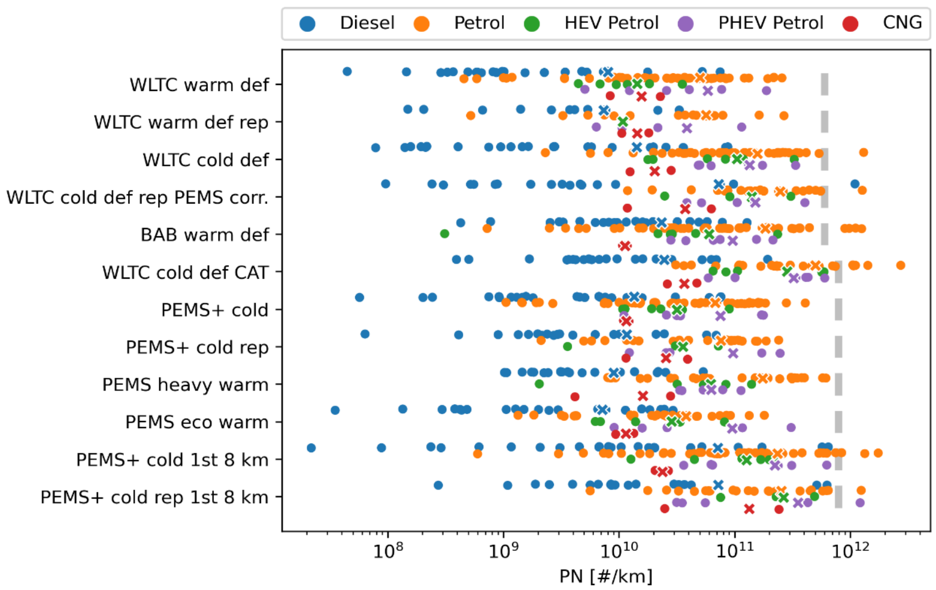


Figure 3.3: PN emissions as averaged over the entire trip. The Green NCAP thresholds are shown in grey. Averages per fuel type per test type are shown by crosses.

These 1st 8 km-averaged emissions are shown compared to the total trip average PN emissions in Figure 3.4.

There is only one diesel vehicle which has 1st 8 km average emissions above the WLTP PN limit, and most are well below, showing that DPF technology is highly effective in mitigating the cold start PN emissions. As also observed in our previous analysis, there is a general clustering of DPF, GPF and no particulate filter technologies, 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 comparison between PN emissions measured during laboratory tests and the corresponding PM emissions is made in Section 3.2.3.

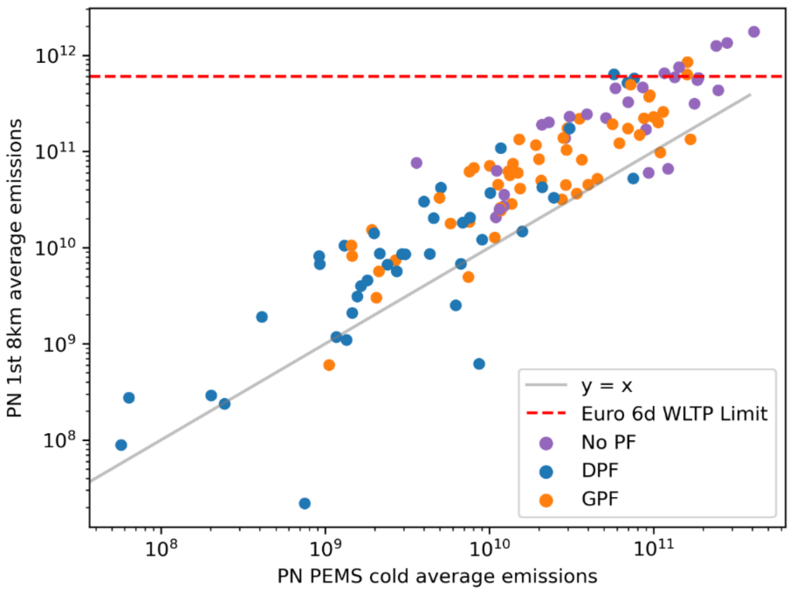


Figure 3.4: PN emissions as averaged over the first 8 km of a trip, as compared to the average over the entire trip. Blue points indicate diesel vehicles with DPF, orange petrol vehicles with GPF, and purple vehicles without a particulate filter. The dashed red line indicates the Euro 6d WLTP limit for PN.

3.2 Laboratory measurements

CH_4 and THC measurements are only performed in the laboratory on a chassis dynamometer. Most tests stay within the thresholds, though there are a number of outliers. Although our analysis considers THC, Green NCAP considers CH_4 a greenhouse gas instead of a pollutant, and as such for the Green NCAP evaluation procedure NMHC is of interest.

3.2.1 CH_4

Considering the trip-averaged CH_4 emissions, the emissions of the WLTC diesel tests and the CNG WLTC cold CAT tests stand out. The two different CNG vehicles have a large difference between them for both the WLTC cold CAT and BAB tests, which reaffirms the need for non-standard dyno cycles. Of note is also the unexpected difference between the two CNG WLTC warm rep tests, though the WLTC warm tests are very close. The average over all diesel tests for the WLTC cold test is almost the same as the WLTC cold CAT test (9.6 mg/km and 9.7 mg/km respectively), though taking the WLTC cold rep tests into account, this is somewhat lower (7.8 mg/km).

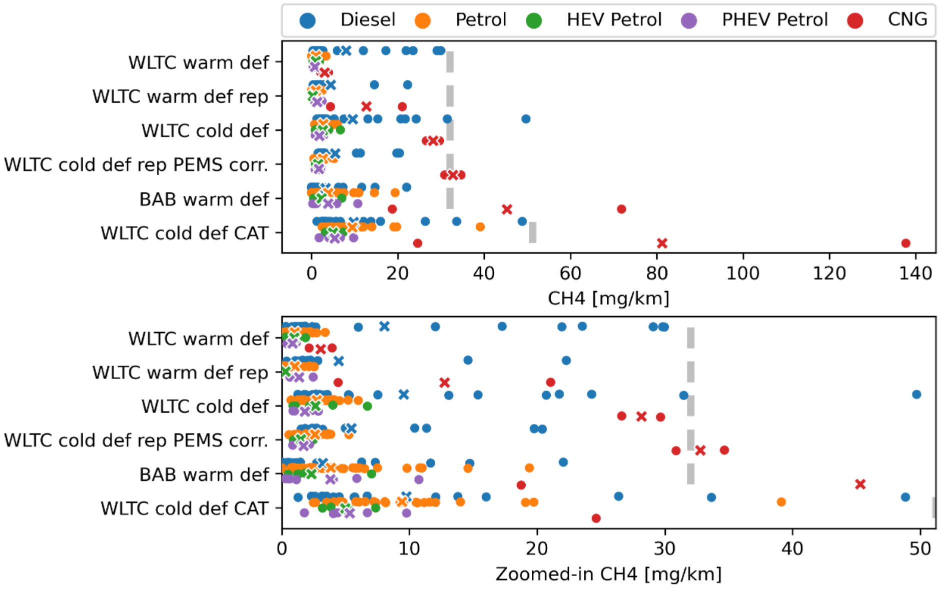


Figure 3.5: CH4 emissions as averaged over the entire trip. The top panel shows all data measured on the chassis dyno including the Green NCAP thresholds in grey. Averages per fuel type per test type are shown by crosses. The bottom panel shows the zoomed-in version of the top panel.

3.2.2 THC

The average THC emissions during the WLTC cold CAT tests are obviously higher than the other tests (Figure 3.6), though for diesel the difference is smaller than the other technologies. The large differences observed for the CH_4 emissions of the CNG vehicles are also echoed here.

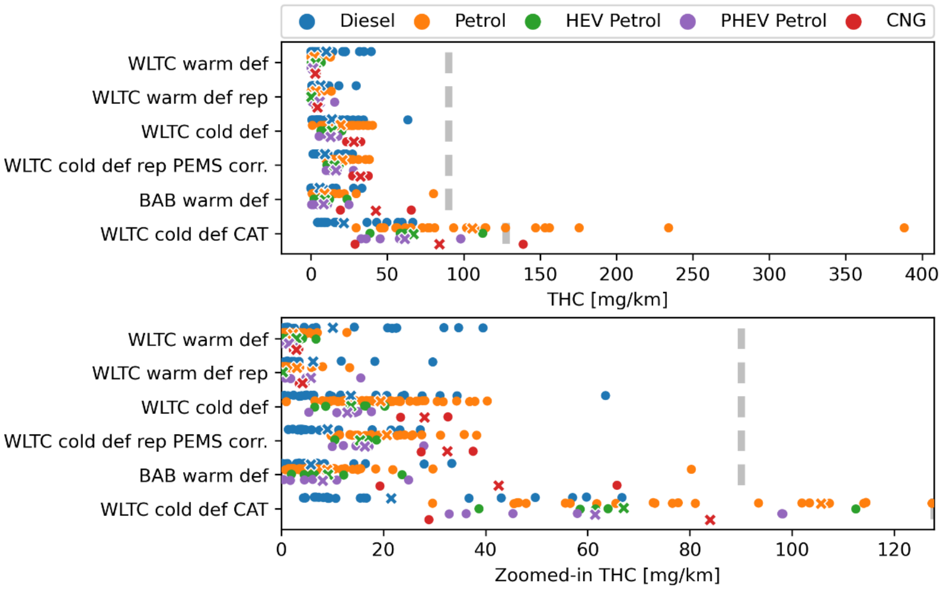


Figure 3.6: THC emissions as averaged over the entire trip. The top panel shows all data measured on the chassis dyno including the Green NCAP thresholds in grey. Averages per fuel type per test type are shown by crosses. The bottom panel shows the zoomed-in version of the top panel.

3.2.3 PM emissions are approaching the limits of measurement resolution

Total PM emissions are available for most of the measurements performed in the laboratory. As shown in Figure 3.7, most of the trip-averaged PM emissions are fairly low: in many cases the average PM emissions are around 0.1 mg/km or less. In Figure 3.7 the average PM emissions are shown as a function of trip-averaged PN and coloured by trip type. WLTC cold CAT tests seem to lead to the highest PN emissions, while more BAB tests lead to higher PM emissions. Above PN 4×10^{11} /km, a sharp increase in WLTC cold CAT PM emissions is observed. The highest PN emissions are observed for the diesel vehicles that underwent DPF regenerations during the BAB and WLTC warm tests, the latter test also had the highest PM emissions (PM emissions for the REGEN BAB were not available).

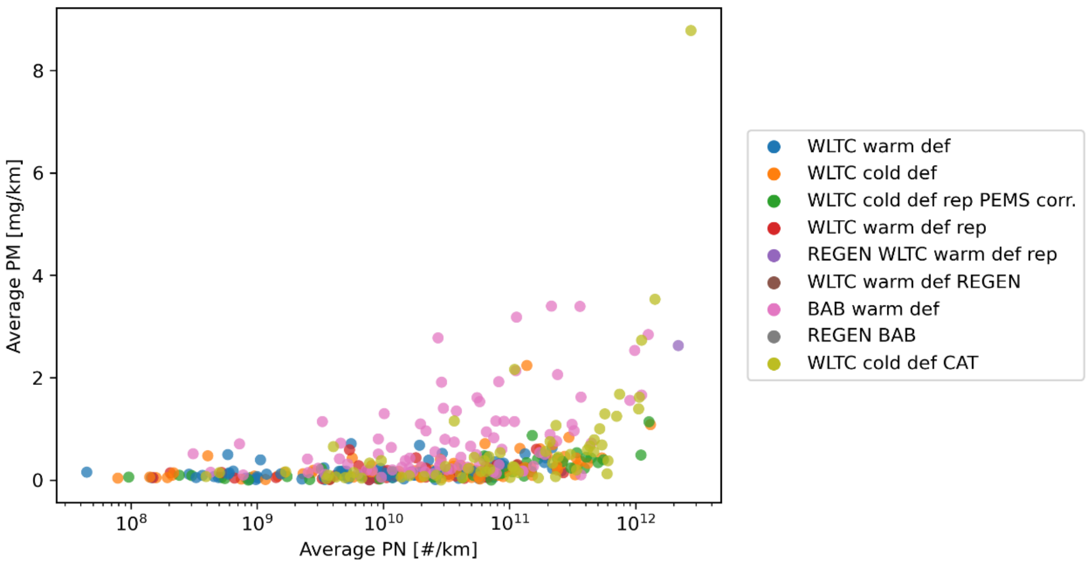


Figure 3.7: Average PM emissions as a function of the corresponding PN emissions. The colours indicate the trip type. Trips prefixed with 'REGEN' are trips during which a DPF regeneration occurred.

When averaging per technology type (Table 3.1), the BAB test led to technology-averaged emissions higher than 1 mg/km for all petrol-based technologies.

Table 3.1: PN and PM emissions averaged per test and technology type, sorted by highest average PN emissions. Tests prefixed with 'REGEN' are trips during which a DPF regeneration occurred.

Test	Technology	Average PN [#/km]	Average PM [mg/km]
REGEN BAB	Diesel	1.3E+13	
REGEN WLTC warm def rep	Diesel	2.2E+12	2.6
WLTC cold def CAT	Petrol	4.9E+11	1.2
WLTC cold def CAT	PHEV Petrol	3.6E+11	0.3
WLTC cold def CAT	HEV Petrol	2.5E+11	0.7
WLTC cold def rep PEMS corr.	Petrol	2.4E+11	0.3
BAB warm def	Petrol	1.8E+11	1.0
WLTC cold def rep PEMS corr.	PHEV Petrol	1.8E+11	0.2
WLTC cold def	PHEV Petrol	1.6E+11	0.3
WLTC cold def	Petrol	1.6E+11	0.3
BAB warm def	HEV Petrol	1.3E+11	1.2
WLTC cold def rep PEMS corr.	HEV Petrol	9.1E+10	0.3
BAB warm def	PHEV Petrol	8.7E+10	1.3
WLTC cold def rep PEMS corr.	Diesel	7.3E+10	0.1
WLTC cold def	HEV Petrol	7.2E+10	0.3
WLTC warm def rep	Petrol	5.7E+10	0.2
WLTC warm def	PHEV Petrol	5.1E+10	0.2
WLTC warm def	Petrol	4.9E+10	0.2
WLTC cold def rep PEMS corr.	CNG	3.7E+10	0.3
WLTC cold def CAT	CNG	3.7E+10	0.2
WLTC warm def rep	PHEV Petrol	3.3E+10	0.2
WLTC warm def	HEV Petrol	2.6E+10	0.2
WLTC cold def CAT	Diesel	2.5E+10	0.2
BAB warm def	Diesel	2.3E+10	0.4
WLTC cold def	CNG	2.0E+10	0.2
WLTC warm def	CNG	1.6E+10	0.2
WLTC warm def rep	CNG	1.4E+10	0.2
WLTC cold def	Diesel	1.4E+10	0.1
BAB warm def	CNG	1.1E+10	0.2
WLTC warm def	Diesel	8.0E+09	0.1
WLTC warm def rep	Diesel	7.4E+09	0.1
REGEN WLTC warm def	Diesel	1.1E+08	

3.3 NH_3 and N_2O measurements show high variations are potentially cause for concern

As we have discussed earlier [TNO 2023; TNO 2022a; TNO 2020], NH_3 and N_2O emissions are pollutants with high potential environmental effects but are as of yet un-regulated by current light-duty vehicle legislation. Comprehensive testing therefore remains crucial, both for the determination of representative emission factors for these pollutants as well as for determining the potential causes of high on-road emissions. The latter could be investigated in detail in future work. As mentioned in our previous analysis, we assume that laboratory tests are indicative for on-road emissions due to the unregulated nature of these pollutants.

3.3.1 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 NOx, so-called 'ammonia slip' can lead to NH_3 emissions.

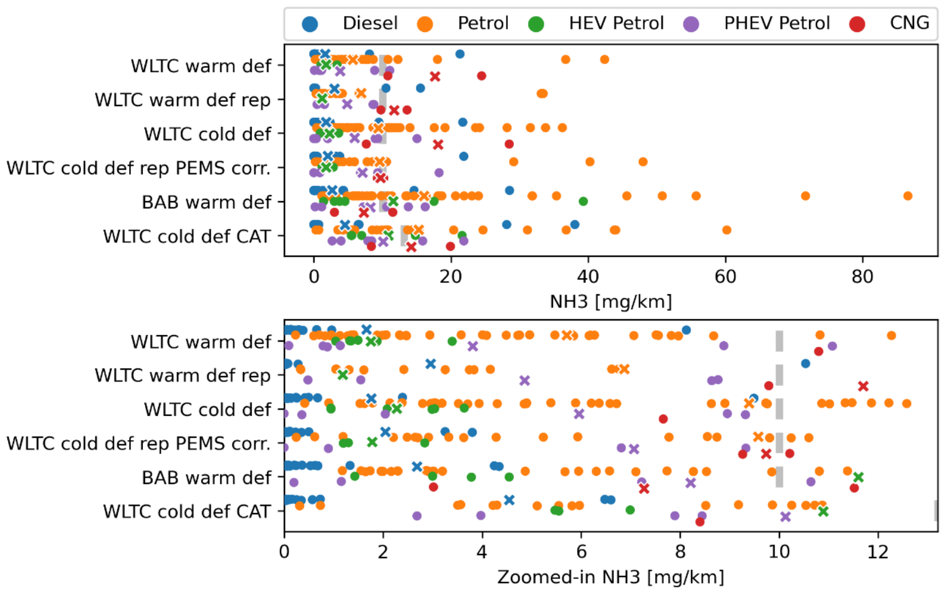


Figure 3.8: NH_3 emissions as averaged over the entire trip. The top panel shows all data measured on the chassis dyno including the Green NCAP thresholds in grey. Averages per fuel type per test type are shown by crosses. The bottom panel shows the zoomed-in version of the top panel.

On average, diesel vehicles have lower NH3 emissions than those with other fuel types (Figure 3.8) though for most tests average emissions are below 10 mg/km. 80% of the diesel tests had an average emission less than 0.7 mg/km. However, high emission also occur for some diesel vehicles. For example, one Euro 6d-Temp had a BAB warm test of around 30 mg/km. Across all performed tests, petrol vehicles emit an average of 11 mg/km, while diesel vehicles emit 2.6 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. The BAB petrol tests especially appear to have tests with higher emissions when compared to our previous analysis, though this only leads to a 2 mg/km difference in the average.

3.3.2 N_2O

N_2O is a greenhouse gas with a significant environmental impact: 1 g of N_2O is equivalent to 265 g of CO_2.[13] Diesel vehicles show consistently high N_2O emissions compared to other fuels; petrol vehicles emit on average 0.96 mg/km N_2O, while diesel vehicles emit around 14 mg/km (3.7 g CO_2 eq.) on average. The average per fuel per test type for diesel is consistently above the Green NCAP threshold with the exception of the BAB test, which has an average of 9.3 mg/km vs 15 mg/km for the WLTC warm tests.

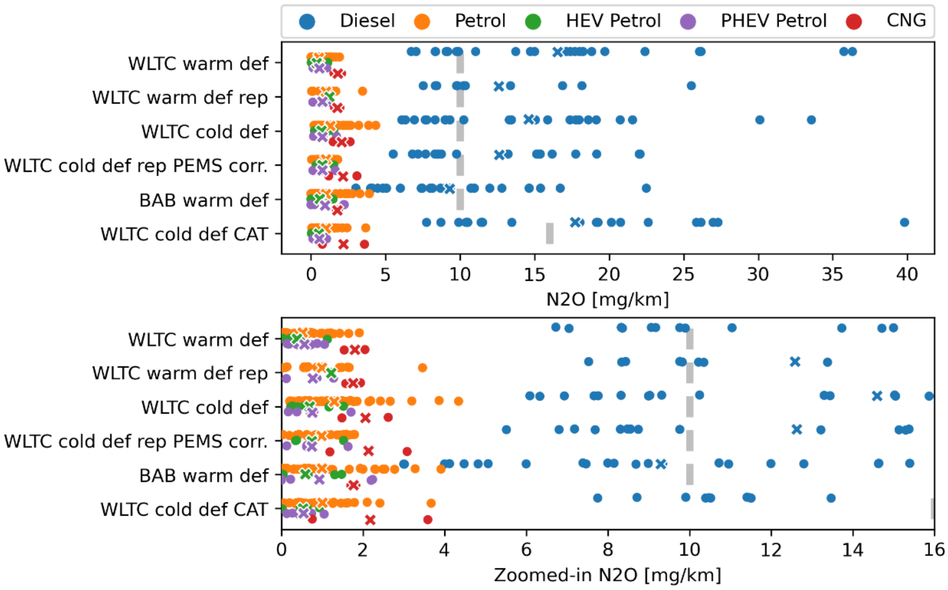


Figure 3.9: N_2O emissions as averaged over the entire trip. The top panel shows all data measured on the chassis dyno including the Green NCAP thresholds in grey. Averages per fuel type per test type are shown by crosses. The bottom panel shows the zoomed-in version of the top panel.

[13] 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.

4 There are a number of changes with respect to VERSIT+

4.1 VERSIT+ now considers a point source the best representation of a cold start

As discussed in [TNO 2022a; TNO 2022b] the high emissions that can be attributed to a cold start happen within increasingly short distances, and can be a significant proportion of the total emissions of a trip. In Figure 4.1 a trip is shown where the cold start emissions form 71% of the total emissions, while NO_x emissions plateau after 2.2 km or 3% of the total distance. For this reason it has been decided that a point source is the best representation of the cold start extra emissions.

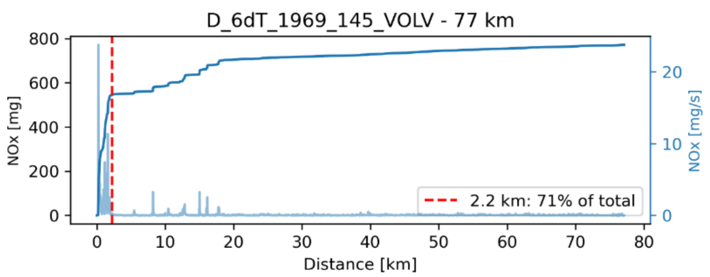


Figure 4.1: NO_x emissions during a PEMS+ cold trip by a Euro 6d-Temp diesel vehicle with taxonomy code D_6dT_1969_145_VOLV as per [uCARe 2021]. The red dashed line indicates where the point after which the exhaust aftertreatment system is working well: the cumulative NO_x emissions (dark blue line) plateau after this point.

In our analysis of the GVI programme, we considered the total cold start emissions (TCSE), which were determined as the sum up to the point at which the cumulative emissions plateaued (red point in Figure 4.2). This plateau could be reached at slightly different distances, depending on the pollutant and technology. However, to determine the point source representation of the cold start extra emissions for VERSIT+ (WKS, or Wegtype Koude Start), we use a uniform distance approach. To calculate WKS, the average emissions per kilometre of the *total trip* are subtracted from the total emitted within the *first kilometre* (orange point in Figure 4.2). Although for the trip shown in Figure 4.2 WKS represents 60% of the TCSE, the large variation in values for both TCSE and WKS shown in Figure 4.3 and the benefits of a uniform distance for WKS have led us to consider this the best approach at this time. TNO aims to perform a measurement campaign in the near future to further investigate WKS and to provide additional input as to the emissions during real-world cold starts.

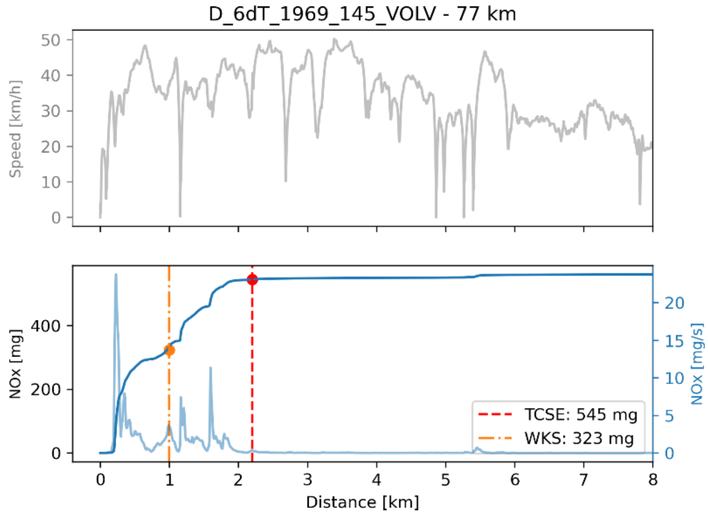


Figure 4.2: Speed (top) and NO_x emissions (bottom) during the first eight kilometres of the PEMS+ cold trip shown in Figure 4.1. The red dotted line shows the distance at which the cold start is considered complete; the red dot shows the total cold start emissions (TCSE). The orange line indicates one kilometre; the sum of the emissions up to this point is used along with the average of the total trip (10 mg/km in this case) to calculate the point source representation of the cold start extra emissions (WKS, yellow dot).

When comparing TCSE and WKS in Figure 4.3, some care should be taken. The Green NCAP data set is larger and includes a number of vehicles with higher cold start emissions for e.g. CO and NO_x. Furthermore, the change in approach from *total* to *extra* cold start emissions leads to some negative values, especially in the case of unregulated pollutants. In this case, emissions during cold starts are lower than during normal driving.

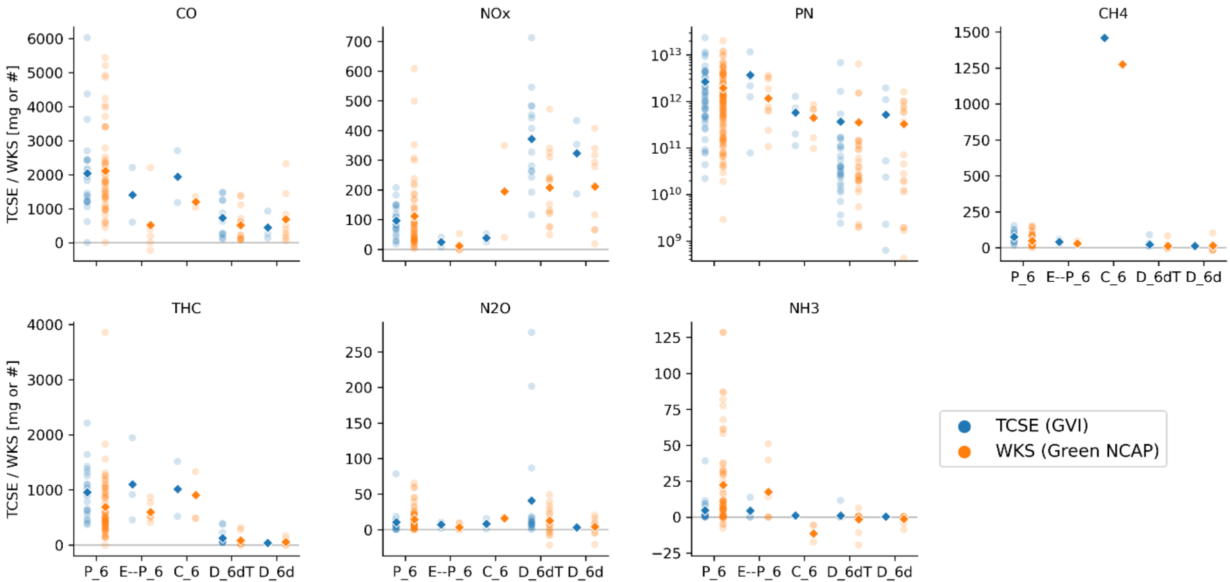


Figure 4.3: The total cold start emissions (TCSE) per vehicle calculated in the previous analysis of the GVI programme (light blue dots), as compared to the point source representation of the cold start extra emissions (WKS) determined in this analysis (light orange dots). The dark dots show the averages per technology type, where the technologies are denoted by the first two fields of their respective taxonomy codes as per [uCARe 2021]. Each frame shows a different pollutant, note that for PN TCSE/WKS are in #, while the other pollutants are in mg. The grey line indicates 0.

4.2 Emission factors calculated show variability

In this section we provide an overview of the comparison between the VERSIT+ road-type dependent emission factors as calculated for the data set made available during the GVI programme, the current Green NCAP data set, and current VERSIT+ emission factors. The emission factors are calculated using the methodology outlined in [TNO 2016] and are reflective of Dutch driving behaviour. Of note is that some deviation is expected for the urban (WT1) emission factors due to the difference in calculation of the cold start contributions: WT1 – WT3 are considered 'hot' emission factors (as the 1st kilometre is separated), and standardising the cold start distance to 1 km for all emissions and technologies will lead to some deviations. To be explicit, the current approach is to calculate WT1 – WT3 excluding the first kilometre of cold start tests. For CO and NO_x the PEMS and BAB tests are used, while CH_4, THC, NH_3 and N_2O are compared using laboratory measurements.

NO_x emission factors (EFs) are consistently higher in urban driving (Figure 4.4), though a large range in values is observed. The addition of several PHEV (LPEBEUR6) vehicles leads to an increase in the respective EFs, though this is still an order of magnitude lower than respective diesel EFs (LPAD...). The difference between diesel Euro 6d-Temp (LPADEDT6) and Euro 6d (LPADEUD6) is also the largest on urban roads, with a difference of 26 mg/km. The petrol EFs (LPABEUR6) are higher than the current VERSIT+ EFs, though in the light of recent plume chasing (measurements behind driving cars) campaigns within the Netherlands, it is likely that the VERSIT+ EFS will be increased substantially in the near future. There is a difference between VERSIT+ and the current analysis for diesel vehicles, but as the former are based on extensive monitoring and measurement campaigns ([TNO 2022b; TNO 2020]) we see no reason for change. It should be noted that although WT1 EFs calculated here exclude the first kilometre of driving, the cold start effect after this point (as described in the previous section) is still included, and thus the emissions are indeed expected to be higher.

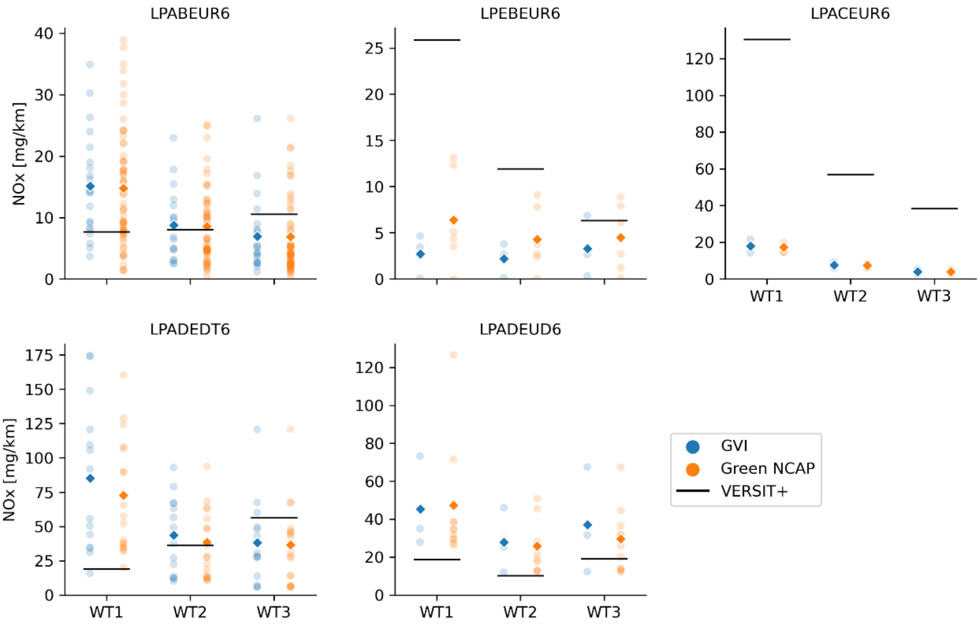


Figure 4.4: Average NO_x emissions calculated per urban (WT1), rural (WT2) and motorway (WT3) VERSIT+ road type, as calculated per vehicle (round points) and averaged per GVI or Green NCAP data set (diamond points). Each pane shows the relevant VERSIT+ classes separately. Black lines indicate the corresponding VERSIT+ emission factor.

N_2O is primarily of interest for diesel vehicles, with a large variation in emission and several outliers. For example, for WT1 the average is around 40 mg/km for Euro 6d-Temp, while the maximum is 140 mg/km. Diesel Euro 6d vehicles do have lower average emissions than Euro 6d-Temp, the latter having several vehicles with much higher N_2O emissions. Current VERSIT+ EFs for diesel were already modified to include insights from the GVI data set and thus a good overlap is observed. Although petrol N_2O emissions are lower, petrol VERSIT+ EFs will be modified using this input.

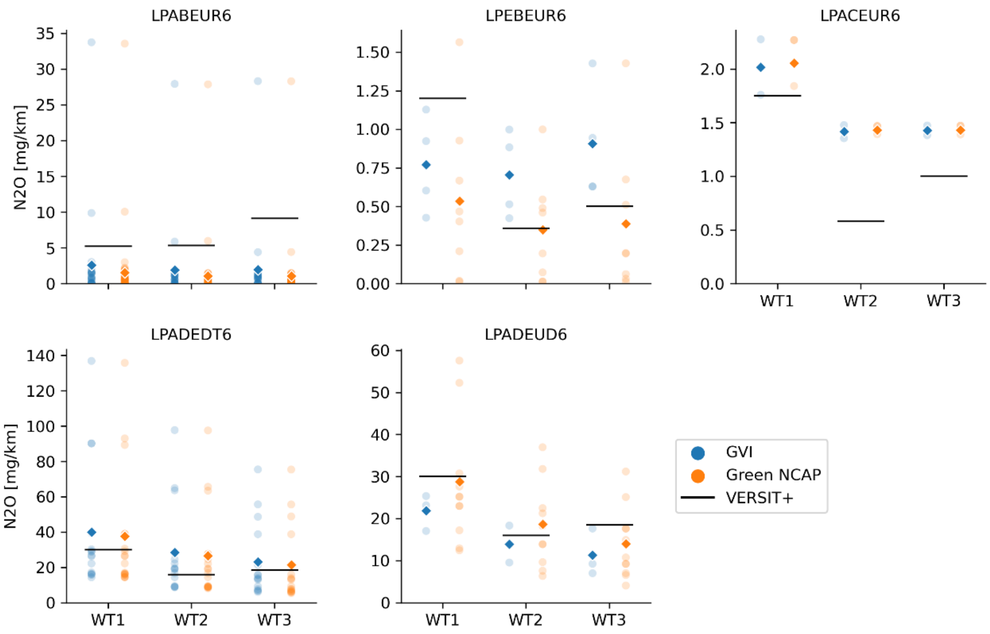


Figure 4.5: Average N_2O emissions calculated per urban (WT1), rural (WT2) and motorway (WT3) VERSIT+ road type, as calculated per vehicle (round points) and averaged per GVI or Green NCAP data set (diamond points). Each pane shows the relevant VERSIT+ classes separately.

Figures for the other pollutants, for which no changes in VERSIT+ are expected, are included in Appendix A, as well as a table comparing the GVI and Green NCAP VERSIT+ road-type dependent emission factors.

The main conclusions are:

- The CO emission factors calculated for Green NCAP are generally lower than those for GVI (Figure A.1). The trend that petrol-based technology has higher emissions on the motorway, while diesel cars have higher emissions on urban roads, has not changed. Petrol cars on the motorway especially show a very large variation in calculated emission factors. Current VERSIT+ emission factors are lower than those measured here, but are based on remote sensing campaigns (such as [Flanders Environment Agency 2020]) which are considered more representative, mainly due to a broader mix of vehicle conditions (e.g. higher mileages).
- NH_3 emissions are generally more relevant for petrol vehicles, than for diesel. However, one diesel 6d-Temp has VERSIT+ road-type emissions in excess of 80 mg/km (Figure A.3). NH_3 was one of the pollutants included in previous TNO monitoring and measurement campaigns, and therefore will not be modified. Though VERSIT+ for petrol is slightly higher than the laboratory measurements shown here, we consider it likely this better reflects real-world use.

- THC emissions of petrol, PHEV and CNG are significantly lower than VERSIT+ (Figure A.4). As for CO, the VERSIT+ EFs are based on remote sensing data, and as such this highlights the potential differences between test programmes with relatively new vehicles, and real-world emissions of the vehicles in-use (likely with a higher mileage). For diesel, this difference is less pronounced, with a fairly good overlap between this work and VERSIT+, though there is a large variation in Euro 6d WT1 emissions. Of note is that the average THC emissions are higher for diesel Euro 6d than Euro 6d-Temp.

4.3 PN emissions are being considered as an addition to the list of emission factors

Increased interest in ultra-fine particles, as well as the importance of non-exhaust particulate emissions, has led to the consideration of the reintroduction of PN emission factors within VERSIT+. Until recently, particle mass was of greater importance for air quality modelling and considerations, for this reason only PM emission factors were included. As mentioned in Section 4.1 above, our intention would be to include cold start emissions via WKS. As shown in Table 4.1, the WKS is equivalent to a significant number of warm kilometres for most technologies, with WKS for petrol cars (LP**A**BEUR6) being equivalent to 34.4 warm kilometres. Care must be taken when considering the WKS for PHEV vehicles (LP**E**BEUR6) as the electro-motor may in operation during the first kilometre, and so the cold-start effect of the ICE engine only occurs later. This is also demonstrated in Section 5.1. The ratio between WKS and warm kilometres for PN has been used in 2023 to update the ratio between WKS and warm kilometres for PM, where the assumption has been made that this ratio remains the same for both PN and PM.

Table 4.1: Number of warm kilometres per PN WKS, as averaged per vehicle, then per VERSIT+ class

VERSIT+ class	WKS in warm km
LPABEUR6	34.4
LPACEUR6	30.2
LPADEDT6	12.6
LPADEUD6	52.2
LPEBEUR6	7.3

A comparison is made between the four VERSIT+ road-types determined for the Green NCAP data set, and the three road-types used in a previous analysis [Keuken et al. 2016] based on [EMEP/EEA et al. 2013]. As shown in Figure 4.6, even though the emission factors calculated using the Green NCAP data set exclude cold starts, the petrol emission factors are still significantly higher than those used previously. The petrol, PHEV, and CNG VERSIT+ emission factors will therefore be updated with the Green NCAP factors, as well as diesel Euro 6d and 6d-Temp. Table 4.2 and Figure 4.7 below show the comparison between emission factors calculated using GVI and Green NCAP datasets, analogous to the comparisons made in Section 4.2 and Appendix A.

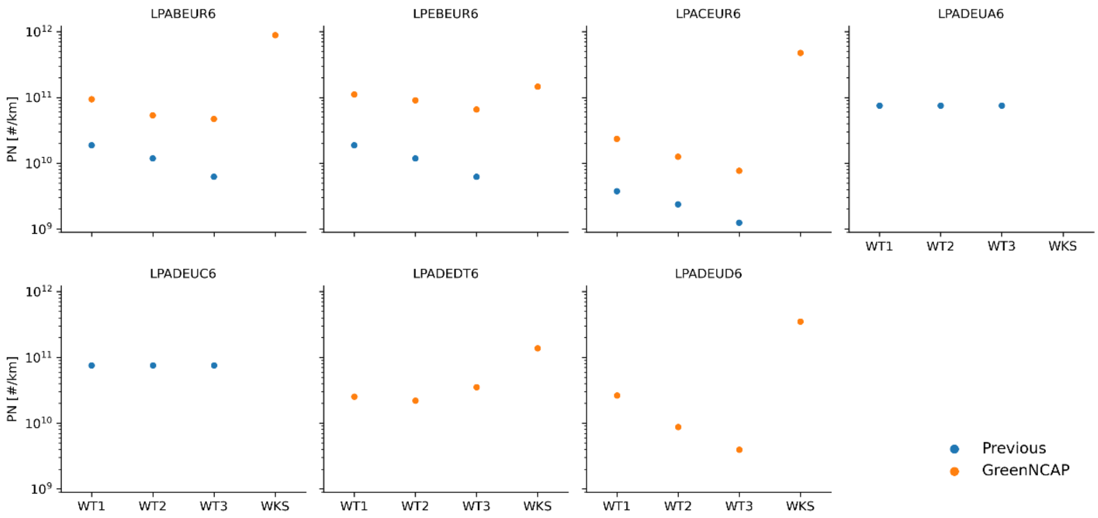


Figure 4.6: Comparison between previously used PN emission factors per road-type as determined from [EMEP/EEA et al. 2013], and those calculated using the Green NCAP data set.

Table 4.2: Average PN emission factors per VERSIT+ class for the VERSIT+ road types urban (WT1), rural (WT2) and motorway (WT3) as calculated using the GVI and Green NCAP data sets. The total cold start emissions (TCSE) and point source representation of cold start extra emissions (WKS) are also listed.

Pollutant	VERSIT+ class	TCSE GVI	WKS Green NCAP	WT1 GVI	WT1 Green NCAP	WT2 GVI	WT2 Green NCAP	WT3 GVI	WT3 Green NCAP
PN [#]	LPABEUR6	2.7E+12	1.9E+12	1.5E+11	1.1E+11	8.6E+10	7.0E+10	5.9E+10	5.9E+10
	LPEBEUR6	3.2E+12	1.2E+12	1.2E+11	1.1E+11	8.5E+10	8.3E+10	5.2E+10	7.3E+10
	LPACEUR6	5.8E+11	4.5E+11	2.4E+10	2.2E+10	1.3E+10	1.3E+10	8.9E+09	8.8E+09
	LPADEDT6	3.7E+11	3.6E+11	3.9E+10	3.7E+10	6.3E+10	6.0E+10	1.4E+11	1.4E+11
	LPADEUD6	5.2E+11	3.3E+11	3.9E+10	2.6E+10	2.6E+10	1.7E+10	3.7E+10	2.1E+10

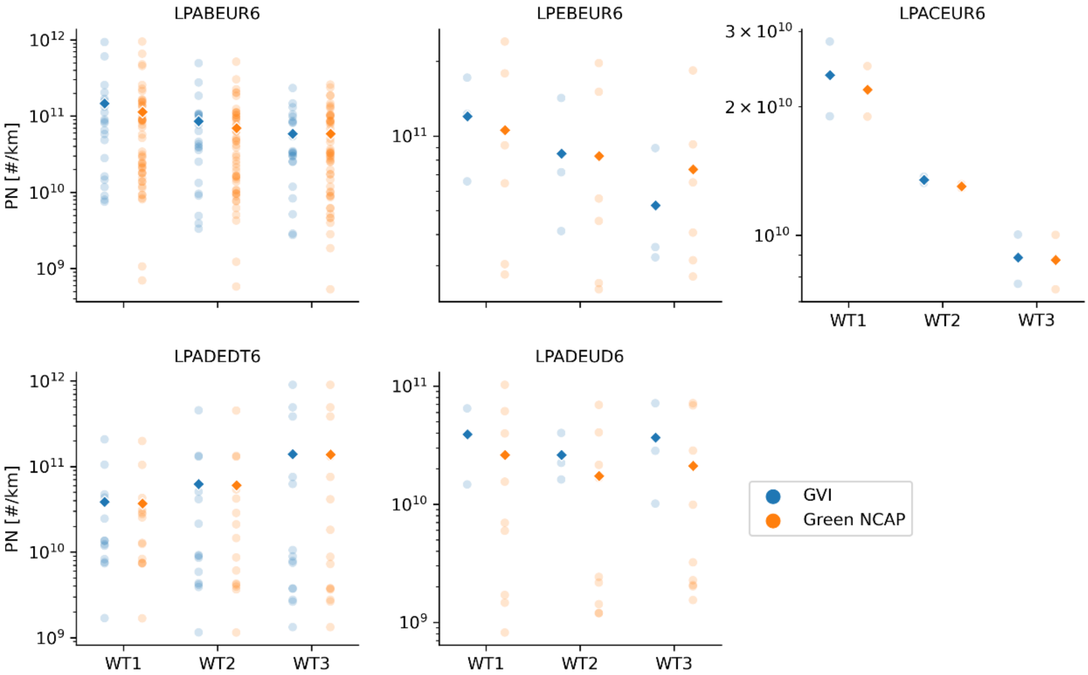


Figure 4.7: Average PN emissions calculated per urban (WT1), rural (WT2) and motorway (WT3) VERSIT+ road type, as calculated per vehicle (round points) and averaged per GVI or Green NCAP data set (diamond points). Each pane shows the relevant VERSIT+ classes separately.

5 Detailed investigations

5.1 Augmented emission maps show significant variation in high PN emissions

With the amount of data that has been collected per vehicle within the Green NCAP programme, behaviour-dependent analyses can be performed on PN emissions using augmented emission maps (Figure 5.1, see also [uCARe 2021]). Four different vehicles have been chosen to give an overview of how the high emission situations vary: for the petrol vehicle P_6d_999_91, high PN emissions are observed for higher CO_2 emissions across the entire speed range. Comparatively, the diesel vehicle D_6d_2997_258 shows high PN mainly at high speeds. The PHEV E--P_6d_X_132 shows a number of peaks across the emission map, when considering the PN emissions per second during the trip, as shown in Figure 5.2, it is observed that these peaks are also the result of the ICE motor switching on partway during the trip therefore leading to cold start emissions during the trip as opposed to at the beginning of them. This phenomenon makes precise modelling of PHEV emissions very difficult.

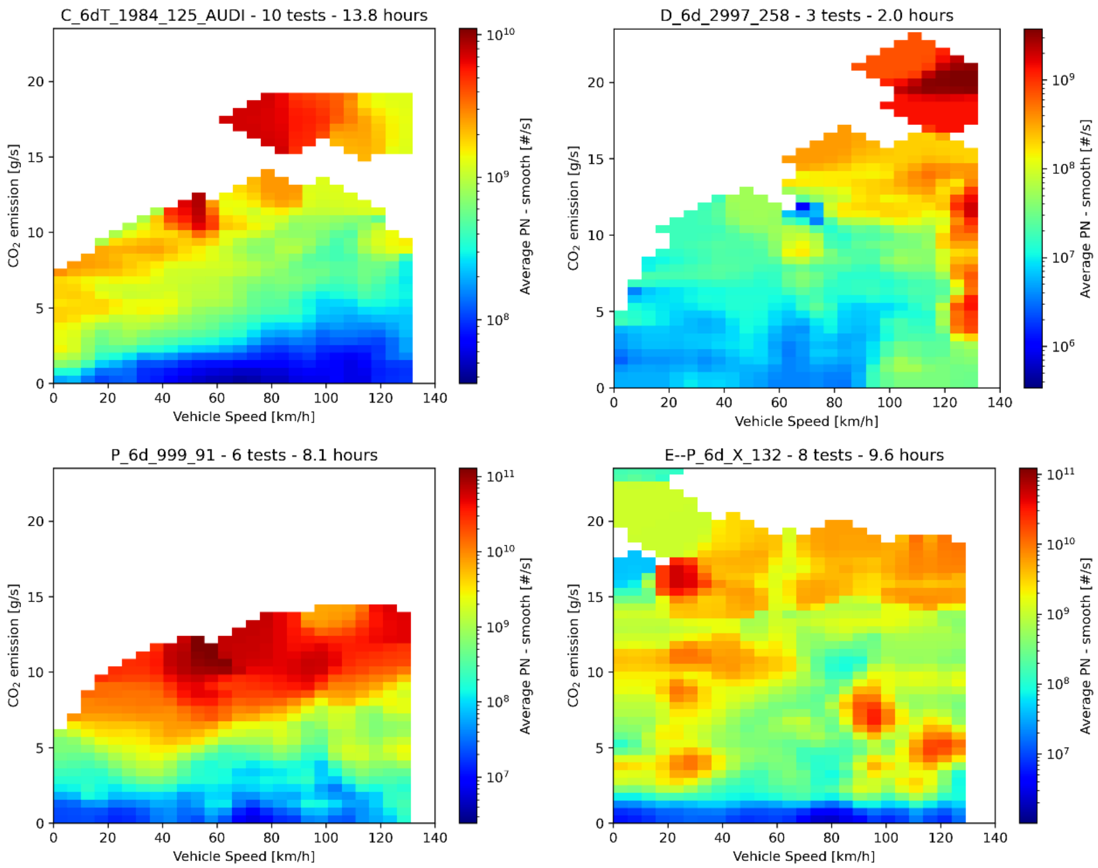


Figure 5.1: PN emissions as a function of vehicle speed and CO_2 emissions for four different vehicles as identified by their [uCARe 2021] taxonomy code. For cold trips, the data after the first kilometre is used.

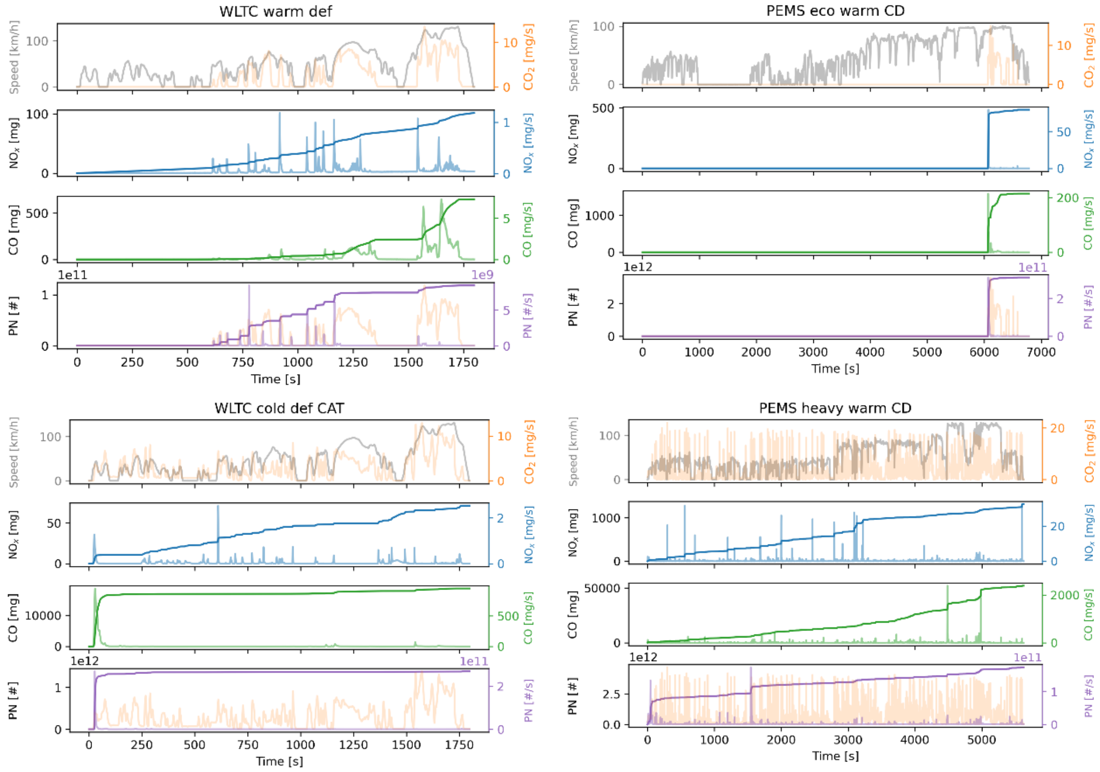


Figure 5.2: Relevant trip details for four different trips driven by E--P_6d_X_132, showing the variation in PN emissions during the trip (lower panel, purple). Per trip, the top panel shows the instantaneous speed in grey, and the CO_2 emissions in orange. The lower three panels show both the cumulative (darker line) and instantaneous (lighter line) emissions for NO_x, CO, and PN respectively. The CO_2 emissions shown in the top panel are repeated in the bottom panel to show the correlation between 'engine-on' and PN peaks.

5.2 CO_2 emissions per v · a bin vary per test type

Dynamic driving has long been described using $v \cdot a_{pos}$, with a the acceleration and v the positive velocities, where the product is positive. High values of $v \cdot a_{pos}$, could be considered aggressive driving at lower speeds. However, at higher speeds, high $v \cdot a_{pos}$ values can also occur when accelerating onto the highway or when passing other cars. Dynamic driving leads to a high power-demand of the engine, which can be linked to higher emissions. In the past, CO_2 has been used as a proxy for power demand (see also [uCARe 2021]). For this reason, we consider the correlation between CO_2 emissions and $v \cdot a_{pos}$ (Figure 5.3). There is a general linear trend observed between CO_2 and $v \cdot a_{pos}$, which would support their link via engine power. However, especially in the case of diesel vehicles, there is a significant bandwidth, especially at higher $v \cdot a_{pos}$. Figure 5.4 shows that the PEMS eco warm trips are distributed below the PEMS+ cold and PEMS heavy trips. In the case of petrol cars there is a clear difference: on average, CO_2 emissions are lower per $v \cdot a_{pos}$ bin for the PEMS eco warm trips, while at $v \cdot a_{pos}$ greater than 10 m^2/s^3, the average CO_2 emissions are higher for the PEMS heavy test. Considering the difference in emissions observed per trip type per $v \cdot a_{pos}$ bin shown in our earlier analysis of GVI data, this reaffirms the selection of CO_2 as one of the independent variables when examining pollutant emissions.

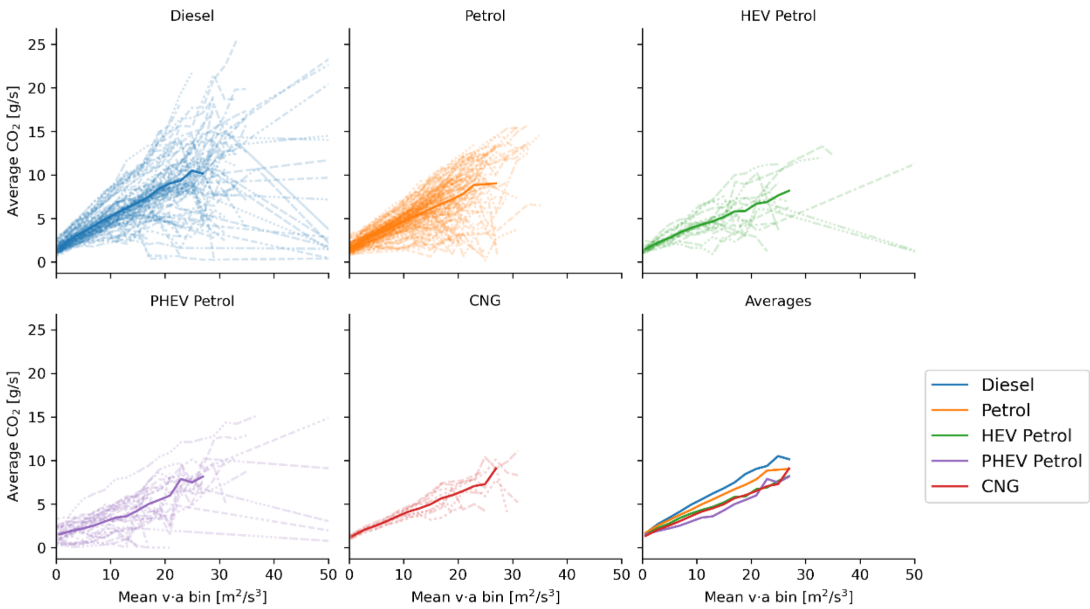


Figure 5.3: CO_2 emissions per v · a bin, per technology type. The bold lines show the averages of all the trips which are shown with the lighter dashed lines. These averages are compared in the bottom-right panel titled 'Averages'.

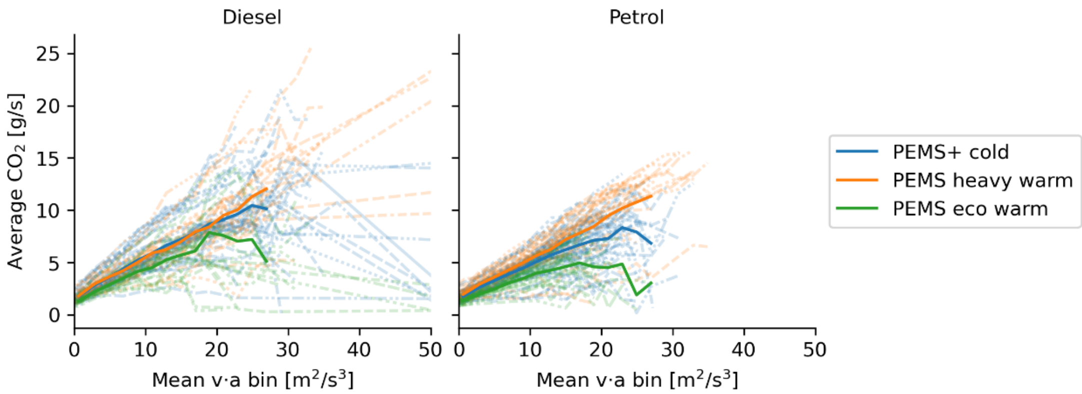


Figure 5.4: CO_2 emissions per v · a bin for diesel and petrol vehicles, as coloured by on-road test type. The bold lines show the averages of the relevant trips which are shown with the lighter dashed lines.

5.3 A number of vehicles likely have a catalyst which is too small

The CO_2 dependence of pollutant emissions can also be used to investigate the efficacy of after-treatment systems. During dynamic or high load driving, the CO_2 emissions will be higher as the power demand of the engine increases. If the power demand is high, the after-treatment system must treat a higher flow of exhaust gas. Installing an after-treatment system with a smaller capacity can be cost-efficient, but may result in the system not being able to sufficiently treat the exhaust gas during moments of higher exhaust flow. This can be observed via higher emissions as a function of CO_2. In Figure 5.5 we observe several diesel vehicles which have relatively higher NO_x emissions as function of CO_2 (where CO_2 is normalised to the respective vehicle's engine power).

One vehicle with an installed engine of around 140 kW shows a very distinct high emission peak around 0.06 g/(s.kW). Comparatively, the petrol vehicles with relatively higher emissions also have relatively higher-powered engines, with engine powers above 110 kW. Especially the diesel results are indicative of multiple vehicles which likely have a catalyst capacity which is too small.

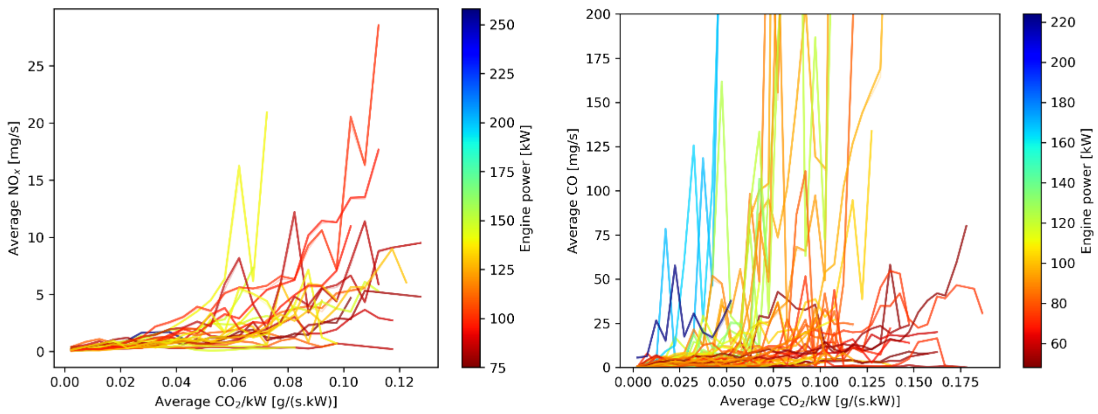


Figure 5.5: (Left) the NO_x emissions per diesel vehicle, and (right) CO emissions per petrol vehicle, as a function of CO_2 normalised to the respective vehicle's engine power. Each line represents a different vehicle, and is coloured according to the respective vehicle's engine power.

5.4 Newer diesels perform better while idling, but still exceed Green NCAP thresholds

Idling is a common occurrence during normal vehicle use but is not accounted for during type approval testing. For this reason, the NO_x emissions during the PEMS+ congestion simulation are evaluated, both with regards to the average emissions during the test, as well as the maximum emissions that occur (Figure 5.6). One petrol vehicle has high average emissions, though most fall below the Green NCAP threshold for average emissions. Only Euro 6d-Temp diesel vehicles do not, on average, meet the *average* emission thresholds (0.5 mg/s).[14] Comparatively, when considering the *maximum* emission thresholds (1.0 mg/s) all diesel vehicles fall above the thresholds, though Euro 6d diesels do, on average, have lower maximum emissions.

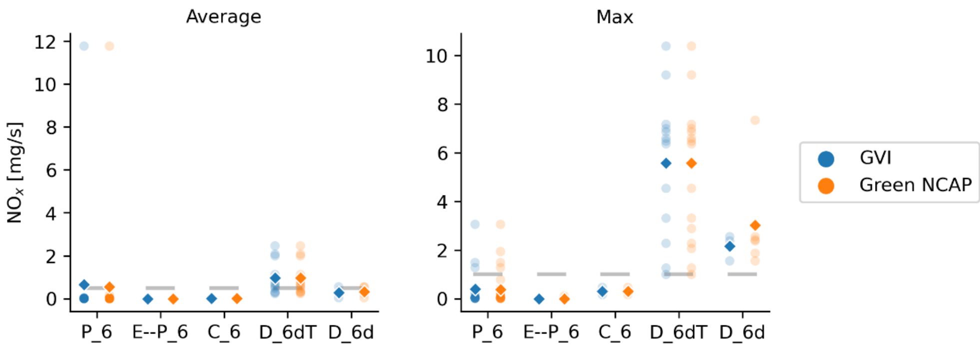


Figure 5.6: Average (left) and maximum (right) NO_x emissions during the congestion test per vehicle (round points) and averaged per GVI or Green NCAP data set (diamond points). The Green NCAP thresholds are shown in grey.

[14] https://www.greenncap.com/wp-content/uploads/Rating_Procedure_2022_v3.0.0.pdf

The differences between diesel Euro 6d and 6d-Temp are also highlighted by the instantaneous NO_x emissions (Figure 5.7): the tested Euro 6d vehicles do not demonstrate increased emissions to the same degree as the Euro 6d-Temp, though there are several with elevated emissions. We also note that a petrol vehicle has been tested which, after 400 seconds, shows emissions oscillating up to 1 mg/s.

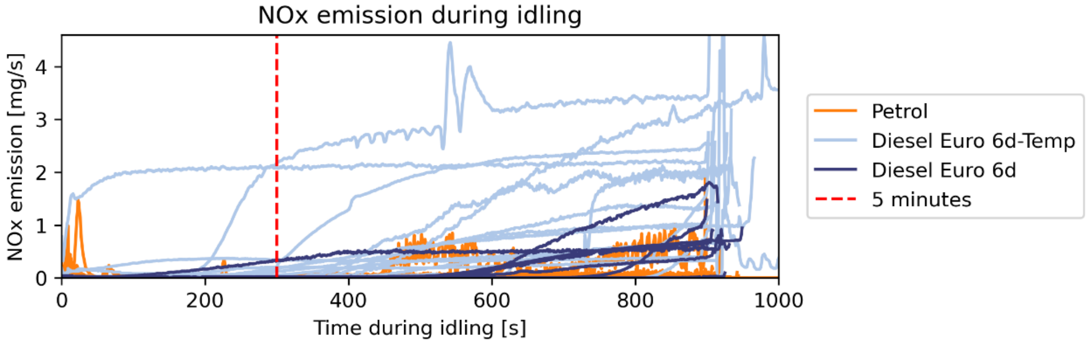


Figure 5.7: Instantaneous NOx emissions during a period of extended idling for a number of different petrol and diesel vehicles. The red line indicates five minutes, which is the maximum duration of idling allowed during an RDE test.

6 Green NCAP tests on battery electric vehicles

6.1 Battery electric vehicles and tests

Detailed descriptions of the test cycles performed on a chassis dynamometer or driven on-road and measured with PEMS within the Green NCAP test programme are given in paragraph 2.1. Of the 101 vehicles measured, 16 were battery electric vehicles (BEVs) of 12 different brands. These 16 BEVs were subjected to chassis dyno lab tests, PEMS on-road tests as well as to charge loss tests. *In this chapter, all vehicle energy use results refer to energy used from and measured at the vehicle battery.*

6.1.1 Chassis dynamometer lab tests on BEVs

In Table 6.1 several characteristics and parameters, calculated from all acquired chassis dynamometer data per vehicle, are given for all 16 BEVs. The BEVs were subjected to a maximum of five different types of tests, differing in driving style and whether a vehicle was cold or warm[15] at the start. See test type id column and table footnotes as well as § 2.1.

As can be observed in this table, all BEVs were tested with four to five types of chassis dyno tests for a total (fictious) distance of about 90 to 120 km.

Table 6.1: Characteristics and vehicle averaged energy use (from battery) per km results for the Green NCAP **chassis dynamometer lab tests** performed with the 16 BEVs.

chassis dyno lab tests						
vehicle nr.	**vehicle description**	**test type id(s)**	**duration total, s**	**stationary total, %**	**distance total, km**	**average energy use Wh/km**
1	Nissan Ariya (87 kWh) FWD	5, 6, 11, 40	6195	11.9	95.0	222.1
2	Volkswagen ID.5 Pro Performance 150 kW	5, 6, 11, 39, 40	8000	12.1	118.3	190.5
3	NIO ET7 BEV AWD	5, 6, 11, 40	6198	11.9	95.0	194.4
4	Lexus UX300e Electric	5, 6, 11, 39, 40	7998	12.1	118.1	233.1
5	VW ID.3	5, 6, 11, 40	6200	11.9	94.9	215.8
6	DACIA Spring	5, 6, 11, 40	6214	11.8	93.8	172.9
7	TESLA Model3 PEV	5, 6, 11, 40	6198	11.9	94.9	183.4
8	Hyundai IONIQ5	5, 6, 11, 39, 40	8001	12.2	118.2	213.4
9	Audi Q4 Sportback e-tron 50	5, 6, 11, 40	6198	11.7	94.9	218.6
10	Cupra Born	5, 6, 11, 39, 40	8000	12.1	118.4	200.3
11	RENAULT MEGANE E-TECH ELECTRIC	5, 6, 11, 40	6200	11.8	94.9	195.4
12	Hyundai Kona Electric	5, 6, 11, 40	6200	12.0	94.8	208.7
13	Nissan Leaf e+	5, 6, 11, 39, 40	8000	12.1	118.4	200.5
14	Ford Mustang Mach-E C2LS4YX (2021)	5, 6, 11, 39, 40	8035	12.6	118.1	239.6
15	Renault ZOE	5, 6, 11, 40	6220	11.8	94.7	190.0
16	Fiat 500e	5, 6, 11, 40	6200	11.8	94.9	174.5

test type id = test type description = description in § 2.1
5 = 'WLTC, warm, def, CS' = 'No description yet'
6 = 'WLTC, cold, def' = '1 WLTC+ cold engine start'
11 = 'BAB, warm, def' = '2 BAB 130 (ADAC highway cycle) warm engine start'
39 = 'WLTC, warm, def, rep' = 'No description yet'
40 = 'WLTC, cold, def, CAT' = 'No description yet'

[15] The measurement programme is shared with internal combustion engine vehicles. For battery electric vehicles, the difference between a 'cold start' and a 'warm start' is limited.

6.1.2 PEMS on-road tests on BEVs

In Table 6.2 several characteristics and parameters, calculated from all acquired PEMS data per vehicle, are given for the tested 16 BEVs. The BEVs were subjected to three different types of on-road tests, differing in driving style and whether a vehicle was cold or warm at the start[15]. See test type id column and table footnotes as well as paragraph 2.1.

As can be observed in this table, seven BEVs were tested over three PEMS test types for a summed total distance of over 240 km for each vehicle. And nine BEVs were tested with only one test type for a total distance of over 80 km each. All tests had urban, rural and motorway parts, where the rural and motorway parts were of comparable length and the urban part roughly half that length.

Table 6.2: Characteristics and vehicle averaged energy use (from battery) per km results for the Green NCAP PEMS on-road tests performed with the 16 BEVs.

PEMS on-road tests						
vehicle nr.	**vehicle description**	**test type id(s)**	**duration total, s**	**stationary total, %**	**distance total, km**	**average energy use Wh/km**
1	Nissan Ariya (87 kWh) FWD	21	6018	6.3	86.2	220.1
2	Volkswagen ID.5 Pro Performance 150 kW	21	5690	8.5	82.7	159.5
3	NIO ET7 BEV AWD	21	6005	9.2	86.8	169.8
4	Lexus UX300e Electric	21, 24, 30	19112	13.4	260.2	171.7
5	VW ID.3	21, 24, 30	19589	15.5	262.2	157.5
6	DACIA Spring	21	5923	11.1	87.6	126.2
7	TESLA Model3 PEV	21	6239	10.5	86.9	139.6
8	Hyundai IONIQ5	21	6075	7.5	92.3	159.0
9	Audi Q4 Sportback e-tron 50	21	6287	9.8	87.7	171.7
10	Cupra Born	21	5786	7.5	82.6	153.8
11	RENAULT MEGANE E-TECH ELECTRIC	21	6317	5.9	101.8	167.4
12	Hyundai Kona Electric	21, 24, 30	20303	18.2	262.8	147.2
13	Nissan Leaf e+	21, 24, 30	17621	12.4	244.6	177.0
14	Ford Mustang Mach-E C2LS4YX (2021)	21, 24, 30	19136	14.9	262.8	222.3
15	Renault ZOE	21, 24, 30	19966	9.6	308.5	153.9
16	Fiat 500e	21, 24, 30	19357	16.0	256.0	140.1
test type id = test type description = description in § 2.1						
21 = 'PEMS, regular, cold' = '3 PEMS+ regular'						
24 = 'PEMS, heavy, warm' = '5 PEMS+ warm heavy load'						
30 = 'PEMS, eco, warm' = '4 PEMS+ warm eco'						

6.2 Charging losses of BEVs

Of course, for battery electric vehicles not only the average energy use is of key importance but also the losses during charging. For that reason special charging tests were performed on the vehicles during which the charging losses were measured. The results for the 16 BEVs, are tabulated in Table 6.3 and are shown in Figure 6.1. For twelve vehicles the charging losses lie around 10% (of the actual charge) and for four they are higher, from about 16 to 21%. There seems to be no clear relationship between the charging power and the charging losses. Nevertheless, it is striking that the five vehicles with the highest charging losses were all charged at 7 kW or less.

Table 6.3: Characteristics and results of the Green NCAP charging loss tests for the 16 BEVs.

vehicle nr.	vehicle description	charging loss %	charging power kW
1	Nissan Ariya (87 kWh) FWD	8.4	11.0
2	Volkswagen ID.5 Pro Performance 150 kW	8.9	11.0
3	NIO ET7 BEV AWD	9.6	11.0
4	Lexus UX300e Electric	10.3	6.6
5	VW ID.3	10.8	11.0
6	DACIA Spring	10.9	3.7
7	TESLA Model3 PEV	10.9	11.0
8	Hyundai IONIQ5	11.6	11.0
9	Audi Q4 Sportback e-tron 50	12.0	11.0
10	Cupra Born	12.0	11.0
11	RENAULT MEGANE E-TECH ELECTRIC	12.2	11.0
12	Hyundai Kona Electric	13.1	3.7
13	Nissan Leaf e+	16.4	6.6
14	Ford Mustang Mach-E C2LS4YX (2021)	18.3	3.7
15	Renault ZOE	19.0	3.7
16	Fiat 500e	20.8	2.3

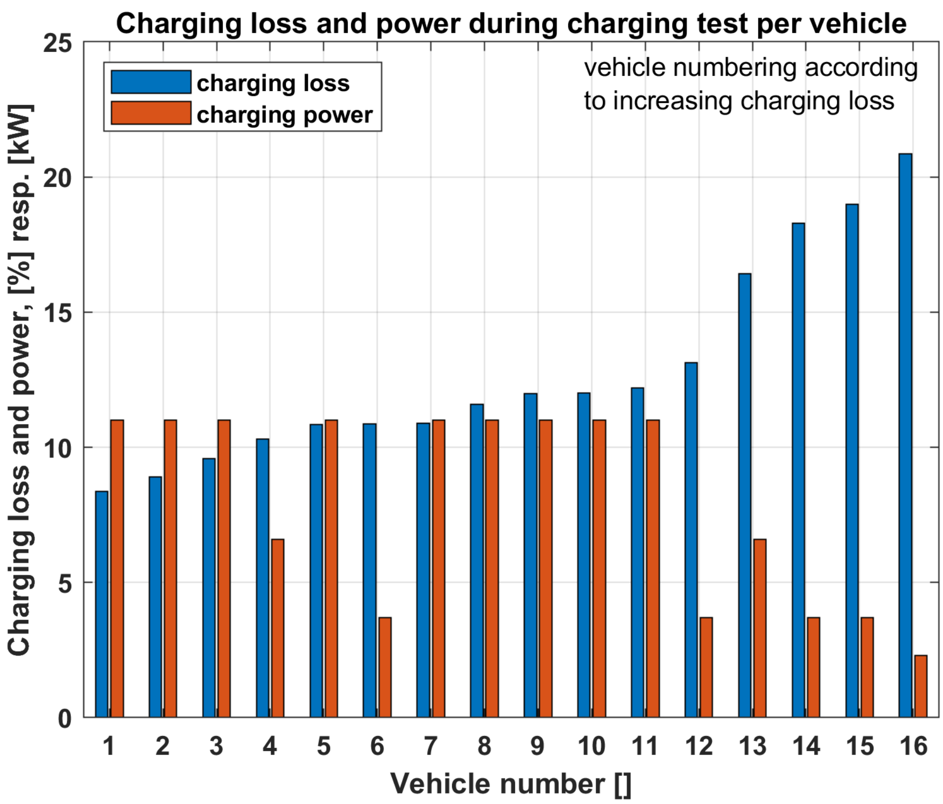


Figure 6.1: Charging losses (blue bars) as measured and power used (red bars) during charging of the 16 BEVs.

6.3 Average power and energy use of BEVs

6.3.1 Power use during stationary moments

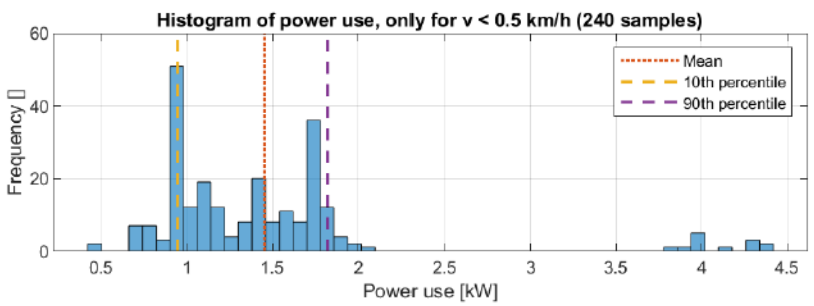
To obtain an impression of the energy consumption of auxiliary systems in electric vehicles, the energy consumption was investigated while the vehicle is 'on' but stationary, e.g. at a traffic light.

The energy consumption while stationary may include:

- Electronic systems
- Comfort systems such as heating, ventilation and air conditioning
- Light, power steering, power brakes
- Thermal conditioning of battery

'Stationary' is here defined as the condition where a vehicle has a speed below 0.5 km/h. Each test can be readily evaluated for the average power use during such moments. Example results, for a single vehicle in a single chassis dyno test (top) as well as in a single on-road PEMS test (bottom), are given in Figure 6.2 and shows that even when stationary the power drawn from the battery can be considerable. Here, the average stationary power use (vertical dotted red lines) is just below 1.5 kW in the chassis dyno test (top) and 1 kW in the PEMS on-road test (bottom).

The graphs also show lines at the 10-percentile and 90-percentile (dashed yellow resp. purple lines, where 10% of the time a lower resp. a higher value was observed). The large variation is likely caused by on-board appliances that can draw a lot of power, such as the aircon compressor and heater matrix, for the conditioning of interior or battery temperature.



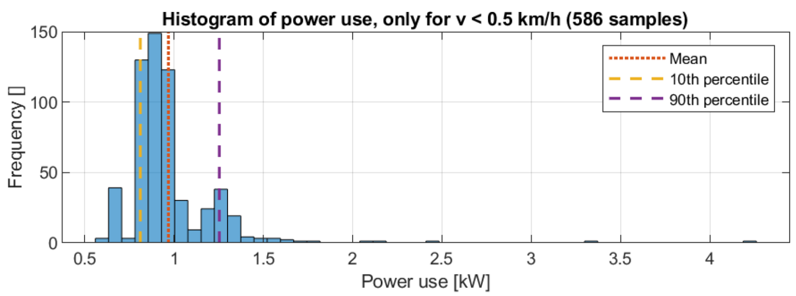


Figure 6.2: Example of power use while stationary of the VW ID.3 in a chassis dyno test of type 'WLTC, cold, def' (top) and the same vehicle in an on-road PEMS test of type 'PEMS, regular, cold' (bottom).

Averaged over all tests, the average power use while stationary is about 1.9 kW for the chassis dyno lab tests and 1.2 kW for the PEMS on-road tests.

6.3.2 Power and energy use during constant speed

Interesting is also the power and energy use during driving at more or less constant speed, where constant speed is defined here as an absolute acceleration of less than or equal to 0.2 m/s^2.

In Figure 6.3 the average power as a function of binned speed is depicted, for a single vehicle in a single chassis dyno test (left) as well as in a single on-road PEMS test (right). As expected the power use increases with increasing speed at an increasing rate.

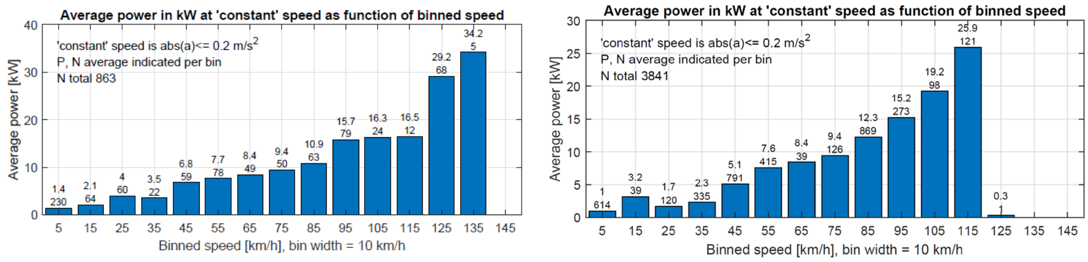


Figure 6.3: Example of average power use while driving at 'constant' speed of the VW ID.3 in a chassis dyno lab test of type 'WLTC, cold, def' (left) and an on-road PEMS test of type 'PEMS, regular, cold' (right). The two numbers above each bar are the average power and respectively the number of seconds averaged over for that bar.

In a similar way, the average energy use per kilometre driven can be calculated. The results of which are shown in Figure 6.4. Both graphs more or less show the familiar 'bath tub' shape of the energy use per kilometre as a function of vehicle speed.

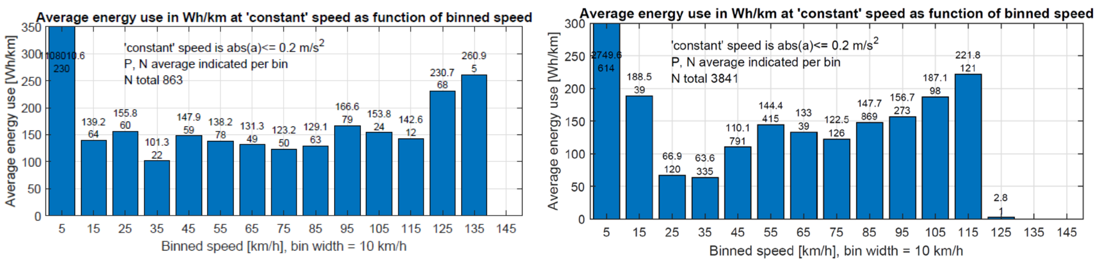


Figure 6.4: Again vehicle 5 driving at 'constant' speed but shown is now average energy per kilometre driven of the VW ID.3 in a chassis dyno lab test of type 'WLTC, cold, def' (left) and an on-road PEMS test of type 'PEMS, regular, cold' (right). The two numbers above each bar are the average power and respectively the number of seconds averaged over for that bar.

6.3.3 Energy use averaged per vehicle per test

In this paragraph, the energy use averaging is done per vehicle per test. For the chassis dynamometer lab tests the results are shown in Figure 6.6 and Table 6.4. For the PEMS on-road tests the results are shown in Figure 6.7 and Table 6.5.

<u>Chassis dyno lab tests</u>
In the right-hand top corner of Figure 6.6, the legend explains which average energy result, a coloured circle, corresponds with what chassis dyno lab test.

Note that each test type has its own colour, which is also used in Table 6.4. The '5 WLTC, warm, def, CS' test results, for example, all have a blue circle.

Also note that only seven vehicles were subjected to 'test 39' alias the '39 WLTC, warm, def, CAT' test, designated with yellow circles, whereas all vehicles were subjected to the other four test types. See also Table 6.4.

There are also 16 black stars in the graph. These designate the per vehicle averaged energy use for all tests except test 39 and were used for the vehicle plotting order (in-order-of-increasing-energy-use) along the X-axis. The black stars are distance weighted averages of all the coloured circles except the yellow ones. See also Table 6.4 (last column).

The graph clearly illustrates that there are two chassis dyno test types that lead to significantly higher average energy use per kilometre than the other three. These are the '11 BAB, warm def' test (green circles), which corresponds to a high-speed motorway test and the '40 WLTC, cold, def, CAT' test (magenta circles), which corresponds to a test with a cold ambient temperature.

Table 6.4: Average energy use (from battery) per vehicle per test for the chassis dyno lab tests.

chassis dyno lab tests							
vehicle	vehicle description	test 5	test 6	test 11	test 39	test 40	average of all but 39
nr.		Wh/km	Wh/km	Wh/km	Wh/km	Wh/km	Wh/km
6	DACIA Spring	144.3	144.7	200.7		200.9	172.9
16	Fiat 500e	141.2	152.5	198.3		204.2	174.5
7	TESLA Model3 PEV	144.5	151.1	180.5		257.7	183.4
15	Renault ZOE	144.3	155.3	233.8		223.3	190.0
3	NIO ET7 BEV AWD	153.0	159.2	204.6		260.1	194.4
11	RENAULT MEGANE E-TECH ELECTRIC	143.1	148.1	224.8		263.3	195.4
2	Volkswagen ID.5 Pro Performance 150 kW	148.8	146.3	193.2	159.6	304.2	198.1
12	Hyundai Kona Electric	164.2	177.3	232.2		259.3	208.7
10	Cupra Born	171.6	163.6	219.7	163.4	281.9	209.3
13	Nissan Leaf e+	159.4	169.0	242.7	160.7	267.7	210.2
5	VW ID.3	149.9	168.3	209.7		335.8	215.8
9	Audi Q4 Sportback e-tron 50	174.1	182.4	248.0		267.5	218.6
1	Nissan Ariya (87 kWh) FWD	169.3	176.6	254.0		286.0	222.1
8	Hyundai IONIQ5	163.3	166.3	260.9	165.6	307.6	225.2
4	Lexus UX300e Electric	185.4	203.2	259.5	192.6	323.1	243.1
14	Ford Mustang Mach-E C2LS4YX (2021)	192.6	217.6	267.6	194.1	323.9	250.8

test type id = test type description = description in § 2.1	vehicle numbering according
5 = 'WLTC, warm, def, CS' = 'No description yet'	to increasing charging loss
6 = 'WLTC, cold, def' = '1 WLTC+ cold engine start'	AND vehicle listing order
11 = 'BAB, warm, def' = '2 BAB 130 (ADAC highway cycle) warm engine start'	according to increasing
39 = 'WLTC, warm, def, rep' = 'No description yet'	average energy use (all but 39)
40 = 'WLTC, cold, def, CAT' = 'No description yet'	

PEMS on-road tests

In the right-hand top corner of Figure 6.7 a similar legend explains the average energy use results for the PEMS on-road tests. Each of the three PEMS on-road test types has its own colour and these colours are also used in Table 6.5.

Note that only seven BEVs were subjected to all three PEMS on-road test types. For these seven vehicles, the red results, corresponding with a 'heavier' (driving style and vehicle settings) test, usually have a higher energy use than the blue results, corresponding with a more 'average' (driving style) test.

And also, the green results, corresponding with a more ‘eco’ (driving style and vehicle settings) test, usually have a lower energy use than the blue results. The other nine BEVs were subjected to only one PEMS test type, i.e. ‘test 21’ alias ‘21PEMS+ cold’ designated with the blue circles. Note that test 21 is the only test that was performed on all 16 vehicles. See also Table 6.5.

Besides the coloured circles, for energy use per vehicle per whole test, there are also coloured squares and down- and upward pointing triangles. These three new symbols designate the results per road type parts of a test, i.e. the urban, rural and motorway parts[16]. Mostly, but not always, the energy use increases from urban to rural to motorway.

In Figure 6.7 again 16 black stars are used. These designate the vehicle plotting order (in-order-of-increasing-energy-use) along the X-axis and for these the results of test 21 were used, as this was the only PEMS test performed on all 16 vehicles.

<u>Comparison of a chassis dyno lab test and a PEMS on-road test</u>

In Figure 6.5 two roughly similar tests are compared. These are chassis dyno lab test 6 alias ‘WLTC, cold, def’ and PEMS on-road test 21 alias ‘PEMS, regular, cold’. For both graphs the vehicle display ordering (along X-axis) was chosen such that the test averaged energy use per kilometre increases. Both graphs show a narrow energy range of about 30 Wh/km in which 14 of 16 vehicles fall and two vehicles that have a slightly (left) or distinctly higher energy use. The horizontal vehicle ordering shows both similarities as dissimilarities.

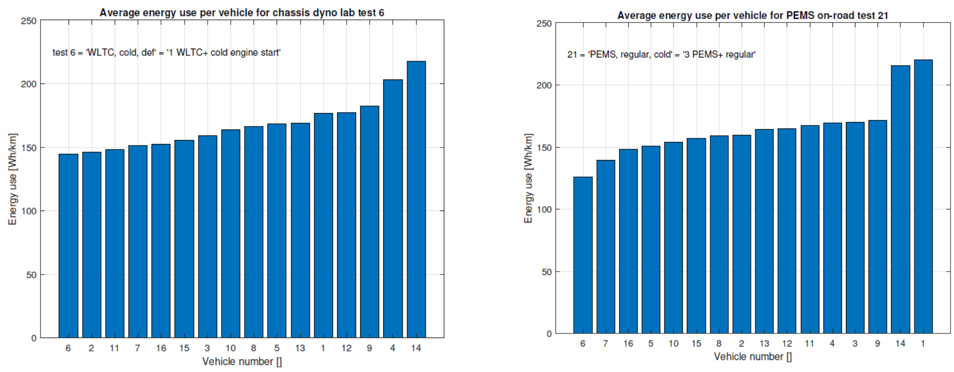


Figure 6.5: Two roughly similar tests compared: chassis dyno lab test 6 alias ‘WLTC, cold, def’ (left graph) and PEMS on-road test 21 alias ’PEMS, regular, cold’ (right graph).

[16] The road type information for the chassis dyno test data was not yet available when writing the report, hence it is lacking in Figure 6.6 and Table 6.4.

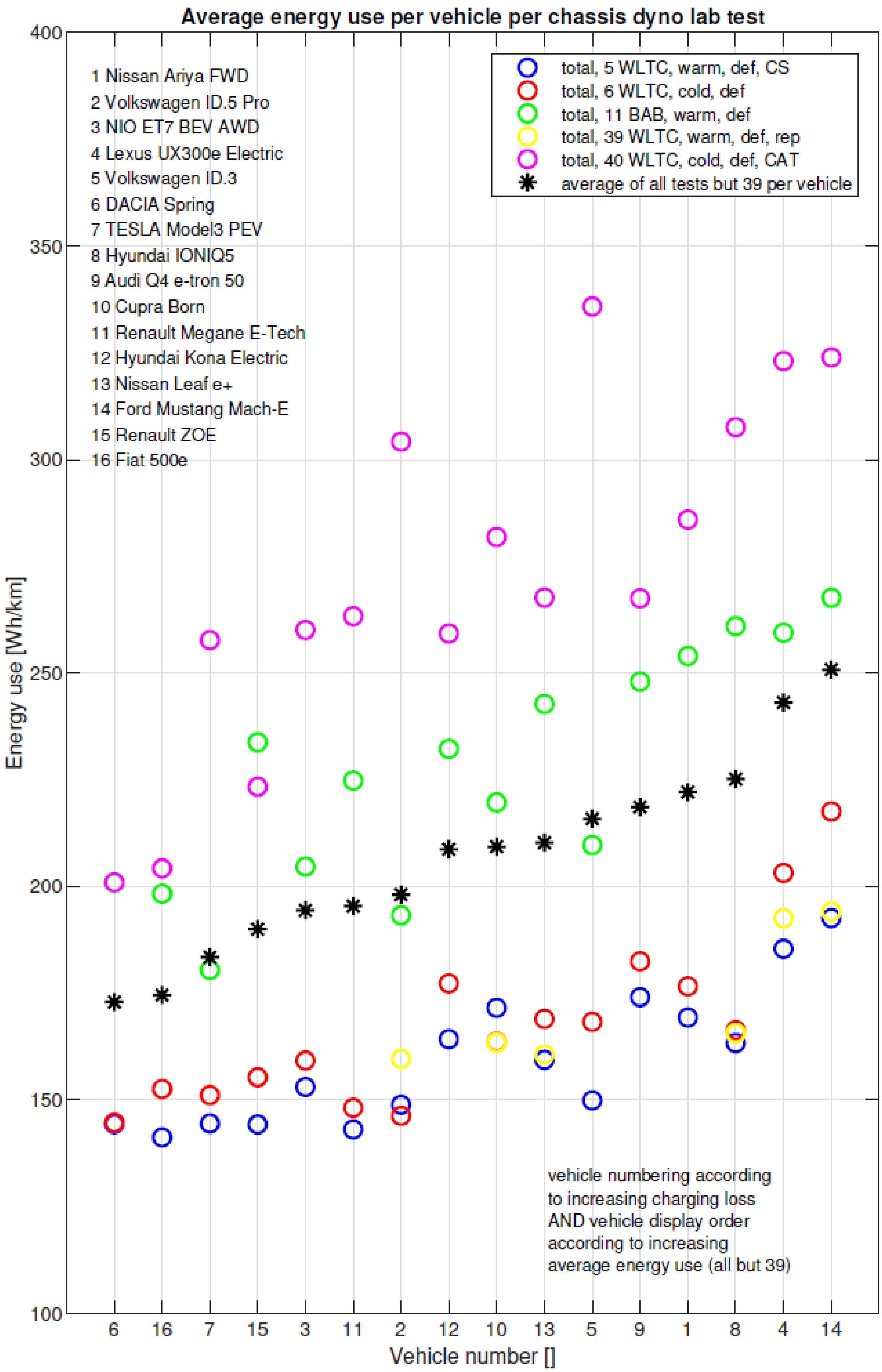


Figure 6.6: Average energy use (from battery) per vehicle per test for the chassis dyno lab tests.

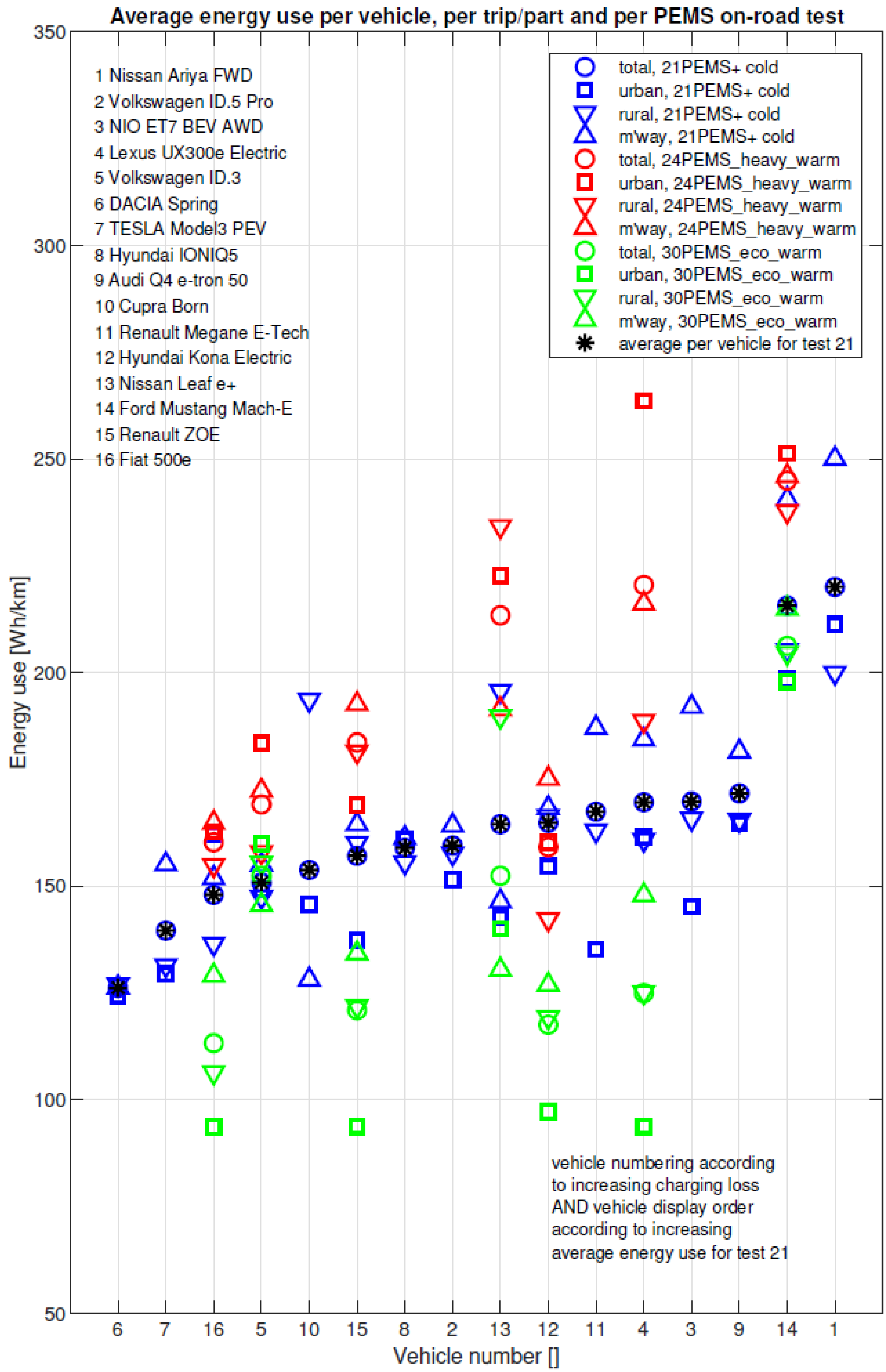


Figure 6.7: Average energy use (from battery) per vehicle per test, and per road type, for the PEMS on-road tests.

Table 6.5: Average energy use (from battery) per vehicle per test and road type for the PEMS on-road tests.

		PEMS on-road tests											
vehicle	**vehicle description**	test 21	21 urban	21 rural	21 m'way	test 24	24 urban	24 rural	24 m'way	test 30	30 urban	30 rural	30 m'way
nr.		**Wh/km**	**Wh/km**	**Wh/km**	**Wh/km**	**Wh/km**	**Wh/km**	**Wh/km**	**Wh/km**	**Wh/km**	**Wh/km**	**Wh/km**	**Wh/km**
6	DACIA Spring	126.2	124.4	127.0	126.3								
7	TESLA Model3 PEV	139.6	129.5	131.4	155.2								
16	Fiat 500e	148.0	162.1	136.5	151.9	160.3	162.7	154.9	164.8	113.3	93.6	106.4	129.1
12	VW ID.3	150.9	149.3	147.5	155.0	169.1	183.5	158.0	172.4	152.4	160.0	155.4	145.6
10	Cupra Born	153.8	145.8	193.6	128.2								
15	Renault ZOE	157.1	137.3	160.1	164.5	183.7	169.0	181.5	192.7	121.0	93.7	121.9	134.3
5	Hyundai IONIQ5	159.0	160.9	155.6	161.3								
8	Volkswagen ID.5 Pro Performance 150 kW	159.5	151.5	157.7	164.2								
2	Nissan Leaf e+	164.5	142.7	195.7	146.4	213.4	222.7	234.2	191.4	152.4	140.1	189.7	130.5
11	Hyundai Kona Electric	164.8	154.7	166.4	168.3	159.2	160.3	142.2	175.2	117.6	97.2	119.3	127.0
3	RENAULT MEGANE E-TECH ELECTRIC	167.4	135.3	163.0	187.1								
4	Lexus UX300e Electric	169.7	161.5	160.8	184.3	220.5	263.6	188.7	216.2	125.0	93.7	125.1	147.9
9	NIO ET7 BEV AWD	169.8	145.3	165.8	192.0								
13	Audi Q4 Sportback e-tron 50	171.7	164.7	165.4	181.5								
1	Ford Mustang Mach-E C2LS4YX (2021)	215.7	198.4	205.3	240.6	245.0	251.3	237.8	246.0	206.3	197.9	204.6	215.0
14	Nissan Ariya (87 kWh) FWD	220.1	211.3	199.9	250.1								

test type id = test type description = description in § 2.1
21 = 'PEMS, regular, cold' = '3 PEMS+ regular'
24 = 'PEMS, heavy, warm' = '5 PEMS+ warm heavy load'
30 = 'PEMS, eco, warm' = '4 PEMS+ warm eco'

vehicle numbering according to increasing charging loss AND vehicle listing order according to increasing average energy use for test 21

6.4 Other insights

This paragraph contains a small selection of graphs, from the many hundreds of graphs generated in the first analysis of the Green NCAP tests on BEVs. All sample graphs are based on the on-road 'PEMS, regular, cold' test of the VW ID.3.

Figure 6.8 shows a scatter plot of the power drawn from the battery during the PEMS regular cold test. Negative values (in red) indicate brake energy recovery.

The top of the graph gives an impression of the power curve. The peak power during this test is approximately 23 Wh/s, which corresponds to about 83 kW. More interesting is the straight line that can be drawn through the lowest red points, as indicated by the dashed line in the diagram. This is the maximum possible regeneration. As can be seen, and this holds for the other electric vehicles as well, no energy is recovered below around 10 km/h.

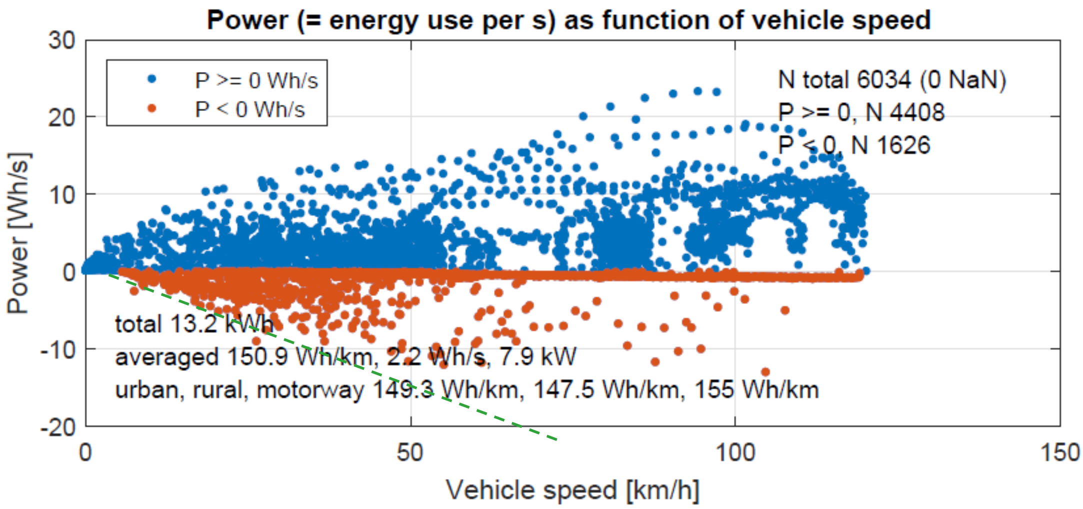


Figure 6.8: Power as function of vehicle speed for the VW ID.3 in the on-road 'PEMS, regular, cold' test.

Also interesting in this graph are the printed (calculated) average consumptions for urban, rural and motorway parts, i.e. 149.3, 147.5, 155 Wh/km for urban, rural and motorway respectively. Even though the speeds are much lower in the city and brake energy consumption partly reduces the losses due to frequent deceleration, the average consumption per km is hardly any lower than on the highway. The same is seen for most other EVs.

For the PEMS on-road tests, the energy consumption while stationary is on average 1.2 kW. See also § 6.3.1 and in particular the PEMS on-road example in Figure 6.2. The average speed of the urban part of that test was 22 km/h. This means that the consumption not related to propulsion would be 45 Wh/km (1000 W / 22 km), or a third of the total consumption. This under the assumption that the value of 1 kW (not related to propulsion) remains the same when the vehicle is moving.

In Figure 6.9 the average power is shown for bins of speed and acceleration of the VW ID.3 in the on-road 'PEMS, regular, cold' test. Acceleration is an important factor in the instantaneous power demand. Driving at constant speed of about 100 km/h on the highway requires a power in the order of 20 kW.

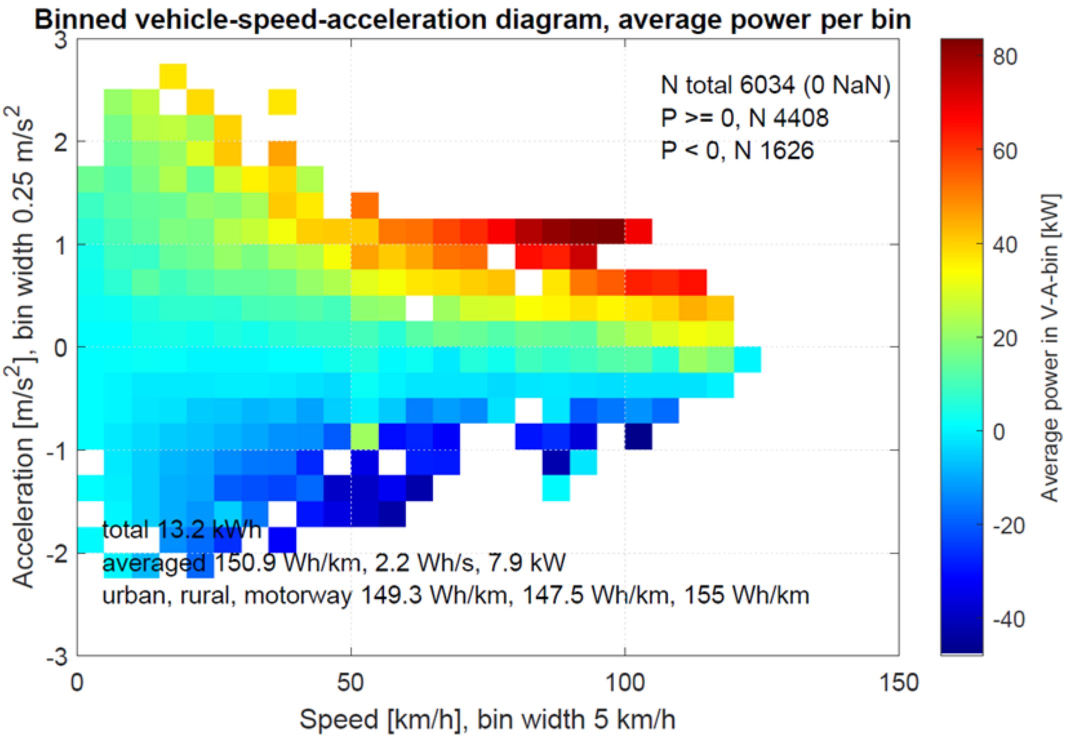


Figure 6.9: Bin-averaged power as function of vehicle speed and acceleration for the VW ID.3 in the on-road 'PEMS, regular, cold' test

In Figure 6.10 the vehicle speed of the VW ID.3 during the 'PEMS, regular, cold' test is shown. The urban, rural and motorway parts can be readily distinguished, i.e.: urban: 0 to 1900 s and 5200 to 6000 s; rural: 1900 to 3900 s; motorway: 3900 to 5200 s and again urban from 5200 to 6034 s.

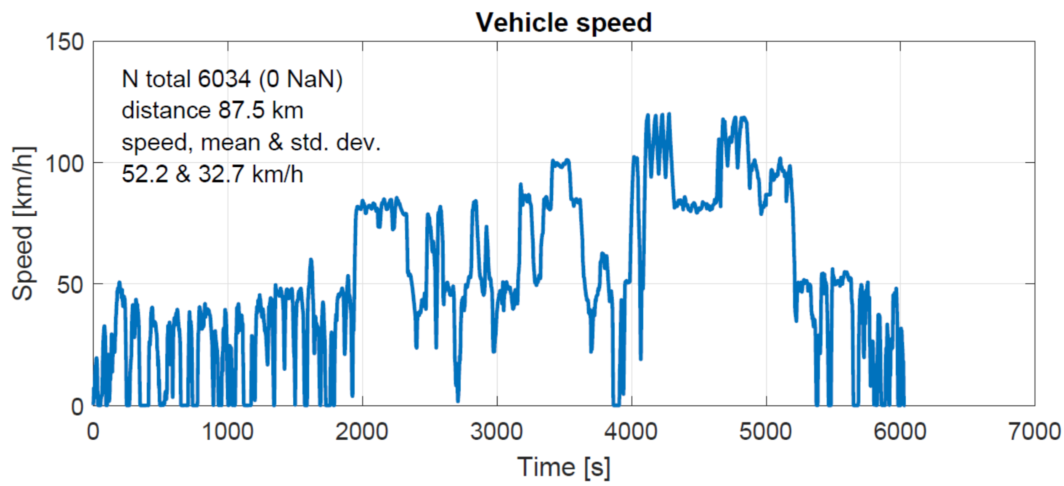


Figure 6.10: Vehicle speed for the VW ID.3 in the on-road 'PEMS, regular, cold' test.

Besides acceleration, elevation is a large factor in the instantaneous power demand. Figure 6.11 shows the elevation profile of the PEMS test shown in the above graphs.

For a 100 m increase in altitude during a test, a vehicle with 1812 kg mass in running order would require an additional 0.49 kWh plus drivetrain losses. The tests in Green NCAP were all done in such a way that start and end are at the same altitude.

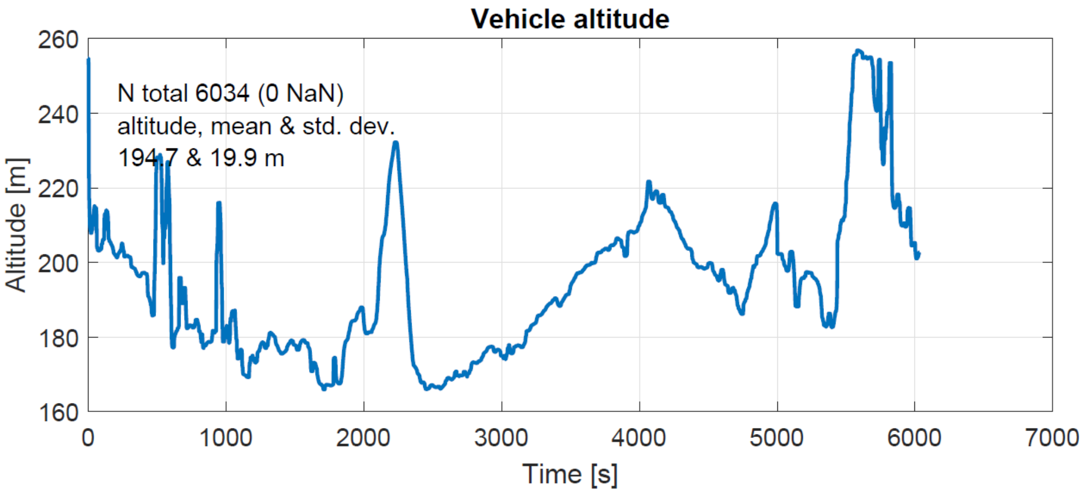


Figure 6.11: Elevation profile for the VW ID.3 in the on-road 'PEMS, regular, cold' test.

6.5 Conclusions

From the previously presented and discussed tests - i.e. the charging tests, the chassis dynamometer lab tests and the PEMS on-road tests - as performed on the 16 Green NCAP battery electric vehicles, the following more general conclusions can be drawn.

The charging losses are substantial and vary from about 8 to 21%.

Even during stationary moments (defined as speed < 0.5 km/h), the power use can be substantial. Averaged over all stationary moments per single test the mean power use is roughly between 0.5 and 2.5 kW. For urban use with an average speed of about 30 km/h that means that, of the total energy consumption, 17-80 Wh/km is not related to propulsion, which can be up to half of the total consumption.

7 Conclusion

Comprehensive testing programmes, both on-road and in the laboratory, give insight into emission behaviour in different potentially high-emission situations.
In this report, 101 vehicles were analysed, including a range of Euro 6d-Temp and Euro 6d diesel, petrol, plug-in petrol, petrol hybrid, CNG and BEV vehicles.

This results in the following main conclusions:

- *High trip-averaged emissions for regulated pollutants are primarily observed during the high speed (BAB) and cold ambient temperature (-7 °C) laboratory tests, and heavy on-road tests.*
  Even though most of the vehicles tested performed well within the thresholds for the RDE-like on-road tests, these three tests especially demonstrated high average emissions for regulated pollutants. This re-emphasises the need for comprehensive testing.

- *Non-regulated pollutants N_2O and NH_3 deserve continued monitoring*
  Diesel vehicles show consistently high N_2O emissions compared to other fuels; petrol vehicles emit a trip-averaged 0.96 mg/km N_2O, while diesel vehicles emit around 14 mg/km (3.7 g CO_2 eq.). However, several vehicles showed VERSIT+ road-type emissions of over 40 mg/km (11 g CO_2 eq.). This reduces the benefits of the typical lower CO_2-emissions of diesel vehicles. Across all tests, petrol vehicles emit an average of 11 mg/km NH_3, while diesel vehicles emit 2.6 mg/km. There are several petrol vehicles with VERSIT+ road-type emissions higher than 20 mg/km, though one diesel 6d-Temp has emissions in excess of 80 mg/km.

- *Cold starts are now considered best represented by a point source*
  Extended testing has shown that high emissions due to a cold engine occur over increasingly short distances. A technology-neutral approach has been taken where cold start extra emissions are determined using the difference between the average emissions during the first kilometre and the average over an entire trip. This has been implemented within VERSIT+ as the road-type 'WKS' (Wegtype Koude Start (road type cold start)).

- *PN emissions vary significantly depending on engines and how they're used*
  When considering PN emissions as a function of both CO_2 and velocity, the localisation of high emissions varies between vehicles as well as technologies. PN emission factors have been reintroduced to VERSIT+ using the emission factors calculated here, for petrol cars this is an order of magnitude higher than previously used emission factors.

- *Several of the tested vehicles likely have an insufficiently large catalyst*
  Relatively high pollutant emissions as a function of CO_2 can indicate the inability of the after-treatment system to effectively treat the exhaust gas flow due to its size. Several diesel vehicles have been observed which demonstrate this.

- *Energy consumption of BEVs, caused by propulsion or auxiliaries, can be substantial.* The charging losses of the 16 tested BEVs are substantial and vary from about 8 to 21 %. Also during stationary moments (speed < 0.5 km/h), the power use can be substantial. Averaged over all stationary moments per single test the mean power use is roughly between 0.5 and 2.5 kW. For urban use with an average speed of 30 km/h that means that, of the total energy consumption, 17-80 Wh/km is not related to propulsion, which can be up to half of the total consumption.

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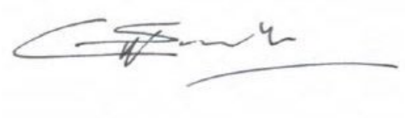

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Appendix A
VERSIT+ road-type emission factor comparison

A.1 Pollutants measured on-road

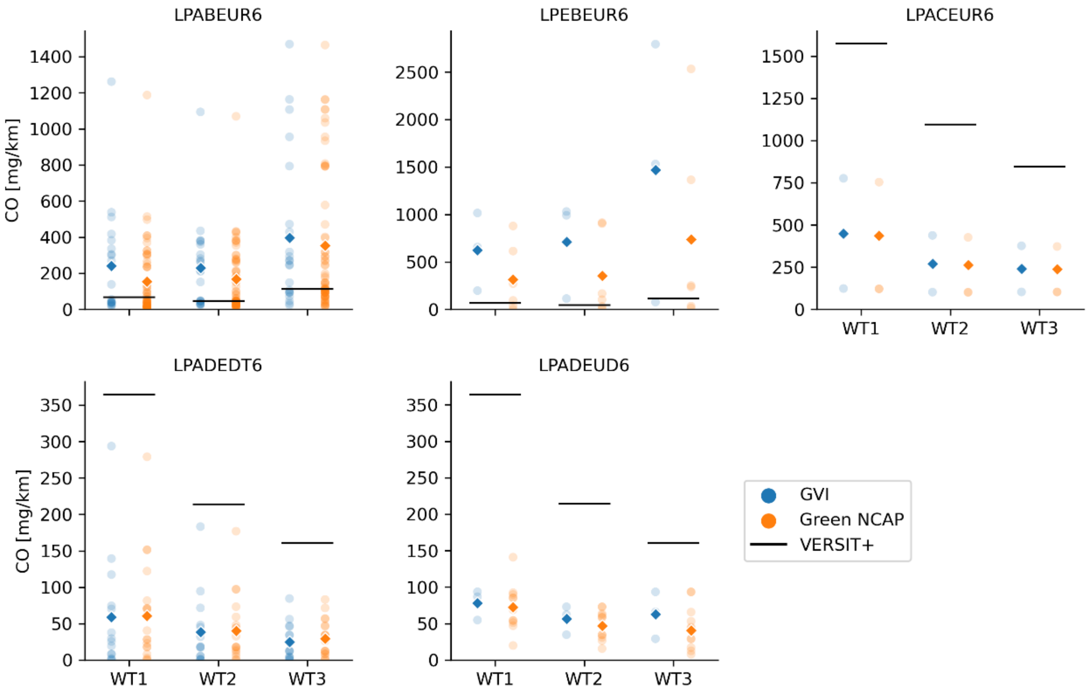

Figure A.1: Average CO emissions calculated per urban (WT1), rural (WT2) and motorway (WT3) VERSIT+ road type, as calculated per vehicle (round points) and averaged per GVI or Green NCAP data set (diamond points). Each pane shows the relevant VERSIT+ classes separately.

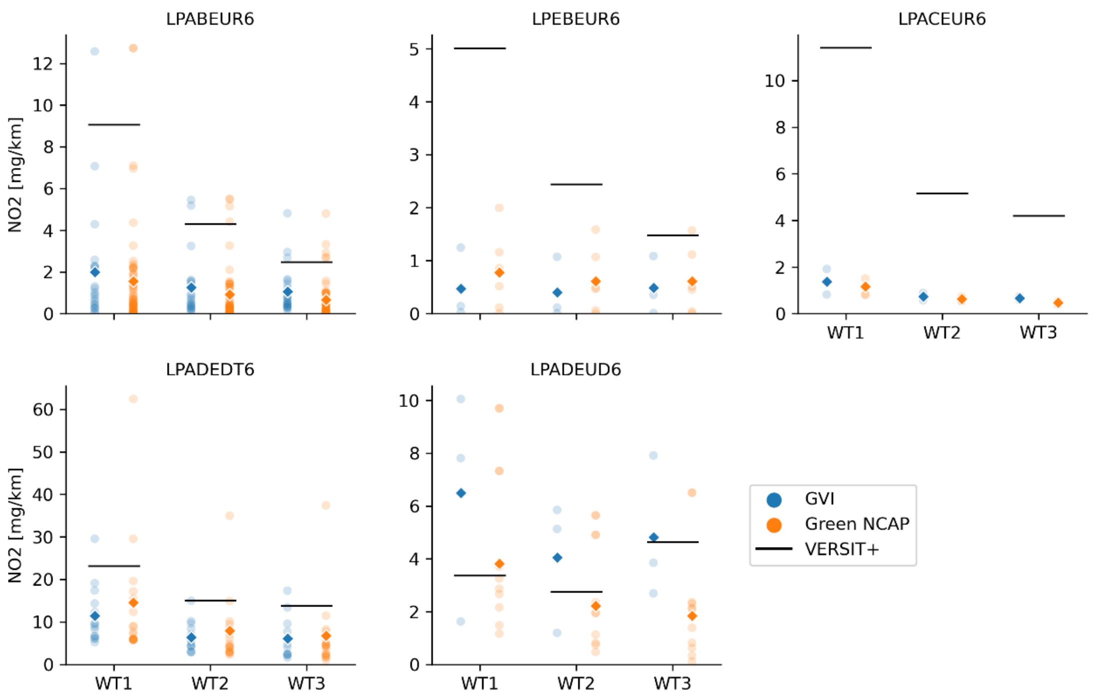

Figure A.2: Average NO_2 emissions calculated per urban (WT1), rural (WT2) and motorway (WT3) VERSIT+ road type, as calculated per vehicle (round points) and averaged per GVI or Green NCAP data set (diamond points). Each pane shows the relevant VERSIT+ classes separately.

A.2 Pollutants measured in the laboratory

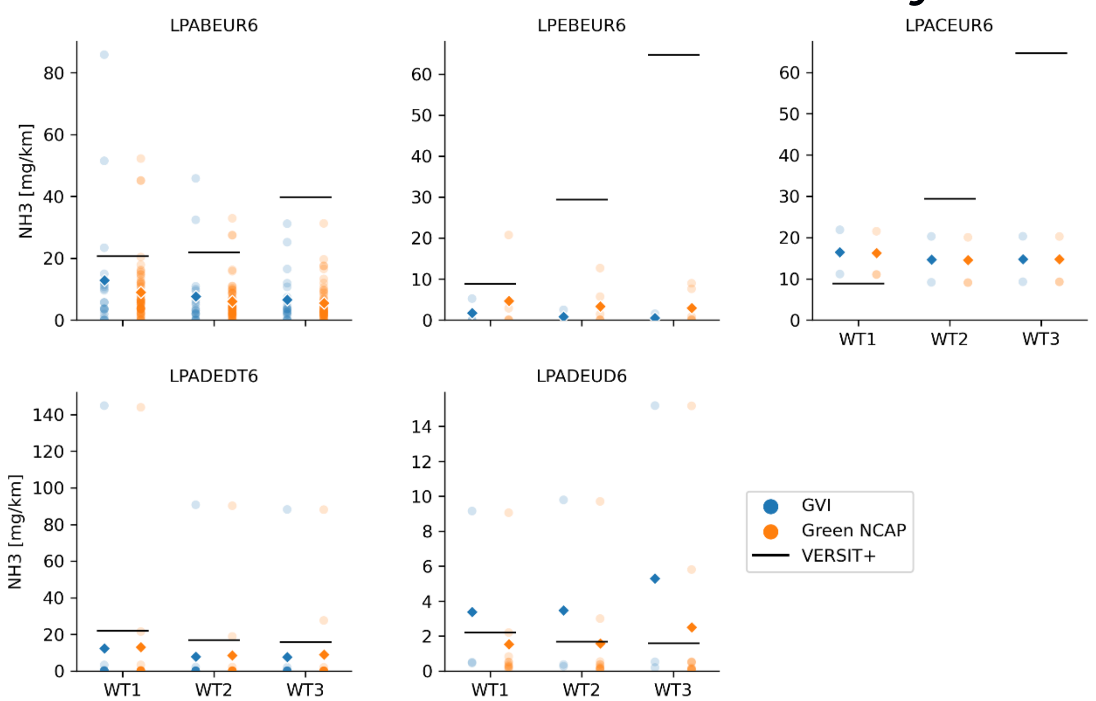

Figure A.3: Average NH_3 emissions calculated per urban (WT1), rural (WT2) and motorway (WT3) VERSIT+ road type, as calculated per vehicle (round points) and averaged per GVI or Green NCAP data set (diamond points). Each pane shows the relevant VERSIT+ classes separately.

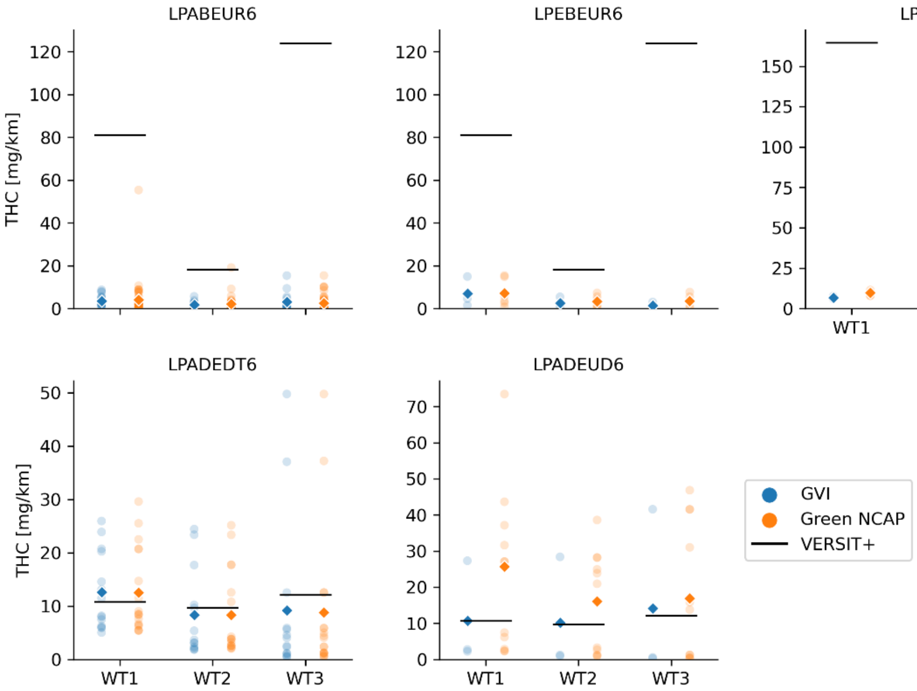

Figure A.4: Average THC emissions calculated per urban (WT1), rural (WT2) and motorway (WT3) VERSIT+ road type, as calculated per vehicle (round points) and averaged per GVI or Green NCAP data set (diamond points). Each pane shows the relevant VERSIT+ classes separately.

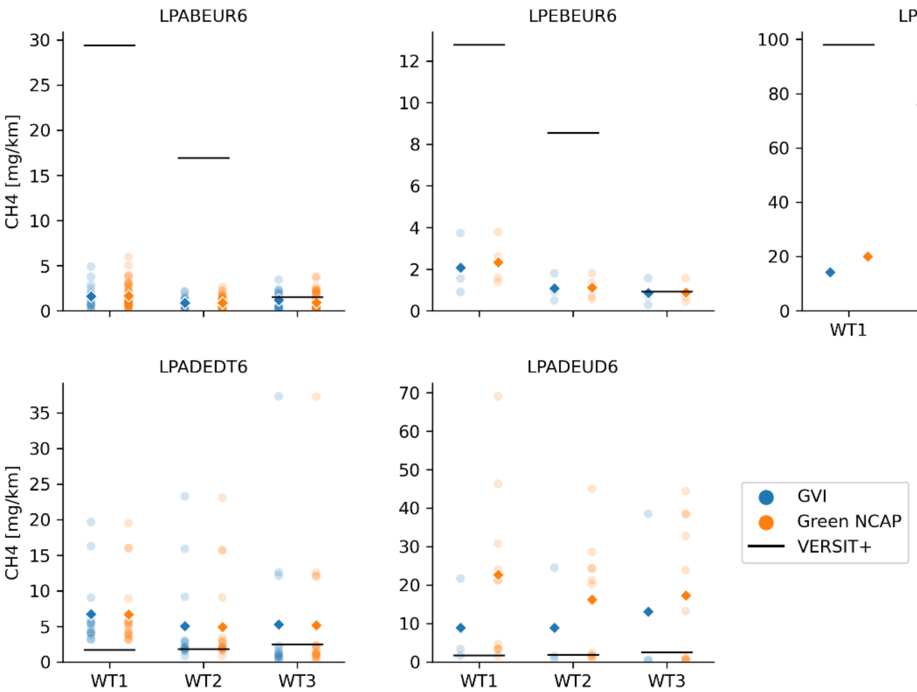

Figure A.5: Average CH_4 emissions calculated per urban (WT1), rural (WT2) and motorway (WT3) VERSIT+ road type, as calculated per vehicle (round points) and averaged per GVI or Green NCAP data set (diamond points). Each pane shows the relevant VERSIT+ classes separately. Note that CH_4 emissions were only measured for one of the CNG vehicles.

A.3 VERSIT+ emission factors comparison table

Table A.1: Average emission factors per VERSIT+ class for the VERSIT+ road types urban (WT1), rural (WT2) and motorway (WT3) as calculated using the GVI and Green NCAP data sets and shown in the figures above. The total cold start emissions (TCSE) and point source representation of cold start extra emissions (WKS) are also listed.

Pollutant	VERSIT+ class	WT1 GVI	WT1 Green NCAP	WT2 GVI	WT2 Green NCAP	WT3 GVI	WT3 Green NCAP	TCSE GVI	WKS Green NCAP
CH4 [mg]	LPABEUR6	1.6	1.6	0.89	0.88	1.2	0.93	76	49
	LPEBEUR6	1.9	2.3	1	1.1	0.82	0.88	43	31
	LPACEUR6	14	20	5.1	8	4	4.5	1500	1300
	LPADEDT6	6.7	6.7	5.1	4.9	5.3	5.2	24	14
	LPADEUD6	8.9	23	8.9	16	13	17	12	15
CO [mg]	LPABEUR6	240	150	230	170	400	350	2000	2100
	LPEBEUR6	620	320	710	350	1500	740	1400	510
	LPACEUR6	450	440	270	260	240	240	1900	1200
	LPADEDT6	59	61	39	40	25	30	730	520
	LPADEUD6	78	72	57	47	63	41	440	690
N2O [mg]	LPABEUR6	6.8	4.4	5.5	3.5	5.5	3.5	21	14
	LPEBEUR6	0.66	0.36	0.61	0.24	0.81	0.27	7.4	2.4
	LPACEUR6	2.0	2.1	1.4	1.4	1.4	1.4	8.3	16
	LPADEDT6	65	64	46	45	37	36	99	21
	LPADEUD6	22	29	14	19	11	14	3.4	4.4
NH3 [mg]	LPABEUR6	13	9.0	7.6	6.1	6.6	5.5	4.6	22
	LPEBEUR6	1.7	4.7	0.84	3.3	0.52	2.9	4.6	18
	LPACEUR6	17	16	15	15	15	15	1.2	-12
	LPADEDT6	12	13	7.8	8.6	7.6	9.1	1.1	-1.5
	LPADEUD6	3.4	1.5	3.5	1.6	5.3	2.5	0.28	-1.3
NO2 [mg]	LPABEUR6	2.0	1.6	1.2	0.92	1.1	0.65	2.5	1.4
	LPEBEUR6	0.47	0.77	0.4	0.61	0.48	0.61	1.5	-0.022
	LPACEUR6	1.4	1.2	0.73	0.63	0.66	0.46	0.72	5.3
	LPADEDT6	11	15	6.4	8.0	6.1	6.8	13	8.3
	LPADEUD6	6.5	3.8	4.1	2.2	4.8	1.8	5.8	0.39
NOx [mg]	LPABEUR6	15	15	8.8	8.6	7.0	6.8	97	110
	LPEBEUR6	2.7	6.4	2.2	4.3	3.3	4.5	24	12
	LPACEUR6	18	17	7.6	7.3	4.0	4.0	38	190
	LPADEDT6	85	73	44	38	38	37	370	210
	LPADEUD6	45	47	28	26	37	30	320	210
THC [mg]	LPABEUR6	3.6	4.1	1.9	2.1	3.1	2.6	960	690
	LPEBEUR6	7.0	7.2	2.6	3.4	1.5	3.5	1100	600

Pollutant	VERSIT+ class	WT1 GVI	WT1 Green NCAP	WT2 GVI	WT2 Green NCAP	WT3 GVI	WT3 Green NCAP	TCSE GVI	WKS Green NCAP
	LPACEUR6	6.8	9.7	3.5	4.9	3.3	3.6	1000	910
	LPADEDT6	13	13	8.4	8.3	9.2	8.9	130	82
	LPADEUD6	11	26	10	16	14	17	42	61

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