Update of real-world emissions of temperature-controlled road transport in the Netherlands

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Management samenvatting

In 2023 presenteerde het Ministerie van Infrastructuur en Waterstaat een plan van aanpak voor de verduurzaming van geconditioneerd transport.[1] In het verleden is slechts beperkt gemeten aan de uitlaatemissies van koelsystemen, waardoor de inzichten in de emissiebijdrage beperkt is. Om een beter inzicht te krijgen in de uitlaatgasemissies en de inzet van koelsystemen bij geconditioneerd transport over de weg, heeft het Ministerie van Infrastructuur en Waterstaat aan TNO gevraagd daar onderzoek naar te verrichten. Dit rapport is een update van het tussentijdse overzicht van de meetresultaten die in 2024 zijn gerapporteerd.[2] De meetresultaten voor NO_x- en CO_2-emissies zijn nu gebaseerd op meer data, aanvullend is van een koelmachine de fijnstofemissie gemeten. De rapportage geeft ook een inschatting van de impact van de meetresultaten op de berekende emissietotalen van koelsystemen in geconditioneerd transport over de weg in Nederland.

Door te meten is een beter beeld verkregen van de NO_x-, fijnstof en CO_2-uitstoot van diesel-aangedreven koelmachines op vrachtwagens in Nederland. Daarmee zijn de emissiefactoren voor koelmachines (deels) bijgesteld en zijn ze betrouwbaarder geworden. Emissiefactoren zijn kengetallen voor de gemiddelde uitstoot per machine. Deze worden gebruikt om de totale emissies van geconditioneerd transport over de weg in Nederland te schatten. Op basis van de meetresultaten is de voorgaande emissiefactor voor NO_x-emissies van koelmachines omlaag bijgesteld. Ten gevolge van deze aanpassingen is de voorgaande inschatting van 4,6 kton per jaar aan NO_x-emissies door diesel-aangedreven koelmachines op de weg verlaagd naar 1,8 kton per jaar. Voor de CO_2-emissies (0,3 Mton per jaar) is er een zeer kleine wijziging ten gevolge van de gemeten uitstoot. Voor fijnstof is slechts aan één koelmachine uitgebreid gemeten binnen dit onderzoek, wat onvoldoende is om de huidige emissiefactor bij te stellen. Daarmee blijft de totale fijnstof-emissie (PM2,5) door koelmachines op de weg 0,13 kton per jaar.

Ondanks de voorziene daling in de emissietotalen kan de NO_x-uitstoot van een individuele koelmachine van dezelfde ordegrootte zijn als de uitstoot van een moderne dieselaangedreven vrachtwagen. Hetzelfde geldt voor fijnstofemissies omdat koelmachinemotoren geen roetfilter hebben. Dit komt grotendeels doordat voor dieselmotoren van koelmachines een minder strenge emissienorm van toepassing is dan voor vrachtwagenmotoren.

Naast de emissieprestaties is ook onderzoek gedaan naar de inzet van koelmachines. De jaarlijkse intensiteit van de inzet varieert fors tussen de langdurig gemonitorde koelmachines, maar de resultaten komen gemiddeld wel overeen met huidige inschattingen.

Vanwege de potentiële negatieve gezondheidseffecten van fijnstof en het beperkte inzicht in de fijnstofemissies van koelmotoren, wordt aanbevolen om deze emissies bij meerdere typen koelmachines beter in kaart te brengen.

[1] https://open.overheid.nl/documenten/dpc-efe48a0d7d708f727b8acf9ddc1c11e360aa3827/pdf
[2] TNO 2024 R11647 - Real-world emissions of temperature-controlled road transport in the Netherlands

Samenvatting

In 2023 presenteerde het Ministerie van Infrastructuur en Waterstaat een plan van aanpak voor de verduurzaming van geconditioneerd transport.[3] In het verleden is slechts beperkt gemeten aan de uitlaatemissies van koelsystemen, waardoor de inzichten in de emissiebijdrage beperkt is. Om een beter inzicht te krijgen in de uitlaatgasemissies en de inzet van koelsystemen bij geconditioneerd transport over de weg, heeft het Ministerie van Infrastructuur en Waterstaat aan TNO gevraagd daar onderzoek naar te verrichten. Dit rapport is een update van het tussentijdse overzicht van de meetresultaten die in 2024 zijn gerapporteerd[4]. De rapportage geeft ook een inschatting van de impact van de meetresultaten op de emissietotalen door koelsystemen in geconditioneerd transport over de weg in Nederland. In deze studie worden de CO_2- en NO_x-emissies uit de uitlaat van acht koelmachines tijdens normaal gebruik in de dagelijkse praktijk gerapporteerd. De acht koelmachines zijn tussen de 231 en 1787 uur gemonitord, waarvan twee een volledig jaar en de rest over diverse seizoenen. De studie geeft eveneens inzicht in de inzet (gebruiksintensiteit) van koelmachines.

Zes van de acht gemeten koelmachines hebben een Stage V (de meest recente emissieklasse) dieselmotor (de andere twee hebben een Stage II en Stage IIIA dieselmotor). De emissiegrenswaarden voor Stage V motoren met een motorvermogen onder de 19 kW zijn minder streng dan voor die met een motorvermogen boven de 19 kW, zowel voor NO_x als voor fijnstof. De meeste Stage V motoren in koelmachines hebben een motorvermogen net onder de 19 kW. Onder de 19 kW is geen roetfilter nodig en zijn ook geen geavanceerde NO_x-reductietechnologieën vereist. Aanscherpingen in de (Europese) emissiewetgeving zijn nodig om emissies van diesel aangedreven koelmachines in deze vermogenscategorie op grote schaal te reduceren.

De gemiddelde jaarlijkse inzet van de gemonitorde acht koelmachines is 900 uur. Dit betreft alleen inzet waarbij de dieselmotor aanstaat. Dit gemiddelde is gebaseerd op 2050 dagen aan monitoringsdata van koelmachines in praktijkomstandigheden. Er is echter aanzienlijke variatie in inzet tussen de verschillende koelmachines. Bij sommige individuele koelmachines varieert het aantal actieve uren per dag (met dieselmotor aan) tijdens de monitoringsperiode van minder dan 1 uur tot 24 uur. Een deel van de variatie wordt verklaard doordat sommige koelmachines een aanzienlijk deel van de tijd ingeschakeld zijn (tot 75%) zonder dat de dieselmotor aanstaat. Dit kan verklaard worden door de aanwezigheid van een start-stop systeem, waarbij de dieselmotor afgeschakeld wordt als de ingestelde temperatuur bereikt is. Een aanvullende mogelijkheid is dat deze koelmachines tijdens het stilstaan aangesloten zijn op het stroomnet. Een aanvullende verklaring van de variatie in actieve uren is mogelijk het type inzet (de mate van koeling/verwarming die nodig is voor de goederen). Op basis van een geanonimiseerde dataset van 850 actieve koelmachines, met informatie over het aantal draaiuren en het bouwjaar, blijkt dat de gemiddelde jaarlijkse draaiuren met een actieve dieselmotor ongeveer 1000 uur bedragen. Dit komt grofweg overeen met de monitoringsdata en komt ook overeen met de huidige inschatting die gebruikt wordt voor de berekening van de landelijke emissietotalen.

[3] https://open.overheid.nl/documenten/dpc-efe48a0d7d708f727b8acf9ddc1c11e360aa3827/pdf
[4] TNO 2024 R11647 - Real-world emissions of temperature-controlled road transport in the Netherlands

Volgens de dataset draaien nieuwere koelmachines doorgaans twee keer zoveel uren per jaar als oudere exemplaren. Ook voor vrachtwagens zelf is het gebruikelijk dat nieuwere voertuigen meer kilometers rijden dan de oudere vrachtwagens.

De gecombineerde gemiddelde NO_x-emissie van de gemonitorde koelmachines bedraagt 36 gram per uur. De gemiddelde CO_2-emissie van de gemonitorde koelmachines is 5,5 kg per uur. In vergelijk met de resultaten uit het tussentijdse rapport, zijn de verschillen klein. Daarbij was de gemiddelde NO_x-emissie circa 39 gram per uur, en de gemiddelde CO_2-emissie is 5,7 kg per uur. De resultaten zijn in lijn met de eerdere meetcampagnes uit 2021 en 2022, maar zijn nu robuuster met gegevens van in totaal acht koelmachines. Op basis van toen geldende inzichten is de gemiddelde emissie van diesel-aangedreven koelmachines destijds geraamd op 100 gram NO_x per uur. Vanuit de metingen kunnen nu meer nauwkeurige inschattingen gemaakt worden en kan geconcludeerd worden dat de inschatting van 100 gram NO_x per uur te hoog is. Op basis van de meetresultaten is de huidige emissiefactor voor NO_x-emissies van koelmachines omlaag bijgesteld naar 39 gram NO_x per uur (de 2024 waarde). Komend jaar wordt bepaald of deze waarde verlaagd moet worden naar 36 gram per uur.

Emissiefactoren zijn kengetallen voor de gemiddelde uitstoot per machine. Deze worden gebruikt om de totale emissie van geconditioneerd transport over de weg in Nederland te schatten. Ten gevolge van deze aanpassingen is de voorgaande inschatting van 4,6 kton per jaar aan NO_x-emissies door koelmachines op de weg verlaagd naar 1,8 kton per jaar (op basis van de 39 gram NO_x per uur). Voor de CO_2-emissies (0,3 Mton per jaar) is er slechts een zeer kleine wijziging ten gevolge van de gemeten uitstoot.

In het kader van de emissieramingen wordt op dit moment nog gesproken over het geschatte aantal koelmachines in Nederland. Toepassing van een alternatieve RDW-classificatie zou in 2025 leiden tot een circa 10% lager geschat aantal voertuigen met een koelmachine (ongeveer 5.000 minder). Dit zou kunnen leiden tot evenredig lagere emissieramingen.

De berekende NO_x-emissies in g/kWh (de eenheid die wordt gehanteerd in de Europese emissiewetgeving) tijdens praktijkomstandigheden blijven onder de typegoedkeurings-limieten voor zowel de Stage IIIA- als de Stage V-koelmachines. De resultaten in g/kWh zijn indicatief omdat het aantal kWh is ingeschat op basis van diverse aannames. De Stage II koelmachine laat NO_x-emissies rondom en hoger dan de limietwaarde zien. Dit is mogelijk het gevolg van een relatief lage motorbelasting die afwijkt van de testcyclus in de emissiewetgeving. De Stage II koelmachine vertoont ook de hoogste emissieniveaus in grammen per uur, wat te verwachten is vanwege de minder strenge emissiegrenswaarden in vergelijking met de Stage IIIA- en Stage V-koelmachines. De gemonitorde Stage V- en Stage IIIA- koelmachines hebben dezelfde emissiegrenswaarden en vertonen vergelijkbare NO_x-emissies, gemiddeld rond de 5,5 g/k[redacted]h. Er zijn echter drie Stage V koelmachines die 15 25% lagere NO_x-emissies laten zien dan het gemiddelde.

In een specifieke meetcampagne is de fijnstofmassa-emissie (PM, Particulate Matter) van één van de Stage V koelmachines onderzocht. De testen zijn uitgevoerd bij vier verschillende motorbelastingen, van maximaal verwarmen en koelen (hoge motorbelasting), tot langzaam koelen/verwarmen rondom de ingestelde temperatuur (lage motorbelasting). Omdat de testen zijn uitgevoerd met een lege trailer, kon de maximale motorbelasting niet bereikt worden.

De resultaten laten zien dat de PM-emissies in gram per uur toenemen met de motorbelasting; van 340 mg/u bij lage motorbelasting (wanneer de ingestelde temperatuur was bereikt) tot 825 mg/u bij hoge motorbelasting.

De emissies per kWh waren relatief constant en bleven met 0,11 g/kWh ruim onder de wettelijke limietwaarde van 0,4 g/kWh. De impact van een koude motorstart was tijdens het meetprogramma minimaal. Omdat de studie slechts metingen aan één koelmachine behelsde voor fijnstof, is dit onvoldoende onderbouwing om de huidige emissiefactor voor fijnstof bij te stellen. Daarmee blijft de totale fijnstof-emissie (PM2,5) door koelmachines op de weg 0,13 kton per jaar.

In vergelijking met moderne Euro VI-vrachtwagens zijn de NO_x-emissies van koelmachines relatief hoog. Bijvoorbeeld, tijdens stadsleveringen met een gemiddelde Euro VI-vrachtwagen is de koelmachine verantwoordelijk voor ongeveer een derde van de totale NO_x-emissies (van koelmachine + vrachtwagen). Sommige Euro VI-vrachtwagens hebben zelfs lagere emissies, waardoor de koelmachine evenveel of zelfs meer NO_x-uitstoot dan de vrachtwagen zelf.

Voor CO_2-emissies is de bijdrage van de koelmachines aan het totaal kleiner dan voor NO_x-emissies, met een ca. 15% bijdrage tijdens rijden in de stad.

Ook voor fijnstof zijn de emissies van koelmachines relatief hoog wanneer deze worden vergeleken met een moderne Euro VI-vrachtwagen. In gram per uur zijn de fijnstof-emissies van de koelmotor vergelijkbaar met die van een gemiddelde Euro VI zware vrachtwagen. De dieselmotor van een vrachtwagen levert echter substantieel meer vermogen tijdens het rijden dan de dieselmotor van een koelmachine. Wanneer de fijnstof-emissies worden beoordeeld in gram per kWh (zoals in de Europese wetgeving gebruikelijk is) zijn deze daarom tien keer hoger dan die van een moderne Euro VI vrachtwagen. De hogere fijnstof-emissieniveaus voor Stage V koelmachines zijn het gevolg van minder strenge emissie-eisen, die geen roetfilter (DPF) vereisen. Dit in tegenstelling tot Euro VI-vrachtwagens die wel uitgerust zijn met roetfilters.

Vanwege de potentiële negatieve gezondheidseffecten van fijnstof en het beperkte inzicht in de fijnstofemissies van koelmotoren, wordt aanbevolen om deze emissies bij meerdere typen koelmachines beter in kaart te brengen.

Summary

In 2023, the Dutch Ministry of Infrastructure and Water Management presented an action plan for enhancing the sustainability of the temperature-controlled transport.[5] In the past, exhaust emissions from transport refrigeration units (TRUs) have only been measured to a limited extent, resulting in limited insight into their contribution to overall emissions. To gain better insight into real-world exhaust gas emissions and the use of TRUs in conditioned road transport, the Ministry of Infrastructure and Water Management asked TNO to conduct research on this topic. This report is an updated version of the interim report of the measurement results which was published in 2024.[6] The report also provides the expected impact of the measurement results on the total emissions caused by TRUs in conditioned road transport in the Netherlands.

This study monitored the CO_2 and NO_x exhaust emissions of eight TRUs while they were used in real-world, everyday operation. The eight TRUs have been monitored 231 to 1787 hours of which two for a complete year, and the other six ranging over the different seasons. Apart from the emissions, this study also provides information on daily run-times.

Six of the eight TRUs have Stage V (the most recent emission class) diesel engines (the other two have Stage II and Stage IIIA diesel engines). Stage V is the most recent emission class for these engines. The emission limits for Stage V TRU engines with an engine power below 19 kW are less stringent than for those with an engine power above 19 kW, for both NO_x and particle emissions. Most of the Stage V TRU engines have an engine power slightly below 19 kW. Below 19 kW no diesel particulate filter (DPF) is needed, also no advanced NO_x-reduction technologies are necessary. Tightening of (European) emissions legislation would be needed to significantly reduce emissions from diesel-powered TRUs in this power category on a large scale.

The average annual usage intensity of the eight monitored TRUs is approximately 900 hours, which only includes usage where the diesel engine is on. This average is based on a total of 2050 days of monitoring data from TRUs in normal operation. However, there is considerable variation in usage intensity between the different TRUs. For some individual TRUs, the number of active hours per day (with the diesel engine on) during the monitoring period varies from less than 1 hour to as much as 24 hours. Part of this variation is explained by the fact that some TRUs are enabled for a significant portion of the time (up to 75%) without the diesel engine running (with no emissions). This can be explained by the presence of a start-stop system, in which the diesel engine is switched off once the set temperature is reached. An additional possibility is that these TRUs are connected to the power grid during stand-still. Another possible explanation of the variation in active hours per day is the type of usage (the level of cooling/heating required for the goods). Based on an anonymized dataset covering 850 active TRUs, which includes information on operating hours and year of manufacture, the average annual runtime with the diesel engine active is approximately 1,000 hours. This is roughly in line with the monitored TRUs and the current assumptions for emission modelling.

[5] https://open.overheid.nl/documenten/dpc-efe48a0d7d708f727b8acf9ddc1c11e360aa3827/pdf
[6] TNO 2024 R11647 - Real-world emissions of temperature-controlled road transport in the Netherlands

According to the dataset, newer TRUs typically operate twice as many hours per year as the older units. Similarly, it is common for newer trucks to cover more kilometers than older trucks.

The average tailpipe NO_x-emission of the eight monitored TRUs is 36 grams per hour, with many of them clustered around this value. The average tailpipe CO_2-emission of these monitored TRUs is 5.5 kg per hour. Compared to the 2024 interim report, the results are roughly the same, which were 39 grams per hour for the NO_x- and 5.7 kg per hour for the CO_2-emissions. Moreover, the results roughly align with the previous measurement campaigns on two TRUs in 2021 and 2022, but are now more robust, with data from eight TRUs in total. Based on the (limited) insights available at the time (before 2024), the average emission from TRUs was estimated at 100 grams of NO_x per hour.

From the measurements, more accurate estimates can now be made, and it can be concluded that the estimate of 100 grams of NO_x per hour is too high. Based on the measurement results, the current emission factor (the value for the average emissions per unit used to estimate the total emissions from conditioned road transport in the Netherlands) for NO_x emissions from TRUs is lowered to 39 grams of NO_x per hour (the 2024 value). It will be discussed if this number will be lowered to 36 grams of NO_x per hour. As a result of these adjustments, the previous estimate of 4.6 kton of annual NO_x-emissions from TRUs on the road will be reduced to 1.8 kton of annual NO_x-emissions. For CO_2-emissions (0.3 Mton annually), there will be only a minor change due to the measured emissions.

In the context of total annual emissions, there is currently an ongoing discussion about the estimated number of TRUs in the Netherlands. If an alternative RDW classification is applied, the estimated number of vehicles equipped with a TRU in 2025 could be 10% lower (approximately 5000 less). This would lead to proportionally lower total emission estimates.

The NO_x emission levels in g/kWh (the unit used in emissions legislation) under real-world conditions remain below the type approval limits (which apply for the formal test procedures) for both Stage IIIA and Stage V TRUs. The results in g/kWh are indicative, as the kilowatt-hours are estimated based on several assumptions. The Stage II TRU shows NO_x emissions around and above the limit. This may be the result of relatively low engine load (engine load refers to the amount of power an engine must produce to meet current demands), which differs from the test cycle in the emissions legislation. The Stage II TRU shows the highest NO_x emission levels in grams per hour, which is to be expected due to the somewhat less stringent emission limits compared to Stage IIIA and Stage V TRUs. The monitored Stage V and Stage IIIA TRUs have the same emission limits and show similar NO_x emissions, averaging around 5.5 g/kWh. However, there are three Stage V TRUs that show 15[redacted]5% lower NO_x-emissions than the average.

In a separate campaign the particle mass (PM) emissions of one Stage V TRU were measured. The tests were conducted under stationary conditions at four different engine load levels, ranging from maximum heating and cooling (high engine load) to slow heating/cooling around the set temperature (low engine load). Since the tests were carried out with an empty trailer, the maximum engine load could not be reached

Results showed that PM emissions in grams per hour increased with engine load, from 340 mg/h at low load (temperature setpoint reached) up to 825 mg/h at high engine load. Emissions per kWh remained relatively constant, staying with 0.11 g/kWh well below the regulatory limit of 0.4 g/kWh. These results are in line with a study performed by the Zero Partnership. The impact of a cold engine start on the PM emissions level was minimal.

As only one TRU has been measured within this study on PM, this is not sufficient to change the current PM emission factor. As a result, the total particulate matter (PM2.5) emissions from TRUs remain at 0.13 kton per year.

Compared to modern Euro VI trucks, the NO_x-emissions from TRUs are relatively high. For example, during city deliveries with an average Euro VI truck, the TRU accounts for approximately one-third of the total NO_x-emissions in refrigerated transport. Several Euro VI trucks have even lower emissions, resulting in the TRU emitting as much, if not more, NO_x than the truck itself.

For CO_2-emissions, the contribution of the TRU to the total is lower than for NO_x-emissions, approximately 15% during city-driving.

Comparisons with an (average) Euro VI heavy-duty (HD) trucks showed that while PM emissions per hour were on a similar level (during the measurement campaign), the TRU emissions per kWh were over ten times higher than the modern truck. This is due to the high PM-emissions in relation to the TRUs lower power output (under 19 kW) compared to HD trucks, which have several hundred kW of engine power available. The higher PM emission levels for Stage V TRUs is the result of non-stringent emission levels, which do not require a diesel particulate filter (DPF), in contrast to Euro VI-trucks which are equipped with DPFs.

Due to the potential negative health effects of particulate matter and the limited data of particulate emissions from TRUs, it is recommended to measure these emissions across various types of refrigeration units.

Contents

1 Introduction

1.1 Background

In the Netherlands, a large share of the 2.1 billion kilograms of goods transported every day are so-called perishables. Examples are fresh food and flowers which must be kept fresh until they reach the consumer, and many pharmaceutical products which must be transported under well-controlled thermal circumstances. In Q1 2025, there are around 50,000 conditioned vehicles registered in the Netherlands. The majority of those vehicles have transport refrigeration units (TRUs) installed to guarantee that cargo can be kept at the required thermal conditions during transport.

Most of the TRUs have diesel engines, which are mostly small, relatively simple (in terms of emission control) and low-powered, which do not fall under a strict regime regarding emissions regulation. While some research has been carried out on the emissions of TRUs in a controlled environment, there have been few investigations into their emissions and usage under real-world conditions. Some first on-road emission measurements on diesel-TRUs, however, indicated that the exhaust emissions of TRUs are still relatively high and have not improved much over the last years [TNO 2021[7] and TNO 2022[8]]. This report is an updated version of the interim report of the measurement results which was published in 2024[9].

Strict emission regulation for road vehicles have had a large effect on real-world tail pipe emissions in recent years. The NO_x emissions of heavy-duty vehicles, for instance, have fallen by 2/3 since 2005. To give an example: under urban conditions, an average Euro VI diesel truck emits around 4 grams of NO_x per km (this value includes ageing effects). At an average speed of 20 km/h in city delivery, the truck would then emit 80 grams of NO_x every hour. Existing (earlier) measurements on several TRUs indicate that they emit around 40 grams of NO_x per hour [1,2,6]. In other words, the cooling machine under these conditions is responsible for around 1/3 of the total NO_x emissions of a temperature-controlled city delivery trip, see Figure 1-1. On the highway, this is about 25% for the same type of vehicle, at 85 km/h. Several Euro VI trucks have even lower emissions, resulting in the TRU emitting as much, if not more, NO_x than the truck itself. Moreover, there is no particulate filter on the monitored TRUs, hence the particulate emissions are expected to be at least 10 times higher than a modern truck, which is further investigated in this research. For CO_2 emissions, the contribution of the TRU to the total is lower than for NO_x, 15% and 8% for city and highway respectively.

[7] R.J. Vermeulen, N.E. Ligterink, P.J. van der Mark, *Real-world emissions of non-road mobile machinery*, TNO 2021 R10221, 11 February 2021

[8] Robin Vermeulen, René van Gijlswijk, Pierre Paschinger, Jessica de Ruiter, *Dutch In-service Emissions Measurement and Monitoring Programme for Heavy-Duty Vehicles 2021*, TNO 2022 R10375, 28 February 2022

[9] TNO 2024 R11647 - Real-world emissions of temperature-controlled road transport in the Netherlands

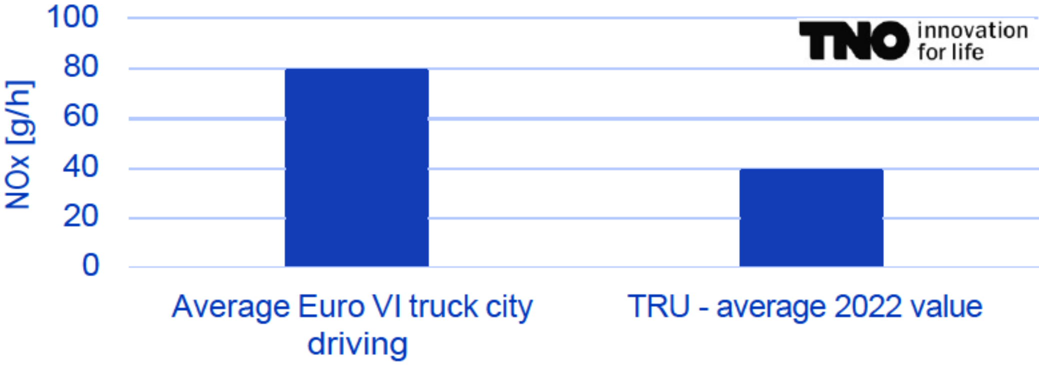


Figure 1-1: A comparison of NO_x-emissions from an average Euro VI diesel truck (accounting for ageing effects) at an average speed of 20 km/h during city deliveries, with the 2021 and 2022 measurement results from two TRUs.

In 2023, the Dutch Ministry of Infrastructure and Water Management presented an action plan for enhancing the sustainability of the temperature-controlled transport.[10] To gain better insight into real-world exhaust gas emissions and the use of transport refrigeration units (TRUs) in conditioned road transport, the Ministry of Infrastructure and Water Management asked TNO to conduct research on this topic.

The report also provides the impact of the measurement results on the total emissions caused by TRUs in conditioned road transport in the Netherlands. The measurement program was continued until the end of 2024.

1.2 Objectives

The objectives of this study are to determine the CO_2 and NO_x emissions of transport refrigeration units under real-world, on-road conditions. Based on this, up-to-date emission factors for temperature-controlled transport are proposed. These emission factors are then used to estimate the total annual NO_x and CO_2 emissions associated to temperature-controlled road transport in the Netherlands. For particle mass (PM) emissions a dedicated measurement is performed on one TRU.

1.3 Approach

Usage and emissions data is collected in a dedicated emissions measurement programme for TRUs. As in most of our emission measurement programmes, TNO asked Dutch transportation companies that provide temperature-controlled transport to collaborate in the programme. If interested, the companies were asked to make available one or more of their vehicles equipped with TRUs. TNO installed an autonomous emissions measurement data collection system called SEMS on the TRU of eight trucks. With SEMS, the NO_x- and CO_2-emissions can be determined. After installation of the TNO equipment, the transport companies used the vehicles in everyday operations. This way, TNO is able to gather emission data for multiple months. The real-world emission- and usage data is used to determine evidence-based emission factors. The emission factors are used to estimate the total emissions from conditioned road transport in the Netherlands.

[10] Plan van aanpak voor de verduurzaming van geconditioneerd transport | Rapport | Rijksoverheid.nl

Next to the monitoring of NO_x- and CO_2-emissions, particle mass (PM) emissions were measured in a dedicated measurement campaign on one TRU.

In addition to the measurement programme, TNO requested operational data from telematics systems (data from the TRU that is accessible online to the owner). Furthermore, TNO conducted multiple interviews with TRU suppliers to gather additional insights into operational characteristics and potential emission reduction measures.

1.4 Reader's guide

This report is structured as follows. First, chapter 2 will provide information on the way TRUs are registered in the Netherlands, on how their emissions are regulated and on the now available studies into their emissions, moreover emission reduction options are discussed. Chapter 3 will then describe which TRUs formed part of this project and the way in which the measurements were carried out. Results of the measurements are presented in chapter 4. Using these results, chapter 5 will assess the total NO_x and CO_2 emissions associated with temperature-controlled transport in the Netherlands. Conclusions and recommendations can be found in chapter 6.

1.5 Acknowledgements

As stated in section 1.3, the success of this study for a significant part lies in the willingness of transport companies to participate and the cooperation of TRU manufacturers. TNO wishes to thank Cornelissen, I&L Logistiek, Jansen Logistics and Euser for making available TRU-equipped vehicles for our measurements. Also, Carrier and Thermoking have been of great help in setting up contacts between TNO and several transport companies and in providing technical details during the measurement programme.

2 Background information

2.1 Registrations of refrigerated trucks

In the Netherlands all road vehicles with a license plate are registered by the Netherlands Vehicle Authority (RDW). The RDW does register conditioned transport, but no information about the TRU itself is registered. Details with regard to type of TRU, fuel type, Stage class and engine power would make the emission calculations on a national scale more accurate. At the moment of writing the report (Q2 2025) there are, based on data from Statistics Netherlands (CBS), around 50,000 conditioned vehicles registered of which:

- ~33,500 semi-trailers
- ~8,500 trucks
- ~3,300 trailers
- ~5,000 vans

The number of total estimated vehicles equipped with a TRU could be approximately 5,000 lower in 2025 if an alternative RDW classification is applied. There is ongoing discussion about whether this lower figure should be adopted.

2.2 Emission regulation of TRU engines

Engines of TRUs as fitted to vans, trucks and trailers fall under the so-called non-road mobile machinery (NRMM) as far as EU emission legislation is concerned. Emissions of refrigeration units' diesel engines must comply with the EU NRMM Regulation 2016/1628[11]. Table 2-1 and Table 2-2 show the emission limits for NO_x and particle emissions, respectively (for the TRU relevant classes only).

As observed in the field, most of the modern TRU diesel engines fall in the <19kW category (there is no registration available). As the tables show, until the introduction of the most recent Stage V legislation, no emission limits were imposed for such engines. The Stage V requirements are rather mild and can easily be met without emission control systems (like a particulate filter and an SCR-catalyst for NO_x-reduction).

Table 2-1: Overview of NO_x limits for non-road diesel engines, the table only shows the most common categories for the TRU diesel engines.

Emission class	P < 19 kW	18/19 ≤ P < 37 kW
Stage I	n/a	n/a
Stage II	n/a	8.0 g/kWh
Stage IIIA	n/a	7.5* g/kWh
Stage IIIB	n/a	n/a

[11] Regulation (EU) 2016/1628 of 14 September 2016", Official Journal of the European Union, L 252, 53-117, http://data.europa.eu/eli/reg/2016/1628/oj

Stage IV	n/a	n/a
Stage V	7.5* g/kWh	4.7* g/kWh
*The limit applies for HC+NO_x		

Table 2-2: Overview of Particulate Matter and Particle Number limits for non-road diesel engines, the table only shows the most common categories for the TRU diesel engines..

Emission class	P < 19 kW	18/19 ≤ P < 37 kW
Stage I	n/a	n/a
Stage II	n/a	0.8 g/kWh
Stage IIIA	n/a	0.6 g/kWh
Stage IIIB	n/a	n/a
Stage IV	n/a	n/a
Stage V	0.4 g/kWh	0.015 g/kWh *
*An additional limit applies for Particle Number emissions of $1x10^{12}$ #/kWh		

2.3 Available data on TRU emissions

As stated in the introduction not many studies into the emissions of TRUs exist.

In the United Kingdom, the Zemo Partnership performed a series of studies into the emissions of TRUs. Emissions were measured under well-controlled, *lab* conditions. In the study "*HGV Auxiliary Engines: Baseline auxTRU testing and modelling of UK impacts*" it was concluded that UK diesel auxTRUs consume around 235 million liters of fuel per annum (uncertainty margin is +/-100 million litres, because low number auxTRUs+low run hours versus high number+high hours)[12]. This leads to a contribution of about 590 kilo-tonnes of tailpipe GHG emissions, 4.4 kilo-tonnes of NO_x emissions and 126 tonnes of $PM_{2.5}$ particulate mass emissions. Annex A provides a short summary of the two Zemo partnership studies.

TNO conducted some first *real-world* measurements for the Ministry of Infrastructure and Water management on two TRUs in real operation, in 2021 and 2022. Annex B provides a short summary of these studies[13, 14]. The emissions found in both studies were at a comparable level.

2.4 Options for emission reduction

As mentioned in paragraph 1.3, TNO conducted multiple interviews with TRU suppliers to gather additional insights into [redacted] amongst others - emission reduction measures. The results are summarized below.

[12] HGV Auxiliary Engines: Baseline auxTRU testing and modelling of UK impacts, February 2024: https://www.zemo.org.uk/assets/reports/HGV%20Auxiliary%20Engines%20Report%202024%20-%20Zemo%20Partnership.pdf

[13] R.J. Vermeulen, N.E. Ligterink, P.J. van der Mark, *Real-world emissions of non-road mobile machinery*, TNO 2021 R10221, 11 February 2021

[14] Robin Vermeulen, René van Gijlswijk, Pierre Paschinger, Jessica de Ruiter, *Dutch In-service Emissions Measurement and Monitoring Programme for Heavy-Duty Vehicles 2021*, TNO 2022 R10375, 28 February 2022

2.4.1 Hybrid system

Most TRUs on trucks in the Netherlands are conventional hybrid systems, a technology that has been available and in use for over 20 years. For smaller light commercial vehicles, the TRU is always powered by the vehicle itself, not by a stand-alone diesel engine. Hybrid systems use - depending on the type - power from a small autonomous diesel engine, or shore power to electrically propel the cooling (or heating) system. TRUs with their own diesel engine have the merit, that in case of parking or standing still of the vehicle, the TRU can operate fully independently of the vehicle or an external power supply. Hybrid systems have the additional advantage of plugging-in to shore power so that the diesel engine can be shut-off.

When cooling (or heating) is initiated (pull-down), it consumes significantly more energy than maintaining a steady temperature. Using shore power during this start-up phase can lead to substantial energy savings and emission reductions.

One of the current barriers to broader use of shore power is the lack of electrical grid connections at some loading and unloading locations.

2.4.2 Start-stop functionality

Start-stop systems have been the standard across several generations of TRUs. In these systems, the diesel engine shuts off once the set temperature is reached and restarts only when the temperature moves outside a predefined range. The allowable temperature margin for restarting depends on the type of cargo. For highly temperature-sensitive goods, such as certain pharmaceuticals or meat, the start-stop functionality is sometimes disabled to ensure tighter temperature control.

2.4.3 Electric TRUs

In recent years, zero-emission (ZE) Transport Refrigeration Units (TRUs) have become increasingly available. For trailer-based ZE TRUs, power can be supplied from several sources.

One option is to install a battery pack on the trailer, with various sizes available depending on the required operating autonomy. Another approach combines a battery pack with an energy recovery system integrated into the trailer axle. In this setup, braking energy is recuperated and stored in the battery to power the TRU. However, a key barrier to adoption is that this type of trailer has not yet been approved for use on public roads in the Netherlands.

Another option is to draw power from the main vehicle engine via a Power Take-Off (PTO) system. This can be an option for conventional (diesel-powered) trucks, preferably with a Euro VI diesel engine (note that this is not ZE).

For rigid electric trucks, there is an additional advantage: the TRU can be powered directly from the vehicle's main battery, eliminating the need for a separate power source.

Despite growing interest and development in fully electric TRUs, the majority still depend on a diesel engine for power, often in combination with shore power. The ZE-options are more expensive than the hybrid systems. A driver for ZE-TRUs are the zero-emission zones.

2.4.4 Diesel particulate filters

Since the implementation of Stage V emission standards for non-road mobile machinery — which includes diesel engines for TRUs— diesel engines with a power output above 19 kW are required to be equipped with a diesel particulate filter (DPF). Prior to Stage V, TRUs with diesel engines exceeding 19 kW were available on the market. However, since the Stage V regulation came into effect, TRUs with diesel engines above this threshold are no longer available in the Netherlands (to the best of TNO's knowledge). This is likely due to the additional space required for a DPF, which can reduce the available loading capacity of the truck or trailer, making such configurations less practical for operators. Moreover, with a DPF there are risks on more maintenance than without a DPF and the costs for a TRU would increase.

3 Measurement programme

3.1 Vehicles and cooling units measured

In total eight TRUs have been monitored with emission measurement equipment during normal daily operation by the transport company. These eight TRUs include the two TRUs which were measured in 2021 and 2022 (Thermoking SLXi Spectrum & Mitsubishi TU100SAE-CNE).[15, 16] All TRUs have a (small) diesel engine without advanced emission reduction technology. Three different brands are measured, with two of them being predominant among the participating TRUs. A market analysis will be necessary to assess the representativeness of these TRUs, including their market share and the sectors in which they operate.

Table 3-1 shows the name, ID, engine manufacturer, emission class, rated power and typeof vehicle of each TRU. These machines were monitored over a long period of time to cover seasonal effects and to get a good insight of the real-world operations. The TRUs were measured in normal operating conditions and cover different types of trips and all available modes: chilled mode, frozen mode and multi-temp mode.

Table 3-1: Details of the monitored cooling units.

Cooling unit	TRU ID	Engine	Fuel	Emission class	Rated Power [kW]	Configuration/ type of vehicle
Thermoking SLXi Spectrum	TH_SPEC_STAIID	Yanmar	Diesel	Stage II	25.3	Cooling unit on semi-trailer
Mitsubishi TU100SAE-CNE	MI_TU_STAIIIA	Yanmar	Diesel	Stage IIIA	19.9	Cooling unit under body
Thermoking SLXi 300 Whisper Pro	TH_300_STAV	Yanmar	Diesel	Stage V	17.9	Cooling unit on semi-trailer
Carrier Vector 1550 City	CA_1550_STAV	Kubota	Diesel	Stage V	16.5	Cooling unit on semi-trailer
Carrier Supra 1150 MT	CA_SUP01_STAV	Kubota	Diesel	Stage V	9	Cooling unit on rigid body
Carrier Supra 1150 MT	CA_SU_STAV	Kubota	Diesel	Stage V	9	Cooling unit on trailer
Thermoking Advancer A500	TH_A500_STAV	Yanmar	Diesel	Stage V	18.9	Cooling unit on semi-trailer
Carrier Vector HE19	CA_VEHE19_STAV	Kubota	Diesel	Stage V	18.2	Cooling unit on semi-trailer

[15] R.J. Vermeulen, N.E. Ligterink, P.J. van der Mark, *Real-world emissions of non-road mobile machinery*, TNO 2021 R10221, 11 February 2021

[16] Robin Vermeulen, René van Gijlswijk, Pierre Paschinger, Jessica de Ruiter, *Dutch In-service Emissions Measurement and Monitoring Programme for Heavy-Duty Vehicles 2021*, TNO 2022 R10375, 28 February 2022

3.2 Measurement equipment and data collection

3.2.1 SEMS

For real-time monitoring, this project uses TNO's Smart Emissions Measurement System (SEMS)[17]. SEMS is a relatively easy-to-install and compact sensor-based system, which is able to measure and record actual NO_x-concentration and O_2 and derive the CO_2-concentration from the TRUs tailpipe.

Because SEMS is compact and requires no user interaction, the TRU and its vehicle can be used normally during monitoring without the driver noticing. This allows for extended measurement periods, enabling the collection of large amounts of real-world data. If possible, SEMS is connected to the 'CANbus' to obtain digital machine data. To process the measured concentrations (ppm) to mass (grams), in addition to the NO_x-sensor, a Mass Air Flow (MAF) sensor is installed and connected to SEMS. The MAF-sensor measures the intake flow, which allows for the calculation of the exhaust gas flow and mass emissions. SEMS is also equipped with an integrated GPS sensor and GSM 4G connectivity. The system sends the collected data to a TNO database several times a day. The instrument remains in the machine/vehicle for several months.

3.2.2 Telematics

TRUs are often connected to a telematics system (data from the TRU which is available online for the TRU owner (often a transport company), which is used by the owners to monitor their status. The available telematics show, amongst other things, data of the temperatures, operating hours and operating mode. As shown in Table 3-2, data of six of the monitored machines was made available. In addition, the participants provided data of one other TRU on a trailer. The current available telematics data shows that data is logged at an irregular basis and at a lower frequency than TNOs SEMS (1Hz), which makes it sometimes less suitable for detailed analysis. It is therefore important to know the exact specification of the way in which telematics logging is implemented (for instance event-triggered or by taking random samples of parameters).

Table 3-2: Availability of telematics per (monitored) TRU.

Cooling unit	TRU ID	Telematics data availability
Thermoking SLXi Spectrum	TH_SPEC_STAIID	-
Mitsubishi TU100SAE-CNE	MI_TU_STAIIIA	-
Thermoking SLXi 300 Whisper Pro	TH_300_STAV	Data from 28-8-2023 to 1-1-2024
Carrier Vector 1550 City	CA_1550_STAV	Data from 28-7-2023 to 19-2-2024.
Carrier Supra 1150 MT	CA_SUP01_STAV	Data from 7-4-2024 to 6-5-2024.
Carrier Supra 1150 MT	CA_SU_STAV	Data from 7-4-2024 to 6-5-2024.
Thermoking Advancer A500	TH_A500_STAV	insufficiënt data
Carrier Vector HE19	CA_VEHE19_STAV	Data from 21-01-2024 to 14-1-2025

[17] https://www.youtube.com/watch?v=0mSbkR2GCw4

3.3 Data analysis

For data analysis it is preferred to have a comprehensive dataset that captures the relevant conditions as much as possible. Therefore, the 1Hz measurement data from the SEMS is, in some cases, combined with telematics data from the TRUs. Since the telematics data is not available in 1Hz, the missing data is filled by propagating the last valid value forward. Next, the data is enriched with solar radiation- and ambient temperature data from the nearest KNMI weather station, in order to provide insights in the effect of relevant weather conditions on the exhaust emissions. Also, based on the GPS coordinates, all data is enriched with the road type from the Open Source Routing Machine (OSRM). By doing so, the type of trip can be determined and gives insight in where the emissions took place.

4 Results: operations and emissions of transport refrigeration units

In this chapter, the monitoring results up to January 2025 are described. The results of the two TRUs measured in 2021 and 2022 are included as well to get an complete overview. First an overview is provided of the operational characteristics, like the monitoring period, running hours and weather conditions. Then, the NO_x and CO_2 emission results are shown.

4.1 Operational characteristics

The eight TRUs have been monitored 231 to 1787 hours of which two for a complete year, and the other six ranging over the different seasons.

Table 4-1 below shows the start- and end date of the monitoring, the cumulative monitoring hours and the hours that the diesel engine was running while the TRU was on. Also, it shows for each TRU the average vehicle speed (including standing still), average ambient temperature and average solar radiation during the monitoring period. The total duration including diesel engine off (TRU cools by using an external source, or is using start-stop), represents all the data that was captured with the SEMS.

Table 4.1 shows that most of TRUs are cooled via an external source or using the start-stop system for a significant share of time (up to 76%). The first TRU in the table (TH_SPEC_STAIID) only has data of a running engine. This does not necessarily mean that the TRU was not cooling while the diesel engine was turned off. It's possible that the moments of the TRU operating with diesel engine off (while getting power via an external source), is not captured by SEMS. An example of this is shown in Figure 4-1, where the 'portal.switchOnHours' (based on the telematics data) significantly deviates from the 'SEMS cumulative hours'.

Tabel 4.1 also shows that the average ambient temperature during the monitoring period of most of the TRUs is between 11 and 16 °C. The second TRU (MI_TU_STAIIIA) covers the coldest ambient temperatures and the least solar radiation. The TRUs with the highest solar radiation have been monitored between spring/summer up to the beginning of the winter.

A short analysis on the impact of ambient temperature and the "share of running diesel engine [%]", does not show a clear trend for most of the machines. Possibly because of other impacts, like the type of cargo (needed set temperature) and the number of door openings. A more detailed analysis is needed to provide better insights in the effect of ambient conditions.

Figure 4-2 shows (as an example) the operation per active calendar day for the TH_500_STAV (Thermoking Advancer A500), the figure includes total hours per day, the share of hours with the diesel engine on and the driven travelled by the vehicle where the TRU is installed on. Figure 4-2 clearly shows the variation in operation over the monitoring period. The hours active vary between less than 1 hour up to 15 hours, and the share with engine on varies between 0 and 100%. These data are also shown for the other TRUs in Appendix C.

Data from telematic systems was requested from the participants, a detailed analysis on the telematics data of a few machines is presented in the next paragraph. Moreover, in chapter 5.2.2. an overview of operating hours in relation to the year of manufacture for approximately 850 active TRUs across multiple transport companies is given.

Table 4-1: Operational characteristics of the monitored cooling units, based on SEMS.

Cooling unit	TRU ID	Startdate	Enddate	Duration_ diesel engine on [h]	Duration total_incl. diesel engine_off [h]	Share of running diesel engine [%]	Vehicle speed [km/h]	T_ambient [degC] mean	Q_sun [J/cm²] mean
Thermoking SLXi Spectrum	TH_SPEC_ STAIID	17-12-2019	6-7-2020	1787	1787	100	42	-	-
Mitsubishi TU100SAE-CNE	MI_TU_ST AIIIA	1-11-2021	9-5-2022	229	231	99	38	4	4
Thermoking SLXi 300 Whisper Pro	TH_300_S TAV	31-8-2023	14-9-2024	359	1.208	30	27	13	48
Carrier Vector 1550 City	CA_1550_ STAV	26-7-2023	17-9-2024	597	814	73	36	12	58
Carrier Supra 1150 MT	CA_SUP01 _STAV	8-4-2024	9-1-2025	366	738	50	33	14	67
Carrier Supra 1150 MT	CA_SU_ST AV	8-4-2024	9-1-2025	240	716	34	30	11	37
Thermoking Advancer A500	TH_A500_ STAV	28-5-2024	20-11-2024	120	505	24	36	16	56
Carrier Vector HE19	CA_VEHE 19_STAV	12-6-2024	14-1-2025	594	855	69	31	14	76

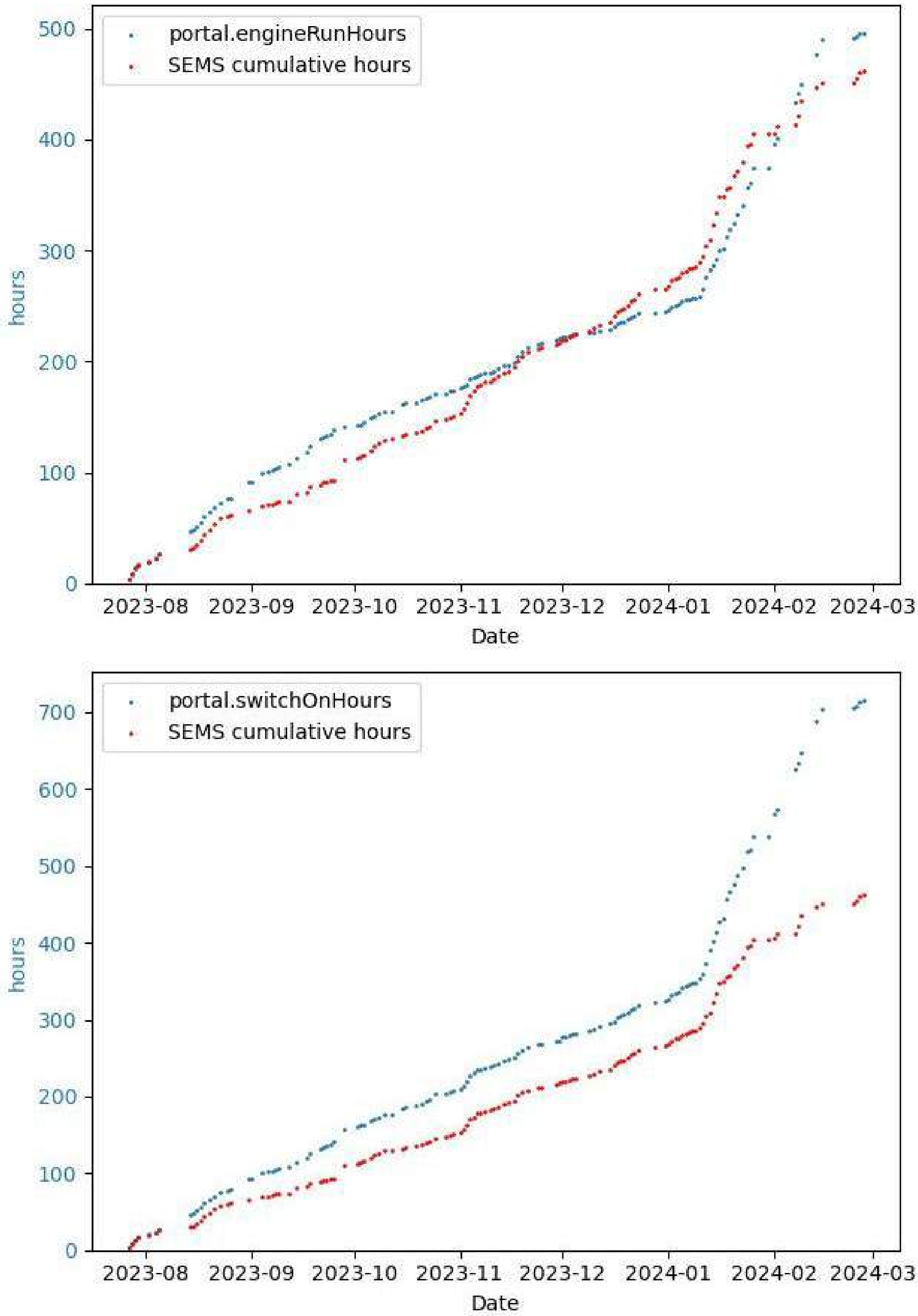


Figure 4-1: Example of cumulative operating hours of the CA_1550_STAV (Carrier Vector 1550 City) from the start of the measurement campaign. The telematics data reports similar hours with a running diesel engine. For this TRU the SEMS does not log all active TRU hours while the diesel engine is off.

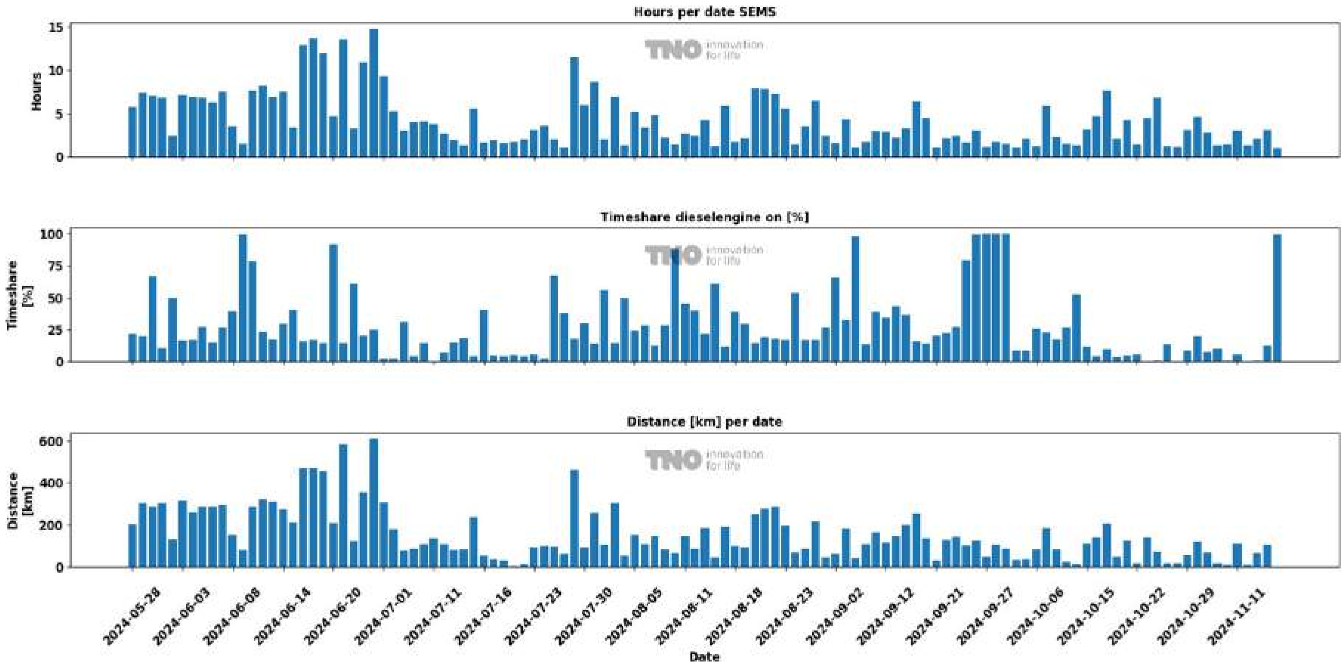


Figure 4-2: Example of operation per active calendar day for the TH_500_STAV (Thermoking Advancer A500).

4.1.1 Data-analysis on telematics data

In this study, data from seven different vehicles equipped with a TRU were analyzed.

The TRU IDs are as follows: [18]

- CA_1550__STAV
- CA_SU_ STAV
- CA_SUP01_STAV
- CA_VEHE19_STAV
- TH_300_STAV
- TH_A500 _STAV
- Other_1

For each TRU, the following topics were determined:

1. The number of hours the TRU was turned on.
2. The number of hours the TRU was powered by the engine or plugged in.
3. The fraction of time the vehicle was driving or stationary when the TRU was powered by the engine or plugged in.

Before the results were derived, the data was filtered. Due to incomplete data coverage for a full year for most vehicles and due to gaps in the data, the available data is not representative for a full year. A more representative data set on operational hours per year is given in paragraph 5.2.2. Moreover, due to the gaps in the data, the absolute hours are uncertain.
Therefore, this analysis is mainly relevant for the distinction between diesel engine on/off (when TRU is on) and if the vehicle was driving or stationary. The time period of the dataset deviates from the time period of SEMS monitoring.

[18] See Table 3-1 for specifications of these TRUs.

Specific considerations:

- For TRU TH_300_STAV and TH_A500_STAV, there was no information about the driving/stationary status.
- For the TRUs CA_SU_ STAV and CA_SUP01_STAV, although the data spanned over 100 days, detailed information about the TRUs status (on/off) and power mode (engine/plugged-in) was only available for the first ~30 days. Therefore, only these initial 30 days were considered for the analysis.

Table 4-2 presents operational data from the various TRUs on vehicles. The table is focusing on two specific performance metrics over different monitoring periods. “Δt” indicates the period where data collection for each TRU took place (including TRU off). “TRU on, diesel engine off [%]” shows the percentage of time the TRU operated while the diesel engine was off—highlighting quiet and zero-emission operation. Due to the variety in data-labelling t was, however, not always clear if both the impact of start-stop and an external power supply (plugged-in) is included. “TRU on, vehicle stationary [%]” reflects the percentage of TRU operation time during which the vehicle was stationary —relevant for assessing the potential for using an external power supply (electricity).

CA_1550_STAV has data for 206 days, with the TRU running 30% of the time while the diesel engine was off, and 48% of the time while the vehicle was stationary. CA_SU_STAV and CA_SUP01_STAV each showed 19% TRU operation with the engine off, and over 60% TRU operation while stationary, over 28-day periods. CA_VEHE19_STAV had the longest monitoring duration (359 days) but showed very low TRU activity with the engine off (1%) and a moderate stationary percentage (24%). Other_1 had the highest percentage of TRU operation with the engine off (47%) and 59% stationary TRU operation over 392 days. TH_300_STAV showed a relatively high 27% TRU operation with the engine off over 125 days, though stationary data was not available. The highest TRU operation with engine off was the TH_A500_STAV, with 68% of the time.

This analysis provides valuable insights into the operational patterns of TRUs in different (diesel-powered) vehicles, which can be used to optimize their usage and improve efficiency. A substantial portion of TRU operation occurs while vehicles are stationary, especially in several cases where this exceeds 60%, further highlighting the opportunity to reduce emissions by using external electric power during these periods.

Table 4-2: Summary of the results for all TRUs, where Δt corresponds to the difference between the start date and the end date.

Vehicle / TRU	Δt [# days]	TRU on, diesel engine off [%] (remaining part is TRU on with diesel engine on).	TRU on, diesel engine on, vehicle stationary [%] (remaining part is a driving vehicle with TRU on and diesel engine on).
CA_1550_STAV	206	30%	48%
CA_SU_ STAV	28	19%*	63%
CA_SUP01_STAV	28	19%*	64%
CA_VEHE19_STAV	359	1%*	24%
Other_1	392	47%	59%
TH_300_STAV	125	27%*	n/a
TH_A500_STAV	87	68%	n/a

** This might be an underestimation because of uncertainty about the meaning of data-labelling and gaps in the data.*

4.2 Emissions

4.2.1 Diesel TRUs

For each measured TRU, the cumulative emissions and the average emissions per hour for NO_x and CO_2 are shown in Table 4-3. Cumulative emissions deviate significantly from each other since TRUs are monitored for different durations. Moreover, some TRUs demand a higher engine load (engine load refers to the amount of power an engine must produce to meet current demands), which increases the fuel consumption and absolute NO_x and CO_2 emissions. To compare the emission levels of the different TRUs, the NO_x/CO_2 ratio may be used as the CO_2 emissions are a good proxy for engine load.

Based on the SEMS data provided by the installed NO_x sensor, the NO_x/CO_2 ratio can be calculated. The calculation method is very simple, as it only requires dividing the NO_x concentrations by the CO_2 concentrations, without the need for any other signals. For example, at a NO_x-concentration of 300 ppm and a CO_2-concentration of 5%, the NO_x/CO_2-ratio is 60 ppm/%. The NO_x/CO_2 ratio clearly shows the distinction in emission levels in Table 4-3. The Stage II TRU (TH_SPEC_STAIID) shows the highest emission levels as NO_x/CO_2, which may be expected due to a less stringent emission limit in comparison to the Stage IIIA and Stage V TRUs (see Table 4-4). The monitored Stage V and Stage IIIA TRUs have the same emission limits. Table 4-3 shows that the NO_x/CO_2-ratio of the monitored Stage V and Stage IIIA TRUs are of the same order of magnitude. However, there are four TRUs which show lower emissions than the rest with ppm/% values below 60.

Figure 4-3 shows the operation per active calendar day for the TH_300_STAV (Thermoking SLXi 300 Whisper Pro), the figure includes the CO_2 percentage (a proxy for engine load) and the NO_x/CO_2 ratio. The figure shows a fairly constant engine load and relatively low variation per day in emission performance. Typically, the days with a higher engine load, show somewhat lower emissions in terms of NO_x/CO_2.

Table 4-3: Running hours, CO_2- and NO_x-emissions in total kilograms and the NO_x/CO_2 ratio [ppm/%] of the monitored cooling units.

Cooling unit	TRU ID [19]	Duration diesel engine on [h]	Total CO_2 [t]	Total NO_x [kg]	Average NO_x/CO_2 [ppm/%]	Estimated average engine load [%]
Thermoking SLXi Spectrum	TH_SPEC_STAIID	1787	10.6	92	90	22-28%
Mitsubishi TU100SAE-CNE	MI_TU_STAIIIA	229	0.75	6.1	83	15-21%
Thermoking SLXi 300 Whisper Pro	TH_300_STAV	359	2.9	14.3	53	50-60%
Carrier Vector 1550 City	CA_1550_STAV	597	3.3	26	79	40-45%
Carrier Supra 1150 MT	CA_SUP01_STAV	366	2.0	11.4	58	70-80%
Carrier Supra 1150 MT	CA_SU_STAV	240	1.4	8	58	75-85%
Thermoking Advancer A500	TH_A500_STAV	120	0.5	4	81	25-30%
Carrier Vector HE19	CA_VEHE19_STAV	594	4.2	22.7	55	45-50%

Figure 4-3: CO_2 and NO_x/CO_2 emissions per active calendar day for the TH_300_STAV.

Table 4-4 below show the emission levels of each TRU in a different way than above. At firsta comparison is made with the applicable EU NRMM NO_x emission limits for type approval (see Table 2-1), which is given in grams per kWh. The emission limit applies for specific type approval test procedures which contain test cycles at specific engine load points with a certain weighting at which the engines are to be tested, whereas during emission monitoring in this study, all real world engine operation is taken into account. The results in g/kWh are indicative, as the kilowatt-hours are estimated based on the MAF-sensor and several assumptions about fuel-efficiency and the air-fuel-ratio. Engine data, like engine-torque, engine speed and/or fuel rate would make the calculation more accurate but are not available on these engines. Due to these uncertainties, the results in g/kWh are indicatively given as an uncertainty range.

[19] See Table 3-1 for specifications of these TRUs.

The TH_SPEC_STAIID (Thermoking SLXi Spectrum) shows NO_x-emissions slightly below the emission limit at the lower end of the uncertainty range and exceeds the emission limit at the higher end of the range. The average engine load is relatively low (22-28%), which may play a part in this. At low engine load relatively little work (kWh) is produced, resulting in a high work specific emission. For a type approval test, the weighted engine load is higher.
It means that when an engine is running in the real-world at low engine loads, this can result in higher work-specific emissions, sometimes even higher than the applicable limit that accounts for the test cycle. This possible exceedance was already noted in the previous study of 2021.[1] The calculated real-world NO_x- emissions of all the other TRUs stay below the levels of the type approval limits for both the Stage IIIA and Stage V TRUs.

Secondly, the results are given in grams per hour. This is a relevant parameter to calculate total emissions, per day or per year, if the running hours are known. These numbers are also part of the basis for the calculation of the total annual emissions on a fleet level. The grams per hour of NO_x depends on the operation. A higher engine load will increase the NO_x and CO_2-emissions in grams per hour, which is a normal trend for the kind of diesel engines without emissions control system as applied in the monitored TRUs. For example, the Stage IIIA and some Stage V TRUs have comparable specific emissions (g/kWh or NO_x/CO_2-ratio), however the Stage IIIA TRU clearly shows the lowest NO_x-emission in grams per hour. The cause of this difference may be found in the operational-use, as the CO_2 in grams per hour is significantly lower than the other TRUs. The average NO_x emissions of the monitored TRUs are 36 grams per hour, with many of them clustering around this value.

Table 4-4: Specific emission results of the monitored cooling units in grams per hour and in grams per kWh. The limit value (NO_x in grams per kWh) according to European legislation is also indicated. The emission test for which this limit value applies differs from real-world operation. The results are based on diesel engine-on data only. The results in g/kWh are indicative and therefore given as an uncertainty range.

Cooling unit	TRU ID	$HC+NO_x$ Emission limit [g/kWh]	Average NO_x [g/kWh]	Average CO_2 [kg/h]	Average NO_x [g/h]
Thermoking SLXi Spectrum	TH_SPEC_STAIID	8*	7.8 – 9.5	5.9	52
Mitsubishi TU100SAE-CNE	MI_TU_STAIIIA	7.5	6.4 – 7.3	3.3	26
Thermoking SLXi 300 Whisper Pro	TH_300_STAV	7.5	3.7 – 4.3	8.2	40
Carrier Vector 1550 City	CA_1550_STAV	7.5	5.9 – 6.9	5.5	43
Carrier Supra 1150 MT	CA_SUP01_STAV	7.5	4.4 – 5.1	5.4	31
Carrier Supra 1150 MT	CA_SU_STAV	7.5	4.4 – 5.1	5.8	33
Thermoking Advancer A500	TH_A500_STAV	7.5	6.0 – 7.0	4.2	33
Carrier Vector HE19	CA_VEHE19_STAV	7.5	4.0 – 4.7	7.1	38

*Stage II does not have a combined limit for NO_x and HC. The limit for NO_x is 8.0 [g/kWh]

As mentioned before, the concentration of CO_2 is correlated with engine load. Figure 4-4 shows for the TH_A500_STAV (Advancer A500) the NO_x per CO_2 [ppm/%] and timeshare of operation as a function of the CO_2 concentration, or engine load. It is shown that the NO_x per CO_2 [ppm/%] is a little lower at higher engine loads.

The figure also shows that this TRU operates at low engine load for more than half of the time. The same graph is given for the TH_300_STAV (Thermoking SLXi 300 Whisper Pro) in Figure 4-5. For the Stage V TRU it is shown more clearly that a higher engine load leads to a lower emissions in terms of NO_x/CO_2. This trend is consistent for all Stage V TRUs, although the effect is most pronounced in the TH_300_STAV.

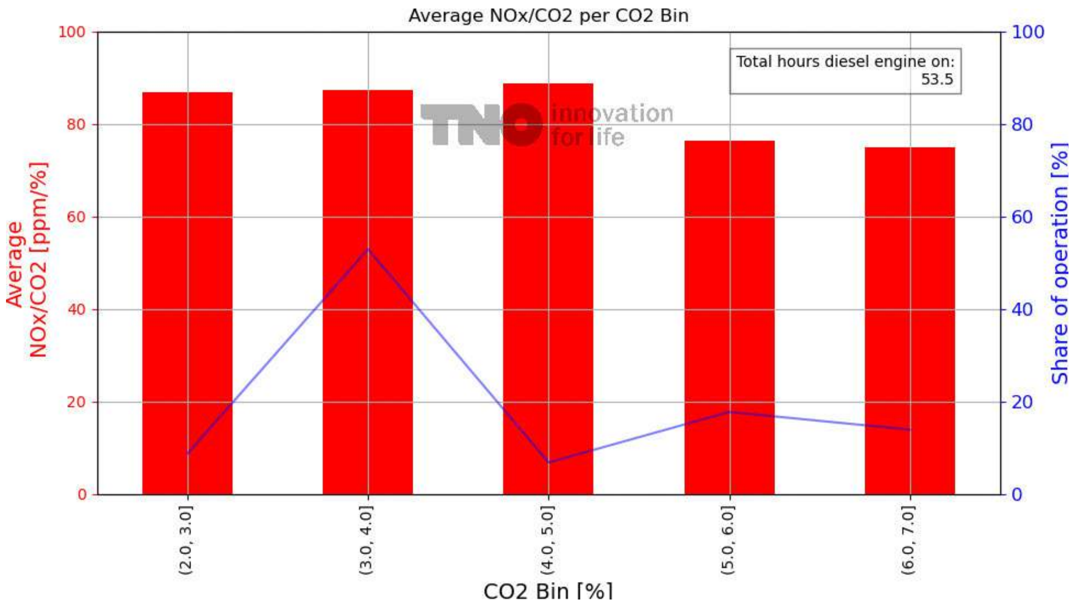


Figure 4-4: The average NO_x per CO_2 [ppm/%] of the TH_A500_STAV (Thermoking Advancer A500) as a function of the CO_2 [%] concentration and the share of operation within each CO_2 bin.

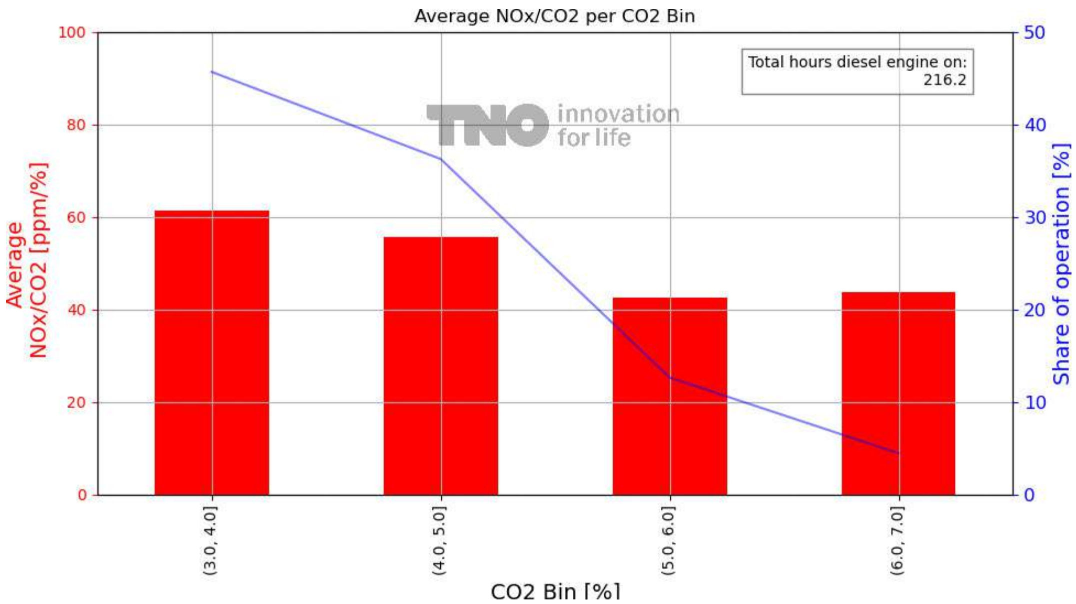


Figure 4-5: The average NO_x per CO_2 [ppm/%] of the TH_300_STAV (Thermoking SLXi 300 Whisper Pro) as a function of the CO_2 [%] concentration and the share of operation within each CO_2 bin.

Figure 4-6 shows the overview of daily averages for the TH_A500_STAV (Thermoking Advancer A500), in which the variation in operational hours, percentage of diesel engine switched on, absolute emissions and ambient temperatures is visible.

Similar daily overviews of the other machines measured in 2023 and 2024 can be found nAnnex C. Significant variations in daily absolute emissions have been observed, and the underlying causes of these fluctuations are being further investigated.

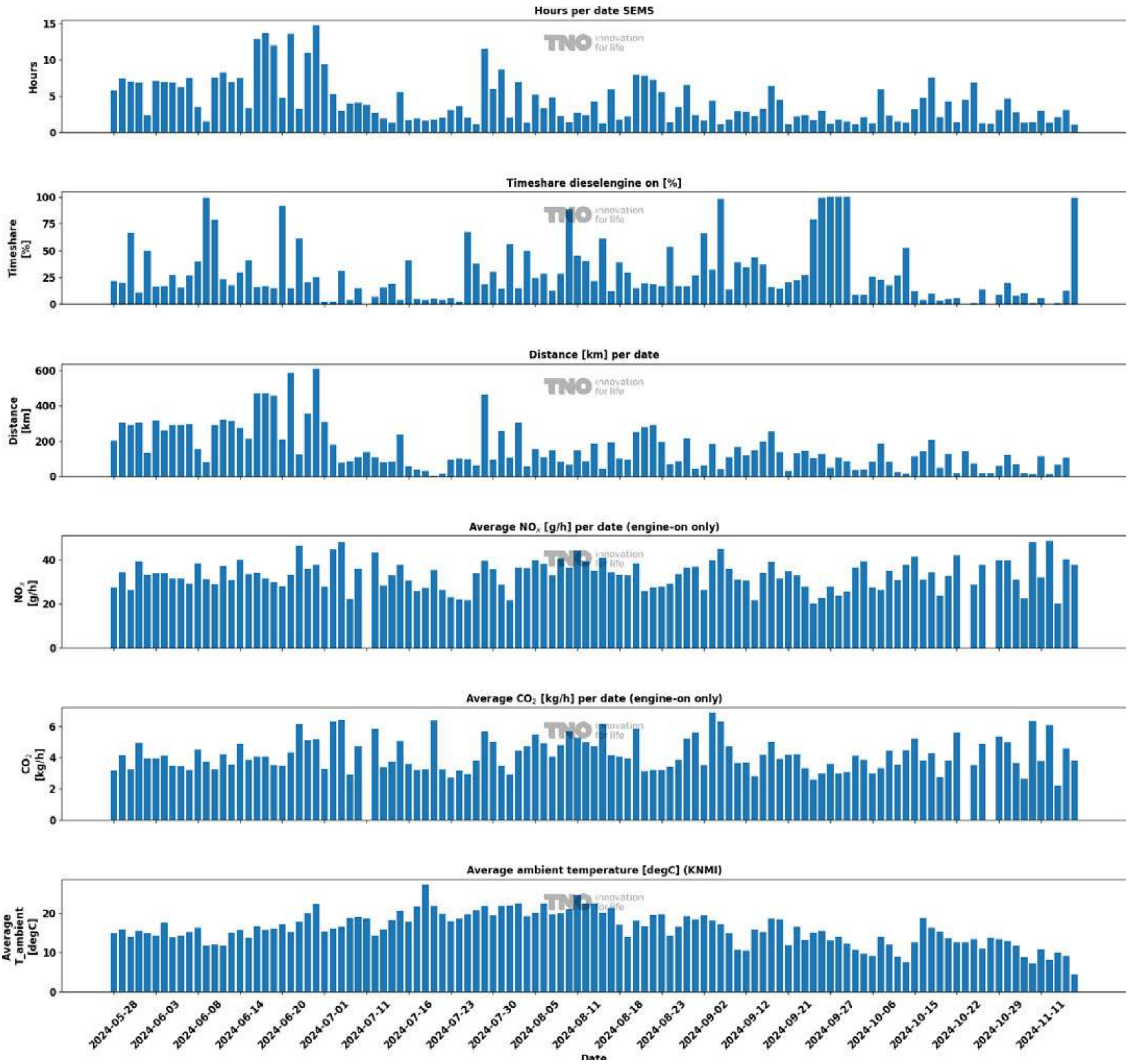


Figure 4-6: An overview of daily averages for the TH_A500_STAV (Thermoking Advancer A500).

4.2.2 Particle emissions

In a dedicated measurement campaign the particle mass (PM) emissions of the Thermoking A500 TRU have been determined. The SEMS monitoring equipment was used in conjunction with a filter-based PM measurement setup.

The setup involves sampling exhaust gases, diluting the sample with dry ambient air to prevent condensation, followed by leading the diluted sample through a filter, increasing the weight due to particle emissions landing on the filter. Before and after the measurements, the mass of the filters is accurately measured (after conditioning of the filters) to determine the mass increase corresponding to the particle emissions. In Appendix D more information can be found on the measurement setup.

Measurements were performed under stationary conditions with an empty trailer as the PM measurement equipment did not allow for driving or monitoring. During the measurement campaign each filter was loaded in 15 minutes, in which the TRU was subjected to a steady engine load. Given the constraints, four stable load conditions have been found and used in the measurement campaign: low load when the setpoint is (nearly) reached, cooling slowly, cooling fast, and heating fast. In total each load point has been measured three times with the PM measurement setup. The average engine load for these measurement points is close to the average load found in the monitoring data (between an estimated 5 and 6 kW), but the maximum load in the measurement campaign (estimated around 7kW) was below the maximum load in real use (above 10kW). This lower maximum load is most likely due to a lack of cargo inside of the trailer. With this measurement campaign the most common engine loads are covered. However, there is a lack of insight on PM emissions under peak engine loads. In addition to the different engine loads, measurements were performed with a cold engine start and a warm engine start.

The results for PM emissions expressed in total mass per hour and per kWh (g/kWh is the unit which is used in emission legislation) are shown in Figure 4-7 and Figure 4-8 respectively. As mentioned in the previous chapter, the results in g/kWh are indicative, as the kilowatt-hours are estimated based on the MAF-sensor and several assumptions about fuel-efficiency and the air-fuel-ratio.

The average PM emissions per hour increase with an increasing load, whereas the average PM emissions per kWh are fairly constant over the four measurement points. The PM emission levels in g/kWh remain well below the type approval limit of 0.4 g/kWh (which apply for the formal test procedures) for every measured load point. The impact of the cold engine start is not shown in this figure, however, the impact of the cold engine start was not substantial during this measurement campaign.

The measurements were repeated three times. While some variation was observed between the repetitions, the source of these deviations is unclear. However, all three measurements followed the same overall trend.

This results are in line with the earlier mentioned study performed by the Zemo Partnership (*"HGV Auxiliary Engines: Baseline auxTRU testing and modelling of UK impacts"* by Zemo Partnership February 2024[20].). In this study average PM-emissions between 0.3 and 2.2 grammes per hour are reported, depending on ambient temperature and cooling mode. In ambient conditions between 5 and 15 degrees Celsius, the average reported PM-emissions are between 0.3 and 0.9 grammes per hour (for post-2019 units). However, one of the tested units showed values up 5.4 grams per hour.

[20] https://www.zemo.org.uk/assets/reports/HGV%20Auxiliary%20Engines%20Report%202024%20-%20Zemo%20Partnership.pdf

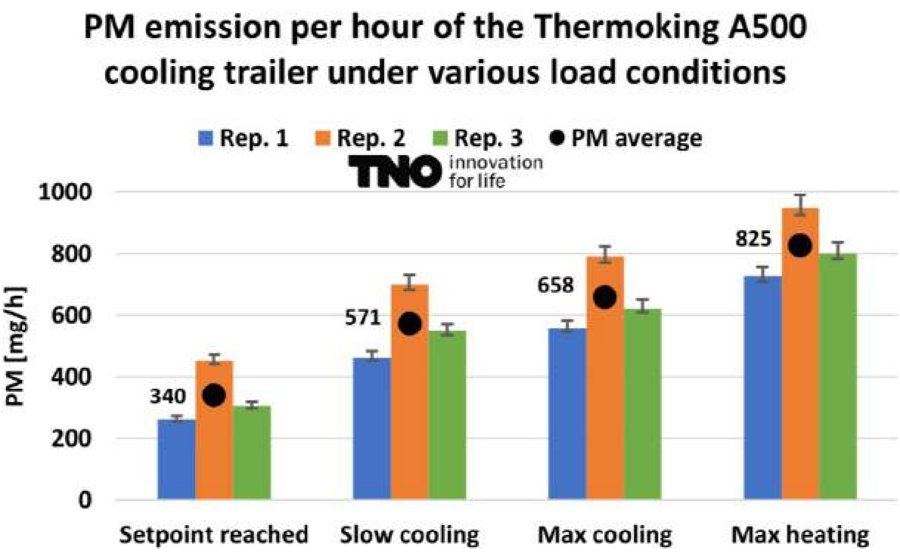


Figure 4-7: PM emissions per hour of the TRU under four conditions (temperature setpoint reached, slow cooling, fast cooling and fast heating) with increasing engine load from left (around 3kW) to right (around 7kW). Each coloured bar represents a measurement repetition, the whiskers on each bar represent measurement uncertainty. The black dots are the average values for each condition.

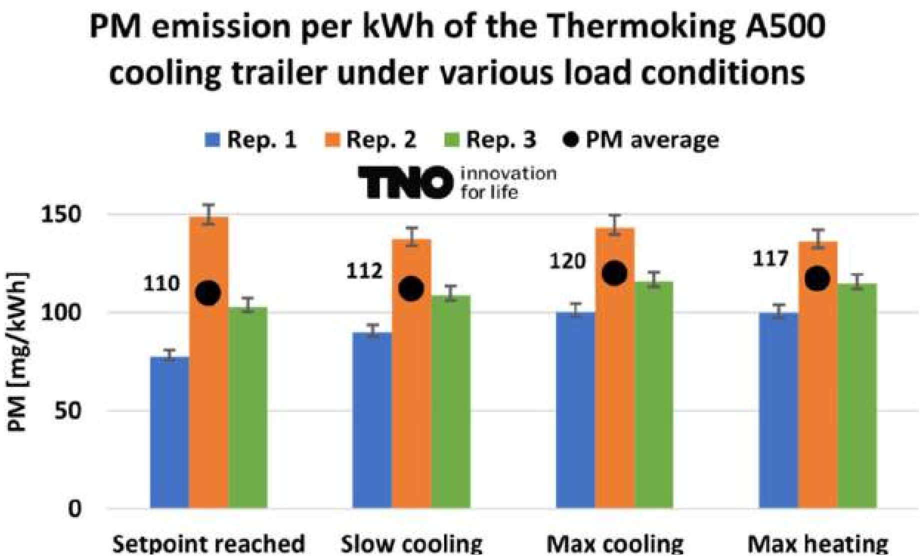


Figure 4-8: PM emissions per kWh of the TRU under four conditions (temperature setpoint reached, slow cooling, fast cooling and fast heating) with increasing engine load from left (around 3kW) to right (around 7kW). Each coloured bar represents a measurement repetition, the whiskers on each bar represent measurement uncertainty. The black dots are the average values for each condition.

The TRU (Stage V) PM emissions results are also compared to the PM emissions of an average Euro VI Heavy-Duty truck. In Figure 4-9 and Figure 4-10 this comparison is shown for PM emissions per hour and per kWh respectively. The average PM emissions per hour are in the same order of magnitude for the measured Stage V TRU as the HD-truck during urban driving conditions. However, the comparison of PM emissions per kWh shows a different trend: the TRU PM emissions are well over 10 times higher than the HD truck PM emissions.

Where the TRU has a maximum engine power of just below 19kW, a typical HD truck has a maximum power of several hundred of kW's. Therefore, the truck delivers significantly more work than the TRU within the same timeframe. The European emission limits show a similar gap: 10 mg/kWh for an Euro VI HD truck, and 400 mg/kWh for a Stage V NRMM up to 19kW. This means that Euro VI HD-trucks have a diesel particulate filter (DPF) installed, while thisis not needed for Stage V TRUs with an engine power below 19 kW. Stage V TRUs with an engine power above 19 kW are not commonly available in the Netherlands.

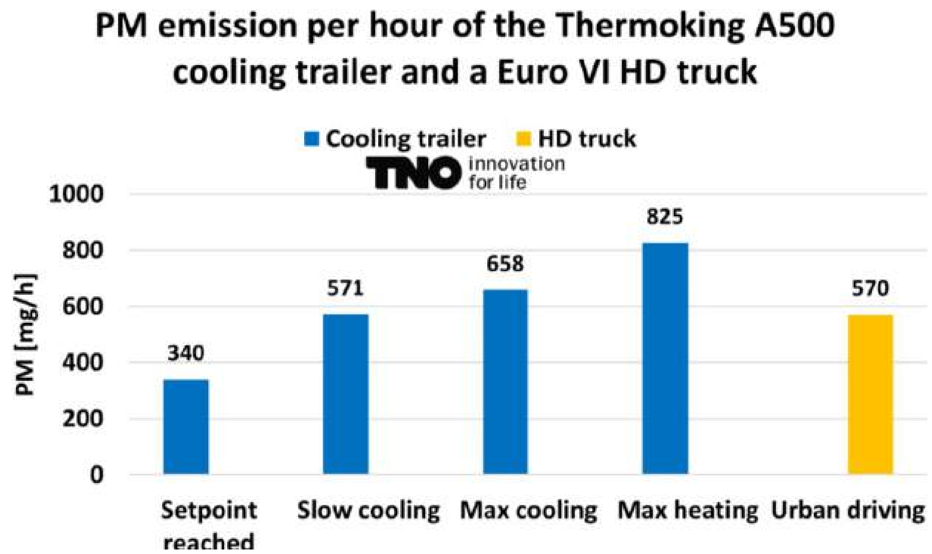


Figure 4-9: Average PM emissions per hour of the TRU under four conditions (temperature setpoint reached, slow cooling, fast cooling and fast heating) with increasing engine load from left (around 3kW) bright (around 7kW) displayed with the blue bars. The yellow bar represents the PM emissions per hour of a Euro 6 HD truck driving under urban conditions, based on the national emission factors.

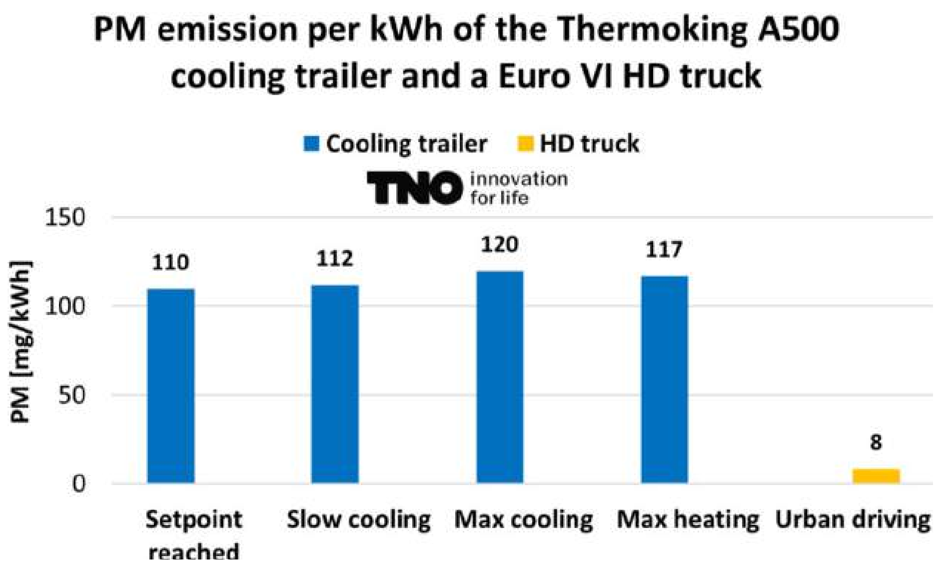


Figure 4-10: Average PM emissions per kWh of the TRU under four conditions (temperature setpoint reached, slow cooling, fast cooling and fast heating) with increasing engine load from left (around 3kW) bright (around 7kW) displayed with the blue bars. The yellow bar represents the PM emissions per kWh of a Euro 6 HD truck driving under urban conditions, based on the national emission factors.

5 Emissions of temperature-controlled transport in the Netherlands

5.1 Fleet

In Table 5.1 the estimated number of TRUs per vehicle type in the Netherlands are given as provided by Statistics Netherlands (CBS). These data are based on the Netherlands Vehicle Authority (RDW) registration data labelled as conditioned transport. The number of vehicles which are labelled as conditioned transport are increasing over the past years. As mentioned in chapter 2, the RDW does register conditioned transport, but no information about the TRU itself is registered. Details with regard to type of TRU, fuel type, Stage class and engine power would make the emission calculations on a national scale more accurate. The number of total estimated vehicles equipped with a TRU could be approximately 5,000 lower in 2025 if an alternative RDW classification is applied. There is ongoing discussion about whether this lower figure should be adopted. If so, it would result in proportionally lower total emission estimates.

Table 5-1: Number of TRUs per vehicle type in the Netherlands from Statistics Netherlands (CBS).

Type of vehicle	Date: 1-1-2023	Date: 1-1-2024	Date: 1-1-2025
		[Number of vehicles]	
Trailer	3152	3238	3309
Semi-trailer	32090	32990	33417
Truck	7934	8239	8646
Van	4380	4758	5065
Other	24	26	45
Total	47580	49251	50482

5.2 Operating hours

To accurately estimate the total annual emissions from TRUs, it is important to make a reliable assessment of their average annual operating hours. Total emissions per year are calculated by multiplying the operating hours per year by the emission factor (in grams per hour). The assumptions used in national emission inventories and the Climate and Energy Outlook (KEV) regarding operating hours have been validated using two datasets. The first dataset is based on monitoring data from measured TRUs collected as part of this program.

The second dataset provides an anonymized overview of operating hours in relation to the year of manufacture for active TRUs across multiple transport companies.

5.2.1 Operating hours of the monitored machines

The data of the eight monitored TRUs gives insight in their operational characteristics. As shown in Table 5-2, the average annual usage intensity of the eight monitored TRUs is approximately 900 hours, which only includes operation where the diesel engine is on. This average is based on 2050 days of monitoring data from TRUs in normal operation. The data consist of 4300 hours of 'active data', where 'active data' refers to data with a switched on diesel engine, which is relevant for the calculation of annual emissions.

However, there is significant variation between the different TRUs. As described in paragraph 4.1, daily active time, with the diesel engine on, ranges from less than 1 hour to as much as 24 hours for some of the individual TRUs within the monitoring period. Part of this variation is explained by the fact that some TRUs are cooling for a significant portion of the time (up to 75%) without the diesel engine running. This can be explained by the presence of a start- stop system, in which the diesel engine is switched off once the set temperature is reached. An additional possibility is that these TRUs are connected to the power grid during stand- still. Another possible explanation of the variation in active hours per day is the type of usage (the level of cooling/heating required for the goods).

A dataset containing operational characteristics was received and is described in the next paragraph.

Table 5-2: Usage hours

Cooling unit	TRU ID	Monitored days	Active days	Active hours with diesel engine on	Average active hours per active day	Estimated average active hours per year
Thermoking SLXi Spectrum	TH_SPEC_STAIID	206	164	1.787	10,9	3166
Mitsubishi TU100SAE-CNE	MI_TU_STAIIIA	81	41	229	5,6	1032
Thermoking SLXi 300 Whisper Pro	TH_300_STAV	385	224	359	0,9	341
Carrier Vector 1550 City	CA_1550_STAV	419	230	597	1,4	520
Carrier Supra 1150 MT	CA_SUP01_STAV	276	92	366	1,3	484
Carrier Supra 1150 MT	CA_SU_STAV	289	94	240	0,8	304
Thermoking Advancer A500	TH_A500_STAV	177	149	120	0,7	247
Carrier Vector HE19	CA_VEHE19_STAV	217	118	594	2,7	1000
Total / average		2050			3 [h/day]	887 [h/yr]

5.2.2 Annual operating hours in relation to the year of manufacture for active TRUs

The dataset includes valid anonymized data on operating hours for approximately 850 TRUs. The dataset contains three types of operating hours. It covers the hours the cooling unit has operated using the diesel engine, the hours using the electric (grid) connection and the hours the cooling unit is switched on without energy consumption (start-stop). In general, the total operating hours decrease with the age of the unit. New machines are turned on for up to 2,500 hours per year in total (diesel, electric, start-stop), whereas older machines are only active for about 1,000 hours annually or less. Furthermore, older machines mainly operate on diesel engines, while newer machines increasingly use electricity or are turned on without active cooling (due to the start-stop systems).

During interviews with TRU suppliers it was highlighted that operating hours vary significantly depending on the type of transport. For example, international transport tends to require substantially more hours than regional transport. Moreover, type of cargo has an impact, like meat, pharma or vegetables. There are (exceptional) examples where the TRU is on for 6000 hours per year due to highly temperature-sensitive goods in combination with international transport. It was estimated that the national distribution typically involves between 750 and 1500 hours annually, where international transport can exceed 3000 hours per year.

Finally, a comparison was made between the number of engine hours (on diesel) in the dataset and the assumptions used in the emission inventory calculations. Figure 5-1 shows that the assumption used for emission inventory (dashed line) aligns well with the engine hours from the dataset. This is especially true considering that the dataset (based on machine serial numbers) consists mostly of TRUs mounted on trailers. For older units, there is a slightly larger deviation, but it is expected that units with very limited usage are monitored less. Moreover, the number of TRUs older than 15 years is very small (both in the dataset and in the total fleet). When looking at the average number of engine hours per year across all age groups (shown in parentheses in the legend), the dataset values are slightly higher than the assumptions for trailers. However, since it is expected that the units in the dataset are slightly newer than the total fleet in the Netherlands, this analysis does not provide sufficient reason to adjust the assumptions used in the calculations for the emission inventory.

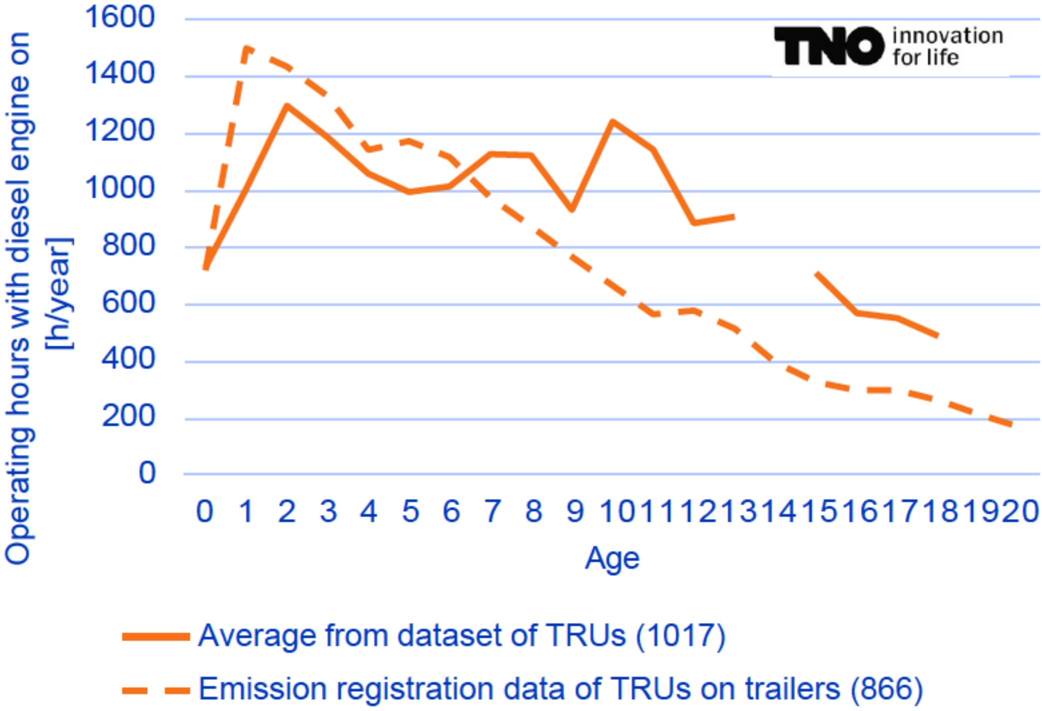


Figure 5-1: Comparison between the operating hours of the dataset and current assumptions in the emission inventory. The average number of engine hours per year across all age groups is shown in parentheses in the legend.

5.3 Emission factors

TNO annually establishes emission factors for [redacted]mongst others - road traffic in collaboration with the Netherlands Environmental Assessment Agency (PBL)[21]. An emission factor is the value for the average emission per type of machine or vehicle. TNO's emission factors are used, among other things, in the calculation of total emissions in the Netherlands by the Traffic and Transport task force of the Emission Inventory. Moreover, these emission factors are used for emission forecasts based on policy initiatives and also for air quality and deposition calculations.

Since 2020, emissions from TRUs have been reported in the Dutch Emission Inventory. Based on the (limited) insights available at the time, the average emission from TRUs was estimated at 100 grams of NO_x per hour.

The real-world emission data is used to make a proposal to update the emission factors for TRUs. Since the measurements on the TRUs mainly provide numbers on NO_x and CO_2 emissions, these two components are determined. For particle-emissions the number of measurements are too low for assessing the current emission factor. The combined average NO_x-emissions of the monitored TRUs are 36 grams per hour (in the 2024 version of this report, this was 39 g/h), with many of them clustering around this value. The average CO_2-emission is 5.5 kg per hour (in the 2024 version of this report, this was 5.7 kg/h). From the measurements, more accurate estimates for the emission factors can be made, and it can be concluded that the estimate of 100 grams of NO_x per hour is too high.

21 https://publications.tno.nl/publication/34642685/NeSvqNye/TNO-2024-R11049.pdf

Based on the measurement results, the current emission factor for NO_x emissions from TRUs is adjusted downwards. As shown in Table 5-3, 39 grams of NO_x per hour is now used as emission factor, based on the 2024 report. In 2025, it will be assessed if this has to be changed to 36 grams per hour. For CO_2 there are only minor changes foreseen with the emission factors of 5.7 and 5.5 kilograms CO_2 per hour.

The emission factors are based on the average emissions per TRU, with a weighting over the emission classes. The weighting is based on the age of the vehicle on which the TRU is mounted, as the age of the TRUs themselves is not registered. For this analysis, Stage V and Stage IIIA TRUs are grouped together, while Stage II TRU' s are considered separately. Since Stage IIIA was introduced in 2007, the weighting is based on whether the vehicles were manufactured before or after this year. The emission factor represents an average across all usage types. Currently, there is insufficient information to differentiate between specific usage patterns such as distribution routes, types of payload, weather conditions and associated differences in cooling demand. However, significant variations in daily absolute emissions have been observed, and the underlying causes of these fluctuations are being further investigated. Moreover, as mentioned in Chapter 3, for now three different brands are measured, with two of them being predominant among the monitored TRUs. To ensure the representativeness of these TRUs, a market analysis will be necessary.

Table 5-3: 2024 emission factors, based on the TRUs real-world measurements, and the average valuesE based on the finished measurement campaign in 2025.

Pollutant	Emission factor 2024	Average measurement value 2025
NO_x	39 [g/h]	36 [g/h]
CO_2	5.7 [kg/h]	5.5 [kg/h]

5.4 Total emissions of temperature-controlled transport in the Netherlands

Based on the proposed emission factors from the previous chapter the preliminary total CO_2 and NO_x-emissions in the Netherlands are calculated. As described in Chapter 4, the annual intensity of usage varies significantly between the monitored TRUs. However, as shown in paragraph 5.2, the data is in line with the current assumptions. Therefore, no adjustments have been made to the usage characteristics in emission modelling.
Figure 5-2 shows the calculated emissions compared to the emissions previously registered in the national emission inventory[22]. Based on the total number of TRUs, their average annual usage intensity, and the 2024 emission factor, the total annual emissions for 2022 (most recent year in the national Emission Inventory) are reduced from 4.6 kton to 1.8 kton NO_x. For CO_2 emissions (0.3 Mton annually), there is no significant change.

[22] Emissieregistratie.nl

Figure 5-2: Emissions of temperature-controlled road transport in the emission inventory compared tothe new emission factors.

6 Conclusions

This study monitored the CO_2 and NO_x exhaust emissions of eight Transport Refrigeration Units (TRUs) in road transport vehicles while they were used in real-world, everyday operation. The eight TRUs have been monitored for 231 to 1787 hours, of which two for acomplete year, and the other six ranging over the different seasons. Apart from the emissions, this study also provides information on daily run-time.

Six of the eight TRUs have Stage V diesel engines (the other two have Stage II and Stage IIIA diesel engines). Stage V is the most recent emission class for these engines. The emission limits for Stage V TRUs with an engine power below 19 kW are less stringent than for those with an engine power above 19 kW, for both NO_x and particle emissions. Most of the Stage V TRUs have an engine power slightly below 19 kW. Below 19 kW no diesel particulate filter (DPF) is needed, also no advanced NO_x-reduction technologies are necessary. Tightening of (European) emissions legislation would be needed to significantly reduce emissions from diesel-powered TRUs in this power category on a large scale.

The average annual usage intensity of the eight monitored TRUs is approximately 900 hours, which only includes usage where the diesel engine is on. This average is based on a total of 2050 days of monitoring data from TRUs in normal operation. However, there is considerable variation in usage intensity between the different TRUs. For some individual TRUs, the number of active hours per day (with the diesel engine on) during the monitoring period varied from less than 1 hour to as much as 24 hours. Part of this variation is explained by the fact that some TRUs are enabled for a significant portion of the time (up to 75%) without the diesel engine running (with no emissions). These TRUs are likely connected to the power grid during stand-still. Another possible cause of the variation is the type of usage. Based on an anonymized dataset covering 850 active TRUs, which includes information on operating hours and year of manufacture, the average annual runtime with the diesel engine active is approximately 1,000 hours. This is roughly in line with the monitored TRUs and the current assumptions for emission modelling. Newer TRUs typically operate twice as many hours per year as the older units.

The combined average tailpipe NO_x-emission of the eight monitored TRUs is 36 grams per hour, with many of them clustered around this value. The average tailpipe CO_2-emission is 5.5 kg per hour. Compared to the 2024 interim report, the results are roughly the same, which were 39 grams per hour for the NO_x- and 5.7 kg per hour for the CO_2-emissions. Moreover, the results roughly align with the previous measurement campaigns on two TRUs in 2021 and 2022, but are now more robust, with data from eight TRUs in total. Based on the (limited) insights available at the time (before 2024), the average emission from TRUs was estimated at 100 grams of NO_x per hour.

From the measurements, more accurate estimates can now be made, and it can be concluded that the estimate of 100 grams of NO_x per hour is too high. Based on the measurement results, the current emission factor (the value for the average emissions per machine used to estimate the total emissions from conditioned road transport in the Netherlands) for NO_x emissions from TRUs is lowered to 39 grams of NO_x per hour (the 2024 value). It will be discussed if this number will be adjusted to 36 grams of NO_x per hour.

As a result of these adjustments, the previous estimate of 4.6 kton of NO_x emissions from TRUs on the road will be reduced to 1.8 kton of NO_x. For CO_2 emissions (0.3 Mton annually), there will be only a minor change due to the measured emissions.

In the context of total annual emissions, there is currently an ongoing discussion about the estimated number of TRUs in the Netherlands. If an alternative RDW classification is applied, the estimated number of vehicles equipped with a TRU in 2025 could be 10% lower (approximately 5000 less). This would lead to proportionally lower total emission estimates.

The NO_x emission levels in g/kWh (the unit used in emissions legislation) under real-world conditions remain below the type approval limits (which apply for the formal test procedures) for both Stage IIIA and Stage V TRUs. The results in g/kWh are indicative, as the kilowatt-hours are estimated based on several assumptions. The Stage II TRU shows NO_x emissions around and above the limit. This may be the result of relatively low engine load (engine load refers to the amount of power an engine must produce to meet current demands), which differs from the test cycle in the emissions legislation. The Stage II TRU shows the highest NO_x emission levels in grams per hour, which is to be expected due to the somewhat less stringent emission limits compared to Stage IIIA and Stage V TRUs. The monitored Stage V and Stage IIIA TRUs have the same emission limits and show similar NO_x emissions, averaging around 5.5 g/kWh. However, there are three Stage V TRUs that show 15[redacted]5% lower NO_x-emissions than the average.

In a separate campaign the particle mass (PM) emissions of one Stage V TRU were measured. The tests were conducted under stationary conditions at four different engine load levels, ranging from maximum heating and cooling (high engine load) to slow heating/cooling around the set temperature (low engine load). Since the tests were carried out with an empty trailer, the maximum engine load could not be reached

Results showed that PM emissions in grams per hour increased with engine load, from 340 mg/h at low load (temperature setpoint reached) up to 825 mg/h at high engine load. Emissions per kWh remained relatively constant, staying with 0.11 g/kWh well below the regulatory limit of 0.4 g/kWh. These results are in line with a study performed by the Zemo Partnership. The impact of a cold engine start on the PM emissions level was minimal. As only one TRU has been measured within this study on PM, this is not sufficient to change the current PM emission factor. As a result, the total particulate matter (PM2.5) emissions from TRUs remain at 0.13 kton per year

Compared to modern Euro VI trucks, the NO_x-emissions from TRUs are relatively high. For example, during city deliveries with an average Euro VI truck, the TRU accounts for approximately one-third of the total NO_x-emissions in refrigerated transport. Several Euro VI trucks have even lower emissions, resulting in the TRU emitting as much, if not more, NO_x than the truck itself.

For CO_2-emissions, the contribution of the TRU to the total is lower than for NO_x-emissions, approximately 15% during city-driving.

Comparisons with an (average) Euro VI heavy-duty (HD) trucks showed that while PM emissions per hour were on a similar level (during the measurement campaign), the TRU emissions per kWh were over ten times higher than the modern truck. This is due to the high PM-emissions in relation to the TRUs lower power output (under 19 kW) compared to HD trucks, which have several hundred kW of engine power available.

The higher PM emission levels for Stage V TRUs is the result of non-stringent emission levels, which do not require a diesel particulate filter (DPF), in contrast to Euro VI-trucks which are equipped with DPFs.

Due to the potential negative health effects of particulate matter and the limited data of particulate emissions from TRUs, it is recommended to measure these emissions across various types of refrigeration units.

Signature

TNO Mobility & Built Environment The Hague, 19 June 2025

Bescherming persoonlijke levenssfeer

Appendix A
Studies into TRU emissions by UK Zemo Partnership

This Appendix provides a brief summary of studies performed by the Zemo Partnership.

"HGV Auxiliary Engines: Baseline auxTRU testing and modelling of UK impacts" by Zemo Partnership February 2024[23].

Outline of the study:

- Methodology and Scope: The research expands beyond transport refrigeration units (TRUs) to include other auxiliary heavy goods vehicle (HGV) engines. It covers emission testing of conventional diesel auxiliary TRUs and a comprehensive aux engine market review. 6 auxTRU units were tested. The study period extends from the end of 2022 to November 2024.
- Measurement Approach: Test procedures involve loading a refrigerated vehicle with pre-conditioned water-filled containers and empty cardboard boxes to simulate [redacted]al-world conditions [redacted]Measurements include fuel consumption, internal and external temperatures, and emissions of oxides of nitrogen (NO_x) and particulates.
- Type of Emissions: Emissions include greenhouse gases (GHGs), NO_x, $PM_{2.5}$, and particle number (PN) emissions.
- Types of Refrigeration Units/Vehicles/Trailers: The research focuses on diesel auxiliary TRUs fitted to full-size semitrailers. Testing includes pre-2019 and post-2019 units manufactured by Thermoking and Carrier. No main engine powered refrigeration.

Results:

- Emissions: UK diesel auxTRUs consume around 235 million liters of fuel per annum (uncertainty margin is +-100 million litres, because low number auxTRUs+low run hours versus high number+high hours), contributing about 590 kilo-tonnes of tailpipe GHG emissions, 4.4 kt of NO_x emissions, 126 tonnes of $PM_{2.5}$ particulate mass emissions, and emit about 330 x 10^{21} particle number emissions. Differences Highlighted between old and new coolers: Pre-2019 and post-2019 (in comparison with EuroVI) consume respectively 1/9th and [redacted]0th the fuel, produce respectively 1/9th and [redacted]0th GHG emissions, produce respectively 2x and 1.5x the NO_x, emit respectively 5x and 3x the $PM_{2.5}$, and emit respectively 400x and 300x the PN.
- Impact of Season/Temperature/Cooling Demand/Cargo Type: Fuel consumption, NO_x, PM, and PN emissions increase substantially during periods of very hot weather, exacerbating emission impacts. All units were tested at 5, 15 and 30 degrees Celsius ambient temperatures. Fuel consumptions is +- doubled for the highest ambient temperature in comparison to the lowest (30 vs 5).

[23] https://www.zemo.org.uk/assets/reports/HGV%20Auxiliary%20Engines%20Report%202024%20-%20Zemo%20Partnership.pdf

"Emissions Testing of Two Auxiliary Transport Refrigeration Units" by Zemo Partnership September 2021[24]

Outline:

- Methodology and Scope: The study undertook the development and validation of a emissions test protocol tailored for auxiliary Transport Refrigeration Units (auxTRUs) within the context of Scotland. This encompassed pilot testing of a single diesel auxTRU in 2019, followed by further emissions testing on two conventional diesel auxTRUs in 2021. The focus was to gauge the environmental impact of auxTRUs, given their crucial role in the cold chain distribution systems of heavy goods vehicles (HGVs).
- Measurement Approach: To simula[redacted] real-world conditi[redacted]s , the study utilized water-filled containers and empty boxes loaded onto vehicles. Subsequently, these vehicles were placed within temperature-controlled test chambers, maintaining predefined internal temperatures. During these tests, measurements were recorded for fuel consumption, temperatures, oxides of Nitrogen (NO_x), and particulate emissions.
- Type of Emissions: Emissions considered in the study encompassed greenhouse gases, NO_x, particle mass, and particle number. These emissions metrics provided a comprehensive overview of the environmental footprint associated with auxTRUs.
- Types of Refrigeration Units/Vehicles/Trailers: The analysis specifically targeted truck or trailer-mounted auxTRUs featuring separate diesel engines. Notably, units powered by the main engine of the vehicle were excluded from the study's purview.

Results:

- Emissions: The study found significant emissions associated with auxTRUs. 4-6% of the HGVs is estimated to have an auxTRU. Greenhouse gas emissions ranged from 14 to 43 ktCO_2e per year (1-2% of total all HGVs). NO_x emissions ranged from 104 to 311 tonnes per year (5-14% of total all HGVs). Moreover, particle mass emissions ranged from 3 to 9 tonnes per year (9-26% of total all HGVs). Vehicles in Scotland, emphasizing the role of auxTRUs in particle pollution. Particle number emissions varied from 11 to 32 $x10^{21}$ per year. Low and high are based on estimations, see table 11 for how low and high are determined. In the paper, it is estimated that asingle diesel auxTRU fitted to a Euro VI HGV wouldconsume about 1/8th the fuel, produce about 1/8th the GHG emissions, produce at least double (2x) the NO_x, emit at least five times (5x) the Particle Mass, and emit about 500 times (500x) the number of particles, in comparison to the vehicle's Euro VI.
- Impact of Season/Temperature/Cooling Demand/Cargo Type: The study incorporated tests conducted at different ambient temperatures, reflecting seasonal variations. This approach enabled the assessment of how temperature fluctuations could influence auxTRU emissions. Additionally, the study examined the potential impact of varying cooling demands and cargo types on emissions, providing insights into operational factors affecting environmental performance.
- Translation to National Emissions for Refrigerated Transport: Estimates suggested that 4-6% of Scottish HGVs utilize auxTRUs, contributing additional emissions. The percentages of all individual emissions are given in bold under the header "Emissions".

[24] https://www.zemo.org.uk/assets/reports/Zemo_TRU_emissions_report2021.pdf

- Difference Between Old and New Coolers: While the study did not explicitly provide comparative emissions data between older and newer auxTRU units, it highlighted the necessity of evaluating the environmental implications of technological advancements in auxTRU design. Also, units powered by the main engine of the vehicle were not included in this study.

Appendix B
Previous TNO studies into TRU emissions

In two programs, conducted for the Ministry of Infrastructure and Water management [TNO 2021[25] and TNO 2022[26]], two TRUs were tested in real operation using a Smart Emissions Measurement System which is able to measure and record actual NO_x concentration and O_2 and derive CO_2 concentration from the TRUs tailpipe. The small engines are quite simple and don't broadcast engine data such as engine speed or load. An overview of TRU specifications and real-world emissions is given in Table B-1. With 26 and 52 g/h the average NO_x emissions differ between the two units. It must be remarked that the usage was different.

In [TNO 2021] it was concluded that the diesel engine of a refrigeration machine on a truck trailer is 1.5 times as high in terms of NO_x emissions and at least 10 times as high for particulate matter as the Euro-VI truck driving in front of it. In [TNO, 2022] it was concluded that with 26 grams of NO_x per hour, the emissions were half of the emissions of the truck with a heavy Euro VI engine. The emissions from the refrigeration unit are about the same level as a standard truck with a Euro VI engine. Like a previously measured cooling machine [TNO, 2021], it appears that the average NO_x emissions of the eight monitored TRUs are comparable in order of magnitude to the emissions of a modern truck and the particulate emissions are at least 10 times higher.

[25] R.J. Vermeulen, N.E. Ligterink, P.J. van der Mark, *Real-world emissions of non-road mobile machinery*, TNO 2021 R10221, 11 February 2021. http://resolver.tudelft.nl/uuid:a1c81fc2-3ad6-4020-a405-bf8d99830fbe

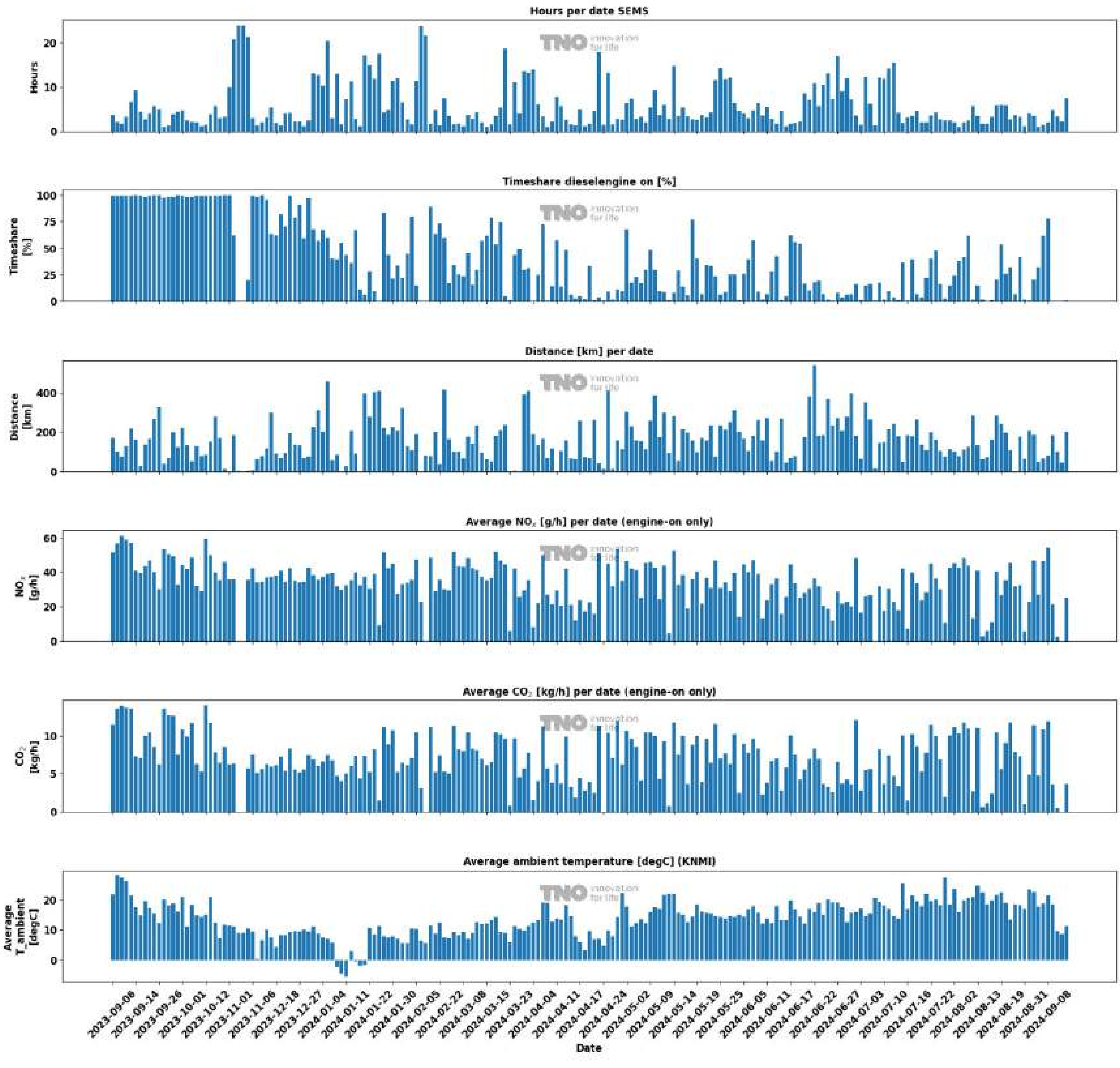
[26] Robin Vermeulen, René van Gijlswijk, Pierre Paschinger, Jessica de Ruiter, *Dutch In-service Emissions Measurement and Monitoring Programme for Heavy-Duty Vehicles 2021*, TNO 2022 R10375, 28 February 2022. http://resolver.tudelft.nl/uuid:aa5ee8b5-d84e-49c2-8d7c-c13761381f8e

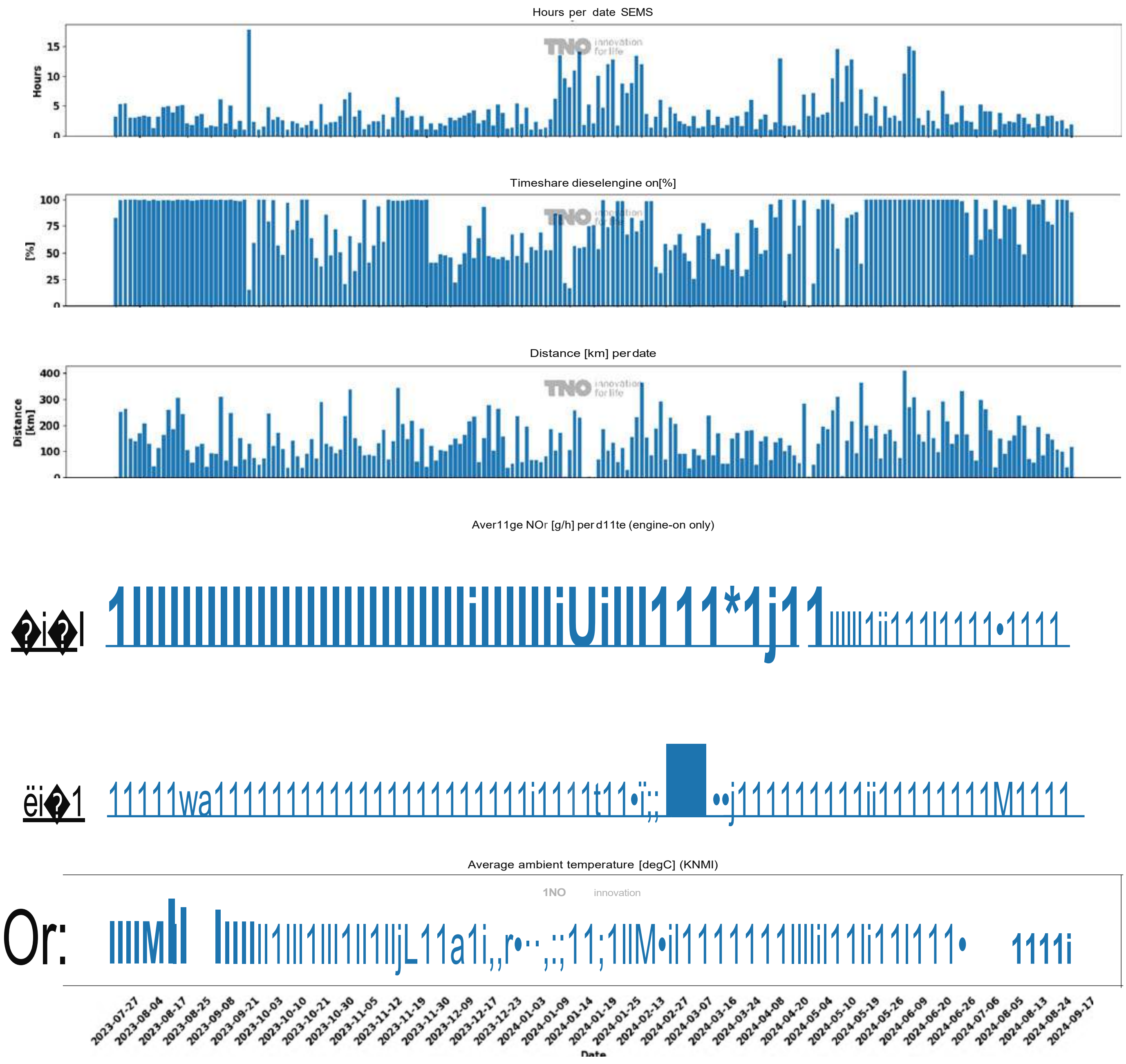
Table B-1: Overview of TRU specifications and real-world emissions measured in the Netherlands.

TNO test code	MI_TU	TK_SL
		
Brand, type	Mitsubishi TU100SAE-CNE Under body	Thermoking, SLXi spectrum Semi-trailer front mount Multi temp zones
Usage	Plants distribution, mainly mild temp (~5⁰C)	Various purposes different cargo
	Engine: Yanmar, 3TNV76-XMR	Engine: Yanmar, TK486V
Configuration	Cooling unit under body	Cooling unit on semi-trailer
Engine power [kW], displacement [l]	19.9 kW, 1.115	25.3, 2.09 l
Emission class	Stage IIIA (K)	II (D)
Emission abatement system	-	-
TA number	Not found on engine/cooling unit.	e13*97/68DA*2012/46KA*557*17
Total test period [days], days active [days]	81, 41	206, 164
Total activity [hours], [hours/day]	229, 5.6	1787, 10.9
Average power [%]	21	22
Stand-by [minutes/hour]	n.a.	6
NO_x [g/h], [g/kWh]	26, 6.4	52, 9.5
Total NO_x [kg] (test period)	6.1	92
CO_2 [kg/h]	3.3	5.9
Total CO_2 [t] (test period)	0.75	10.6
Fuel consumption [l/h]	1.21	2.2
Vehicle	Scania S520 Rigid-dolly-semi-trailer Euro VI (step D) V8 382 kW	Various tractor units
NO_x [g/h]	56	n.a.
CO_2 [kg/h]	45	n.a.
FC [l/h, l/100km]	17, 32.7	n.a.

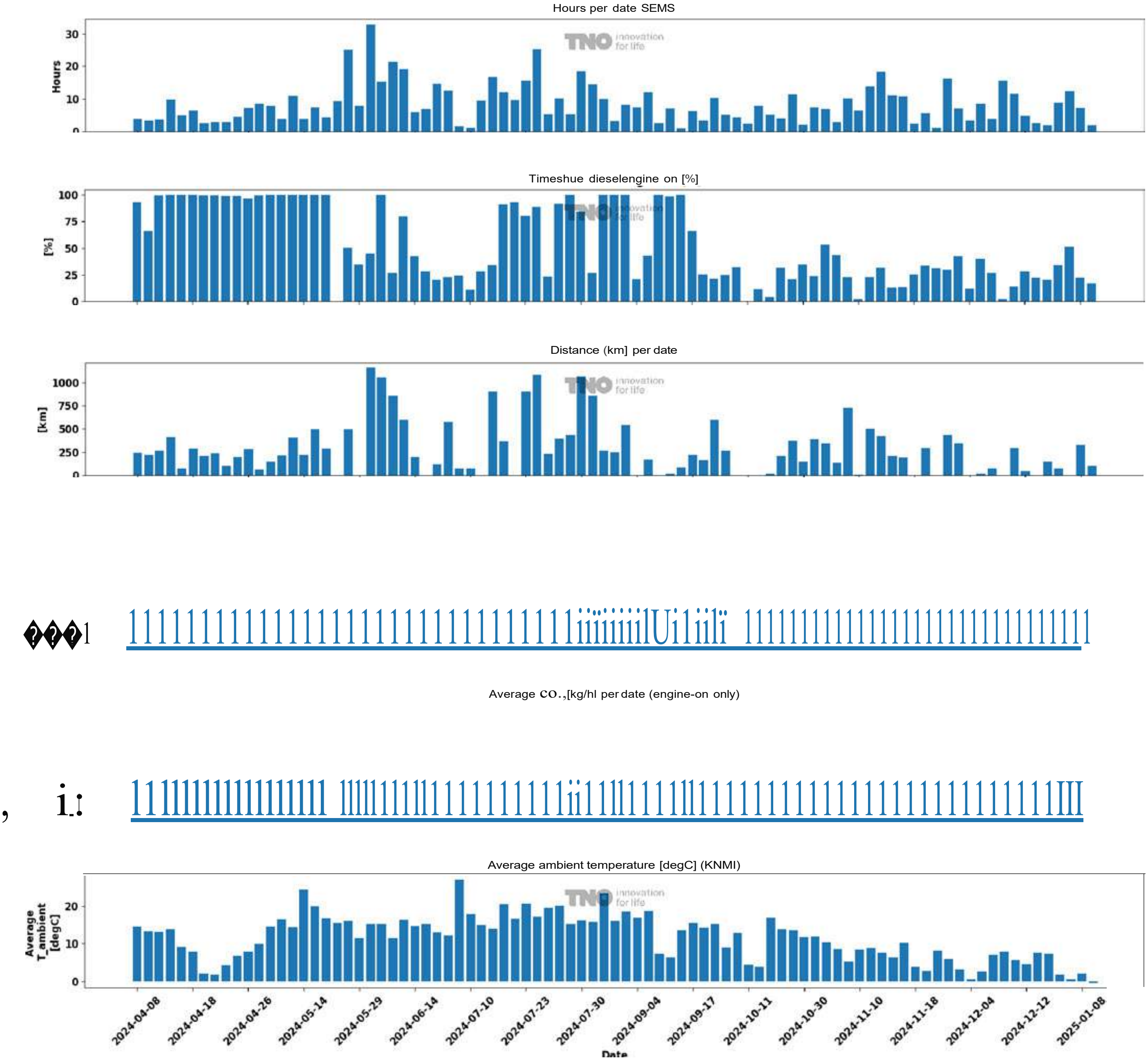
Appendix C
Daily usage conditions and emissions

TH_300_STAV (Thermoking SLXi 300 Whisper Pro)

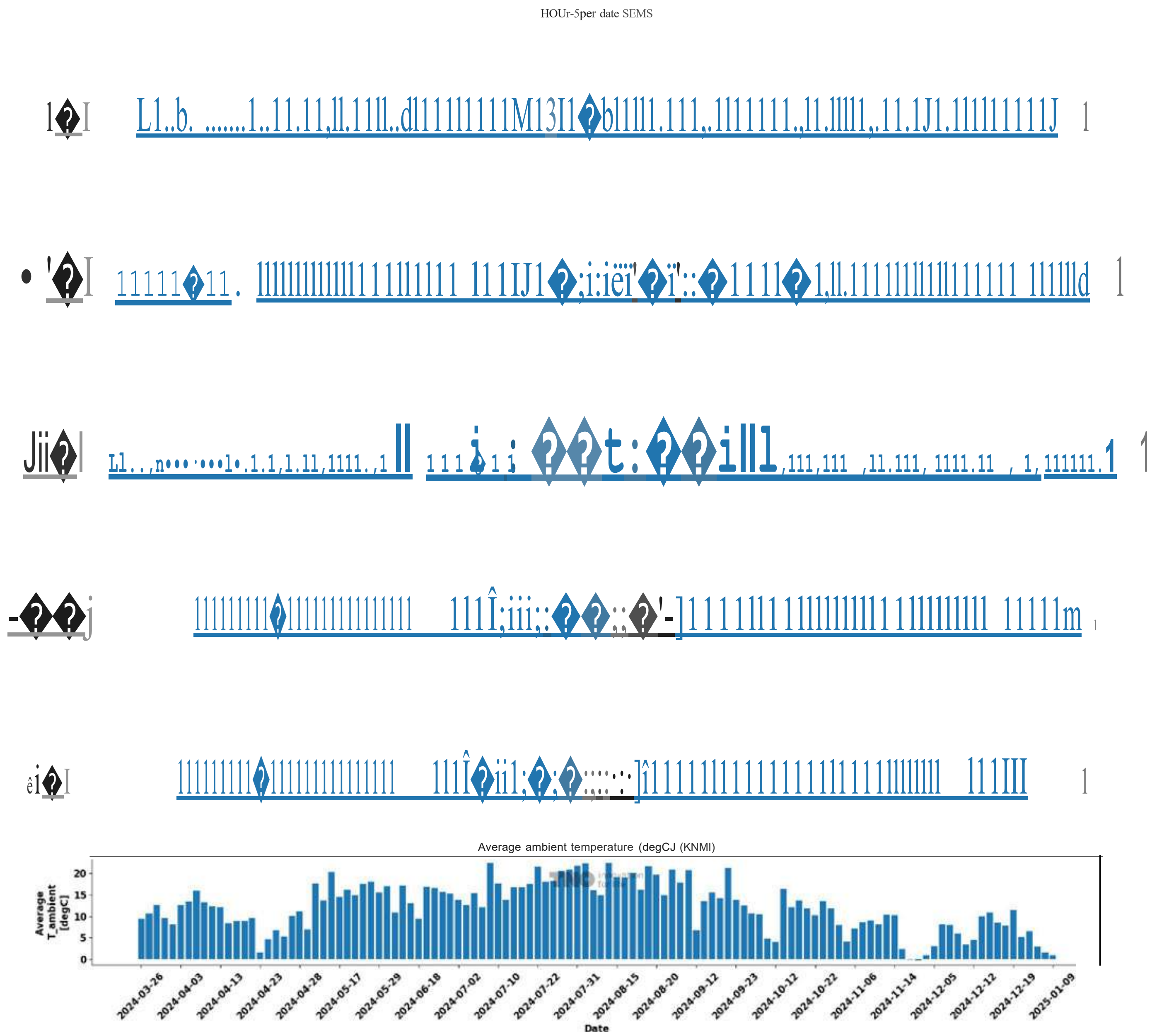



Hours per date SEMS
Hours
Timeshare dieselengine on[%]
[%]
Distance [km] per date
Distance [km]
Average ambient temperature [degC] (KNMI)
Date

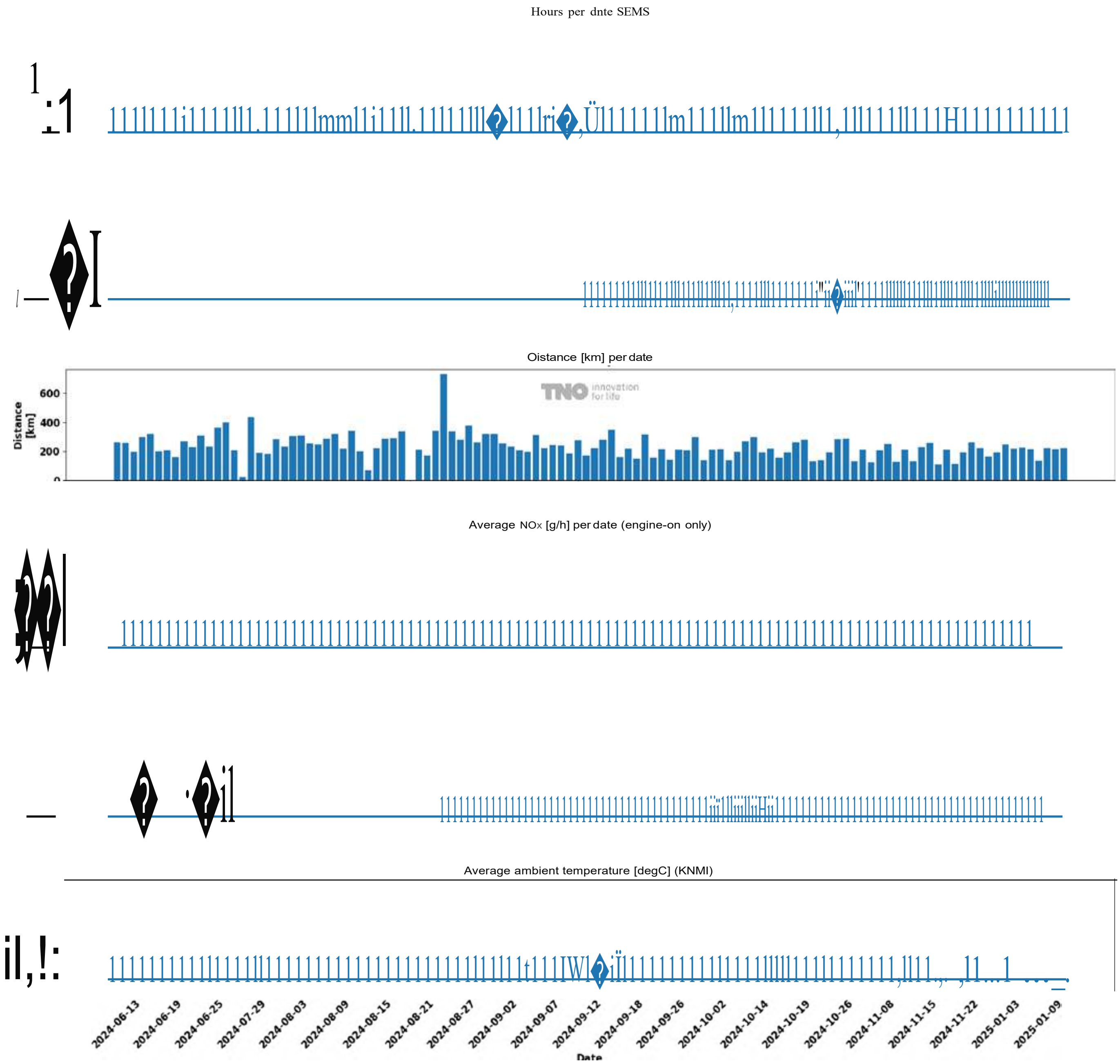
CA_SUP01_STAV (Carrier Supra 1150 MT)



CA_SU_STAV (Carrier Supra 1150 MT)



CA_VEHE19_STAV (Carrier Vector HE19)



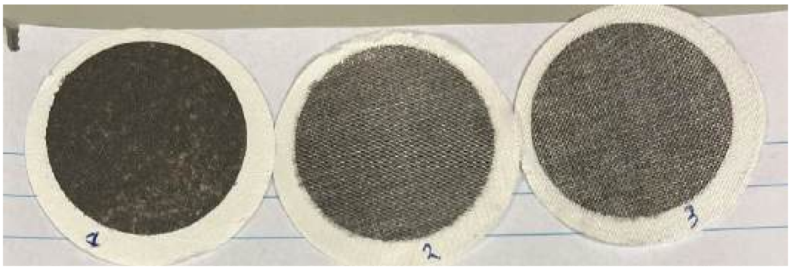
Appendix D
Details on PM measurement campaign

The PM measurement program was performed on a TRU which was on a stationary vehicle, with no cargo inside. Engine load was varied by changing the temperature setpoint on the thermostat of the TRU. Pictures of the trailer and the TRU's thermostat can be found below.

Measurement equipment (TNO SEMS) for the gaseous emissions (CO_2 and NO_x), was already installed on the TRU for the monitoring program. The TNO SEMS system is connected to a stand-alone MAF sensor on the engine inlet as well as a NOx-O_2 sensor on the exhaust. For the PM measurement program, additional particle measurement equipment was installed in the form of a mobile TNO filter-setup.

The basic working principle of the mobile TNO filter-setup involves sampling raw exhaust gas, diluting and cooling the gas sample with dried, filtered air, and finally leading the diluted sample through a PM filter thereby loading it with particulate matter. Below are two pictures of the filter-setup. On the left picture the diluter and the filter holder can be seen, and on the right picture the heating chamber for the dried, filtered air supply to the diluter.

The mass of the PM filter is accurately measured in a conditioned environment before and after measurements to determine the amount of particle matter on the filter. Below a picture is shown of three example filters loaded with particulate matter. The discoloration is a first indication of the amount of particulate matter on the filter, i.e. the darker the filter the more weight has been collected.



After trial and error with various setpoints on the thermostat of the TRU, four unique load points had been identified. The highest engine load was found with the thermostat on maximum temperature, which results in maximum heating. A lower engine load was achieved with setting the thermostat on the minimum temperature, resulting in maximum cooling. Slightly lower engine load was achieved by setting the thermostat setpoint slightly below the measured actual temperature, resulting in slow cooling. The lowest engine load was achieved by setting the setpoint on the actual measured temperature and not letting the engine shut-off (as it would normally do to save fuel). These steps were supplemented by cold and warm starts. It is important to note here that the lack of cargo most likely decreased the ability to achieve higher engine loads. The maximum engine power during these tests was approximately 7 kW. This is in line with the engine power which has been recorded during monitoring of real-world use. The full measurement program and test results can be found in the table below.

	Load	Time	Filter	MAF	PM		NOx		EGT	CO2
Day 1	[kW]	[min]	[mg]	[g/s]	[mg/h]	[mg/kWh]	[g/h]	[g/kWh]	[degC]	[g/s]
1 Cold start max cooling	5.6	15	0.39	15.3	791.7	140.9	47.6	8.48	194	1.26
2 Max heating	7.3	15	0.36	15.0	726.0	99.7	54.8	7.52	276	1.56
3 Temp. setpoint reached	3.4	15	0.15	13.3	261.7	77.5	26.3	7.79	149	0.72
4 Max cooling	5.6	15	0.28	14.9	560.3	100.2	44.2	7.90	221	1.20
5 Slow cooling	5.2	15	0.23	15.0	463.7	89.7	39.6	7.66	205	1.11
6 Max heating	7.0	15	0.48	14.8	948.7	136.2	46.3	6.65	276	1.49
7 Temp. setpoint reached	3.0	15	0.26	13.2	452.8	148.5	21.0	6.90	143	0.65
8 Max cooling	5.5	15	0.40	14.9	790.5	143.3	38.4	6.95	220	1.18
9 Slow cooling	5.1	15	0.35	14.9	700.3	137.3	36.0	7.05	206	1.09
10 Max heating	7.0	15	0.41	14.8	801.5	114.6	46.8	6.69	283	1.50
11 Temp. setpoint reached	3.0	15	0.17	13.2	305.4	102.9	20.2	6.79	138	0.64
12 Max cooling	5.4	15	0.31	14.9	623.0	115.7	37.9	7.04	217	1.16
13 Slow cooling	5.0	15	0.28	14.9	548.6	108.7	35.6	7.05	204	1.08
14 Warm start max cooling	5.0	15	0.26	14.8	507.7	100.8	37.1	7.36	199	1.13
Day 2										
15 Cold start max cooling	5.4	15	0.31	15.3	583.0	107.5	45.2	8.34	183	1.25
16 Warm start max cooling	4.4	15	0.33	15.0	618.2	139.0	42.3	9.52	204	1.20

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