Cold start emissions of petrol vehicles

Emissions measurements and updated emission factors

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Samenvatting

Introductie
Dankzij de wijdverspreide toepassing van effectieve nabehandelingssystemen zijn de uitlaatemissies van wegvoertuigen de afgelopen twintig jaar aanzienlijk afgenomen. Nabehandelingssystemen die ontworpen zijn om gasvormige emissies te verminderen, vereisen echter meestal een bedrijfstemperatuur die boven de omgevingsomstandigheden ligt. Met name tijdens een koude start kunnen gasvormige emissies zoals NO_x sterk toenemen en zo een aanzienlijke impact hebben op de totale emissies van een voertuigrit. Door de verbeterde nabehandeling van nieuwere voertuigmodellen vinden de hoge emissieniveaus die kunnen worden toegeschreven aan een koude start plaats binnen steeds kortere afstanden. Om deze reden wordt een puntbron nu beschouwd als de beste representatie van de extra emissies van een koude start. Deze is nu geïmplementeerd in de emissiefactoren van VERSIT+ en dus ook in de Nederlandse Emissieregistratie. Aangezien de implementatie van puntbronnen aanzienlijk afwijkt van de manier waarop koude starts in het verleden werden benaderd, was breder onderzoek nodig om de huidig afgeleide emissiefactoren voor extra emissies van koude starts te ondersteunen.

Doel van het werk
Het doel van het werk zoals gepresenteerd in dit rapport is niet alleen om de huidige afgeleide emissiefactoren voor extra emissies bij koude start van benzinevoertuigen verder te ondersteunen, maar ook om koude start bij stationair draaien breed te onderzoeken.

Aanpak
In totaal zijn 31 benzinevoertuigen uit het Nederlandse wagenpark gemeten op hun uitstoot. De meeste voertuigen in de set voldoen aan Euro 6 wetgeving en hebben een kilometerstand van minder dan 150.000 km. De PEMS-gegevens (Portable Emission Measurement System) van koudestartmetingen van de geteste voertuigen zijn gebruikt om meer inzicht te krijgen in het gedrag van de uitlaatgastemperatuur en de emissieniveaus na een koude start en na opnieuw starten.

Resultaten, conclusies en aanbevelingen
De resultaten van dit werk tonen het belang aan van de emissies bij een koude start op de totale emissies tijdens een voertuigrit en bieden inzicht in aanvullende testparameters:

- Er werd waargenomen dat de temperatuur van de uitlaatgassen onder de 60°C bleef, zelfs na langdurig stationair draaien. Koud uitlaatgas stijgt niet in dezelfde mate op als warm uitlaatgas, dus dit zou er waarschijnlijk toe leiden dat de gassen lager rond de auto blijven. Omdat de gassen laag blijven, kan dit leiden tot een verhoogde blootstelling van mensen rond of in de buurt van het voertuig.
- Het merendeel van de NO_x-emissies werd waargenomen in de eerste 30 seconden na het starten van de motor, wat de huidige voorstelling van de koude start als puntbron verder ondersteunt.
- De emissieniveaus van NO_x, THC en PN waren aanzienlijk hoger tijdens de koudestarttest. Bij het vergelijken van de gemiddelde NO_x-, THC- en PN-emissieniveaus werd vastgesteld dat de niveaus bij koude start het hoogst waren, bij start van een warme motor het laagst en bij het opnieuw starten van de motor licht hoger dan bij een warme motor.

We hebben de verhoogde emissies bij herstarten nog niet eerder zo gedetailleerd onderzocht; we raden aan om herstarts waar mogelijk op te nemen in toekomstige campagnes.

VERSIT+ Wegtype Koude Start (WKS) emissiefactoren
De dataset van deze meetcampagne is gebruikt om VERSIT+ WKS-emissiewaarden te berekenen, waarbij WKS de puntbronweergave is van extra emissies bij koude start:

- Vergelijking van de met deze campagne berekende NO_x WKS-niveaus met twee andere gegevensbronnen leidde niet tot een significante afwijking van de huidige VERSIT+ WKS-waarde, die daarmee op 236 mg per start blijft.
- De THC WKS-niveaus van deze campagne waren aanzienlijk lager dan de huidige waarde, wat heeft geleid tot een verlaging van de VERSIT+ THC WKS naar 759 mg per start.
- De PN WKS-waarden van deze campagne waren gemiddeld aanzienlijk hoger dan de waarden die we eerder rapporteerden ($8,3 \times 10^{14}$ #/start vs. $1,9 \times 10^{12}$ #/start). Dit kan een aanzienlijke invloed hebben op de lokale luchtkwaliteit en blijft daarom een aandachtspunt. We bevelen verder onderzoek aan naar de PN WKS van (moderne) benzinevoertuigen.
- De metingen doen vermoeden dat de WKS emissieniveaus oplopen bij hogere kilometrages. Dit moet verder onderzocht worden.Er wordt een lichte WKS-afhankelijkheid van het aantal afgelegde kilometers waargenomen die verder onderzoek vereist. De gemiddelde WKS-emissies die in dit werk zijn bepaald, zijn iets hoger voor voertuigen met een kilometrage van meer dan 150.000 km, hoewel de verschillen voor NO_x en THC klein zijn in vergelijking met het verschil bij de nieuwe en huidige VERSIT+-waarden. Het significante verschil in PN-emissies kan ook gedeeltelijk te wijten zijn aan de kilometerafhankelijkheid. Verder onderzoek moet zich richten op zowel correlaties tussen warme en koude emissies als op hoge kilometrages.

Dit project is uitgevoerd in opdracht van het Ministerie van Infrastructuur en Waterstaat.

Summary

Introduction
With widespread implementation of effective aftertreatment systems the exhaust emissions of roadgoing vehicles have decreased significantly in the last two decades. However, aftertreatment systems designed for reducing gaseous emissions typically require an operating temperature that is above ambient conditions. Especially during a so-called cold start, gaseous emissions such as NO_x can be severely elevated and thereby have a significant impact on the total emissions of a vehicle trip. With improving aftertreatment systems in newer vehicle models, the high emissions that can be attributed to a cold start happen within increasingly short distances. For this reason a point source is now considered the best representation of the cold start extra emissions, and has now been implemented within the VERSIT+ emission factors and thus also within the Dutch Emission Inventory.
As the point-source implementation deviates significantly compared to how cold starts were approached in the past, broader research was needed to support currently inferred emission factors for cold start extra emissions.

Goal of the work
The goal of the work as presented in this report is not only to further support the currently inferred emission factors for cold start extra emissions of petrol vehicles, but also to broadly investigate cold starts while idling.

Method
A total of 31 petrol vehicles from the Dutch fleet have been measured on their emission. The majority of the tested vehicles were Euro 6 approved and had odometer readings up to 150,000 kilometres. The PEMS (Portable Emission Measurement System) data from cold start measurements of the tested vehicles has been used to gain further insight into exhaust gas temperature behaviour, emission levels over time after cold start and after restart.

Results, conclusions and recommendations
The results of this work show the significance of the cold start emissions on the total emissions during a vehicle trip and provide insight into additional testing parameters:

- Temperature levels of the exhaust gas were observed to remain below 60°C, even after extended periods of idling. Cold exhaust gas does not rise to the same extent that warm exhaust gas does, so this would likely lead to the gasses remaining lower around the car. Because the gasses remain low, this can lead to increased exposure for people around or close to the vehicle.
- The majority of the NO_x-emissions were observed in the first 30 seconds after engine start, further supporting the current point source representation of the cold start.
- Emission levels of NO_x, THC and PN were observed to be significantly elevated during cold start testing. When comparing the average NO_x, THC and PN emission levels, cold start levels were observed to be the highest, warm engine levels to be the lowest, and engine restart levels to be slightly elevated compared to warm engine levels. We have not investigated the elevated emissions at restart to this level of detail before; we recommend including restarts in our future campaigns where possible.

VERSIT+ WKS emission factors
The dataset from this campaign was used to calculate VERSIT+ WKS emission values, where WKS (Wegtype Koude Start) is the point source representation of cold start extra emissions:

- Comparing the NO_x WKS levels calculated using this campaign with two other data sources did not lead to a significant deviation from the current VERSIT+ WKS value which will remain at 236 mg per start.
- The THC WKS levels from this campaign were significantly lower, which has led to a decrease in the VERSIT+ THC WKS to 759 mg per start.
- The PN WKS values from this campaign were on average significantly higher than those we reported earlier (8.3×10^{14} #/start vs 1.9×10^{12} #/start). This could have a significant impact on local air quality and therefore remains a point of interest. We recommend further investigation of the PN WKS of (modern) petrol vehicles.
- A slight WKS mileage dependency is observed which requires further investigation. The average WKS emissions determined in this work are slightly higher for vehicles with mileages above 150,000 km, though in both the cases of NO_x and THC, the differences are small when compared to the difference with the new and current VERSIT+ values. The significant difference in PN-emissions may also partly be due to mileage dependency. Further investigations should address both correlations between warm and cold emissions as well as with high mileages.

The project was commissioned by the Dutch Ministry of Infrastructure and Water Management.

Contents

1 Introduction

With widespread implementation of effective aftertreatment systems the exhaust emissions of roadgoing vehicles have decreased significantly in the last two decades. However, aftertreatment systems designed for reducing gaseous emissions typically require an operating temperature that is above ambient conditions. Especially during a so-called cold start, pollutant emissions such as NO_x can be severely elevated and thereby have a significant impact on the total emissions of a vehicle trip. In (van Mensch *et al.*, 2022) we showed that over 90% of total trip emissions can occur in the first 1.5 km of a 56 km trip.

As discussed further in earlier works (van Mensch *et al.*, 2022; de Ruiter *et al.*, 2022, 2024), the high emissions that can be attributed to a cold start happen within increasingly short distances with newer vehicle models, and can be a significant proportion of the total emissions of a trip. For this reason a point source is now considered the best representation of the cold start extra emissions, and has now been implemented within the VERSIT+ emission factors (Eijk *et al.*, 2024), and thus also within the Dutch Emission Inventory (see also (TNO, 2024), where emission factors are freely available online). As the point-source implementation deviates significantly compared to how cold starts were approached in the past, broader research was needed to support currently inferred emission factors for cold start extra emissions.

The goal of this work is not only to further support the currently inferred emission factors for cold start extra emissions, but also to broadly investigate cold starts while idling. Cold starts while idling can be considered representative for many cold-start situations, including allowing a car to idle while:

- searching for a destination or connecting to navigation software before departing;
- waiting for passengers to fasten their seatbelts;
- finishing up loading luggage and/or children;
- heating, cooling or demisting before departure.

This report then presents results from a measurement campaign in which the cold-start emissions of a number of petrol vehicles from the Dutch fleet were investigated.
The results obtained through measurements were further processed and analysed and are discussed in this report, as well as the implications for cold-start emission factors. The project was commissioned by the Dutch Ministry of Infrastructure and Water Management.

Readers' guide:
- chapter 2 contains the test methodology and the tested vehicles.
- chapter 3 contains the test results and analysis.
- chapter 4 contains the conclusions and recommendations.
- Appendix A presents measurement results of all the individual vehicles.
- Appendix B has a number of supplementary figures.

2 Method

The goal of the measurement program was to obtain insight into the cold start emissions of several petrol vehicles. Testing was performed on parking locations of office buildings. This allowed participants to perform their regular commute to work and provide access to their vehicles while being parked on the parking lot. After several hours of cooling down, and before the participant returned home with the vehicle, the measurement equipment was attached to the exhaust of the vehicle and the engine of the vehicle was started for cold idle testing. The emission measurement was performed for several minutes until the emissions stabilised, the engine was shut off, and was then restarted for a “warm” start. This process was repeated for multiple vehicles on the parking lot per session. In several testing days a total of 31 petrol vehicles were measured on their cold start idling emissions as well as their “warm” start idling emissions. An example of the measured signals during a test is shown in Figure 2.1.

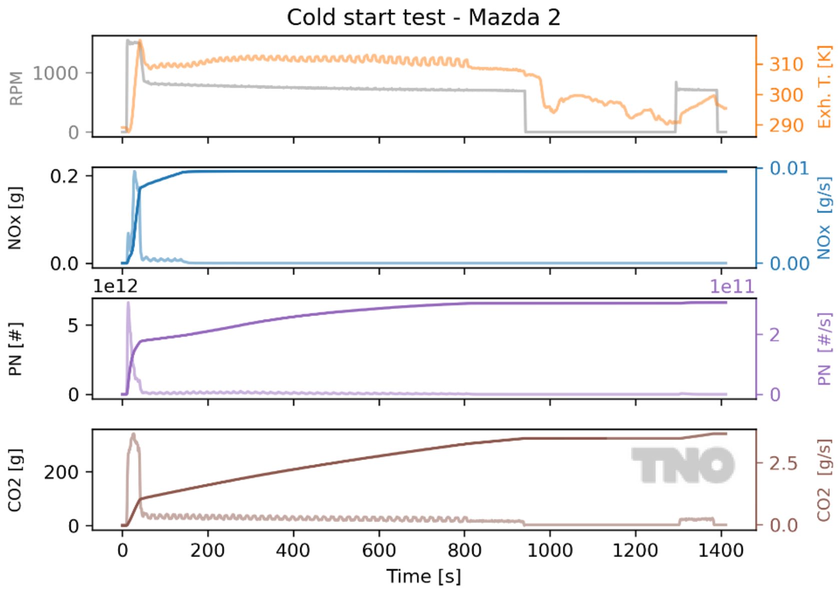

Figure 2.1: An example of the cold start idling tests performed in this campaign: emissions are measured during a cold start followed by extended idling, after which the engine is switched off (around 950 s) then restarted (around 1300 s). The top panel shows the instantaneous RPM in grey, and the exhaust gas temperature in orange. The lower three panels show both the cumulative (darker line) and instantaneous (lighter line) emissions for NO_x, PN, and CO_2 respectively.

2.1 Measurement setup

The emissions of the vehicles were measured by using PEMS (Portable Emission Measurement System) equipment as well as a 5-gas analyser. The exhaust of the vehicle was connected to the flow tube of the PEMS in a similar manner to regular on-road emissions testing with the PEMS. In this setup the connection was simplified as the vehicles would not move during the emissions testing and the measurement equipment was installed in a separate vehicle that could be put close by the test vehicle.

The OBD (On-Board Diagnostics) port of the vehicle was connected to the PEMS system and, when available, vehicle parameters such as RPM were recorded. An example of a measurement setup is seen in Figure 2.2.

Figure 2.2: Image of the measurement equipment attached to a red Fiat 500 test vehicle. The flow tube and sampling lines of the PEMS and 5-gas analyser are directly connected to the red test vehicle, while the measurement equipment is located inside the rear cabin of the grey van. With this approach, the measurement equipment could quickly and easily be positioned next to a test vehicle.

Detailed specifications of the equipment used in the measurement setup can be found in Table 2.1.

Table 2.1: Specifications of the equipment used in the measurement setup.

Equipment	Measured emissions/parameters
Horiba OBS-ONE PEMS Including FID and PN	CO_2 CO, NO, NO_2, EMF, vehicle OBD (if available) THC, PN
TEN Innova 5-gas analyser	CO_2, CO, O_2, THC, NO_x

2.2 Tested vehicles

A total of 31 vehicles have been measured on their emission, of which the specifications are listed in Table 2.2. Euro 6 was most predominant in the set of tested vehicles, as well as odometer readings up to 150 thousand kilometres. The distribution of the Euro norms and odometer readings have been displayed in Figure 2.3.

Table 2.2: List of the 31 tested vehicles, including the most relevant specifications.

Make	Model	Fuel	Year	Euro norm	Engine displacement [cc]	Combustion engine power [kW]	Odometer reading [km]
Mazda	Mazda 2	Petrol	2016	Euro 6b	1496	66	133000
Seat	Ibiza	Petrol	2023	Euro 6d	999	70	14472
Fiat	500	Petrol hybrid	2023	Euro 6d	999	52	14424
Skoda	Scala	Petrol	2022	Euro 6d	999	81	16782
Opel	Corsa	Petrol	2015	Euro 6b	999	66	76982

Hyundai	i20	Petrol hybrid	2024	Euro 6d	998	74	1719
Peugeot	3008	Petrol	2023	Euro 6d	1199	96	20907
Volkswagen	T-ROC	Petrol	2022	Euro 6d	999	81	19582
Peugeot	5008	Petrol	2023	Euro 6d	1199	96	27174
Hyundai	Bayon	Petrol hybrid	2024	Euro 6d	998	74	22
Hyundai	i10	Petrol	2022	Euro 6d	998	49	34701
Hyundai	Kona	Petrol hybrid	2022	Euro 6d	1580	77	38309
Mitsubishi	Colt	Petrol	2007	Euro 4	1499	80	328076
Alfa Romeo	Giulietta	Petrol	2018	Euro 6b	1368	125	56260
Renault	Twingo	Petrol	2009	Euro 4	1149	43	149644
Opel	Insignia	Petrol	2019	Euro 6d-Temp	1490	121	73581
Toyota	Aygo	Petrol	2015	Euro 6b	998	51	62000
Toyota	Aygo	Petrol	2010	Euro 4	998	50	75876
Skoda	Fabia	Petrol	2012	Euro 5a	1197	63	96502
Volvo	XC60	Petrol	2012	Euro 5b	1999	177	244519
Renault	Twingo	Petrol	2012	Euro 5a	1149	55	85621
Seat	Leon ST	Petrol	2015	Euro 6b	999	85	146995
Alfa Romeo	Giulietta	Petrol	2011	Euro 5b	1368	125	148818
Mazda	Mazda 5	Petrol	2011	Euro 5a	1798	85	143330
Hyundai	Getz	Petrol	2003	Euro 3	1599	77	142082
Volvo	V60	Petrol	2018	Euro 6d-Temp	1969	228	101009
Opel	Mokka	Petrol	2019	Euro 6d-Temp	1364	103	86596
Volkswagen	Golf	Petrol	2018	Euro 6b	999	81	80026
Fiat	Panda	Petrol	2012	Euro 5b	875	63	178454
Volkswagen	UP!	Petrol	2016	Euro 6b	999	44	205698
Mercedes-Benz	A180	Petrol	2014	Euro 6b	1595	90	132888

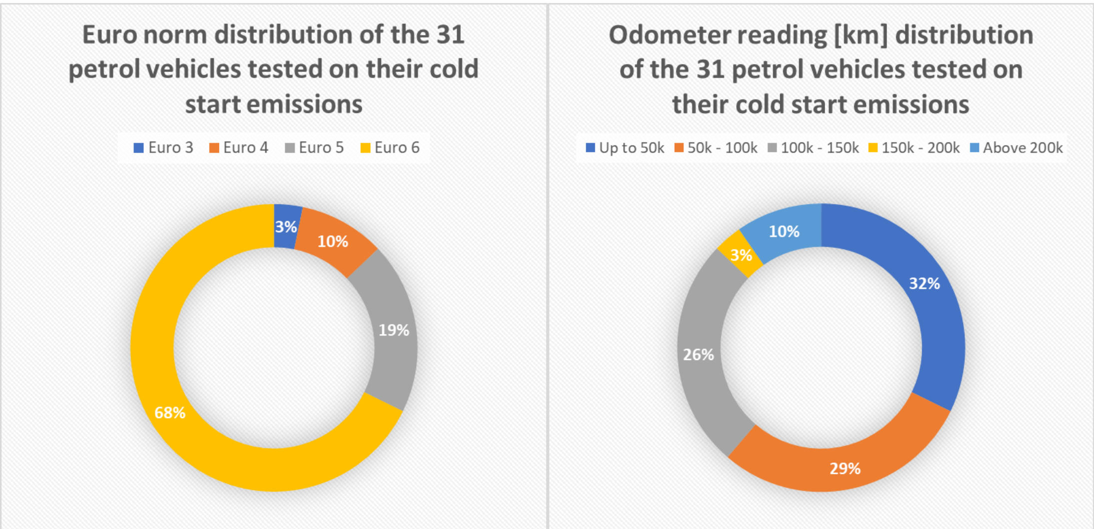

Figure 2.3: Distribution of the Euro norms of the tested vehicles on the left and distribution of the odometer readings on the right.

3 Results and analysis

The data from the cold start measurements of the 31 tested vehicles has been used to gain further insight into:

- exhaust gas temperature behaviour.
- emission levels over time after cold start.
- emission levels over time after restart.

As discussed in the introduction, cold starts show elevated emissions at increasingly shorter distances, so much so that the cold start extra emissions are now considered a point source within VERSIT+ and therefore also where these emission factors are used e.g. the Dutch Emission Inventory (Emissieregistratie), AERIUS (used for permit applications and assessment of potential nitrogen emissions), and the calculation of the national GCN/GDN maps (large scale concentration- and deposition maps). Changing how cold start emissions are considered has had significant impact on how the models that use these emission factors (can) apply them. These changes are supported by the results below in 3.4.

3.1 Exhaust gas temperatures remain below 60°C

Examining the exhaust gas temperatures gives insight both into the warm-up behaviour of a certain vehicle as well as the potential implications for local air quality. As hot gas rises, the colder the exhaust gas the more likely it is to remain at a level where it can have a larger impact e.g. on people in the vicinity of the vehicle.

The exhaust gas temperature was measured inside the flow tube of the PEMS system. In Figure 3.1 the exhaust gas temperature of all 31 vehicles has been plotted against time, starting from the cold start. As expected, the starting temperatures (at t=0) are between 5 and 20 °C, similar to ambient temperature levels. The temperature increases after engine start, starts stabilising around 400 seconds after the cold start, and reaches temperatures between 30 and 60 °C. The exact temperature levels after stabilisation are also expected to be influenced by the measurement setup, as each individual vehicle exhaust required a different connection to the flow tube. At PEMS tests of petrol vehicles during on-road driving, exhaust temperatures are usually on average around 130°C (with dependencies on vehicles and set-up as mentioned above). Considering that in the test performed here the exhaust remains colder than 60 °C this would likely lead to the gasses remaining lower around the car. Because the gasses remain low, this would lead to increased exposure for people in the vicinity of the vehicle.

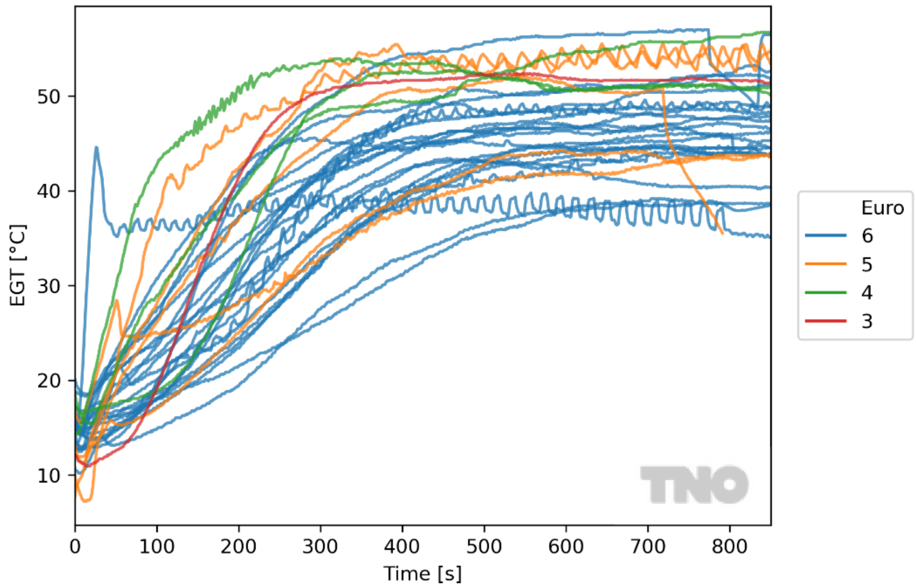

Figure 3.1: Warm-up behaviour of the 31 test vehicles demonstrated by exhaust gas temperatures (EGT) expressed in °C plotted over time. Most signals show a very similar trend, with values stabilising between 30 and 60 °C. Colours indicate the different Euro classes of the vehicles, which shows that there is no significant Euro-dependent trend.

The majority of the temperature signals show a similar shape, but there are several deviating warm-up patterns. In Figure 3.2 we show two variations of the typical shape (the two Toyota Aygos, green and red lines), a very rapid warm-up (Mitsubishi Colt, orange), a very rapid start to the warm-up followed by a slower typical shape towards stabilisation (Skoda Fabia, purple), and an extremely rapid warm-up showing instant stabilisation after a spike in temperature (Mazda 2, blue). The Mazda 2 also shows sawtooth fluctuations observed for a number of different vehicles in Figure 3.1. These fluctuations are correlated with the individual CO_2 signals as shown in Appendix A. The variation in these warm-up patterns could be attributed to a number of different factors, including how a vehicle was used before the hours of cooling down prior to the cold start, warm-up behaviour as determined by the vehicle manufacturer, or even just that particular individual vehicle's technical state influenced by wear and maintenance. The warm-up behaviour is highly likely to influence the cold start emissions discussed below.

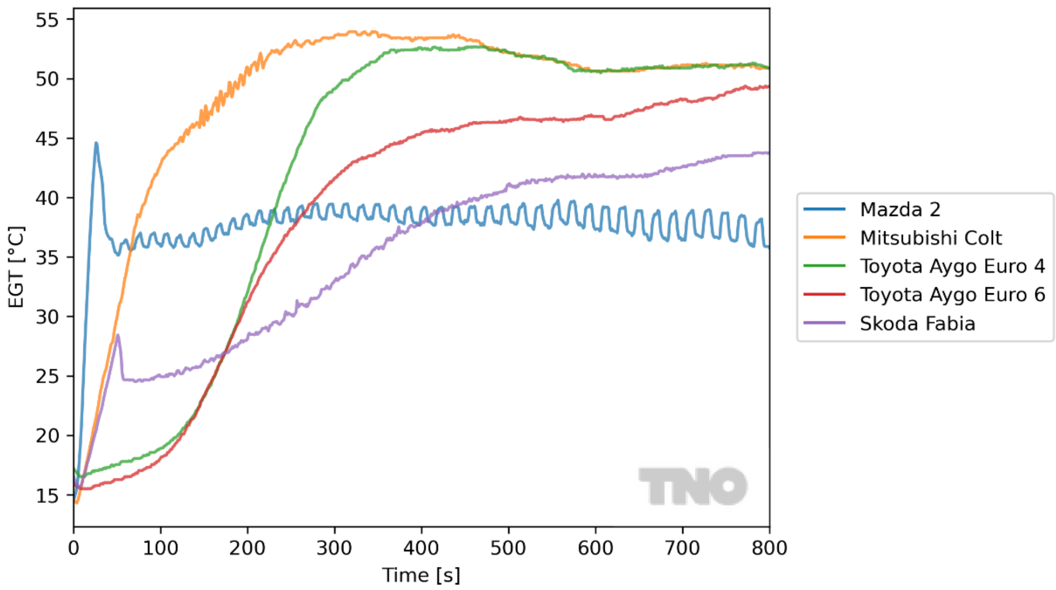

Figure 3.2: Exhaust gas temperature (EGT) during the cold start of five different petrol vehicles. Colours indicate the different individual vehicles. These vehicles give an indication of the variety of warm-up behaviours that were observed during the cold starts.

3.2 Most NO_x-emissions occur within the first 30 seconds after cold start

As shown in Figure 3.3, most of the NO_x-emissions occur within the first 30 seconds after the cold start. To facilitate comparison, the NO_x behaviour has been split up into three observed sections:

1. The first 30 seconds after engine start with the highest levels of NO_x for the majority of vehicles (plotted in blue).
2. 30 – 60 seconds after engine start where levels are significantly lower than the initial 30 seconds, though some final stabilisation to low NO_x levels occurs (plotted in orange).
3. After 60 seconds where NO_x-emissions remain low for all vehicles (plotted in green). We therefore consider the emission levels after 60 seconds as warm emissions, while all the emissions up to 60 seconds are taken into account as the higher NO_x-emissions due to cold start.

We propose that the observed cold start durations are sufficiently short as to further support our consideration to model the cold start extra emissions as a point source.

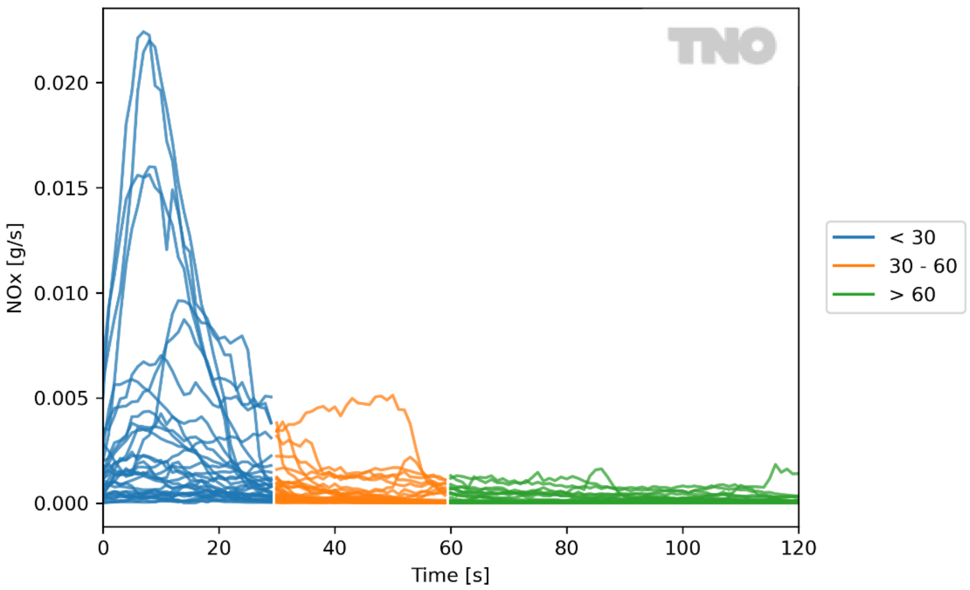

Figure 3.3: NO_x emission levels expressed in grams per second plotted against the time in seconds. Three phases are indicated: most cold start NO_x-emissions occur in the first 30 seconds (blue, '< 30'); some vehicles show some residual high emissions until 60 s (orange, '30 – 60'); and after 60 seconds the cold start is considered to be finished. Beyond 60 seconds is therefore considered as warm emissions.

To further investigate NO_x-emissions during idling, we examined the cumulative NO_x-emissions as shown in Figure 3.4. As discussed above, most of the emissions occur in the first 60 seconds, which is shown by steep gradients observed for most vehicles. Following this, emissions quickly stabilise to an almost horizontal line. In other words, most of the NO_x-emissions occur during the cold start after which very little NO_x is emitted. The majority of the NO_x-signals show this behaviour, but there are some deviations. A number of vehicles took up to 200 seconds to reach significant reduction in gradient. For three vehicles the cumulative NO_x-emissions after the cold start do not appear horizontal: for these vehicles emissions appear to stabilise after the cold start, but then show higher emissions from around 350 seconds. This may indicate some correlation with earlier examples of elevated emissions during 'extended' idling (more than 5 minutes/300 seconds) as displayed by new Euro 6 vehicles (de Ruiter *et al.*, 2024). Alternately, there may be some link to type approval legislation which defines the duration of the cold start as the time until either the engine coolant temperature reaches 70°C or five minutes has passed (whichever comes first). Interestingly, the lowest and highest observed cumulative NO_x values (Figure 3.4) are both from vehicles with the newest emissions norm, Euro 6.

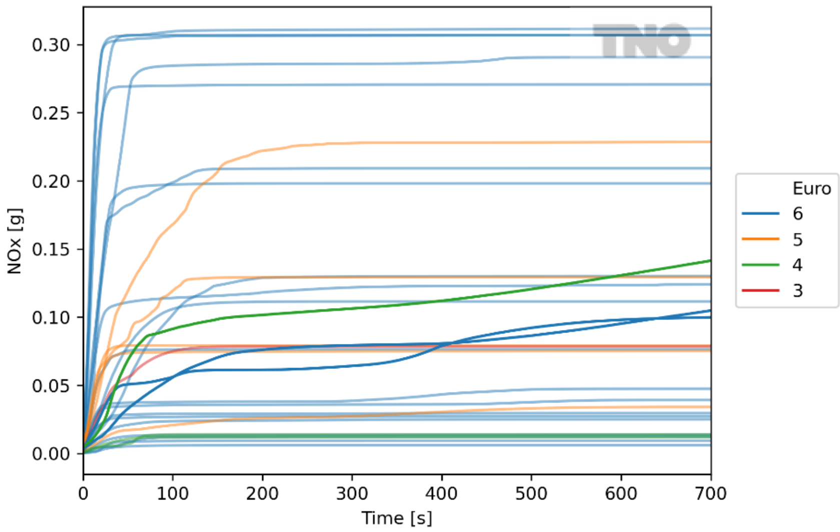

Figure 3.4: Cumulative NO_x-emissions per vehicle expressed in grams plotted against the time in seconds. The majority of the vehicles show a very steep initial gradient directly after engine start followed by a significant reduction in gradient resulting in an almost horizontal line. Three vehicles showing relatively significant NO_x-emissions after stabilisation are plotted with a bold line. Colours indicate the Euro class per vehicle.

3.3 Restarts can still have significant emissions

In this measurement campaign we have also investigated the emissions due to restart after extended idling as shown an Figure 3.5. In this example of the cold start test the engine is turned off around 900 seconds and restarted around 1000 seconds after the initial cold start. For this vehicle, all emissions show a peak directly after the engine is restarted. After this 'restart' peak, the emissions levels return to warm levels, i.e. similar to those just before the engine was turned off at around 900 seconds. Restarts can therefore still have significant emissions.

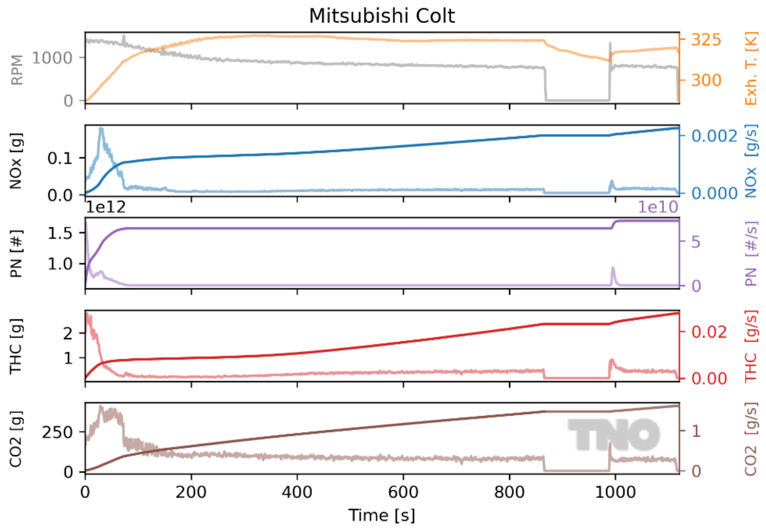

Figure 3.5: Emission measurement of a cold start followed by extended idling, after which the engine is switched off (around 900 s) then restarted (around 1000 s). The top panel shows the instantaneous RPM in grey, and the exhaust gas temperature in orange. The lower three panels show both the cumulative (darker line) and instantaneous (lighter line) emissions for NO_x, PN, THC and CO_2 respectively.

Per vehicle, the average NO_x, PN and THC emissions during the cold start, warm idling, and restart are compared as shown in Figure 3.6. Note that for this comparison the cold start and restart emissions are averaged over the first 30 seconds of the respective start, while warm emissions are averaged from 60 – 700 seconds from the initial start.
The NO_x-emissions for cold start show significant elevation over warm and restart conditions, but not for all vehicles. The difference between warm and restart is only slightly visible in the graph, with a slight elevation for restart. For THC all vehicles show significantly elevated average emissions during the cold start, and most of them also show somewhat higher emissions during the restart. Warm average THC emissions during idling vary from very low to 6 mg/s. The PN-emissions show a different pattern. Warm engine emissions are generally lowest in PN-emissions, but the difference between cold start and restart is much less obvious on a logarithmic scale.

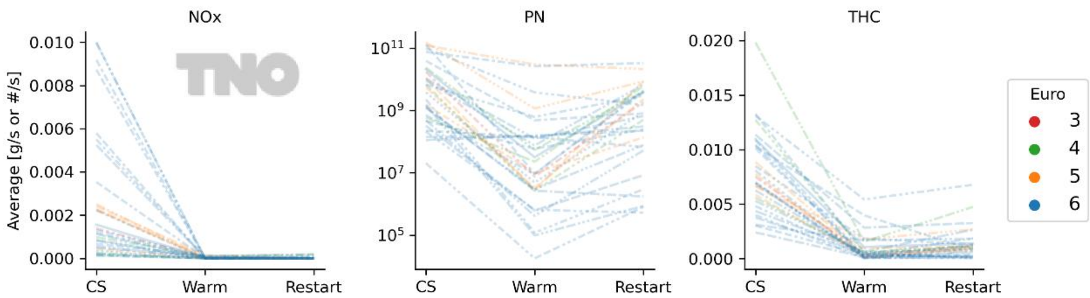

Figure 3.6: Average NO_x, PN and THC emission levels expressed in grams per second or number per second plotted for cold start (CS), warm engine and engine restart. Cold start emissions are highest for all vehicles and engine restart emissions are generally higher than warm engine emissions. Each line represents the emissions for an individual vehicle where the lines are coloured by the vehicle's respective Euro class.

In Figure 3.7 the same average NO_x, PN and THC emissions are plotted for cold start, warm engine, and restart, but as points aligned per Euro norm. The large spread in the emissions performance of the Euro 6 vehicles indicates that there is not a direct correlation with Euro norm visible in this dataset.

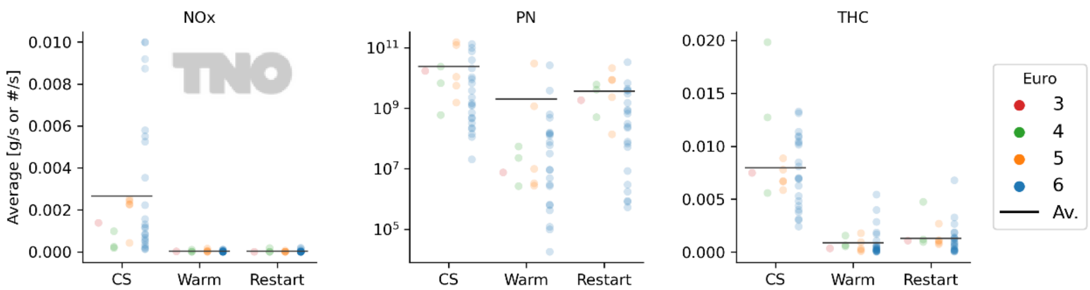

Figure 3.7: Average NO_x, PN and THC emission levels per vehicle expressed in grams per second or number per second plotted for cold start (CS), warm engine and engine restart. The data points have been aligned and coloured per Euro norm. Cold start emissions are highest for all vehicles and engine restart emissions are generally higher than warm engine emissions.

The ratio between the average emissions during the first 30 seconds and warm emissions indicates how much higher these emissions are. There is a large spread in these ratios (as shown in Figure B.7), also linked to the range of low warm emissions. The medians for the different pollutants are shown in Table 3.1.

Table 3.1: Median ratio between the average emissions during the first 30 seconds of a start and the average warm idling emissions. A cold start/warm ratio of 2 indicates that the average cold start emissions are twice that of the average warm emissions.

Pollutant	Cold start/Warm	Restart/Warm
CO_2	1.9	1.0
NO	170	0.3
PN	320	14
THC	17	1.7

3.4 Comparison with previous work and implications for VERSIT+ emission factors

The insights obtained from the data analysis in the previous sections are used to improve the cold start emission factors used within the Dutch Emission Inventory for road traffic (TNO, 2024). In this section both the newly obtained cold start data is examined and compared to two other recent sources: our 2022 measurement campaign (Vroom *et al.*, 2023) and data made available via Green NCAP and investigated in (de Ruiter *et al.*, 2024). The 2022 measurement campaign included both stationary as well as extended on-road tests of petrol vehicles with higher mileages, while the Green NCAP data discussed here is based on the results from 'PEMS+ cold' tests of newer Euro 6d and 6d-Temp vehicles (see the respective reports for more details on the relevant tests).

As per (de Ruiter *et al.*, 2024) the point-source emission factor for the cold start extra emissions per start is denoted as 'WKS' (Wegtype Koude Start; measured in grams or # per start) and defined as the *average emissions* per kilometre of the total trip (dominated by warm emissions) subtracted from the *total* emitted within the first kilometre (cold start emissions). For the idling tests investigated in this work, we consider the warm emissions as the emissions 60 – 700 s after the cold start, and the cold emissions 0 – 60 s. WKS is then the total emissions in the first minute minus the average warm emissions per minute between 60 – 700 seconds.

There are therefore differences in methodology for the calculation of WKS for stationary testing (time-based) and on-road testing (distance-based). We currently consider this the best implementation given the differences in test procedures and how WKS is implemented within the Dutch Emission Inventory and related models and applications.

3.4.1 THC VERSIT+ WKS emission factors will be changed, while NO_x remains the same

As discussed above the VERSIT+ point source emission factor for cold start extra emissions is denoted as WKS, and defined as the difference between the higher emissions during cold start, and average warm emissions. In Figure 3.8 **the** WKS values for NO_x and THC in milligrams are plotted for the 2024 test programme discussed in this report, and compared to the Green NCAP and 2022 measurement campaign data as discussed above, (de Ruiter *et al.*, 2024; Vroom *et al.*, 2023).

The 2024 WKS NO_x-emissions show overlap with the two older datasets, and including these points for the average WKS does not lead to a significant deviation from the current VERSIT+ WKS emission factor. For this reason, we have opted not to change NO_x WKS as a result of this campaign. However, the observed THC emission levels from the 2024 dataset are lower than in those observed in the Green NCAP dataset, as well as the current VERSIT+ THC WKS. Combining these sources has led to a lower THC WKS of 759 mg ('New' in Figure 3.8). This change has been implemented for the 2024 Dutch Emission Inventory.

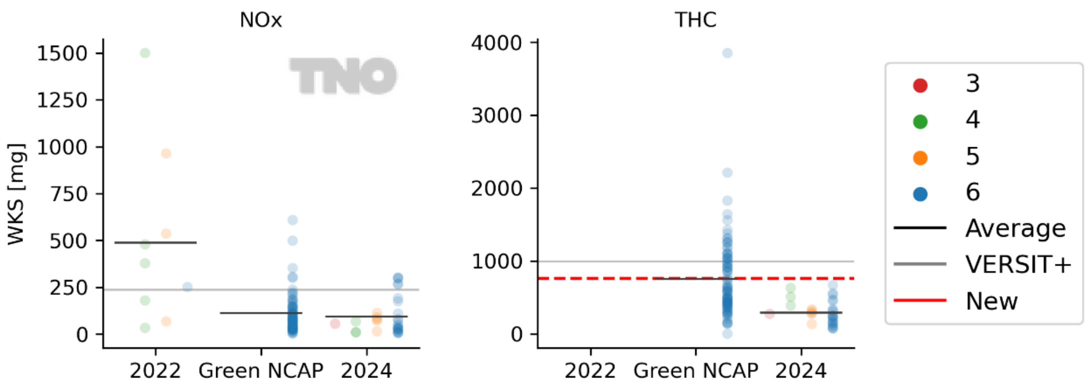

Figure 3.8: VERSIT+ cold start extra emissions, denoted as WKS, plotted per vehicle for the dataset obtained in this report ('2024') and two other sources ('2022', 'Green NCAP', (de Ruiter *et al.*, 2024; Vroom *et al.*, 2023)). The current VERSIT+ WKS emission factor is shown with the grey line and the new WKS for THC is shown with the dotted red line. Averages per data set are indicated by thin black lines. The data points are aligned and coloured per Euro class.

3.4.2 High PN WKS emissions are observed and remain a point of interest

Although currently not considered within the Dutch Emission Inventory to the same degree as NO_x and THC emissions, PN-emissions are of increasing interest in the context of the ultrafine particles. Here PN refers to PN23. In Figure 3.9 PN WKS emission factors are compared for this campaign (2024) and the Green NCAP dataset. PN WKS factors in the 2024 dataset are significantly higher than in the Green NCAP: on average the Green NCAP WKS is 1.9×10^{12} #/start while that for the current campaign is 8.3×10^{14} #/start. Comparatively, the current type-approval limit is 6.0×10^{12}#/km. The difference in PN-emissions between the two campaigns is also observed for warm idling emissions: for the Green NCAP petrol vehicles this was on average 8.9×10^{7} # per second, compared to the average 2.0×10^{9} # per second shown in Section 3.3. It should be noted that the Green NCAP data does include vehicles with petrol particulate filters which may contribute to the lower PN-emissions: "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 (petrol particle filter)" (de Ruiter *et al.*, 2024).

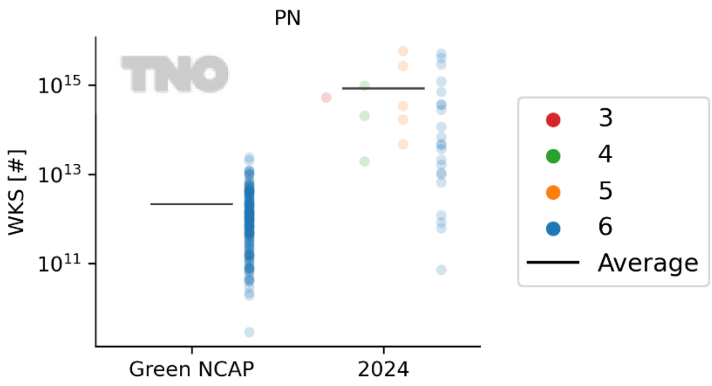

Figure 3.9: PN WKS emissions per vehicle as measured in this campaign ('2024') as compared to the Green NCAP data (de Ruiter *et al.*, 2024). Averages per data set are indicated by thin black lines. The data points are aligned and coloured per Euro class.

Besides the use of a petrol particle filter other factors contributing to the differences in average PN WKS could include the higher odometer readings from the vehicles in the 2024 dataset (as discussed in the next section) as well as differing measurement conditions. There is a difference in test set-up (on-road vs stationary) between the two datasets (the impact on calculation of WKS was discussed earlier in Section 3.4, though in all cases the calculated PN WKS is orders of magnitude higher than average warm emissions for both idling and driving. Using the warm emissions per test in the calculation should account for some dependencies on relative measurement conditions, but these different conditions could still contribute to the observed variation in WKS.

3.4.3 Slight WKS mileage dependency requires further investigation

Deterioration is currently not included within the determination of extra emissions due to cold start (Eijk *et al.*, 2024). However, when considering WKS as determined in the current work in Figure 3.10, the average emissions are slightly higher for vehicles with mileages above 150,000 km, though this was only four vehicles. Furthermore, in both the cases of NO_x and THC, the differences are small when compared to the difference with current VERSIT+ values. When plotting WKS as a function of mileage along with the other two reference datasets ('Green NCAP' and '2022', (de Ruiter *et al.*, 2024; Vroom *et al.*, 2023)) as shown in Figure 3.11, there is a weak positive correlation for NO_x and PN. Of note is that the Green NCAP data (shown by triangles) generally have much lower mileages than the vehicles tested in the '2022' and '2024' campaigns. For PN and NO_x these lower mileages skew quite low (though there are incidences of higher emissions at low mileages), while for THC low mileages also have much higher emissions. The high emitter tested in 2022 (NO_x WKS around 1.5 g) skews much higher than the high mileage WKS NO_x determined in this work (the orange and green dots above 240 000 km in the NO_x panel).

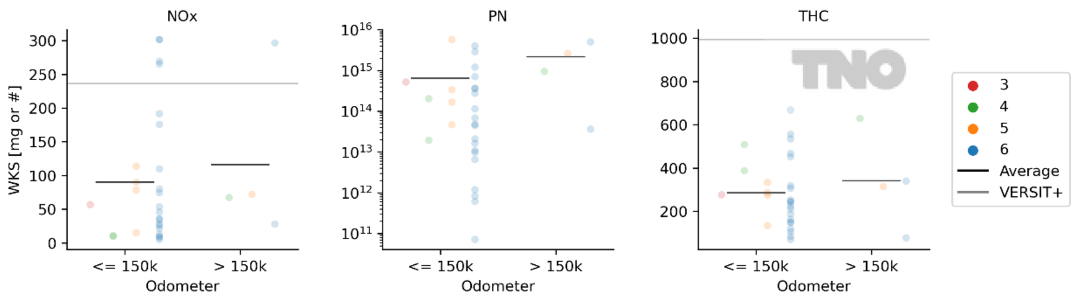

Figure 3.10: WKS (VERSIT+ cold start extra emissions per start), plotted per vehicle as investigated in the 2024 measurement campaign. The current VERSIT+ WKS emission factor is shown with the grey line. Averages per data set are indicated by thin black lines. The data points are aligned and coloured per Euro class.

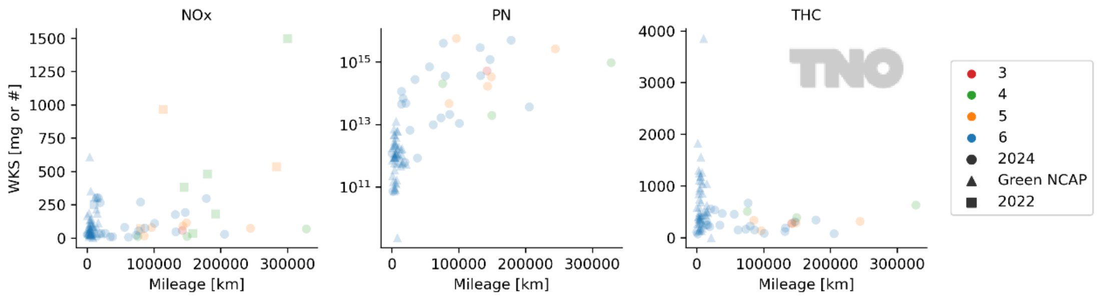

Figure 3.11: Mileage-dependent cold start extra emissions, denoted as WKS, plotted per vehicle for the dataset obtained in this report (‘2024’) and two other sources (‘Green NCAP’ and ‘2022’, (de Ruiter et al., 2024; Vroom et al., 2023)). The data points are coloured per Euro class.

4 Conclusions and recommendations

The results of this work in which cold start emissions of petrol vehicles are investigated further show the significance of the cold start emissions and provided insight into additional testing parameters.

Temperature levels of the exhaust gas were observed to remain below 60 °C, even after extended periods of idling. Cold exhaust gas does not rise to the same extent that warm exhaust gas does, so this would likely lead to the gasses remaining lower around the car. Because the gasses remain low, this can lead to increased exposure for people around or close to the vehicle.

The majority of the NO_x-emissions were observed in the first 30 seconds after engine start, further supporting the current point source representation of the cold start.

Emission levels of NO_x, THC and PN were observed to be significantly elevated during cold start testing. When comparing the average NO_x, THC and PN emission levels, cold start levels were observed to be the highest, warm engine levels to be the lowest, and engine restart levels to be slightly elevated compared to warm engine levels. We have not investigated the elevated emissions at restart to this level of detail before; we recommend including restarts in future campaigns where possible. In the case of our monitoring campaigns, it is likely that relevant warm restarts are already included in the respective road types, though this could be investigated further to quantify their contribution.

The dataset from this campaign was used to calculate VERSIT+ WKS emission values, where WKS (Wegtype Koude Start) is the point source representation of cold start extra emissions. Comparing the NO_x WKS levels calculated using this campaign with two other data sources did not lead to a significant deviation from the current VERSIT+ WKS value which will remain at 236 mg per start. The THC WKS levels from this campaign were significantly lower, which has led to a decrease in the VERSIT+ THC WKS to 759 mg/start. The PN WKS values from this campaign were on average significantly higher than those we reported earlier (8.3×10^{14} #/start vs 1.9×10^{12} #/start). This could have a significant impact on local air quality and therefore remains a point of interest. We recommend further investigation of the PN WKS of (modern) petrol vehicles.

A slight WKS mileage dependency is observed which requires further investigation. The average WKS emissions determined in this work are slightly higher for vehicles with mileages above 150,000 km, though in both the cases of NO_x and THC, the differences are small when compared to the difference with the new and current VERSIT+ values. The significant difference in PN-emissions may also partly be due to mileage dependency. Further investigations should address both correlations between warm and cold emissions as well as with high mileages. Current work is ongoing with regards to the incidence of high emitters in the Dutch fleet which may provide additional insight in this respect.

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Signature

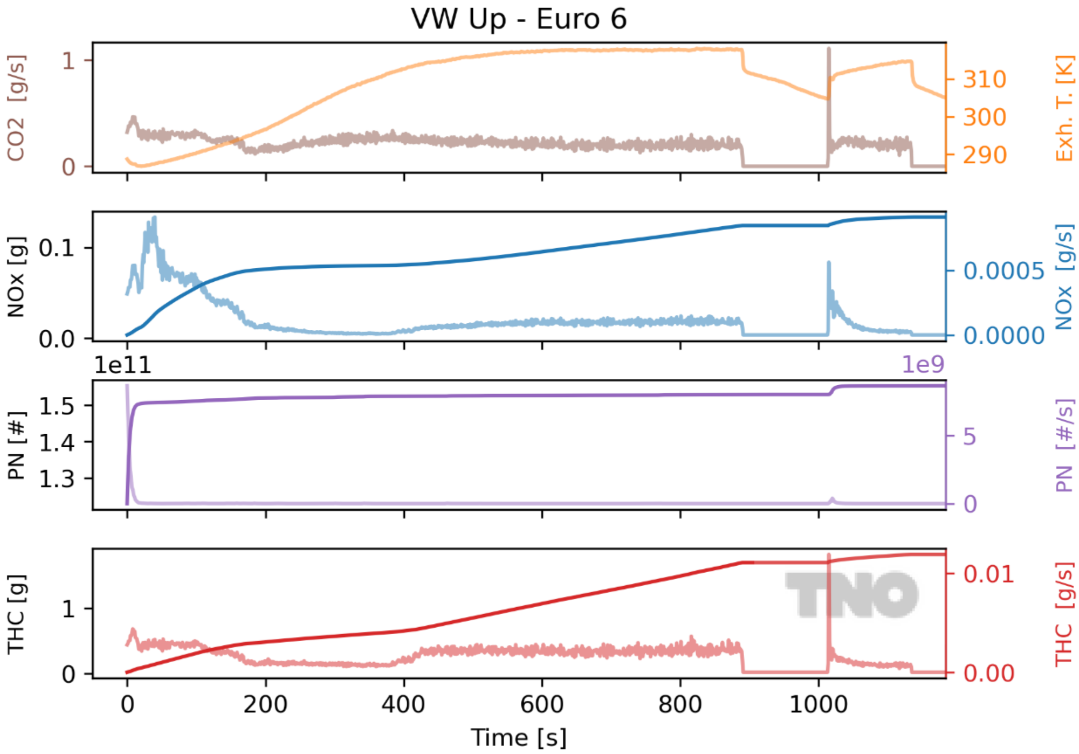
TNO ⟩ Mobility & Built Environment ⟩ Den Haag, 25 March 2025

Jan Hoegee
Interim Research manager

Quinn Vroom
Author

Appendix A
All test results

Time based test results for all 31 vehicles can be found in the graphs below.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Exh. T. [K]
NOx [g]
NOx [g/s]
PN [#]
PN [#/s]
THC [g]
THC [g/s]
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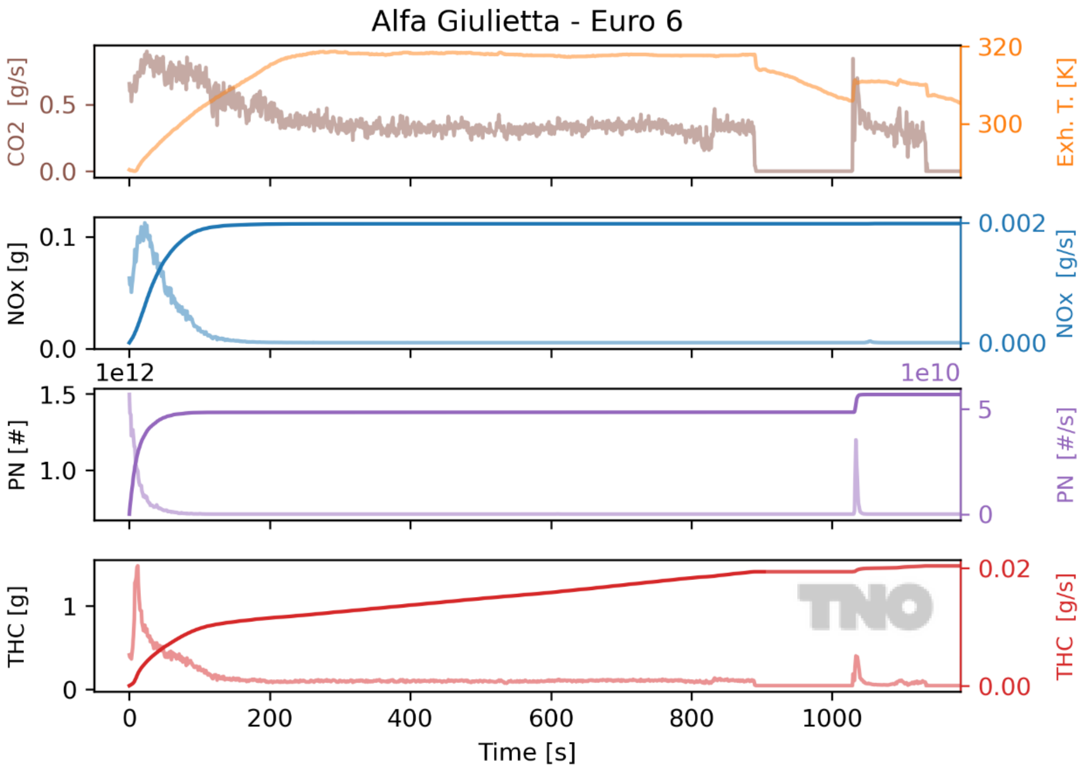
1e9
Time [s]
TNO


Alfa Giulietta - Euro 6
CO2 [g/s]
Exh. T. [K]
NOx [g]
NOx [g/s]
PN [#]
PN [#/s]
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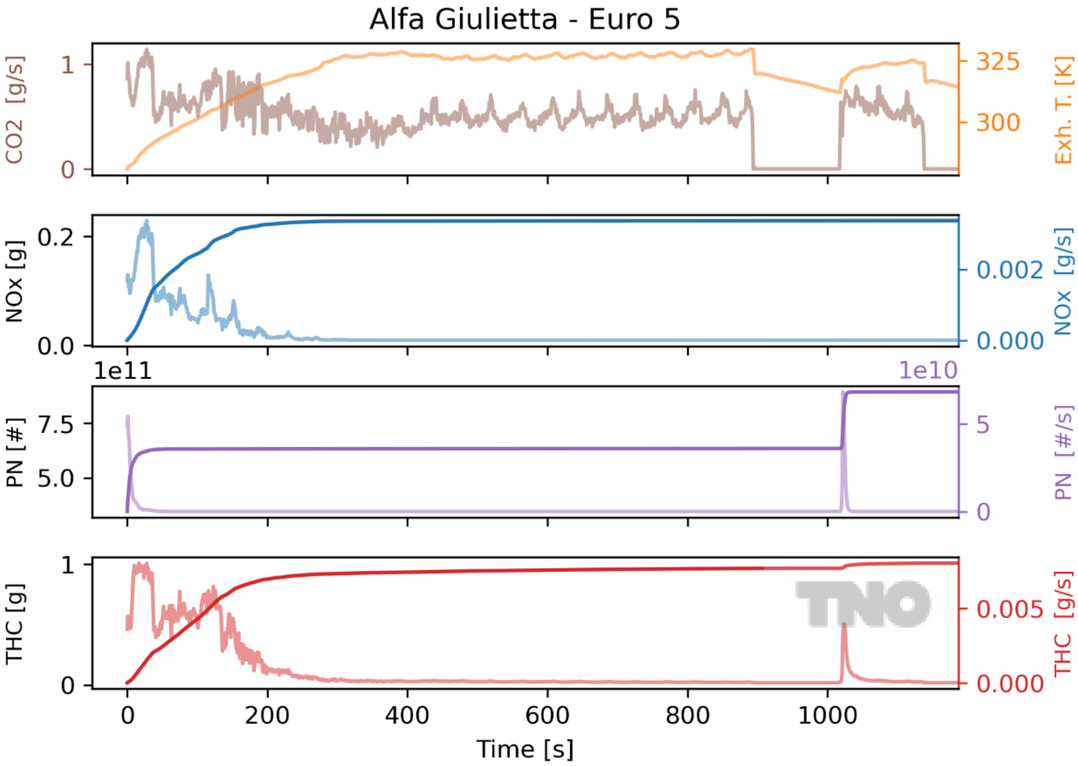
THC [g/s]
1e12
1e10
Time [s]
TNO


Alfa Giulietta - Euro 5
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NOx [g/s]
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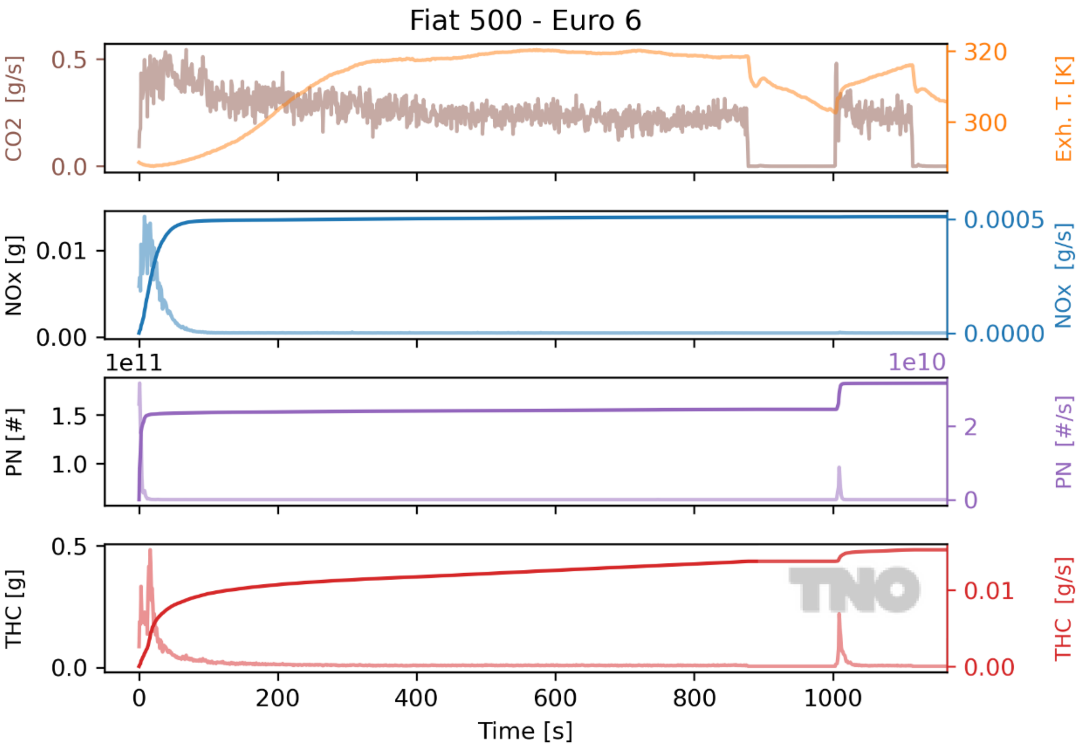
1e10
PN [#]
PN [#/s]
THC [g]
THC [g/s]
Time [s]


Fiat 500 - Euro 6
CO2 [g/s]
Exh. T. [K]
NOx [g]
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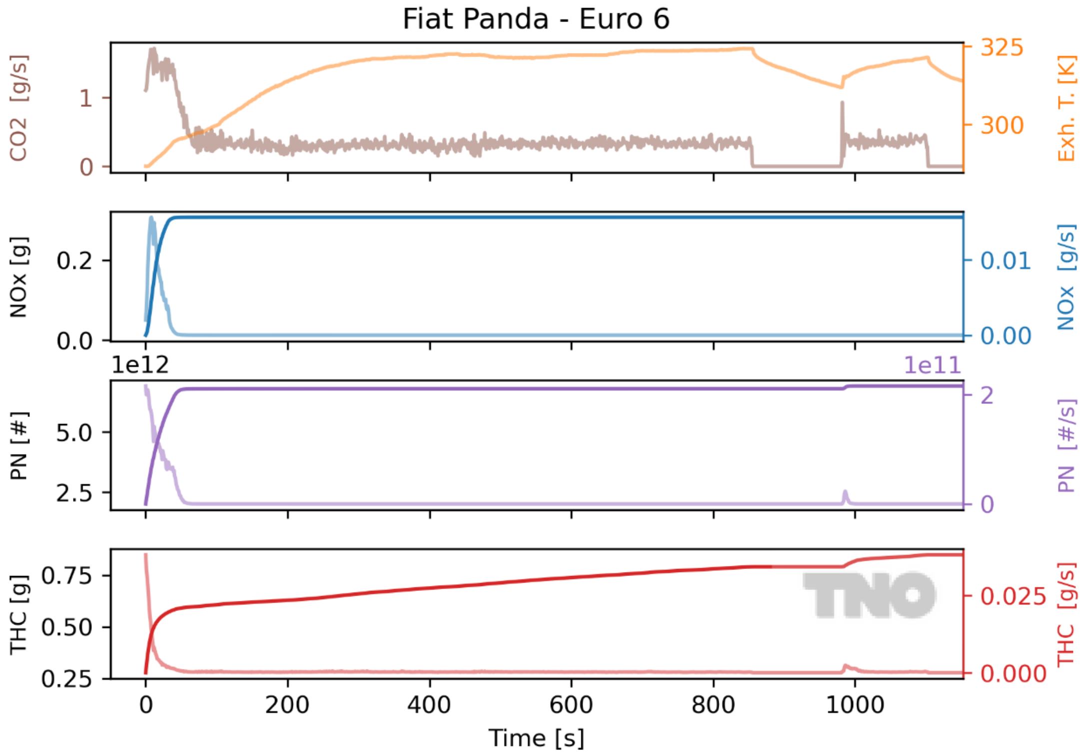
1e11
1e10
PN [#]
PN [#/s]
THC [g]
THC [g/s]
Time [s]


Fiat Panda - Euro 6
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NOx [g]
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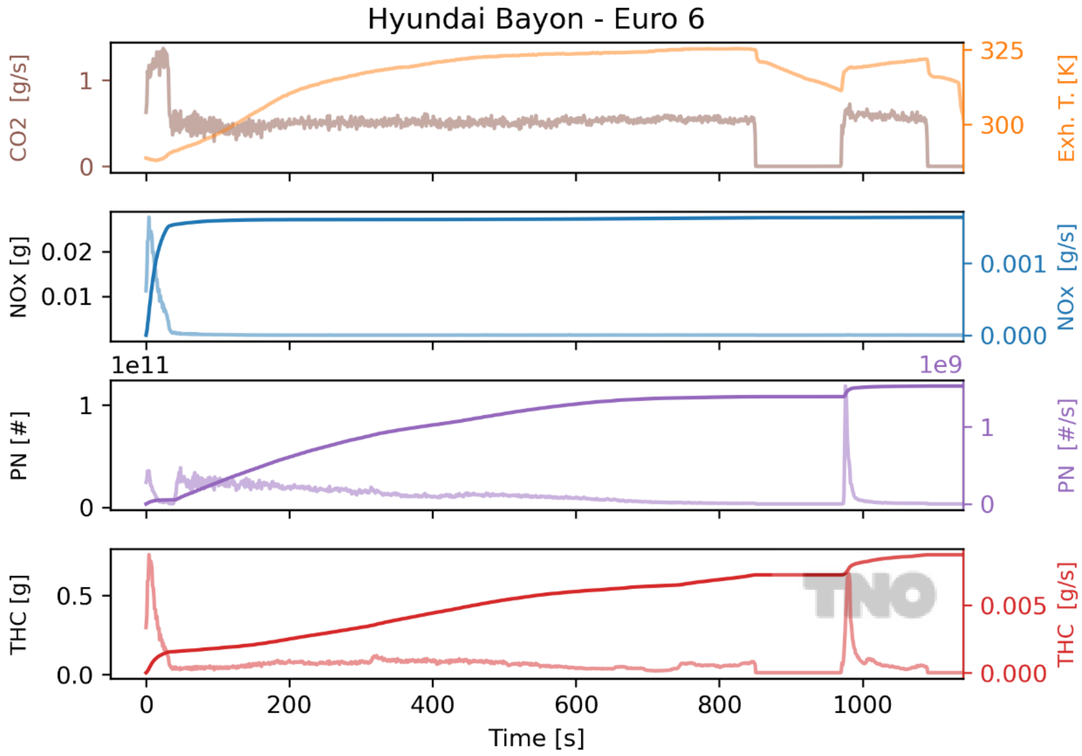
PN [#]
PN [#/s]
THC [g]
THC [g/s]
Time [s]


Hyundai Bayon - Euro 6
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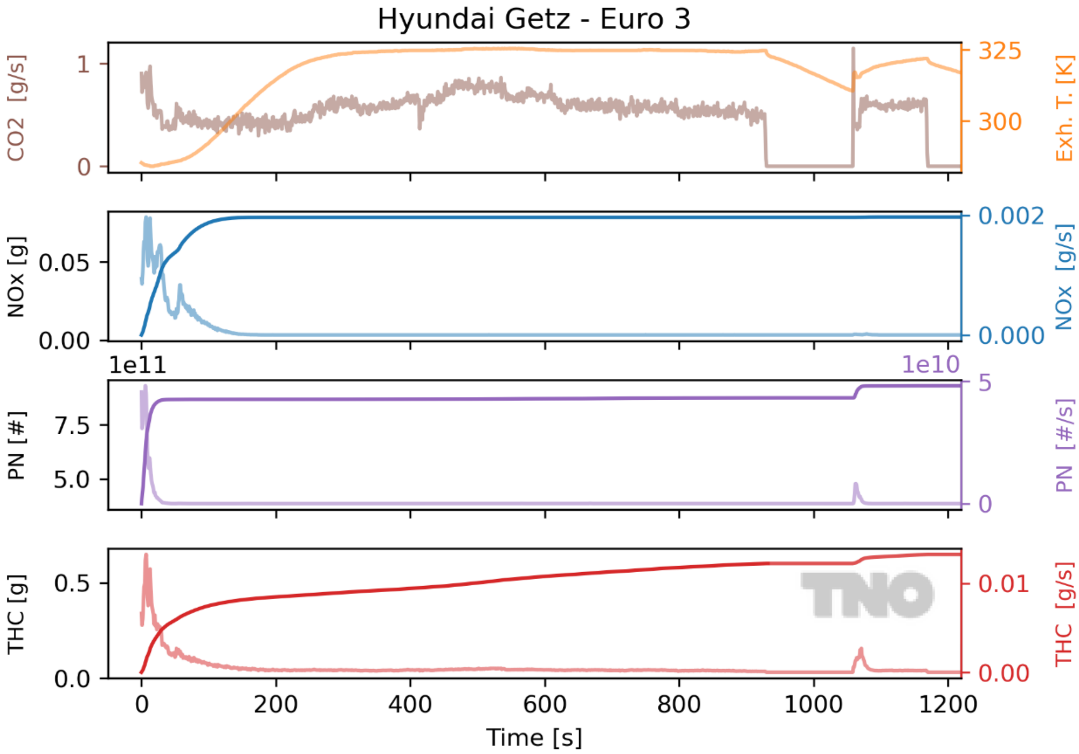
NOx [g/s]
PN [#]
PN [#/s]
THC [g]
THC [g/s]
Time [s]


Hyundai Getz - Euro 3
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NOx [g/s]
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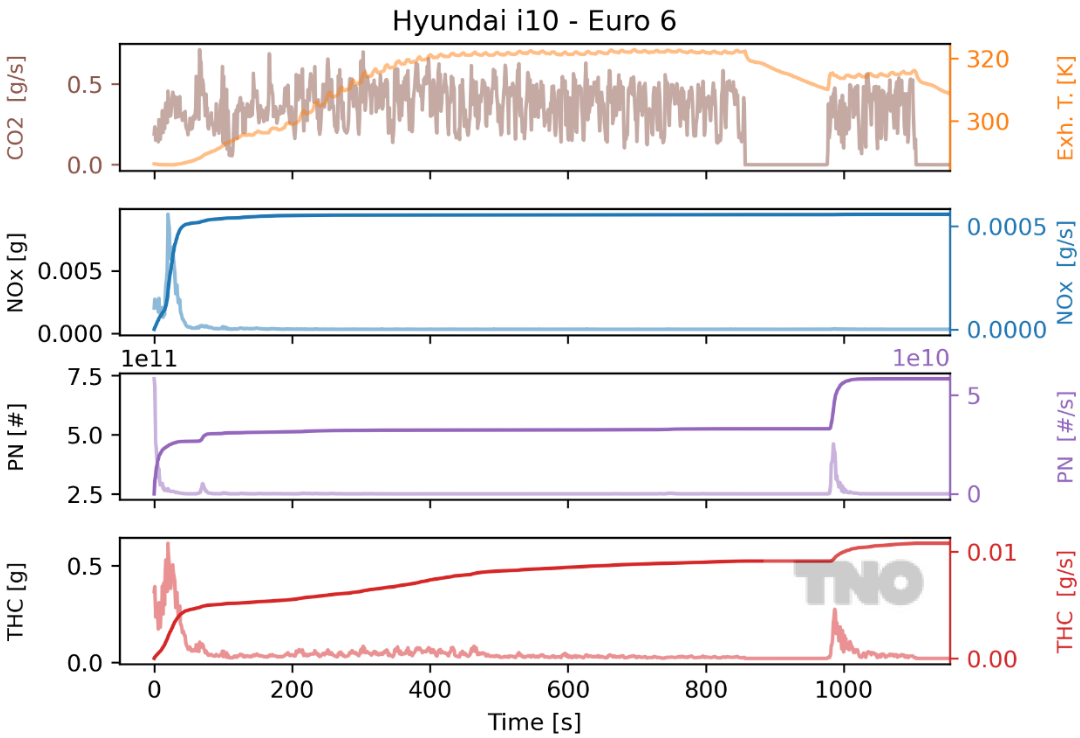
THC [g]
THC [g/s]
Time [s]


Hyundai i10 - Euro 6
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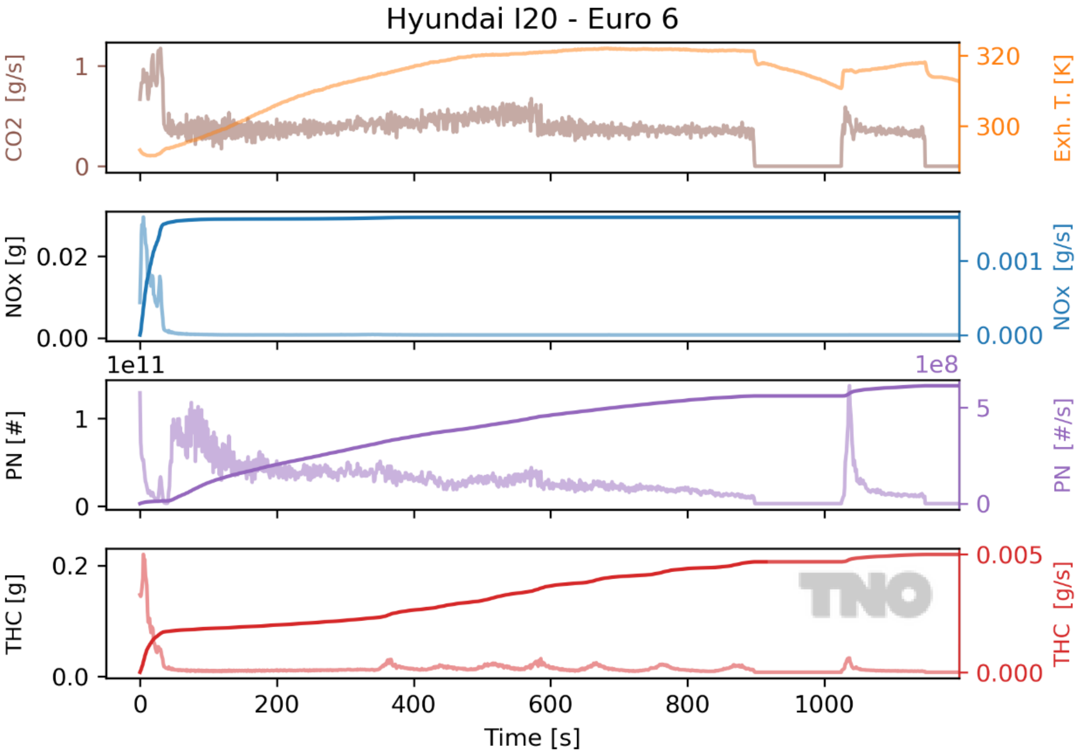
Time [s]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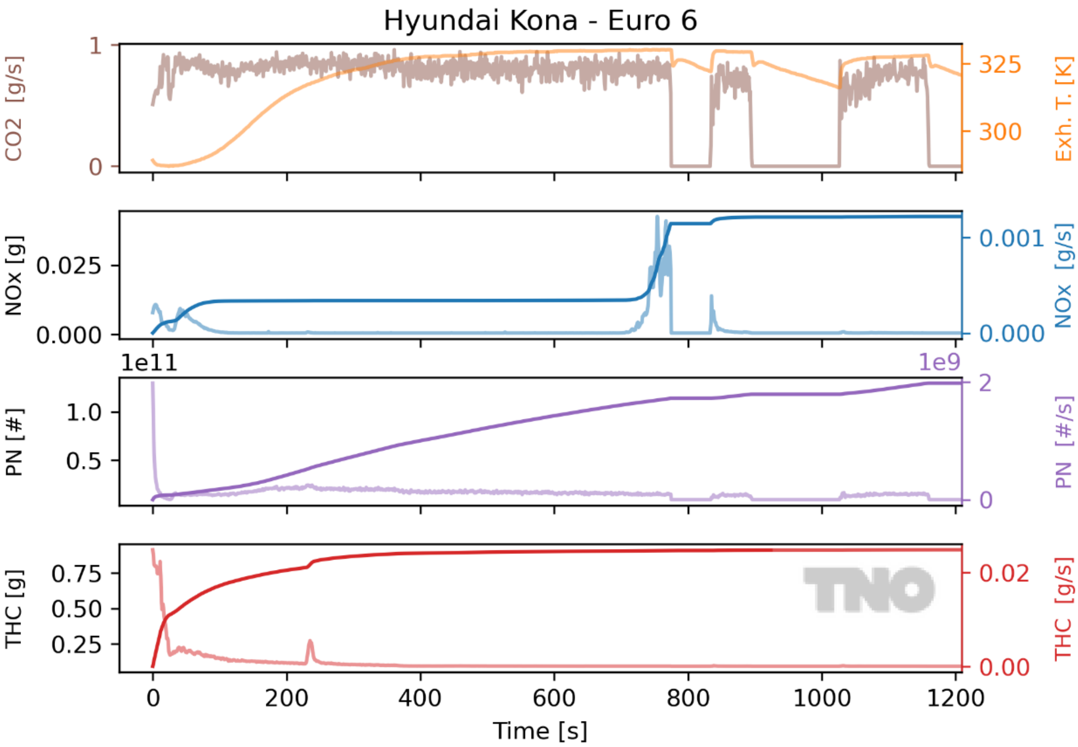
1e8
Time [s]


Hyundai Kona - Euro 6
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Exh. T. [K]
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NOx [g/s]
PN [#]
PN [#/s]
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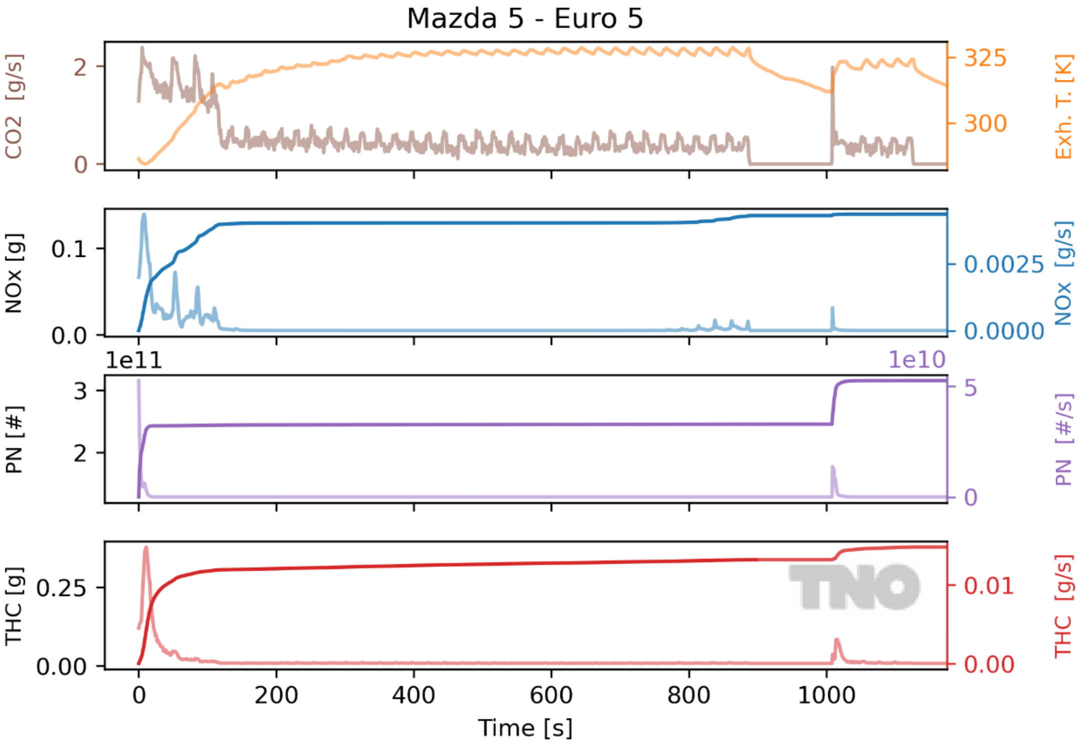
1e11
1e9
Time [s]


Mazda 5 - Euro 5
CO2 [g/s]
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NOx [g]
NOx [g/s]
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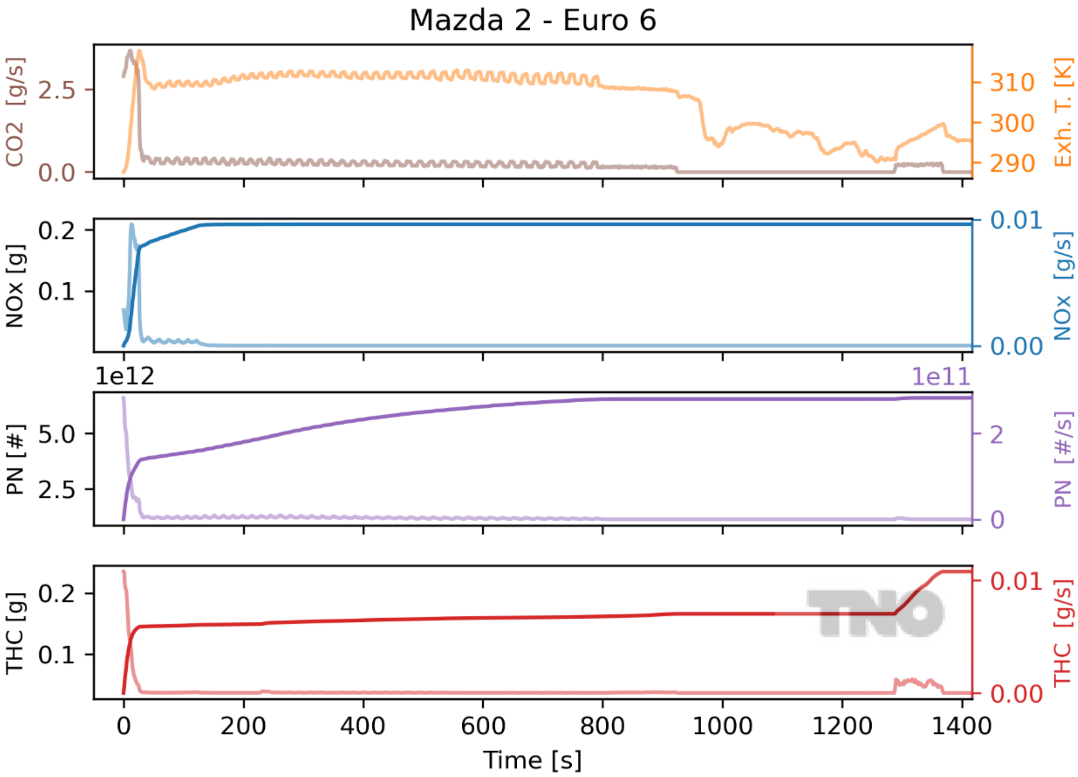
THC [g/s]
Time [s]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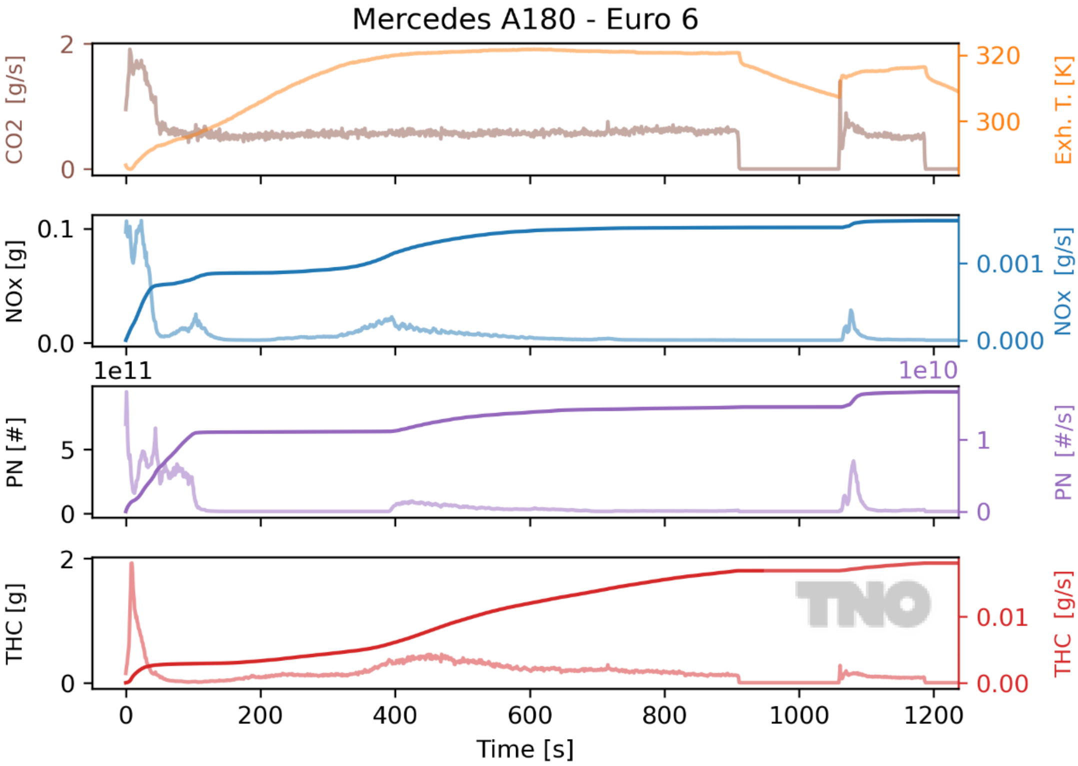
THC [g/s]
Time [s]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NOx [g]
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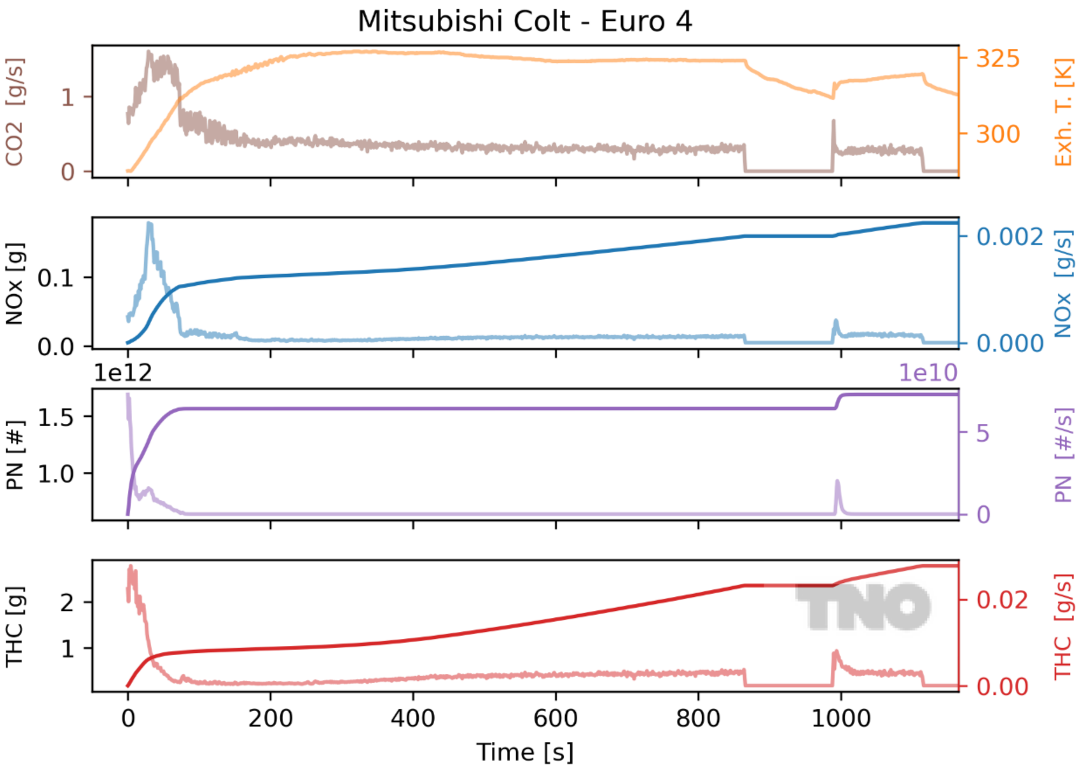
1e10
THC [g]
THC [g/s]
Time [s]
TNO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NOx [g]
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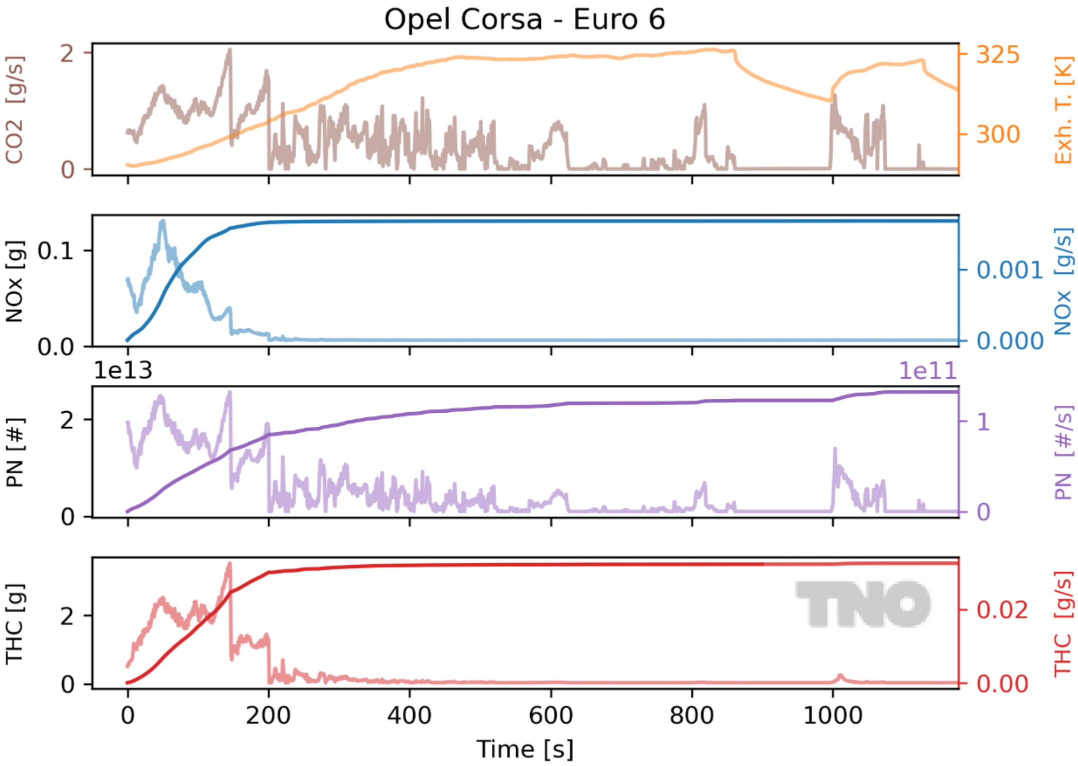
1e10
THC [g]
THC [g/s]
Time [s]
TNO


Opel Corsa - Euro 6
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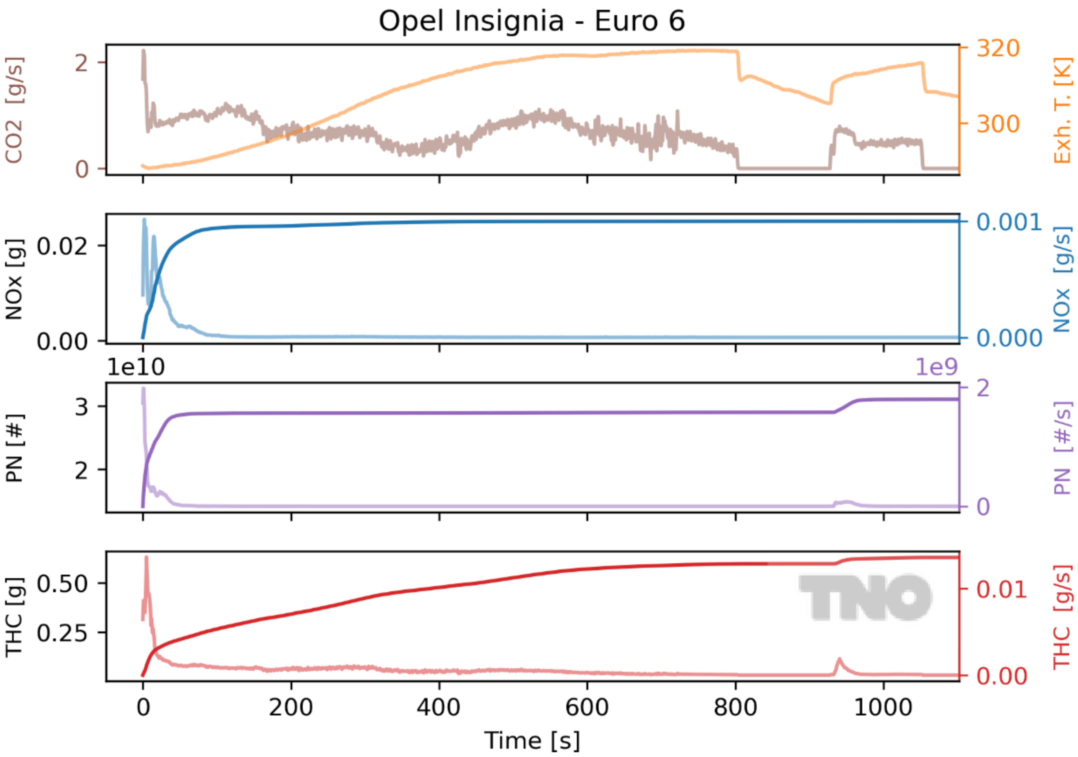
THC [g]
THC [g/s]
TNO
Time [s]


Opel Insignia - Euro 6
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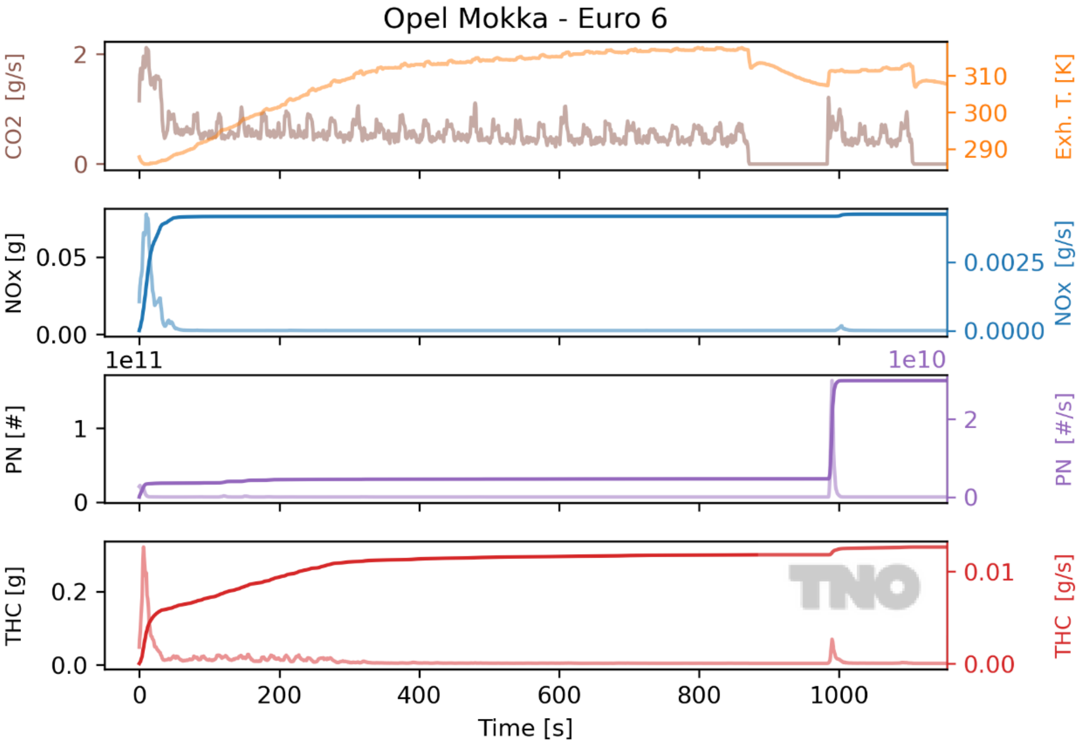
THC [g]
THC [g/s]
TNO
Time [s]



Opel Mokka - Euro 6
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NOx [g/s]
PN [#]
PN [#/s]
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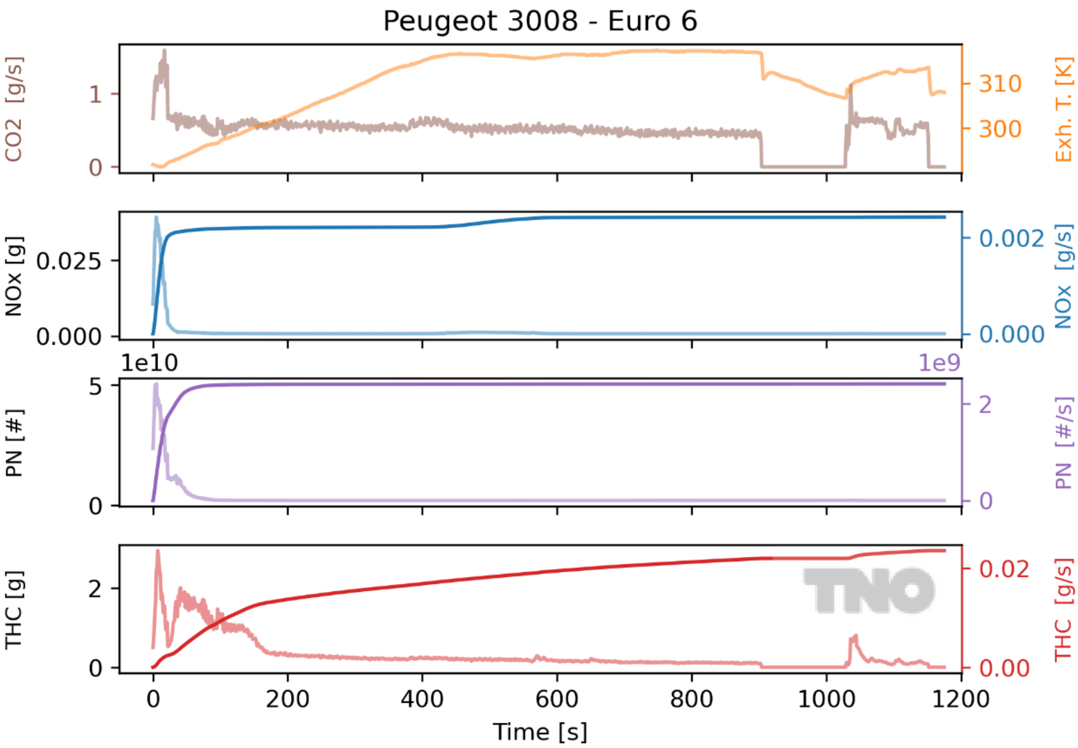
THC [g/s]
Time [s]



Peugeot 3008 - Euro 6
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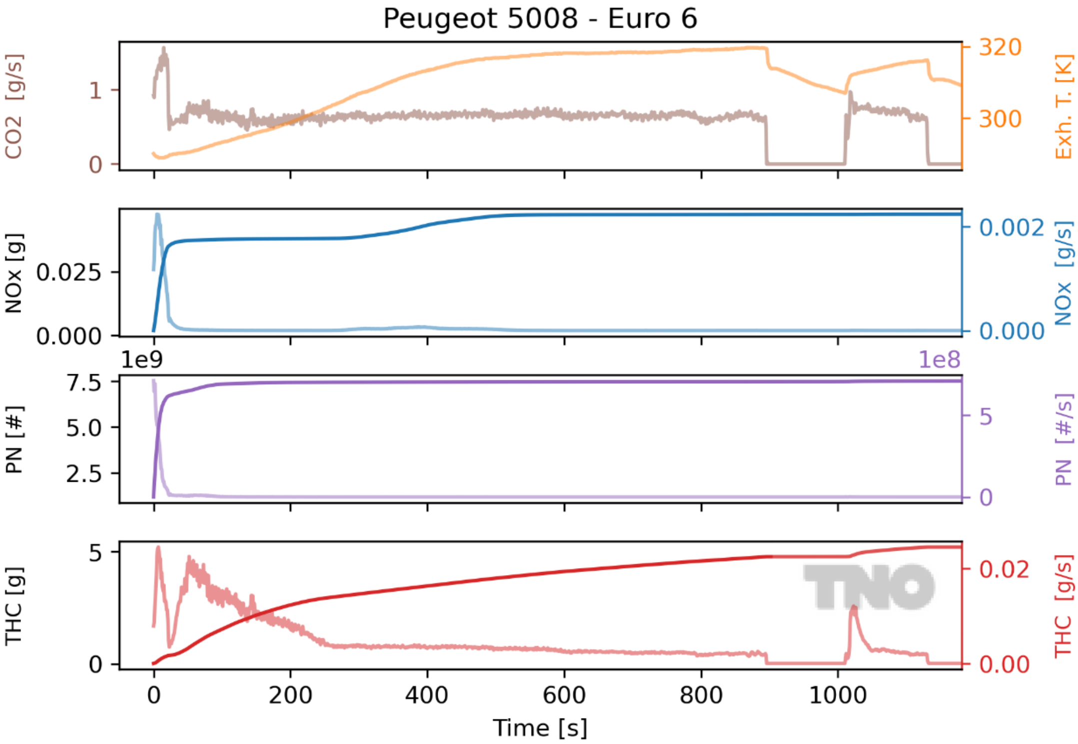
NOx [g/s]
PN [#]
PN [#/s]
THC [g]
THC [g/s]
Time [s]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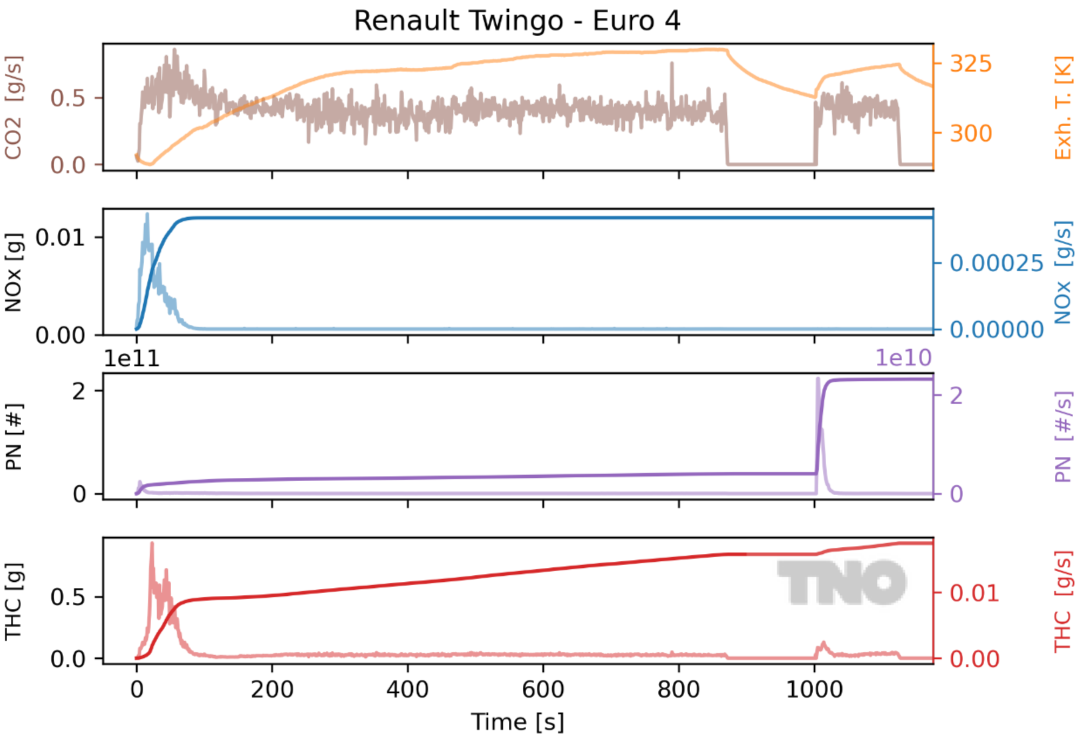
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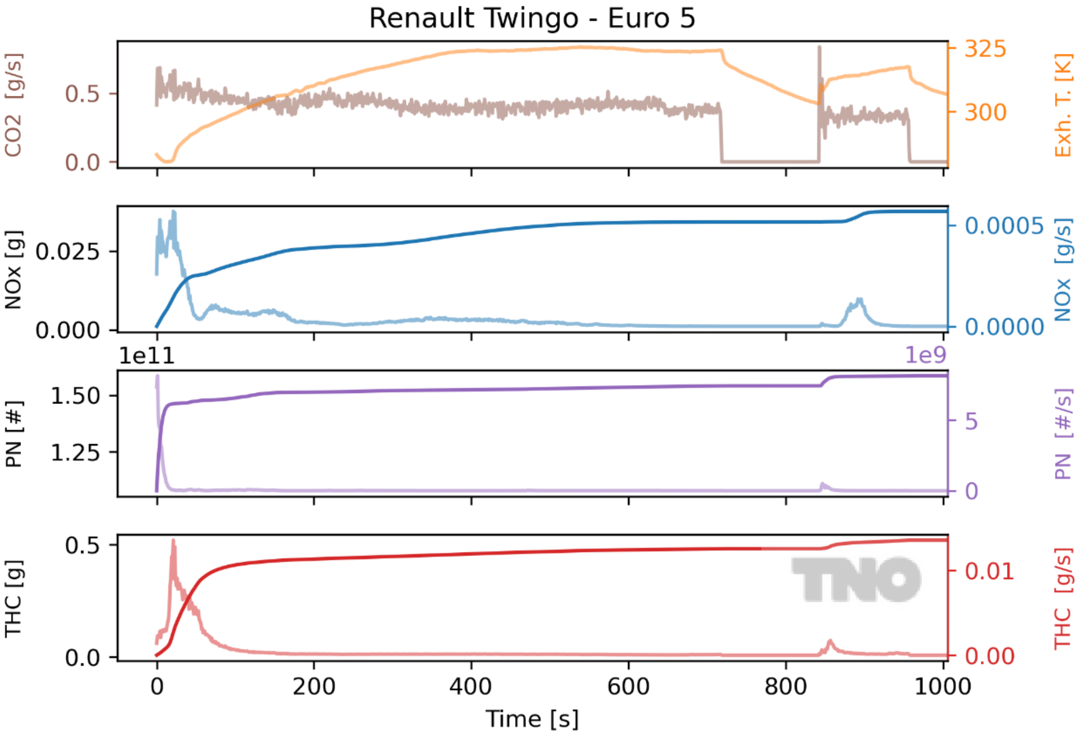
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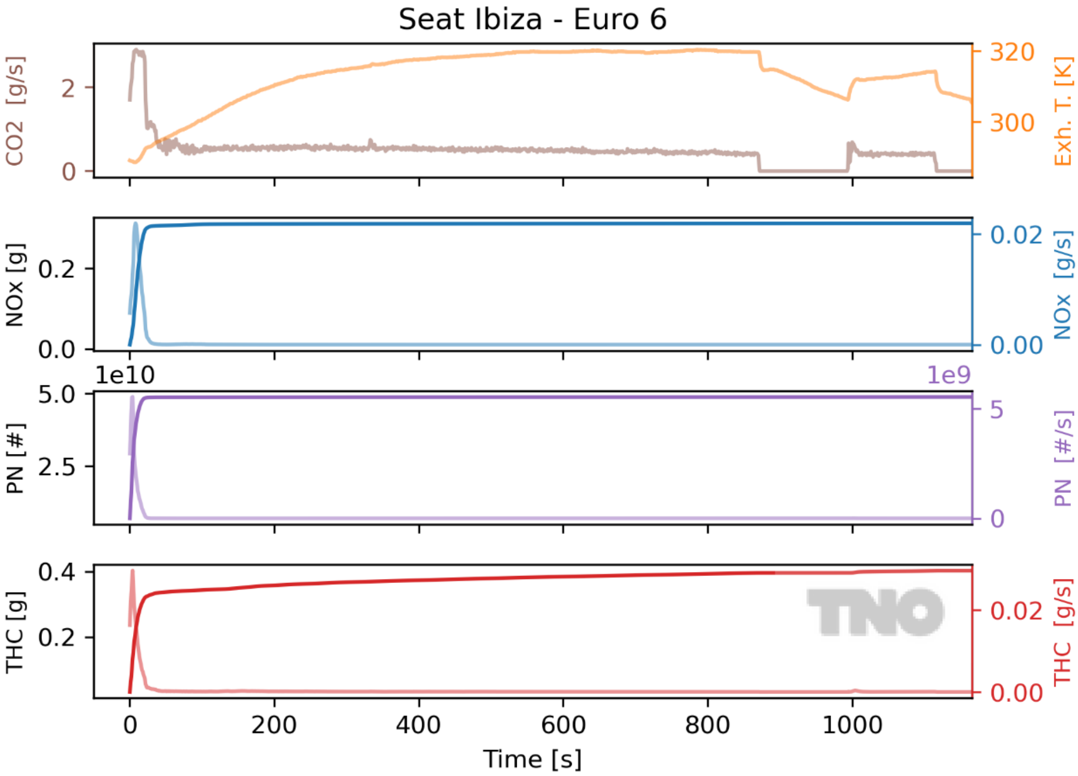
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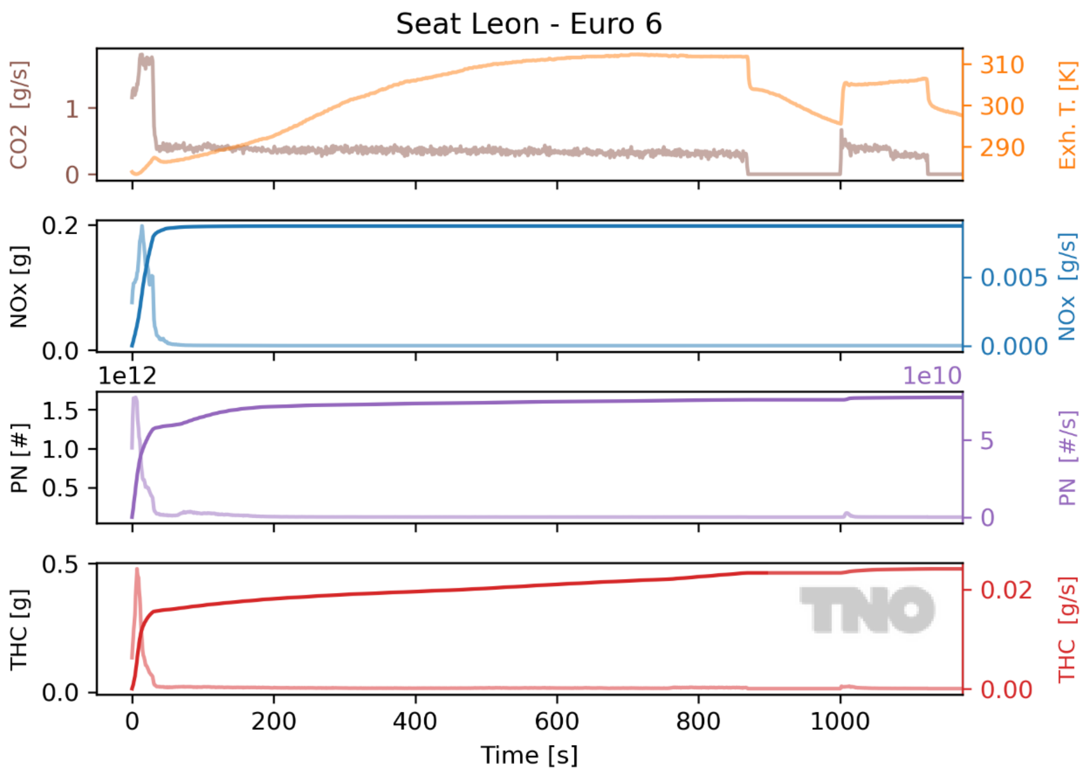
Time [s]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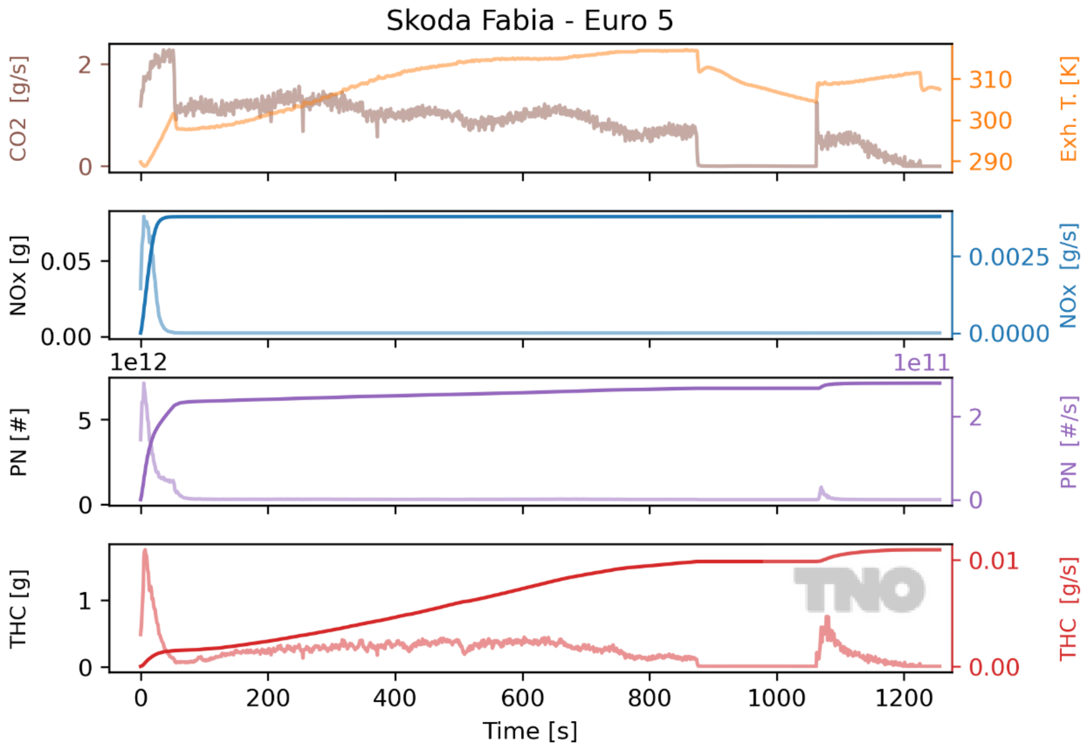
Time [s]
TNO


Skoda Fabia - Euro 5
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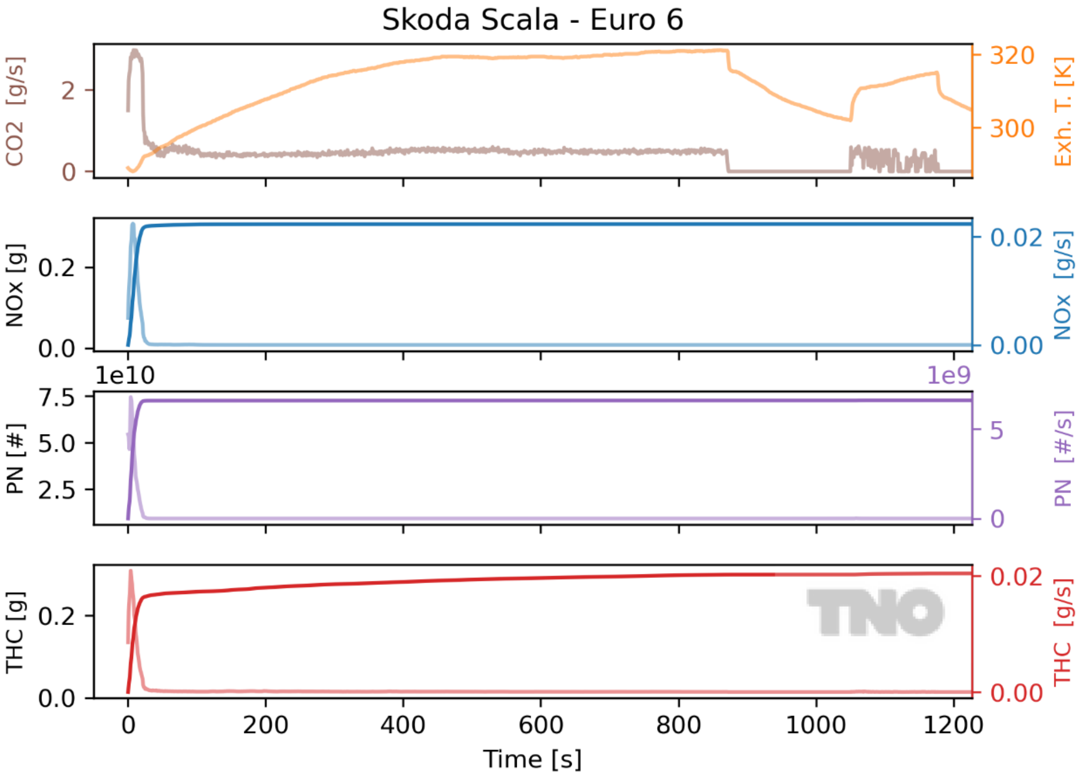
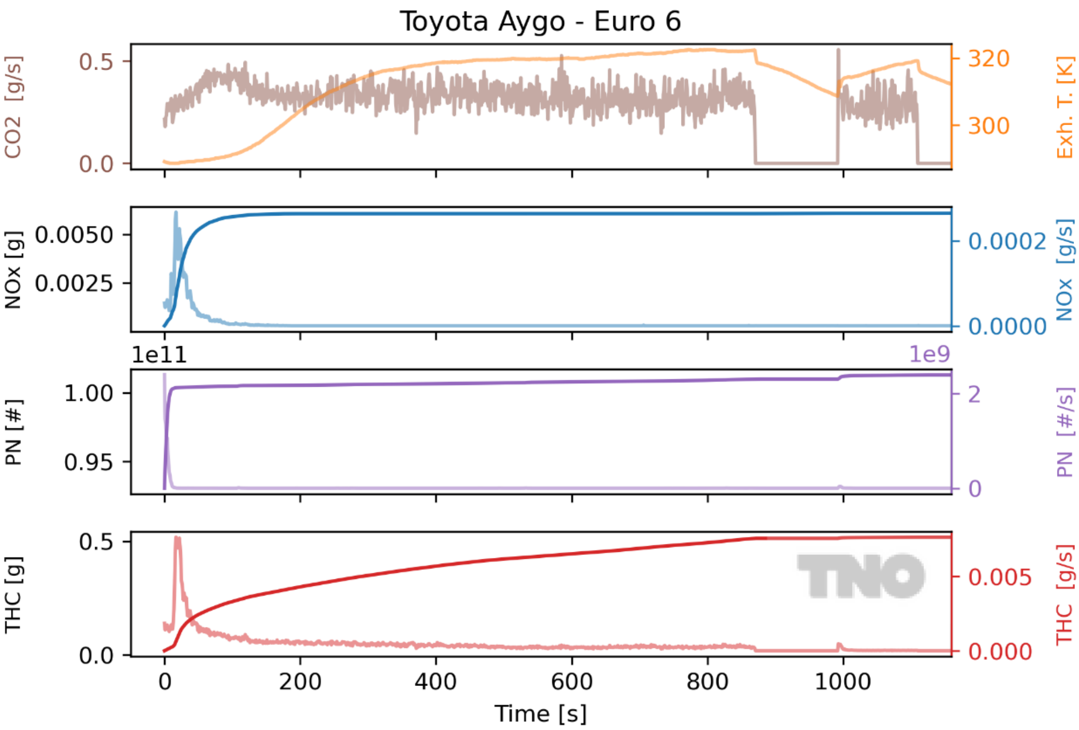
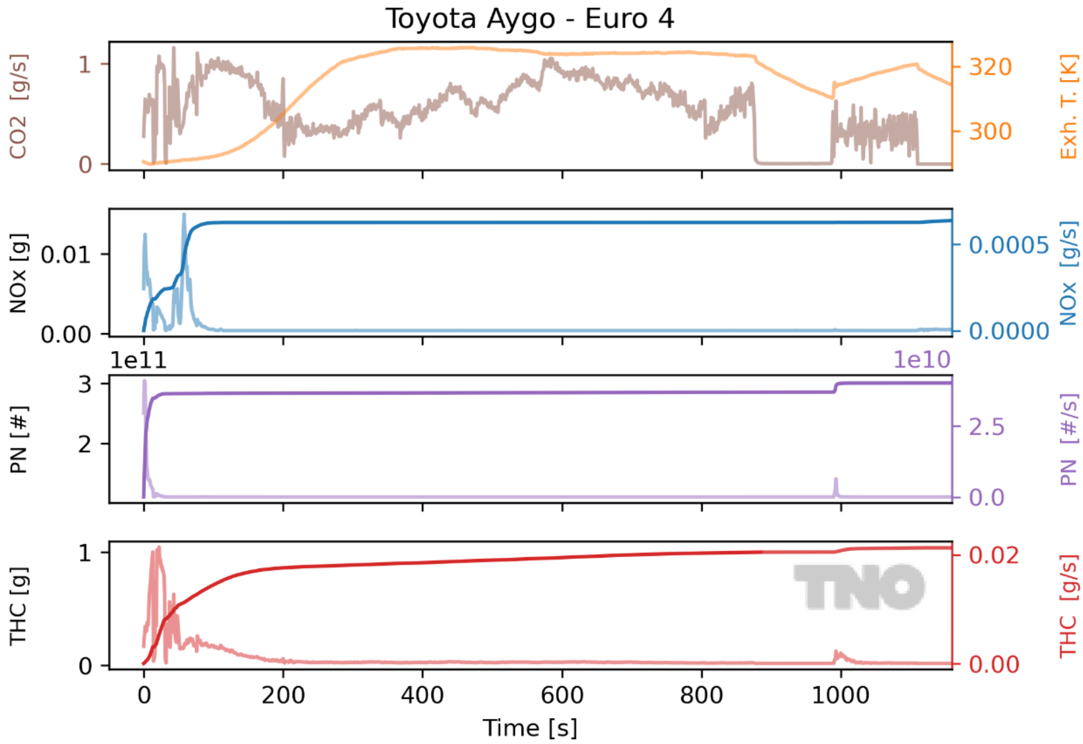
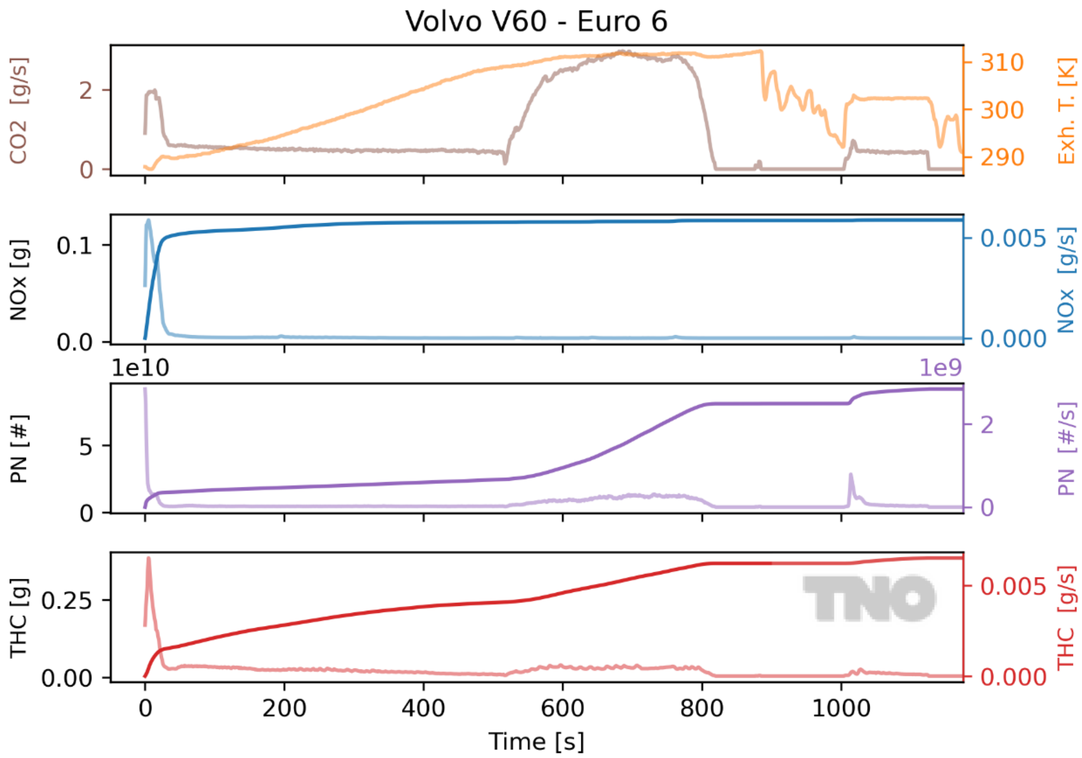
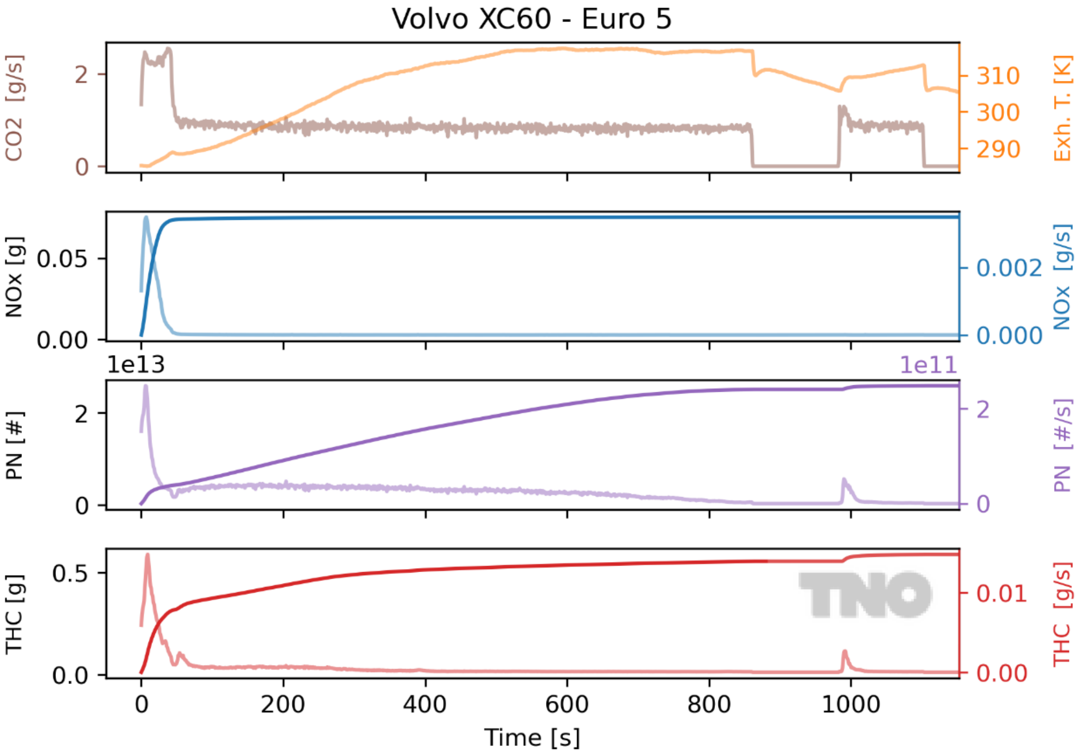
NOx [g/s]
PN [#]
PN [#/s]
THC [g]
THC [g/s]
Time [s]
TNO

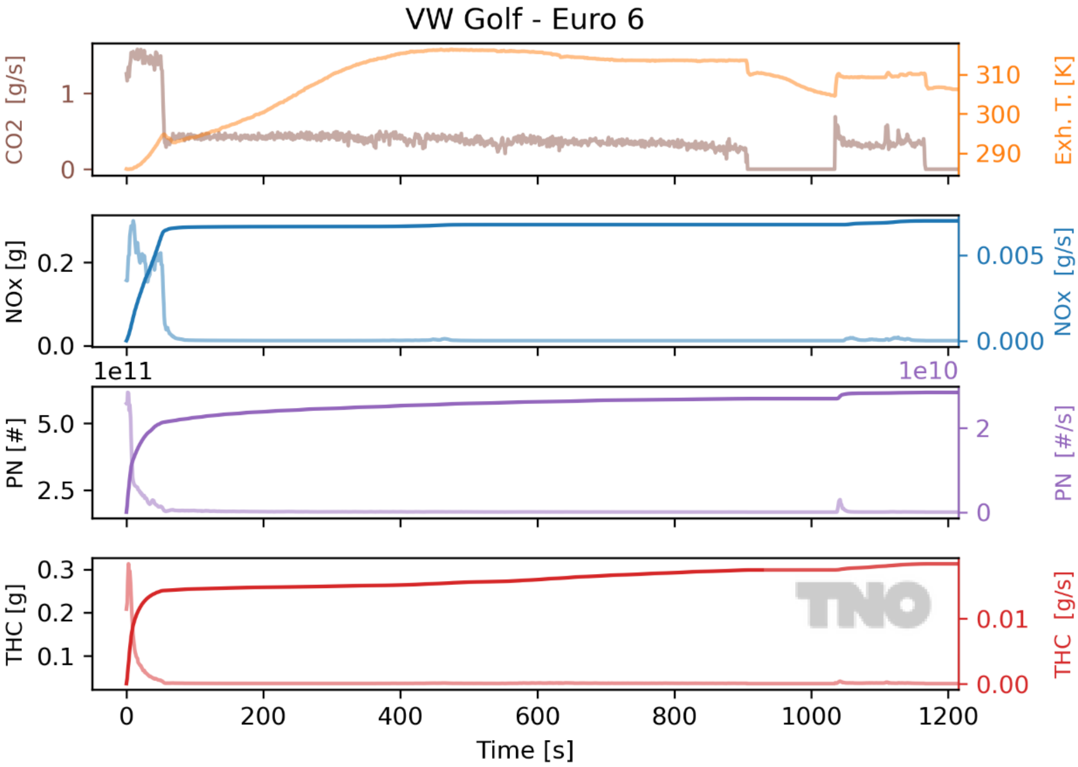

Skoda Scala - Euro 6
CO2 [g/s]
Exh. T. [K]
NOx [g]
NOx [g/s]
PN [#]
PN [#/s]
1e10
1e9
THC [g]
THC [g/s]
Time [s]
TNO

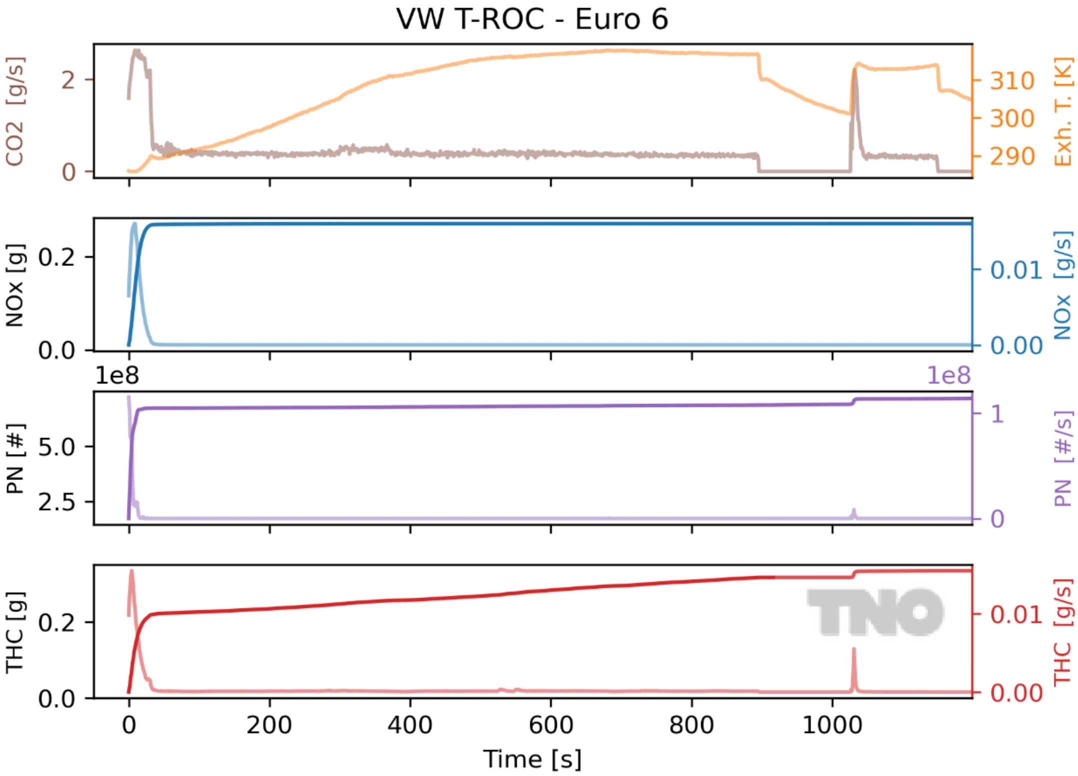

Toyota Aygo - Euro 6
CO2 [g/s]
Exh. T. [K]
NOx [g]
NOx [g/s]
PN [#]
PN [#/s]
1e11
1e9
THC [g]
THC [g/s]
Time [s]
TNO


Toyota Aygo - Euro 4
CO2 [g/s]
Exh. T. [K]
NOx [g]
NOx [g/s]
PN [#]
PN [#/s]
THC [g]
THC [g/s]
1e11
1e10
Time [s]
TNO


Volvo V60 - Euro 6
CO2 [g/s]
Exh. T. [K]
NOx [g]
NOx [g/s]
PN [#]
PN [#/s]
THC [g]
THC [g/s]
1e10
1e9
Time [s]
TNO


Volvo XC60 - Euro 5
CO2 [g/s]
Exh. T. [K]
NOx [g]
NOx [g/s]
1e13
1e11
PN [#]
PN [#/s]
THC [g]
THC [g/s]
Time [s]


VW Golf - Euro 6
CO2 [g/s]
Exh. T. [K]
NOx [g]
NOx [g/s]
1e11
1e10
PN [#]
PN [#/s]
THC [g]
THC [g/s]
Time [s]


VW T-ROC - Euro 6
CO2 [g/s]
Exh. T. [K]
NOx [g]
NOx [g/s]
1e8
PN [#]
PN [#/s]
THC [g]
THC [g/s]
TNO
Time [s]

Appendix B
Supplementary figures

- Comparisons for PN, THC, CO_2 of the cold start phases and cumulative emissions during cold start and idling.
- Comparison of restart time-series and distribution of starts compared to warm emissions

B.1 Time series cold starts

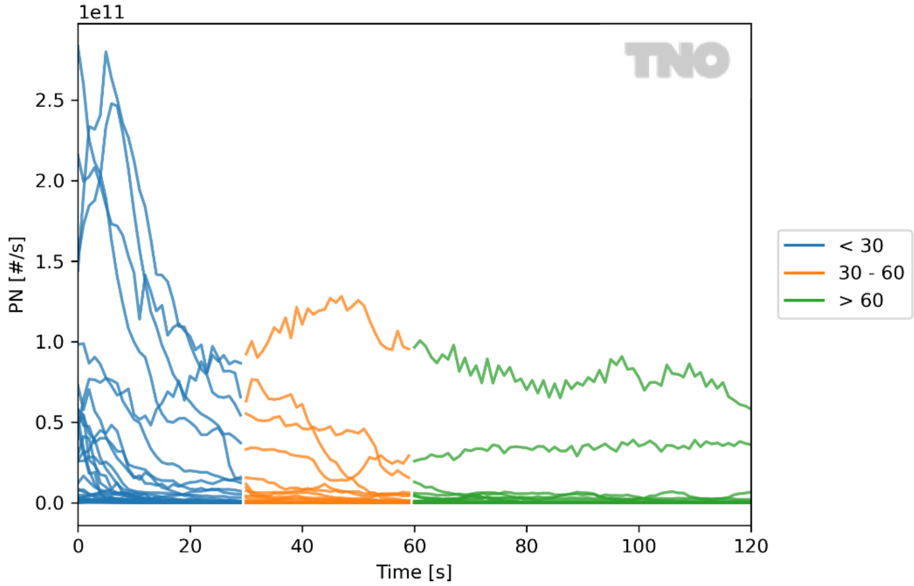


Figure B.1: PN-emissions during cold start. Three phases are indicated: 1) highest cold start emissions during the first 30 seconds (blue, '< 30'); 2) stabilisation to warm emissions (orange, '30 – 60'); 3) warm emissions (green, '>60'). Note that there are two vehicles whose PN-emissions differ: one appears to decrease until 50 seconds, then increases slowly into the warm emissions phase, and another with a peak around 50 seconds that then continues to decrease.

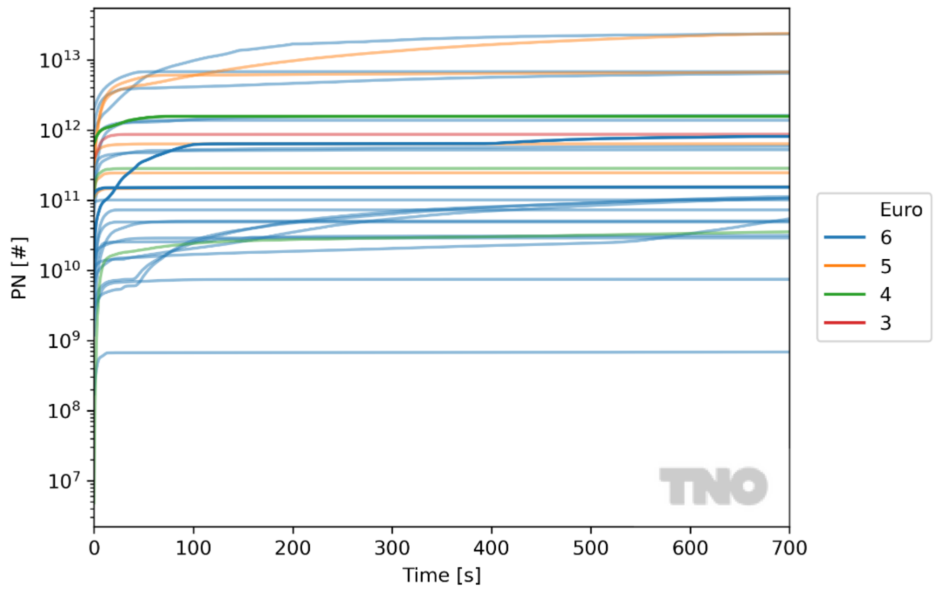


Figure B.2: Cumulative PN-emissions per vehicle during a cold start and extended idling. The majority of the vehicles show a very steep initial gradient directly after engine start followed by a significant reduction in gradient resulting in an almost horizontal line (i.e. very little to no emissions). A number of vehicles show an initial stabilisation after high cold start emissions, followed by more PN-emissions during idling. Colours indicate the Euro class per vehicle.

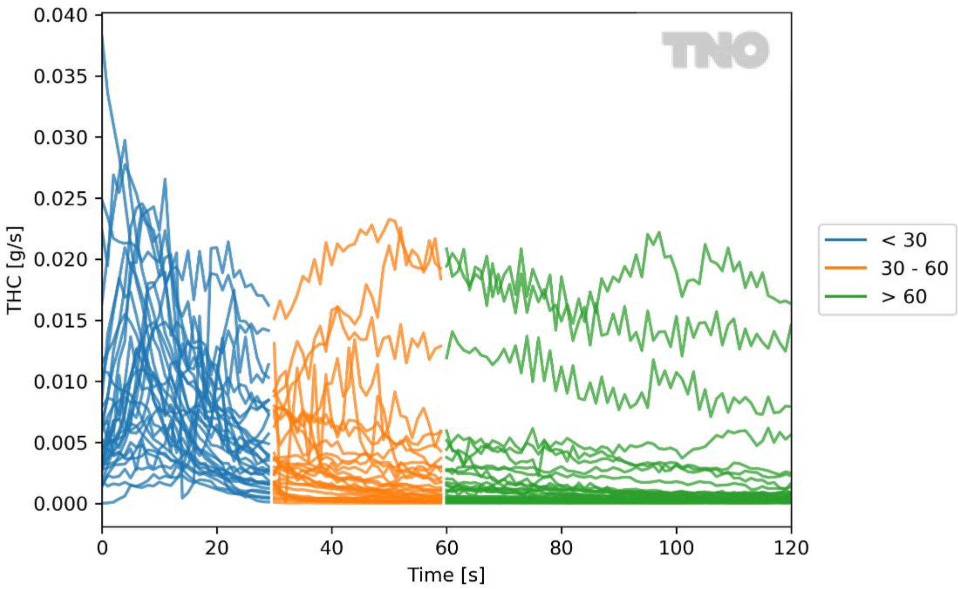


Figure B.3: THC emissions during cold start. Three phases are indicated: 1) highest cold start emissions during the first 30 seconds (blue, '< 30'); 2) stabilisation to warm emissions (orange, '30 – 60'); 3) warm emissions (green, '>60'). Note that there are three vehicles whose THC emissions remain relatively high.

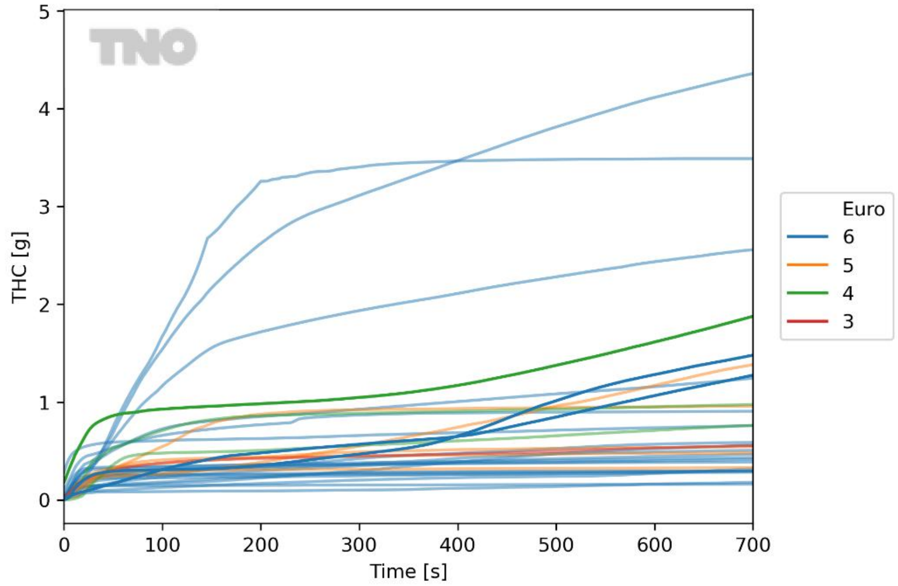


Figure B.4: Cumulative THC emissions per vehicle during a cold start and extended idling. The majority of the vehicles show a very steep initial gradient directly after engine start followed by a significant reduction in gradient resulting in an almost horizontal line (i.e. very little to no emissions). Three vehicles show generally high THC emissions, while another three vehicles show relatively significant THC emissions after stabilisation and are plotted with a bold line. Colours indicate the Euro class per vehicle.

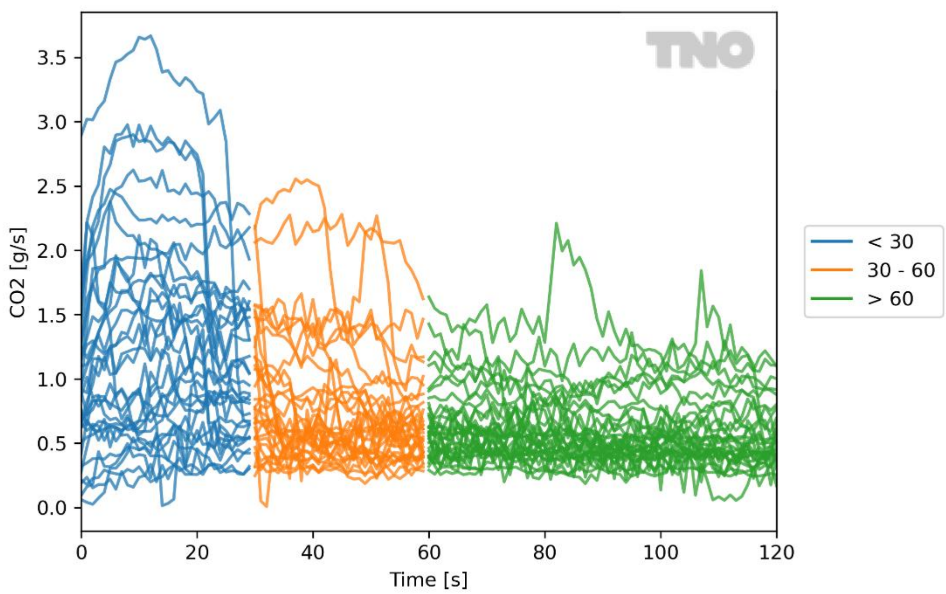


Figure B.5: CO_2 emissions during cold start. Three phases are indicated: 1) highest cold start emissions during the first 30 seconds (blue, '< 30'); 2) stabilisation to warm emissions (orange, '30 – 60'); 3) warm emissions (green, '>60'). Note that the cold start effect is less obvious for CO_2 as it is for other pollutants.

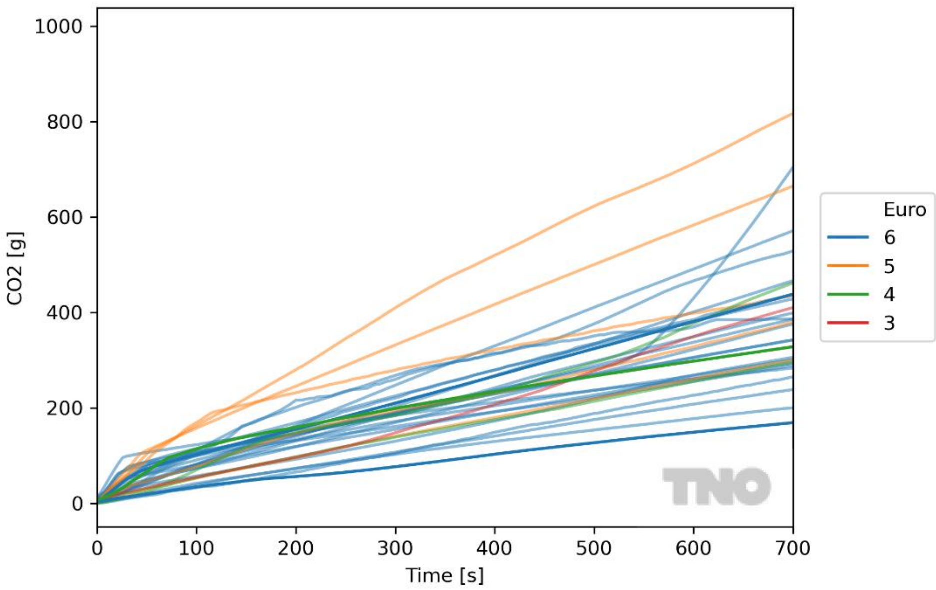


Figure B.6: Cumulative CO_2 emissions per vehicle during a cold start and extended idling. The majority of the vehicles show a slight cold start effect, as there are still significant CO_2 emissions during idling. Of note are the two Euro 5 vehicles with significantly higher CO_2 emissions, and the Euro 6 vehicle which shows an increase in emissions after 550 seconds. Colours indicate the Euro class per vehicle.

B.2 Restarts

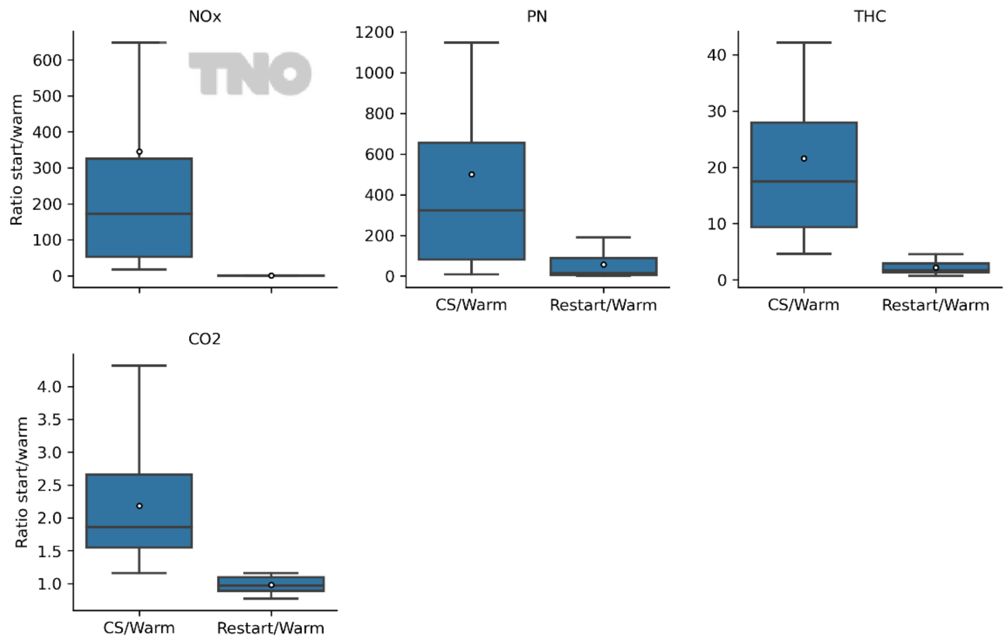


Figure B.7: Box plot of the ratio between the average emissions per second during the first 30 seconds of a start (for cold start CS and restart) and the average warm idling emissions per second. White dots indicate the means, and the whiskers data 1.5 times the interquartile range. The boxes indicate the 25th to 75th quantile, the contained line the median. There is a wide range of ratios linked also to low warm emissions: a median value of CS/Warm for NO_x of 170 indicates that the average cold start emissions in mg/s are 170 times higher than the average warm idling emissions.

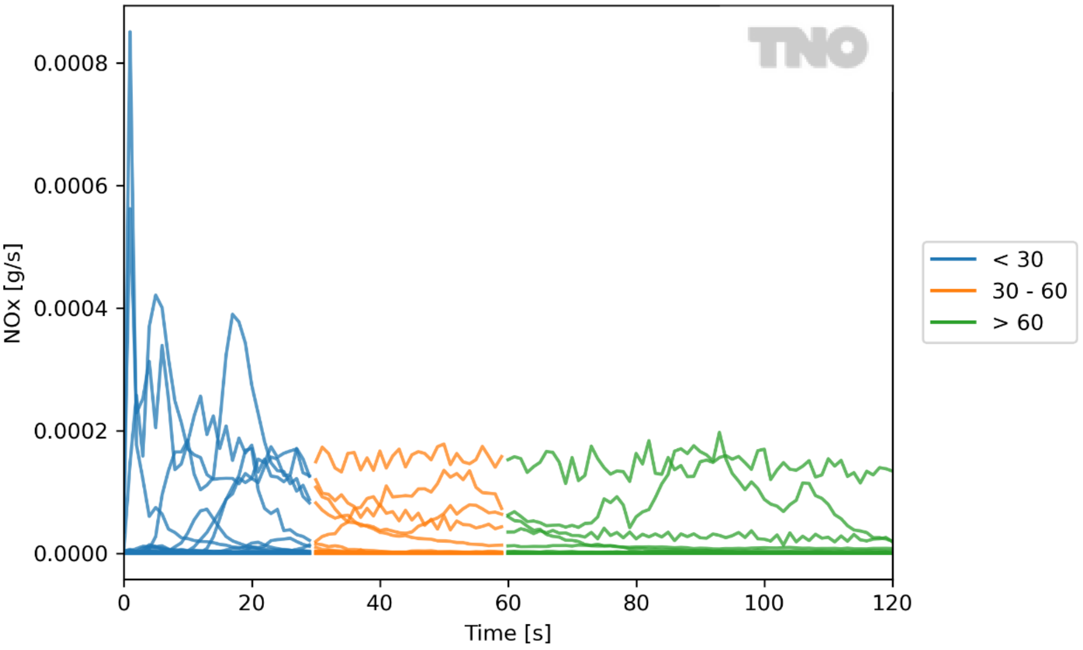


Figure B.8: NO_x-emissions during a restart. Three phases are indicated: 1) highest restart emissions during the first 30 seconds (blue, '< 30'); 2) stabilisation to warm emissions (orange, '30 – 60'); 3) warm emissions (green, '>60'). The NO_x-emissions during the restart are substantially lower than the cold start, but there are still higher restart emissions observed.

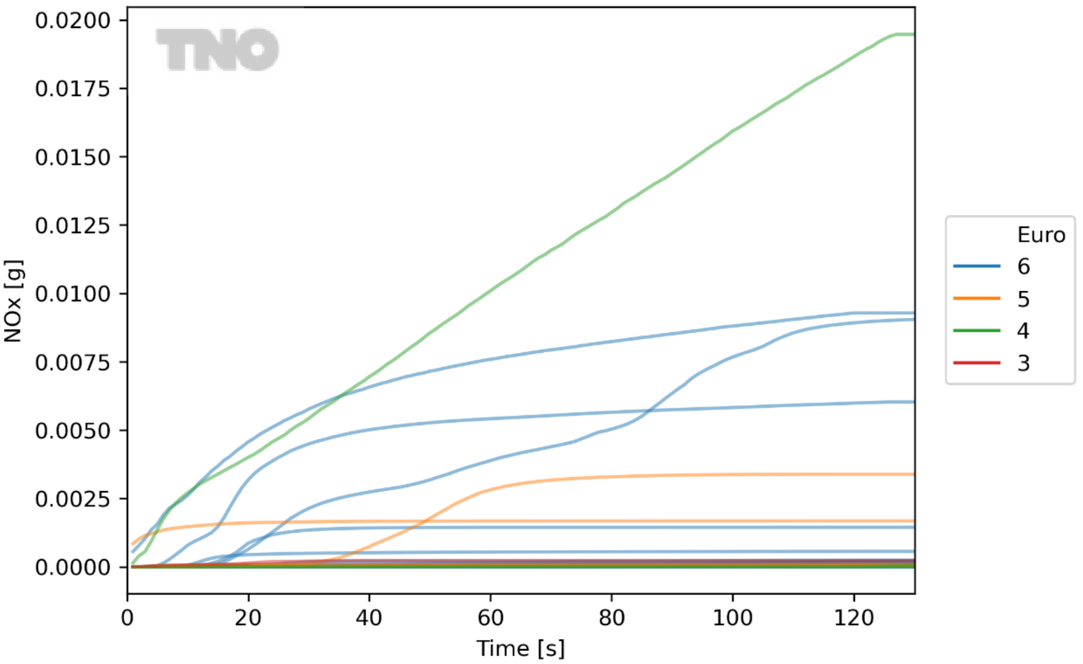


Figure B.9: Cumulative NO_x-emissions during restart. A steep gradient indicates higher NO_x-emissions. The relatively higher NO_x-emissions are less pronounced for the restart. Note that the absolute values for restart are also substantially lower.

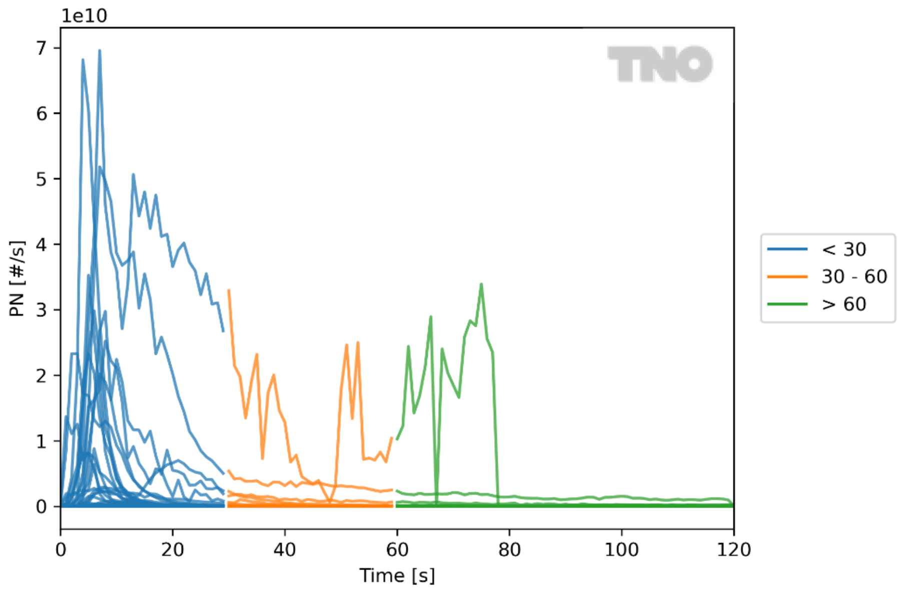


Figure B.10: PN-emissions during a restart. Three phases are indicated: 1) highest restart emissions during the first 30 seconds (blue, '< 30'); 2) stabilisation to warm emissions (orange, '30 – 60'); 3) warm emissions (green, '>60'). Note the vehicle with high emissions until 80 seconds.

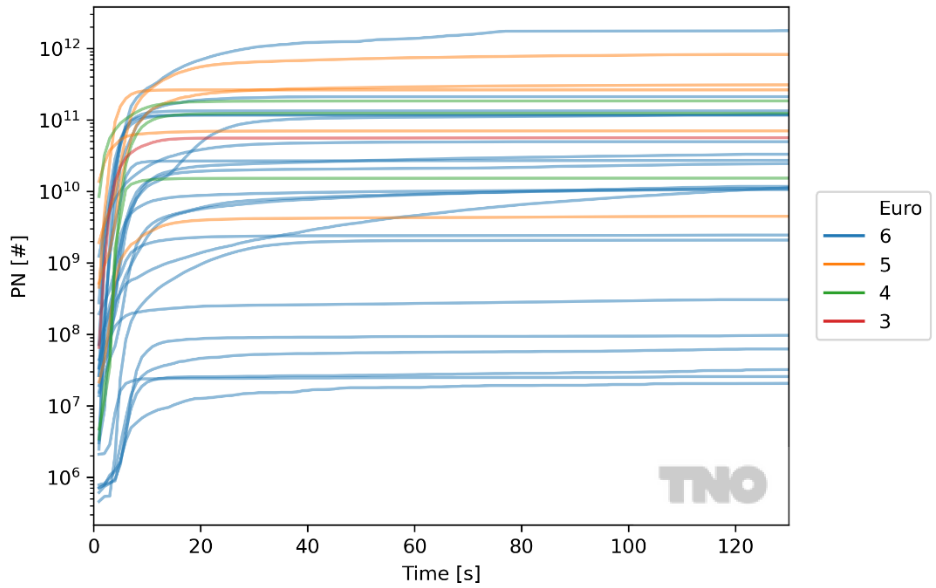


Figure B.11: Cumulative PN-emissions per vehicle during a restart. The majority of the vehicles show a very steep initial gradient directly after engine start followed by a significant reduction in gradient resulting in an almost horizontal line (i.e. very little to no emissions). A number of vehicles show an initial stabilisation after high initial emissions, followed by more PN-emissions during idling. Colours indicate the Euro class per vehicle.

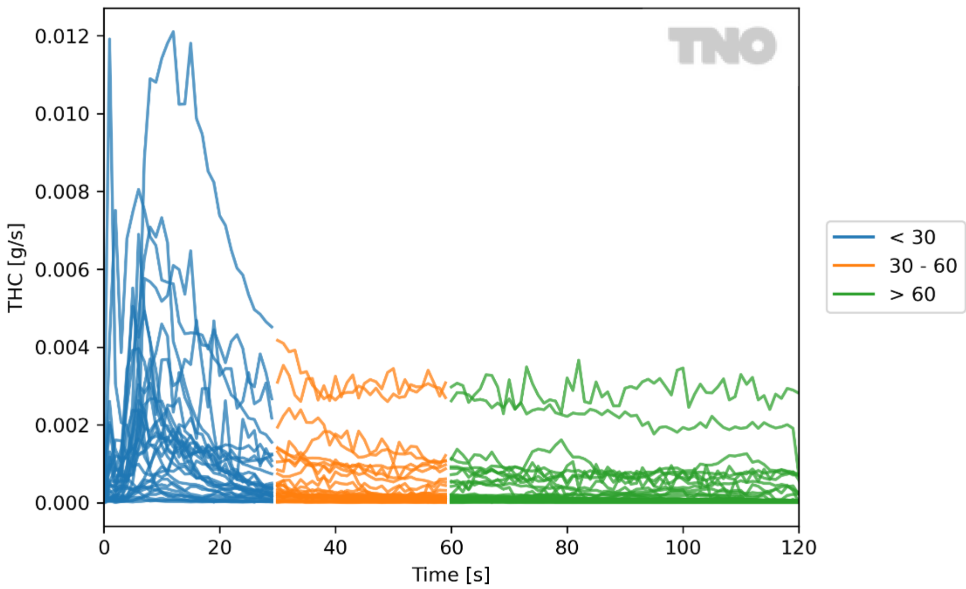


Figure B.12: THC emissions during a restart. Three phases are indicated: 1) highest restart emissions during the first 30 seconds (blue, '< 30'); 2) stabilisation to warm emissions (orange, '30 – 60'); 3) warm emissions (green, '>60'). Note that there are two vehicles whose THC emissions remain higher.

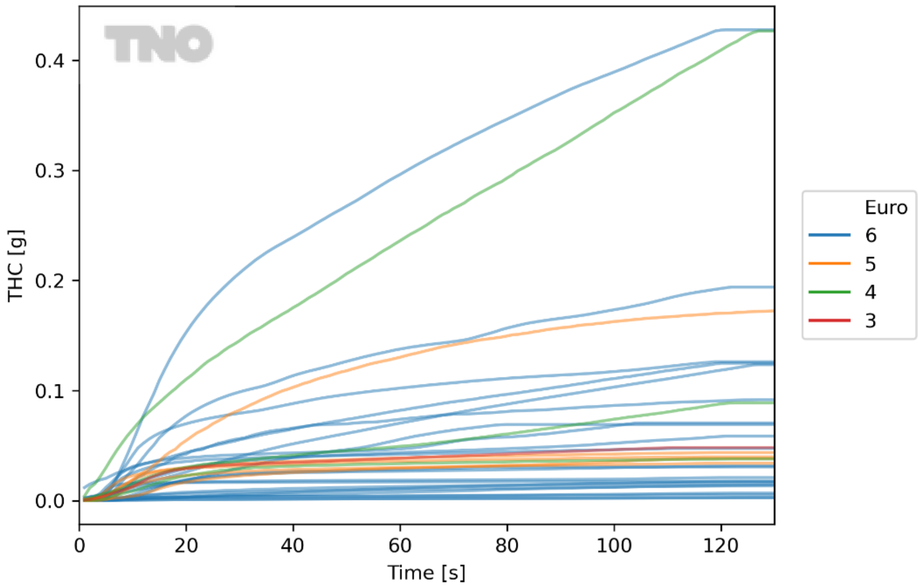


Figure B.13: Cumulative THC emissions per vehicle during a restart. The majority of the vehicles show a steeper initial gradient directly after engine start followed by a significant reduction in gradient. A number of vehicles continue to emit relatively high THC during the idling following restart. Colours indicate the Euro class per vehicle.

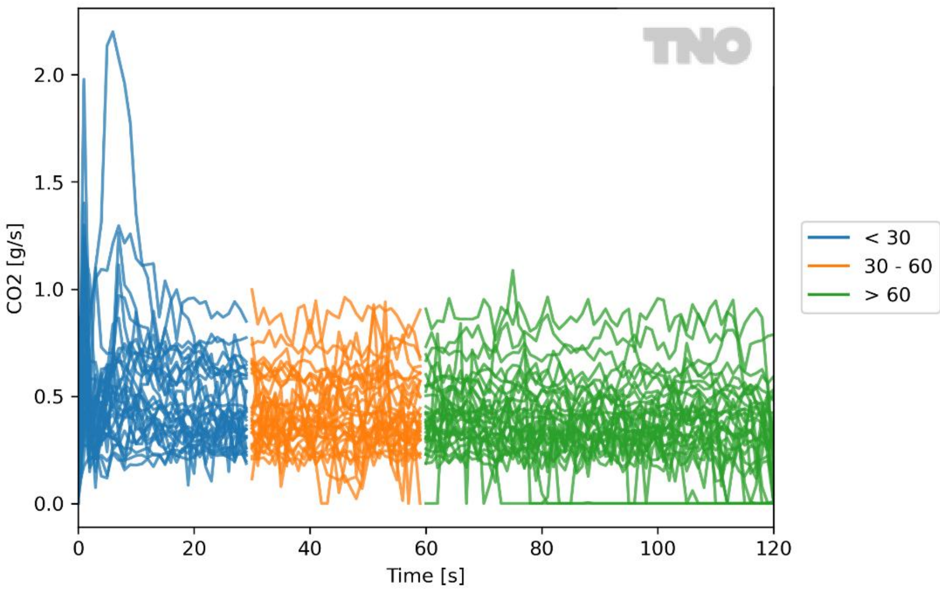


Figure B.14: CO_2 emissions during a restart. Three phases are indicated: 1) highest restart emissions during the first 30 seconds (blue, '< 30'); 2) stabilisation to warm emissions (orange, '30 – 60'); 3) warm emissions (green, '>60').

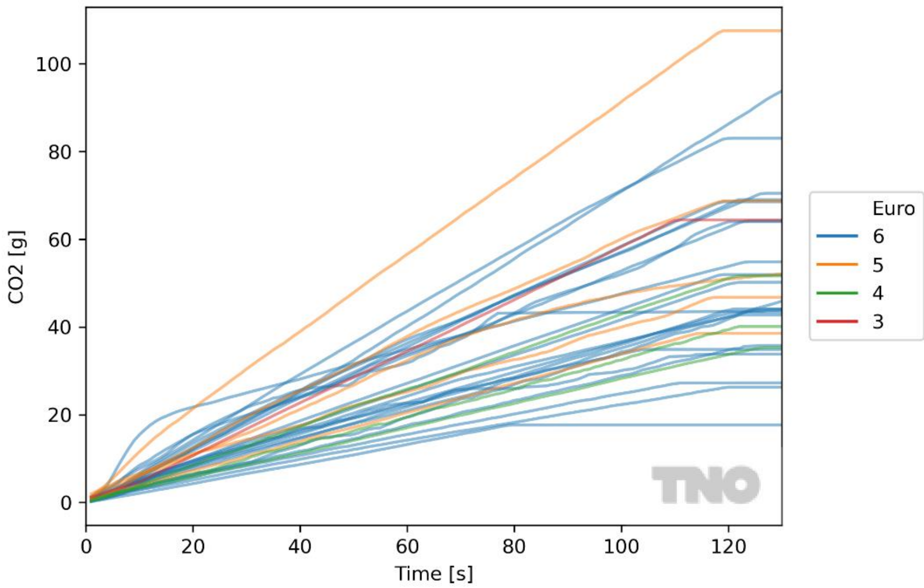


Figure B.15: Cumulative CO_2 emissions per vehicle during a restart. Colours indicate the Euro class per vehicle.

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