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. 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 geeft een tussentijds overzicht van de meetresultaten.
De rapportage geeft ook een voorlopige inschatting van de verwachte impact van de meetresultaten op de emissietotalen door koelsystemen in geconditioneerd transport over de weg in Nederland.

Door te meten is een voorlopig (verbeterd) beeld verkregen van de NO_x- en CO_2-uitstoot van diesel aangedreven koelmachines op vrachtwagens in Nederland. Daarmee zijn de emissiefactoren voor koelmachines bijgesteld en zijn ze betrouwbaarder. 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. Op basis van de meetresultaten wordt verwacht dat de huidige emissiefactor voor NO_x-emissies van koelmachines omlaag kan worden bijgesteld. Ten gevolge van deze aanpassingen is het de verwachting dat de huidige inschatting van 4,6 kton aan NO_x-emissies door koelmachines op de weg met ruim een factor twee naar beneden gaat. Voor de CO_2-uitstoot (0,3 Mton) wordt geen grote wijziging verwacht ten gevolge van de gemeten uitstoot. Voor fijnstof zijn vooralsnog geen metingen uitgevoerd binnen dit onderzoek. De voorgestelde emissiefactor en de totale emissies zijn voorlopig en nog niet vastgesteld door de taakgroep Verkeer en Vervoer van de Emissieregistratie.

Ondanks de voorziene daling in emissietotalen is de NO_x-uitstoot van een koelmachine significant vergeleken met de uitstoot van een moderne vrachtwagen. Hetzelfde is te verwachten (gezien de afwezigheid van een roetfilter) voor fijnstof emissies. Dit komt grotendeels door de beperkte emissie-eisen die gelden voor koelmachines in vergelijk met de strengere emissie-eisen voor vrachtwagens.

Naast de emissieprestaties is ook onderzoek gedaan naar de inzet van koelmachines.
De jaarlijkse intensiteit van de inzet varieert fors tussen gemonitorde koelmachines.
Dit is nog een onzekerheid in de berekende emissietotalen.

Het huidige onderzoek loopt nog door tot eind 2024 zodat meer gegevens over emissies en inzet kunnen worden ingewonnen, dit is relevant voor een verdere verbetering van de inzichten in inzet en NO_x- en fijnstofemissies door koelmachines. Begin 2025 wordt de definitieve eindrapportage verwacht.

Samenvatting

In 2023 presenteerde het Ministerie van Infrastructuur en Waterstaat een plan van aanpak voor de verduurzaming van geconditioneerd transport. 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 geeft een tussentijds overzicht van de meetresultaten. De rapportage geeft ook een voorlopige inschatting van de verwachte impact van de meetresultaten op de emissietotalen door koelsystemen in geconditioneerd transport over de weg in Nederland. Het meetprogramma loopt nog door tot eind 2024. Begin 2025 wordt de definitieve eindrapportage verwacht.

In deze studie worden de CO_2- en NO_x-emissies uit de uitlaat van zeven koelmachines tijdens normaal gebruik in de dagelijkse praktijk gerapporteerd. De zeven koelmachines zijn tussen 122 en 1787 uur gemonitord, waarvan één in het voorjaar, drie van de winter/voorjaar tot de zomer, twee van de zomer tot de winter en één van het najaar tot het voorjaar. De studie geeft eveneens inzicht in de inzet van koelmachines.

Vijf van de zeven 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 koelmachines 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 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 benodigd om emissies van diesel aangedreven koelmachines in deze vermogenscategorie op grote schaal te reduceren.

De gemiddelde jaarlijkse inzet van de gemonitorde zeven koelmachines is 900 uur, dit betreft alleen inzet waarbij de dieselmotor aanstaat. Dit gemiddelde is gebaseerd op 861 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 wel 24 uur. Een deel van variatie wordt verklaard doordat sommige koelmachines een aanzienlijk deel van de tijd koelen (tot wel 75%) zonder dat de dieselmotor aanstaat. Waarschijnlijk worden deze koelmachines tijdens het stilstaan aangesloten op het stroomnet. Een aanvullende oorzaak van de variatie is mogelijk het type inzet, dit wordt in het lopende onderzoek nog nader onderzocht. Daarnaast wordt momenteel aanvullende data rondom operationele karakteristieken verzameld.

De gecombineerde gemiddelde NO_x-emissie van de gemonitorde koelmachines bedraagt circa 39 gram per uur. De gemiddelde CO_2-emissie is 5,7 kg per uur. De resultaten zijn in lijn met de eerdere meetcampagnes, maar zijn nu robuuster met gegevens van in totaal zeven koelmachines. Op basis van toen geldende inzichten is de gemiddelde emissie van 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 wordt verwacht dat de huidige emissiefactor voor NO_x-emissies van koelmachines omlaag kan worden bijgesteld. 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. Het voorlopige voorstel is om de emissiefactor voor koelmachines te verlagen naar 39 gram NO_x per uur.

Ten gevolge van deze aanpassingen is het de verwachting dat de huidige inschatting van 4,6 kton aan NO_x-emissies door koelmachines op de weg met ruim een factor twee naar beneden zal gaan. Voor de CO_2-uitstoot (0,3 Mton) wordt geen grote wijziging verwacht ten gevolge van de gemeten uitstoot. Voor fijnstof zijn vooralsnog geen metingen uitgevoerd binnen dit onderzoek. De voorgestelde emissiefactor en de totale emissies zijn voorlopig en nog niet vastgesteld door de taakgroep Verkeer en Vervoer van de Emissieregistratie. Zoals hierboven beschreven varieert de jaarlijkse intensiteit van de inzet fors tussen gemonitorde koelmachines. Vooralsnog zijn geen aanpassingen gedaan aan de inzetcijfers in de emissiemodellering, dit is een onzekerheid in de berekende emissietotalen.

De berekende NO_x-emissies in g/kWh (de eenheid die wordt gehanteerd in de emissiewetgeving) tijdens praktijkomstandigheden blijven onder de typegoedkeuringslimieten voor zowel de Stage IIIA- als 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, welke 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 emissieprestaties, gemiddeld rond de 5,5 g/kWh. Er zijn echter drie Stage V koelmachines die 15 – 25% lagere NO_x-emissies laten zien dan het gemiddelde.

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. Bovendien hebben de gemonitorde koelmachines geen roetfilter, waardoor de fijnstofemissies naar verwachting minstens 10 keer hoger zijn dan die van een moderne vrachtwagen met roetfilter. Voor CO_2 emissies is de bijdrage van de koelmachines aan het totaal kleiner dan voor NO_x, met een ca. 15% bijdrage tijdens rijden in de stad.

Summary

In 2023, the Dutch Ministry of Infrastructure and Water Management presented an action plan for enhancing the sustainability of the temperature-controlled transport. To gain better insight into real-world exhaust gas emissions and the use of transport refrigeration units (TRU's) in conditioned road transport, the Ministry of Infrastructure and Water Management asked TNO to conduct research on this topic. This report provides an interim overview of the measurement results. The report also provides a preliminary estimate of the expected impact of the measurement results on the total emissions caused by TRU's in conditioned road transport in the Netherlands. The measurement program will continue until the end of 2024. The final report is expected in early 2025.

This study looked into the CO_2 and NO_x exhaust emissions of seven TRU's while they were used in real-world, everyday operation. The seven TRU's have been monitored 122 to 1787 hours of which one during the spring, three from winter/spring till summer, two from summer to winter and one from autumn till spring. Apart from the emissions, this study also provides information on daily run-time.

Five of the seven TRU's have modern 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's 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's have an engine power slightly below 19 kW. Below 19 kW no particulate filter is needed, also no advanced NO_x-reduction technologies are necessary. Tightening of (European) emissions legislation is needed to significantly reduce emissions from diesel-powered TRU's in this power category on a large scale

The average annual usage of the seven monitored TRU's is 900 hours, which only includes usage where the diesel engine is on. This average is based on 861 days of monitoring data from TRU's in normal operation. However, there is considerable variation in usage between the different TRU's. For some individual TRU's, 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 TRU's cool for a significant portion of the time (up to 75%) without the diesel engine running. These TRU's are likely connected to the power grid during stand-still. Another possible cause of the variation could be the type of usage, which is being further investigated in the ongoing research. Additionally, further data on operational characteristics is currently being collected.

The combined average tailpipe NO_x-emission of the monitored TRU's is 39 grams per hour, with many of them clustering around this value. The average tailpipe CO_2-emission is 5.7 kg per hour. The results roughly align with the previous measurement campaigns on two TRU's, but are now more robust, with data from seven TRU's in total. Based on the (limited) insights available at the time, the average emission from TRU's 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, it is expected that 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 TRU’s will be lowered. The preliminary proposal is to reduce this to 39 grams of NO_x per hour. As a result of these adjustments, it is expected that the current estimate of 4.6 kton of NO_x emissions from cooling units on the road will be reduced by more than a factor of two. For CO_2 emissions (0.3 Mton), no significant change is expected due to the measured emissions. No particulate matter measurements have yet been conducted within this study. The proposed emission factors and the total emissions are preliminary and have not yet been confirmed by the taskforce on traffic and transport of the Netherlands’ Emission Registration.

As described above, the annual intensity of usage varies significantly between the monitored TRU’s. So far, no adjustments have been made to the usage characteristics in emission modelling, which may present an uncertainty in the calculated emission totals.

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 TRU’s. 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, 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 TRU’s. The monitored Stage V and Stage IIIA TRU’s have the same emission limits and show similar NO_x emissions, averaging around 5.5 g/kWh. However, there are three Stage V TRU’s that show 15–25% lower NO_x emissions than the average.

Compared to modern Euro VI trucks, the NO_x emissions from TRU’s 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. Moreover, there is no particulate filter on the monitored TRU’s, hence the particulate emissions are expected to be at least 10 times higher than a modern truck with a diesel particulate filter. For CO_2 emissions, the contribution of the TRU to the total is lower than for NO_x, approximately 15% during city-driving.

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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. Today, some 55000 transport refrigeration units (TRU's) on road vehicles are registered in the Netherlands to perform this task.

To guarantee that cargo can be kept at the required thermal conditions during transport, cooling vans, trucks and trailers are fitted with so-called transport refrigeration units (TRU's).

Conventional systems have their own autonomous diesel engine. Hybrid systems use - depending on the type - power from an autonomous diesel engine, the vehicle's main engine or shore power to electrically propel the cooling system. TRU's with their own diesel engine have the merit, that in case of parking or standing still of the vehicle, the cooling unit 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. Although the number of pure electrical engines in TRU's is growing, most of them still rely on the power of a diesel engine.

The autonomous engines are mostly small, relatively simple and low-powered diesel engines, which do not fall under a strict regime regarding emissions regulation. While some research has been carried out on the emissions of aux TRU's 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-TRU's, however, indicated that the exhaust emissions of auxiliary transport refrigeration units are still relatively high and have not improved much over the last years [TNO 2021[1] and TNO 2022[2]].

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/hr in city delivery, the truck would then emit 80 grams of NO_x every hour. Existing (earlier) measurements on a limited number of TRU's indicate that they emit around 40 grams of NO_x per hour [1] [2]. 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.

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[1] 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

[2] 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

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 TRU's, hence the particulate emissions are expected to be at least 10 times higher than a modern truck. 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.

In 2023, the Dutch Ministry of Infrastructure and Water Management presented an action plan for enhancing the sustainability of the temperature-controlled transport[3]. To gain better insight into real-world exhaust gas emissions and the use of transport refrigeration units (TRU's) in conditioned road transport, the Ministry of Infrastructure and Water Management asked TNO to conduct research on this topic. This report provides an interim overview of the measurement results. The report also provides a preliminary estimate of the expected impact of the measurement results on the total emissions caused by TRU's in conditioned road transport in the Netherlands. The measurement program will continue until the end of 2024. The final report is expected in early 2025.

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 can be proposed. These (preliminary) emission factors are then used to estimate the total NO_x and CO_2 emissions associated to temperature-controlled road transport in the Netherlands. Particle emissions are not part of this study; they will be assessed at a later stage. The real-world emission- and usage data is used to determine evidence-based emission factors. The emission factors the value for the average emissions per machine used to estimate the total emissions from conditioned road transport in the Netherlands

1.3 Approach

Usage and emissions data is collected in a dedicated emissions measurement programme for TRU's. 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 TRU's. Depending on the vehicle and/or cooling unit configuration, TNO installed an autonomous emissions measurement and vehicle data collection system called SEMS either on the refrigeration unit or on the truck or van. 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 weeks or even 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

1.4 Reader's guide

This report is structured as follows. First, chapter 2 will provide information on the way TRU's are registered in the Netherlands, on how their emissions are regulated and on the now available studies into their emissions.

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

Chapter 3 will then describe which TRU's 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 assistance during the measurement programme.

2 Background information

2.1 Registration 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 (summer 2024) there are just under 55 thousand vehicles with a cooling unit registered of which:

- ~36000 semi-trailers
- ~10000 trucks
- ~3500 trailers
- ~5500 vans

2.2 Emission regulation of TRU engines

Engines of auxiliary transport refrigeration units as fitted to vans, trucks and trailers fall under the so-called non-road mobile machinery (NRMM) as far as emission legislation is concerned. Emissions of refrigeration units' diesel engines must comply with the EU NRMM Regulation 2016/1628[4]. Table 1 and Table 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 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
Stage IV	n/a	n/a
Stage V	7.5* g/kWh	4.7* g/kWh
*The limit applies for HC+NO_x		

[4] 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

Table 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 emission

As stated in the introduction not many studies into the emissions of TRU's exist.

In the United Kingdom, the Zemo Partnership performed a series of studies into the emissions of TRU's. 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 auxTRU's consume around 235 million liters of fuel per annum (uncertainty margin is +-100 million litres, because low number auxTRU's+low run hours versus high number+high hours) [5]. 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 TRU's in real operation, in 2021 and 2022. Annex B provides a short summary of these studies[6] [7]. The emissions found in both studies were at a comparable level.

[5] 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

[6] 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

[7] 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 Measurement programme

3.1 Vehicles and cooling units measured

In total seven TRU's have been monitored with emission measurement equipment during normal daily operation by the transport company. These seven TRU's include the two TRU's which were measured in 2021[6] and 2022[7]. All TRU's have a (small) diesel engine without advanced emission reduction technology. Three different brands are measured, with two of them being predominant among the participating TRU's. To ensure the representativeness of these TRU's, a market analysis will be necessary. Table 3 shows the name, ID, engine manufacturer, emission class, rated power and type of vehicle of each TRU. These machines should be monitored over a long period of time to cover seasonal effects and to get a good insight of the real-world operations. At the time of writing, the gathered monitoring data is not yet sufficient to provide sound insights on seasonal effects. The TRU's have been or will continue to be measured in normal operating conditions and mostly cover different types of trips and all available modes: chilled mode, frozen mode and multi-temp mode.

Table 3: 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_250_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	<19	Cooling unit on semi-trailer

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)[8]. 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 TRU's 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, the system 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. The MAF-sensor measures the intake flow, which allows for the calculation of the exhaust gas flow. 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

TRU's are often connected to a telematics system (data from the TRU which is available online for the owner), 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 4, data of four machines is available, however in small quantities for three of them. A request has been made to the owners for more telematics data. The current available telematics data shows that data is logged at an irregular basis and at a lower frequency than TNOs SEMS (1Hz). 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 4: Availability of telematics per TRU.

Cooling unit	TRU ID	Telematics data availability
Thermoking SLXi Spectrum	TH_250_STAIID	Data requested
Mitsubishi TU100SAE-CNE	MI_TU_STAIIIA	Data requested
Thermoking SLXi 300 Whisper Pro	TH_300_STAV	Data from 28-8-2023 to 3-3-2024. Update requested
Carrier Vector 1550 City	CA_1550_STAV	Data from 26-7-2023 to 28-3-2024. Update requested
Carrier Supra 1150 MT	CA_SUP01_STAV	Data from 7-4-2024 to 23-4-2024. Update requested
Carrier Supra 1150 MT	CA_SU_STAV	Data from 7-4-2024 to 23-4-2024. Update requested
Thermoking Advancer A500	TH_A500_STAV	Data requested

[8] 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, where possible, combined with telematics data from the TRU's. 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 July 2024 are described. The results of the two TRU's 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 seven TRU's have been monitored 122 to 1787 hours of which one during the spring, three from winter/spring till summer, two from summer to winter and one from autumn till spring. Table 5 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 speed, 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), represents all the data that was captured with the SEMS.

Table 5 shows that most of TRU's are cooled for a significant share of time (up to 75%) via an external source. The first TRU in the table 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'.

table 5 also shows that the average ambient temperature during the monitoring period of most of the TRU's is between 13 and 15 °C. The second TRU covers the coldest ambient temperatures and the least solar radiation. The TRU's with the highest solar radiation have been monitored during spring and summer. In a later stage the impact of ambient conditions on emissions will be included in the analysis.

Figure 4.2 shows the operation per active calendar day for the TH_300_STAV (Thermoking SLXi 300 Whisper Pro), 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 24 hours, and the share with engine on varies between 0 and 100%. More data from telematic systems are requested at the participants, in a later stage these data will be included in the data-analysis.

Table 5: Operational characteristics of the monitored cooling units, based on SEMS.

Cooling unit	TRU ID	Startdate	End date	Duration diesel engine on [h]	Duration total incl. diesel engine off [h]	Share of running diesel engine [%]	Speed [km/h]	T_ambient [degC] mean	Q_sun [J/cm²] mean
Thermoking SLXi Spectrum	TH_250_STAIID	17-12-2019	6-7-2020	1787	1787	100	42	-	-
Mitsubishi TU100SAE-CNE	MI_TU_STAIIIA	1-11-2021	9-5-2022	229	231	99	38	4	4
Thermoking SLXi 300 Whisper Pro	TH_300_STAV	14-9-2023	2-3-2024	216	481	45	32	10	23
Carrier Vector 1550 City	CA_1550_STAV	27-7-2023	27-2-2024	317	457	69	37	11	45
Carrier Supra 1150 MT	CA_SUP01_STAV	8-4-2024	28-6-2024	69	122	57	43	13	72
Carrier Supra 1150 MT	CA_SU_STAV	9-4-2024	18-6-2024	73	175	42	44	13	61
Thermoking Advancer A500	TH_A500_STAV	28-5-2024	4-7-2024	40	206	19	40	15	70

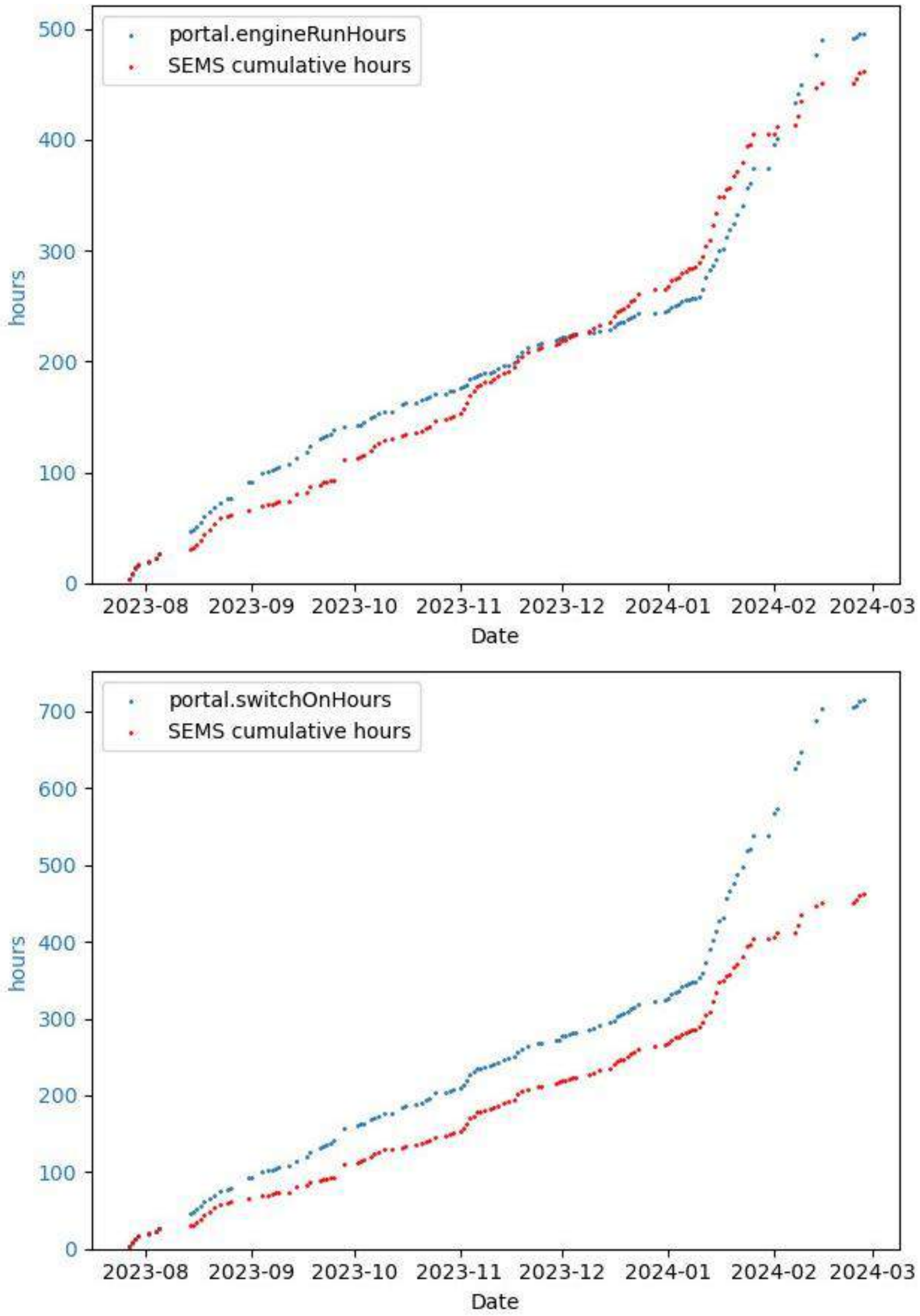


Figure 4.1: Example of cumulative operating hours of the CA_1550_STAV (Carrier Vector 1550 City) from the start of the measurement campaign. The telematics data reports similar hours with a running diesel engine. For this TRU the SEMS does not log all active TRU hours while the diesel engine is off.

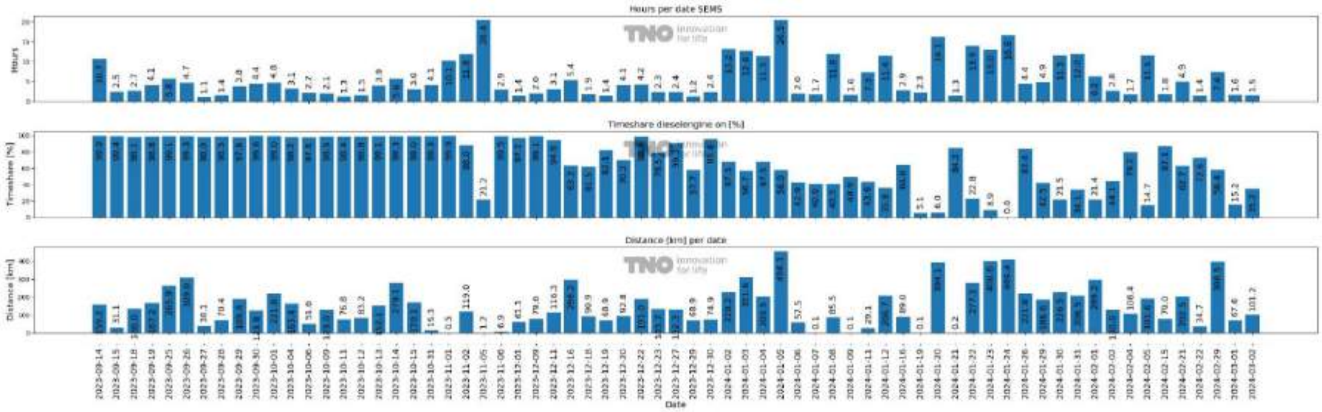


Figure 4.2: Example of operation per active calendar day for the TH_300_STAV (Thermoking SLXi 300 Whisper Pro).

4.2 Emissions

4.2.1 Diesel TRU's

For each measured TRU, the cumulative emissions and the average emissions per hour for NO_x and CO_2 are shown in Table 6. Cumulative emissions deviate significantly from each other since one TRU is monitored for more hours than the other. Moreover, some TRU's demand a higher engine load, which increases the fuel consumption and absolute NO_x and CO_2 emissions. To compare the emission levels of the different TRU's 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 6. The Stage II TRU (TH_250_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 TRU's (see Table 7). The monitored Stage V and Stage IIIA TRU's have the same emission limits. Table 6 shows that the NO_x/CO_2-ratio of the monitored Stage V and Stage IIIA TRU's are om same order of magnitude. However, there are three TRU's which show lower emissions than the rest.

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 6: 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	Duration diesel engine on [h]	CO_2 [t]	NO_x [kg]	NO_x/CO_2 [ppm/%]	Estimated average engine load [%]
Thermoking SLXi Spectrum	TH_250_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	216	1.6	8.4	56	50-55%
Carrier Vector 1550 City	CA_1550_STAV	317	2.0	16.2	81	45-50%
Carrier Supra 1150 MT	CA_SUP01_STAV	69	0.47	2.7	57	80-95%
Carrier Supra 1150 MT	CA_SU_STAV	73	0.42	2.4	58	70-80%
Thermoking Advancer A500	TH_A500_STAV	40	0.18	1.4	83	25-30%

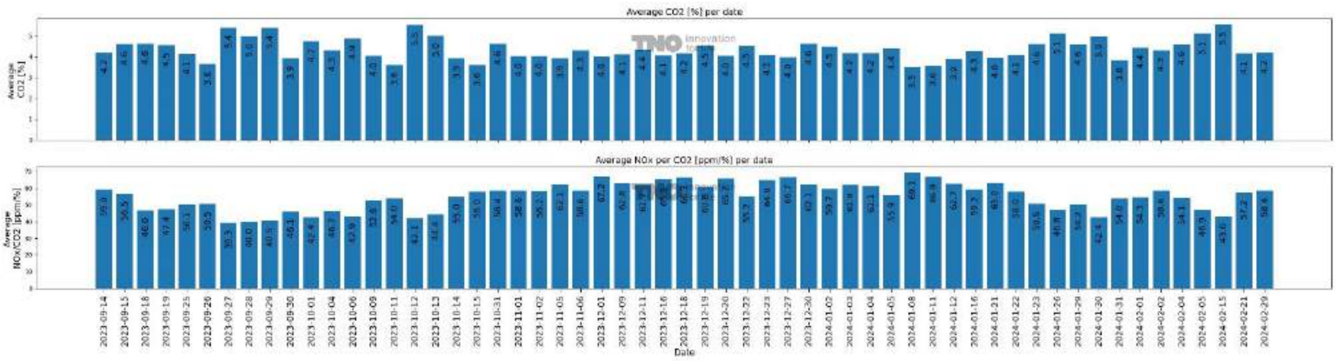


Figure 4.3: CO_2 and NO_x/CO_2 emissions per active calendar day for the TH_300_STAV.

Table 7 below show the emission levels of each TRU in a different way than above. At first a comparison is made with the legislative European NO_x emission limits during type approval (see Table 1), which is given in grams per kWh. The emission limit applies during type approval at specific engine load points with a certain weighting, whereas during emission monitoring in this study, all usage 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. The TH_250_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 TRU's stay below the levels of the type approval limits for both the Stage IIIA and Stage V TRU's.

Secondly, the results are given in grams per hour. This is a relevant parameter to calculate total emissions, per day or even per year, if the running hours are known. These numbers are also part of the basis for the calculation of the total 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. For example, the Stage IIIA and some Stage V TRU's 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 TRU's. The average NO_x emissions of the monitored TRU's are 39 grams per hour, with many of them clustering around this value.

Table 7: 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.

Cooling unit	TRU ID	HC+NO_x Emission limit [g/kWh]	NO_x [g/kWh]	CO_2 [kg/h]	NO_x [g/h]
Thermoking SLXi Spectrum	TH_250_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	3.9 – 4.6	7.5	39
Carrier Vector 1550 City	CA_1550_STAV	7.5	6.0 – 7.0	6.4	51
Carrier Supra 1150 MT	CA_SUP01_STAV	7.5	4.3 – 5.0	6.5	38
Carrier Supra 1150 MT	CA_SU_STAV	7.5	4.4 – 5.1	5.5	33
Thermoking Advancer A500	TH_A500_STAV	7.5	5.8 – 6.8	4.2	34

*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 in 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 the 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 TRU's, although the effect is most pronounced in the TH_300_STAV.

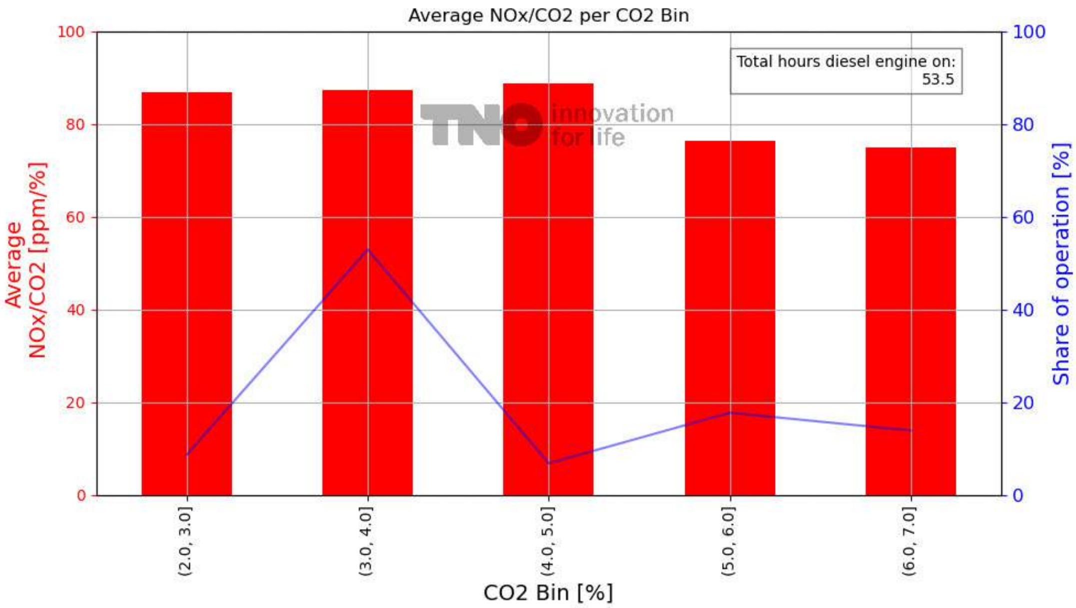


Figure 4.4: The average NO_x per CO_2 [ppm/%] of the TH_A500_STAV (Thermoking Advancer A500) as a function of the CO_2 [%] concentration and the share of operation within each CO_2 bin.

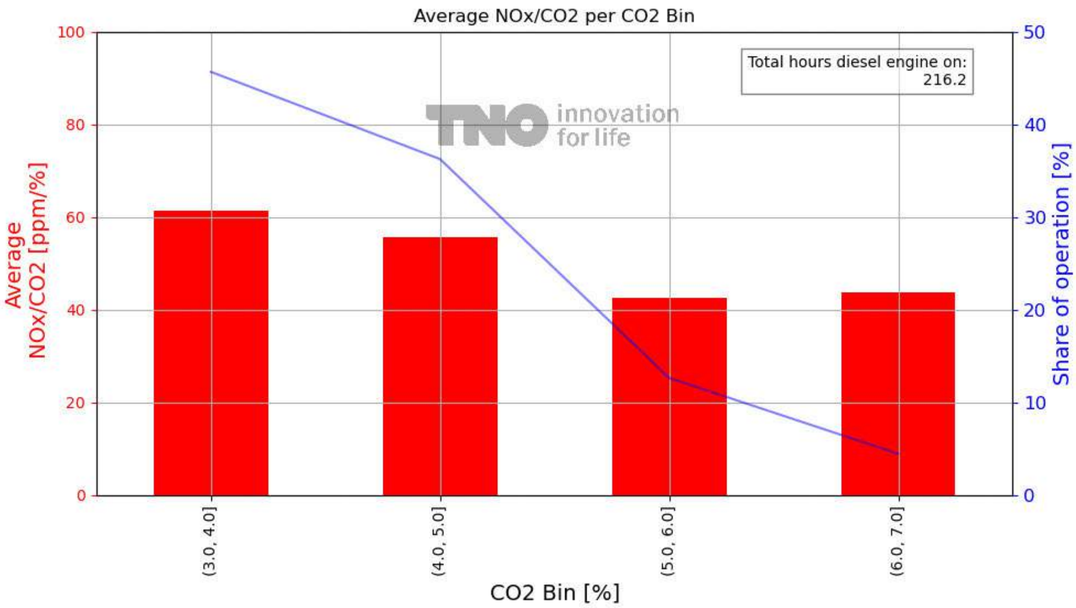


Figure 4.5: The average NO_x per CO_2 [ppm/%] of the TH_300_STAV (Thermoking SLXi 300 Whisper Pro) as a function of the CO_2 [%] concentration and the share of operation within each CO_2 bin.

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 in Annex C. Significant variations in daily absolute emissions have been observed, and the underlying causes of these fluctuations are being further investigated.

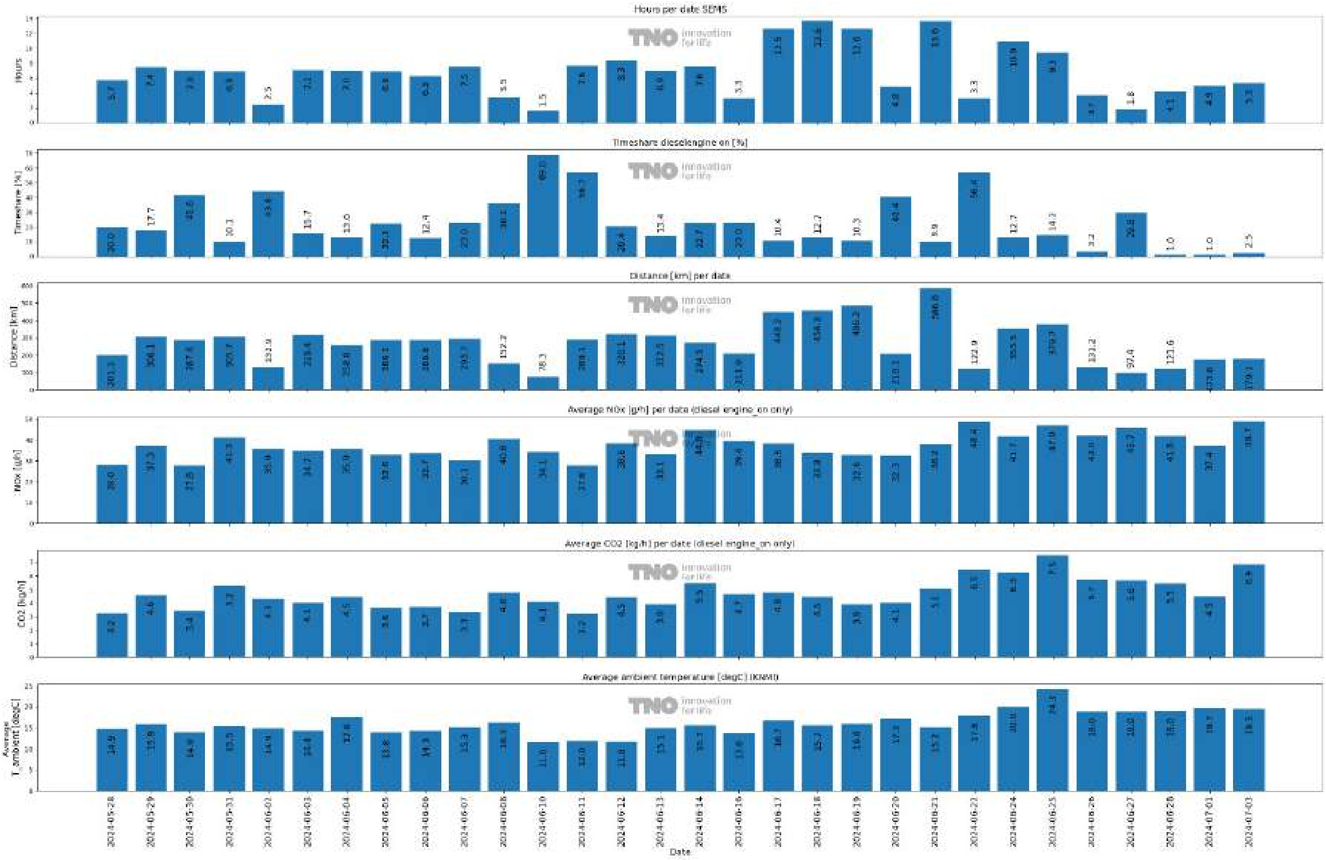


Figure 4.6: An overview of daily averages for the TH_A500_STAV (Thermoking Advancer A500).

5 Emissions of temperature-controlled transport in the Netherlands

5.1 Fleet

In Table 8 the estimated number of TRU's 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.

Table 8: Number of TRU's per vehicle type in the Netherlands from Statistics Netherlands (CBS).

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

5.2 Operating hours

The seven monitored TRU's gives insight in their operational characteristics. As show in Table 9, the average annual usage of the seven monitored TRU's is approximately 900 hours, which only includes usage where the diesel engine is on. This average is based on 861 days of monitoring data from TRU's in normal operation.The data consist of 2731 hours of 'active data', where 'active data' refers to data with a switched on diesel engine, which is relevant in the light of the emission factors.

However, there is significant variation between the different TRU's. As described in paragraph 4.1, daily active hours (with the diesel engine on) range from less than 1 hour to as much as 24 hours for some of the individual TRU's within the monitoring period.

Part of this variation is explained by the fact that some TRU's cool for a significant portion of the time (up to 75%) without the diesel engine running. These TRU's are likely connected to the power grid during stand-still. Another possible cause of the variation could be the type of usage (such as long haul versus city delivery), which is being further investigated in the ongoing research. Additionally, further data on operational characteristics is currently being collected. As the annual intensity of usage varies significantly between the monitored TRU's, no adjustments have been made to the usage numbers for emission modelling, which may present an uncertainty in the calculated emission totals.

Table 9: 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_250_STAIID	206	164	1787	10.9	3166
Mitsubishi TU100SAE-CNE	MI_TU_STAIIIA	81	41	229	5.6	1032
Thermoking SLXi 300 Whisper Pro	TH_300_STAV	170	79	216	2.7	464
Carrier Vector 1550 City	CA_1550_STAV	215	128	317	2.5	538
Carrier Supra 1150 MT	CA_SUP01_STAV	81	27	69	2.6	311
Carrier Supra 1150 MT	CA_SU_STAV	71	31	73	2.4	375
Thermoking Advancer A500	TH_A500_STAV	37	33	40	1.2	395
Total / average		861	503	2731	4 [h/day]	897 [h/yr]

5.3 Emission factors

TNO annually establishes emission factors for – amongst others - road traffic in collaboration with the Netherlands Environmental Assessment Agency (PBL)[9]. 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 TRU's have been reported in the Dutch Emission Inventory. Based on the (limited) insights available at the time, the average emission from TRU's 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 TRU's. Since the measurements on the TRU's provide numbers on NO_x and CO_2 emissions solely, these two components are determined. The combined average NO_x-emissions of the monitored TRU's are 39 grams per hour, with many of them clustering around this value.

[9] https://publications.tno.nl/publication/34642685/NeSvgNye/TNO-2024-R11049.pdf

The average CO_2-emission is 5.7 kg per hour. 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. Based on the measurement results, it is expected that the current emission factor for NO_x emissions from TRU's will be lowered. As shown in Table 10, the preliminary proposal is to reduce this to 39 grams of NO_x per hour. For CO_2 there are no significant changes foreseen with the emission factor of 5.7 kilograms CO_2 per hour. The new emission factors are preliminary and are not yet been set by the taskforce on traffic and transport of the emission inventory.

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 TRU's themselves is not registered. For this analysis, Stage V and Stage IIIA TRU's 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. 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 TRU's. To ensure the representativeness of these TRU's, a market analysis will be necessary.

Table 10: Preliminary emission factors, based on real-world measurements on seven transport cooling units.

Emission	Factor
NO_x	39 [g/h]
CO_2	5.7 [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 TRU's. So far, no adjustments have been made to the usage characteristics in emission modelling, which may presents an uncertainty in the calculated emission totals.

figure 5.1 shows the calculated preliminary emissions compared to the emissions currently registered in the national emission inventory[10]. The total emissions for 2022 are reduced from 4.6 kton to 1.8 kton NO_x. For CO_2 emissions (0.3 Mton), no significant change is expected due to the measured emissions. Note that the proposed total emissions are preliminary and have not yet been set by the taskforce on traffic and transport of the emission inventory.

[10] Emissieregistratie.nl

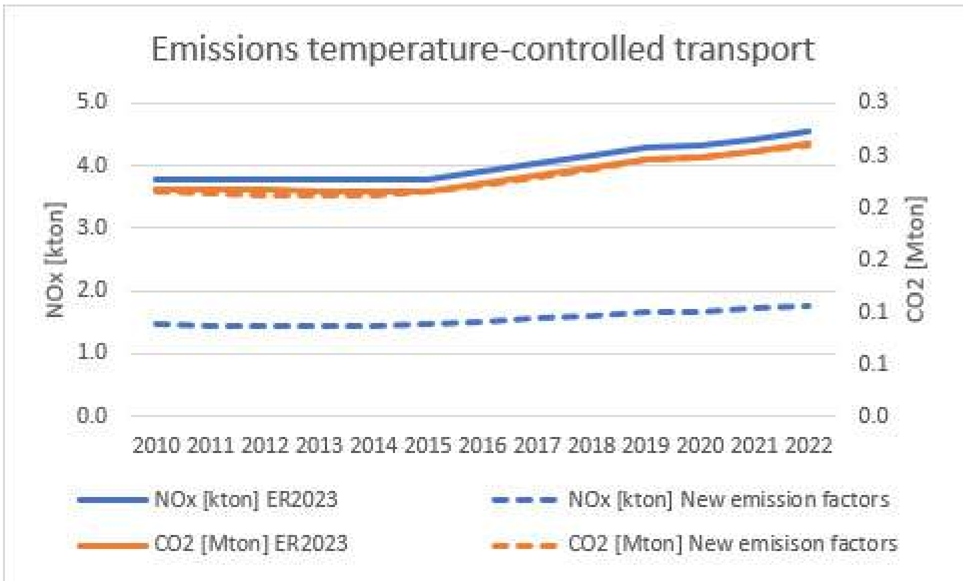


Figure 5.1: Preliminary emissions of temperature-controlled transport in the emission inventory compared to the new emission factors

6 Conclusions

This study looked into the CO_2 and NO_x exhaust emissions of seven TRU's while they were used in real-world, everyday operation. The seven TRU's have been monitored 122 to 1787 hours of which one during the spring, three from winter/spring till summer, two from summer to winter and one from autumn till spring. Apart from the emissions, this study also provides information on daily run-time.

Five of the seven TRU's have modern 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's 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's have an engine power slightly below 19 kW. Below 19 kW no particulate filter is needed, also no advanced NO_x-reduction technologies are necessary. Tightening of (European) emissions legislation is needed to significantly reduce emissions from diesel-powered TRU's in this power category on a large scale

The average annual usage of the seven monitored TRU's is 900 hours, which only includes usage where the diesel engine is on. This average is based on 861 days of monitoring data from TRU's in normal operation. However, there is considerable variation in usage between the different TRU's. For some individual TRU's, 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 TRU's cool for a significant portion of the time (up to 75%) without the diesel engine running. These TRU's are likely connected to the power grid during stand-still. Another possible cause of the variation could be the type of usage, which is being further investigated in the ongoing research. Additionally, further data on operational characteristics is currently being collected.

The combined average tailpipe NO_x-emission of the monitored TRU's is 39 grams per hour, with many of them clustering around this value. The average tailpipe CO_2-emission is 5.7 kg per hour. The results roughly align with the previous measurement campaigns on two TRU's, but are now more robust, with data from seven TRU's in total. Based on the (limited) insights available at the time, the average emission from TRU's 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, it is expected that 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 TRU's will be lowered. The preliminary proposal is to reduce this to 39 grams of NO_x per hour. As a result of these adjustments, it is expected that the current estimate of 4.6 kton of NO_x emissions from cooling units on the road will be reduced by more than a factor of two. For CO_2 emissions (0.3 Mton), no significant change is expected due to the measured emissions. No particulate matter measurements have yet been conducted within this study.

The proposed emission factors and the total emissions are preliminary and have not yet been confirmed by the taskforce on traffic and transport of the Netherlands' Emission Registration.

As described above, the annual intensity of usage varies significantly between the monitored TRU's. So far, no adjustments have been made to the usage characteristics in emission modelling, which may present an uncertainty in the calculated emission totals.

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 TRU's. 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, 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 TRU's. The monitored Stage V and Stage IIIA TRU's have the same emission limits and show similar NO_x emissions, averaging around 5.5 g/kWh. However, there are three Stage V TRU's that show 15–25% lower NO_x emissions than the average.

Compared to modern Euro VI trucks, the NO_x emissions from TRU's 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. Moreover, there is no particulate filter on the monitored TRU's, hence the particulate emissions are expected to be at least 10 times higher than a modern truck with a diesel particulate filter. For CO_2 emissions, the contribution of the TRU to the total is lower than for NO_x, approximately 15% during city-driving.

Signature

TNO ⟩ Mobility & Built Environment ⟩ Den Haag, 16 September 2024

[redacted]

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[11].

Outline of the study:
- Methodology and Scope: The research expands beyond transport refrigeration units (TRU's) to include other auxiliary heavy goods vehicle (HGV) engines. It covers emission testing of conventional diesel auxiliary TRU's 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 "real-world conditions". 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 TRU's 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 auxTRU's consume around 235 million liters of fuel per annum (uncertainty margin is +-100 million litres, because low number auxTRU's+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 1/10th the fuel, produce respectively 1/9th and 1/10th 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).

[11] 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[12]

Outline:
- Methodology and Scope: The study undertook the development and validation of an emissions test protocol tailored for auxiliary Transport Refrigeration Units (auxTRU's) 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 auxTRU's in 2021. The focus was to gauge the environmental impact of auxTRU's, given their crucial role in the cold chain distribution systems of heavy goods vehicles (HGVs).
- Measurement Approach: To simulate "real-world conditions", 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 auxTRU's.
- Types of Refrigeration Units/Vehicles/Trailers: The analysis specifically targeted truck or trailer-mounted auxTRU's 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 auxTRU's. 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 auxTRU's 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 a single **diesel auxTRU fitted to a Euro VI HGV** would: Consume 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 auxTRU's, contributing additional emissions. The percentages of all individual emissions are given in bold under the header "Emissions".

[12] 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[13] and TNO 2022[14]], two TRU's 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 TRU's 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 11. 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 NO_x emissions are comparable in order of magnitude to the emissions of a modern truck and the particulate emissions are at least 10 times higher.

[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. http://resolver.tudelft.nl/uuid:a1c81fc2-3ad6-4020-a405-bf8d99830fbe

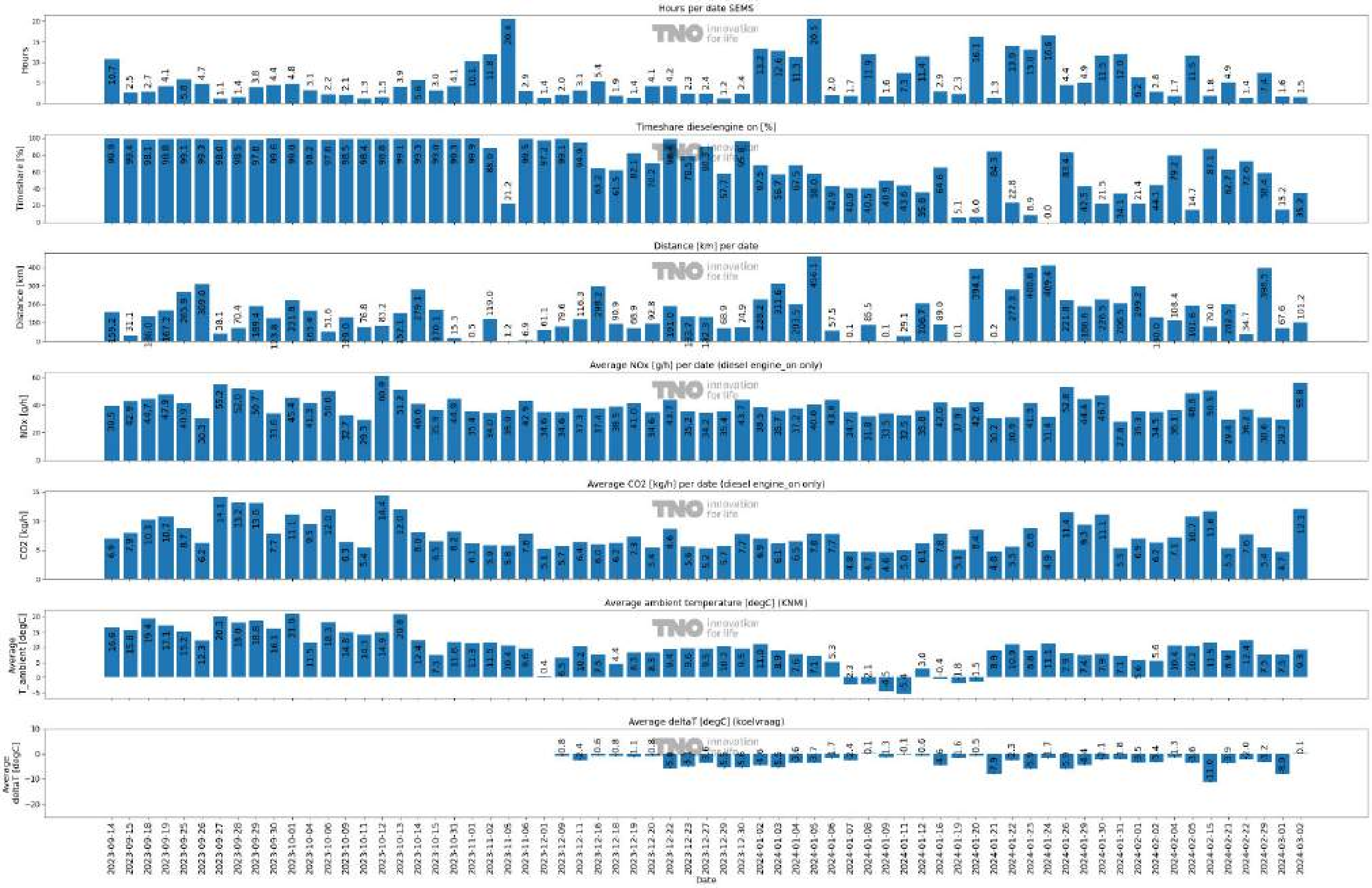
[14] Robin Vermeulen, René van Gijlswijk, Pierre Paschinger, Jessica de Ruiter, *Dutch In-service Emissions Measurement and Monitoring Programme for Heavy-Duty Vehicles 2021*, TNO 2022 R10375, 28 February 2022. http://resolver.tudelft.nl/uuid:aa5ee8b5-d84e-49c2-8d7c-c13761381f8e

Table 11: Overview of TRU specifications and real-world emissions measured in the Netherlands.

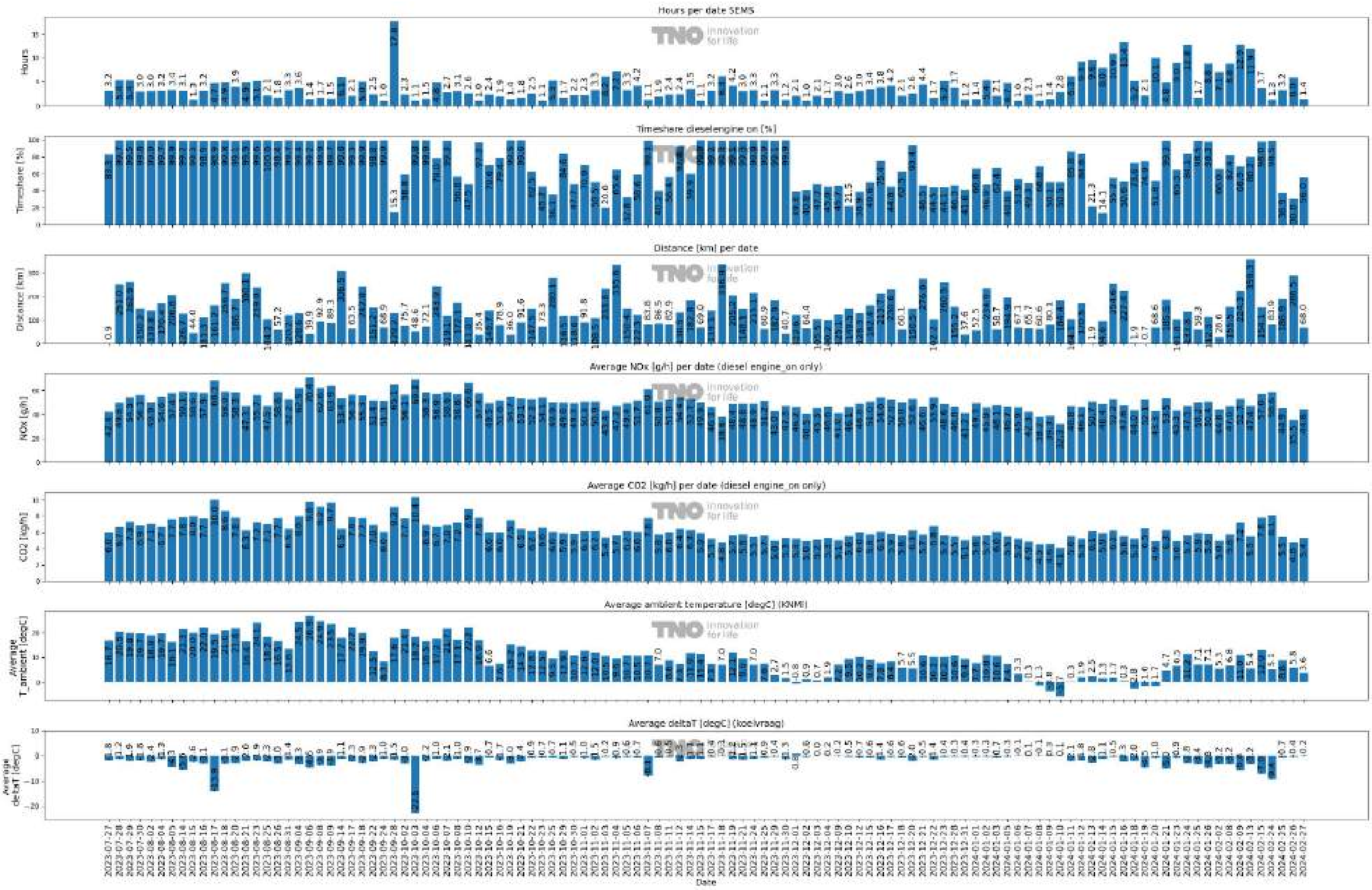
TNO test code	**MI_TU**	**TK_SL**
		
Brand, type	Mitsubishi TU100SAE-CNE Under body	Thermoking, SLXi spectrum Semi-trailer front mount Multi temp zones
Usage	Plants distribution, mainly mild temp (~5^{0}C)	Various purposes different cargo
	Engine: Yanmar, 3TNV76-XMR	Engine: Yanmar, TK486V
Configuration	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
Overviews per day

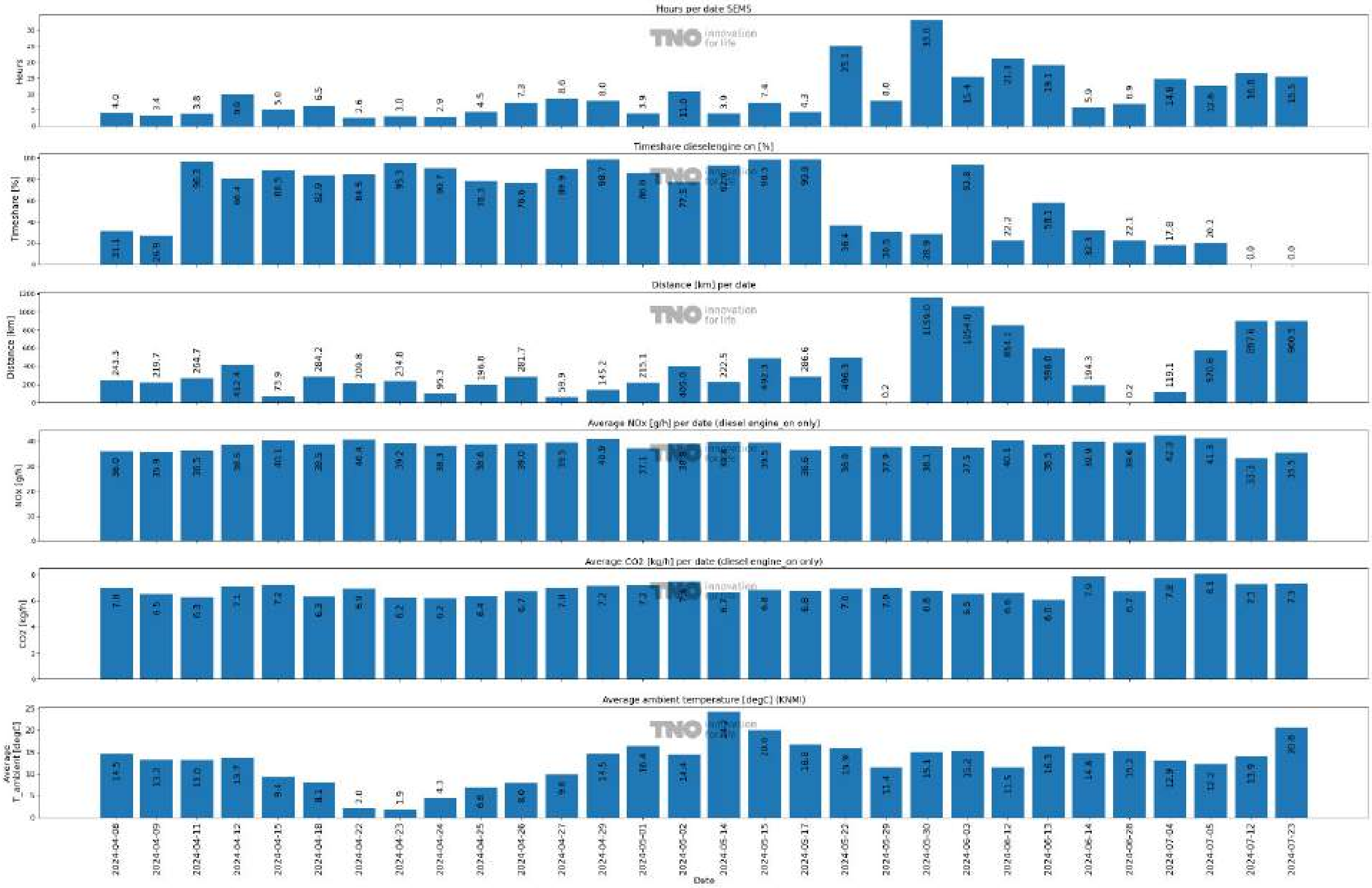
TH_300_STAV (Thermoking SLXi 300 Whisper Pro)



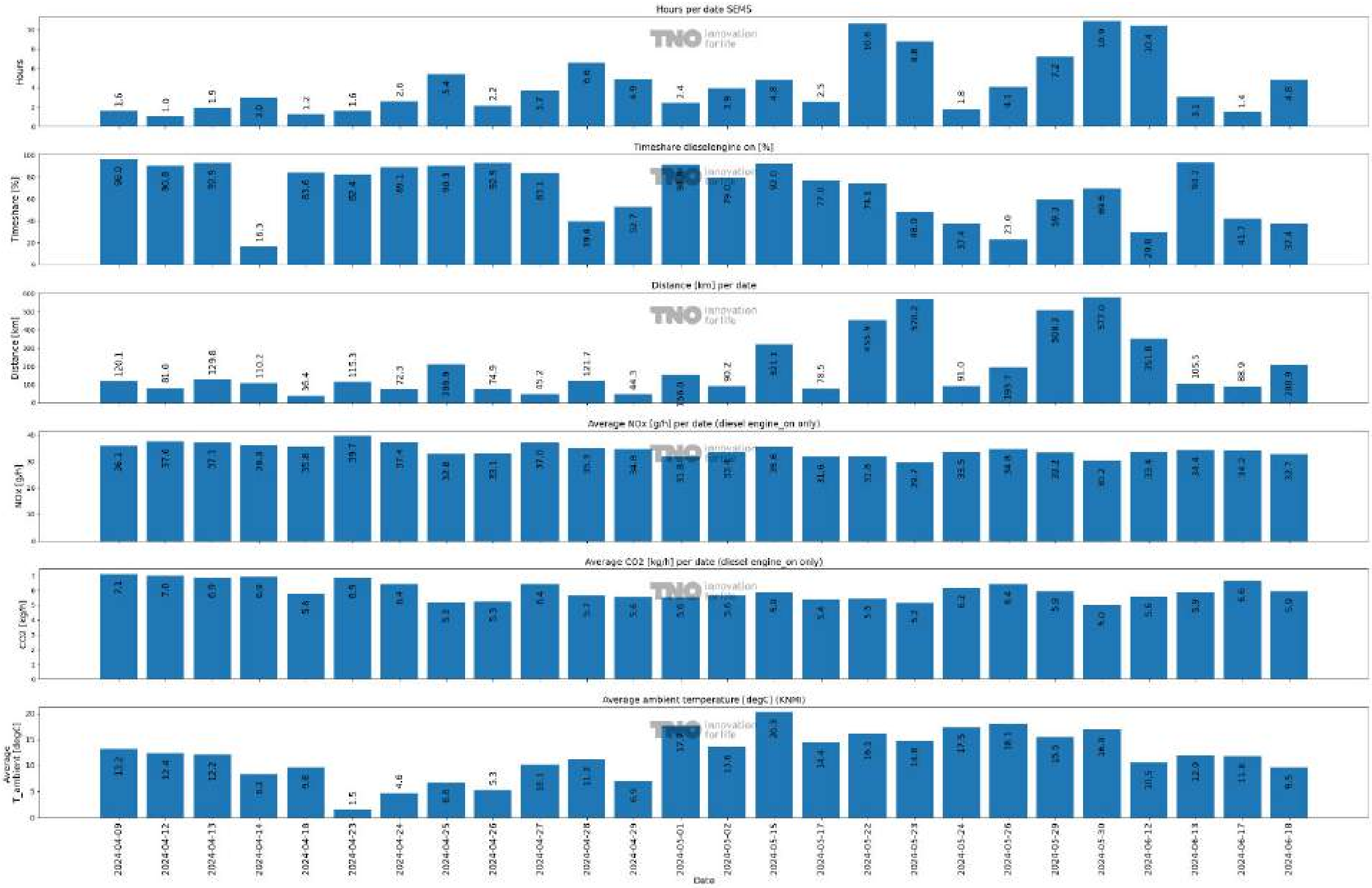
CA_1550_STAV (Carrier Vector 1550 City)



CA_SUP01_STAV (Carrier Supra 1150 MT)



CA_SU_STAV (Carrier Supra 1150 MT)



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