Traffic & Transport
Anna van Buerenplein 1
2595 DA Den Haag
P.O. Box 96800
2509 JE The Hague
The Netherlands

www.tno.nl

T +31 88 866 00 00

TNO report

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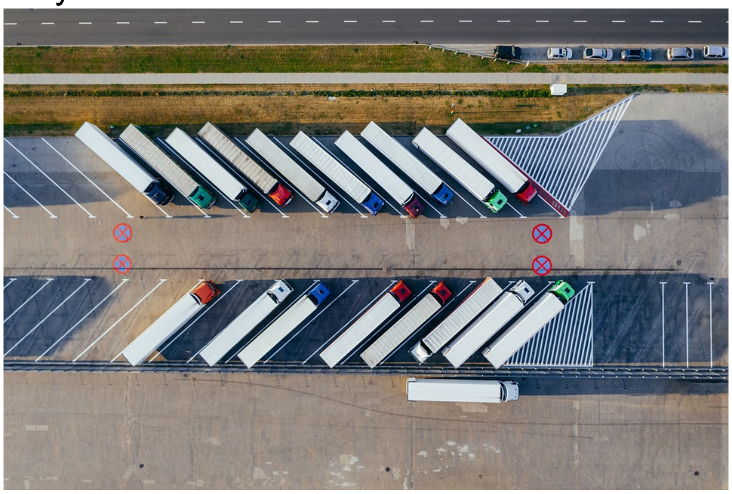
Yard Emission monitoring for Sustainability: Real-world measurements and outlook on Connected Automated Transport development for yards



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Author(s) TNO	Elisah van Kempen, Nico Deschle, Ernst Jan van Ark, Mitch Elsgeest
Author(s) HAN	Frank Ahout
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Summary

Technological advancements are enabling higher levels of automation of vehicles and as such Connected and Automated Transport (CAT). This is an umbrella term for transport with increasing levels of automation facilitated by communication among vehicles (vehicle-to-vehicle or V2V) and infrastructure (vehicle-to-infrastructure or V2I). Especially confined areas such as ports and terminals offer favourable environments for deploying automated trucking applications in the short term. CAT holds potential for improving sustainability and efficiency on yards, yet current baseline yard emission data is lacking. Therefore, **this research aims to identify the potential impact of Connected and Automated Transport on reduction of emissions for freight transport at and to/from yards.**

Approach
For identifying this potential impact we establish baseline measurements of current transport at yards. Specifically the study consists of three parts:

- Real-world monitoring (operational use and CO_2, NO_x emissions) of a terminal tractor operating in an industrial port area and a terminal tractor operating at a logistics site for a period of approximately 3 months;
- Analysis of (6 month) data provided by an OEM's telematics platform (DAF Connect) to assess the extent of congestion of trucks near yards and the related fuel consumption and CO_2 emissions while idling;
- Putting the results in perspective by providing an outlook: comparison of single vehicle measurements with long-haul transport and description of boundary conditions for electrification of autonomous yard vehicles.

Findings
- Using the Smart Emissions Measurements System (SEMS) it is possible to monitor real-world logistics operations and emissions of terminal tractors.
    - Operational usage of the industrial area terminal tractor and on-site terminal tractor are different. For both vehicles, most of the time the vehicles are idling or operating with low engine load and idling accounts for a relatively large proportion of CO_2 and NO_x emissions.
- With the DAF Connect data it was possible to derive turnaround times and variation in these times for the different yards. Also estimated CO_2 emissions from trucks idling at yards were derived. Within the yards, however, the expected variations in turnaround times and peak congestion hours are not observed. Surprisingly, this does not reflect the experiences in the sector (as resulting from consortium discussions, sector publications, and other initiatives that aim to tackle congestion near port terminals). We have not found a logical explanation yet for this discrepancy;
- In comparison with operations of a long-haul truck, emissions of a terminal tractor are relatively high (especially on NO_x), and these are mainly emitted in a dense local area.

Value
This is the first study that makes real-world emission measurements on terminal tractors in their logistics operation.

Also it is rather unique how a OEM telematics platform (DAF Connect) was applied for analysis of trucks at yards. Both analyses provide a baseline measurement for logistics operations and emissions at yards. This can be used as input for further research on scaled-up scenarios of the deployment of Connected Automated Transport at yards and its impact on emission reduction and efficiency improvement.

Keywords
Connected Automated Transport; yards; real-world emissions; CO_2; NO_x; terminal tractors; DAF Connect

Contents

1 Introduction

1.1 Background and context

Connected Automated Transport (CAT) holds potential for improving sustainability and efficiency on yards, yet current baseline yard emission data is lacking

Technological advancements are enabling higher levels of automation of vehicles (Shuttleworth, 2019). Especially off-road, confined areas such as ports and terminals offer more favourable environments for deploying automated trucking applications in the short term (Engström, et al., 2019). This view is also confirmed by the ERTRAC Roadmap for Connected Automated Driving as the automation development path is envisioned to progress from high automation (Level 4) at confined areas, to hub-hub operations and ultimately open roads (ERTRAC, 2019).

Van Kempen et al. (2021) describe that Connected Automated Transport (CAT) and specifically automated vehicles or smart dollies at yards are not an aim in themselves, instead these can be a means towards achieving sustainability on and around yards.

Sustainability improvement by using autonomous vehicles - in combination with logistics concepts such as decoupling points - is expected in three ways:

- **Sustainable first and last mile at yards**. It is expected that smart dollies will have a fossil-free powertrain (e.g. Volvo Vera, Einride T-Pod). This leads to sustainable first- and last mile transport from and to yards if long-haul transport is decoupled at a decoupling point. This also leads to sustainable transport at the yard itself. See also Gerritse & Van Kempen (2022) as explored in this project as well.
- **Reduced congestion of in-and outbound transport at yards.** (Diesel) trucks do not have to wait/ idle unnecessarily before their cargo is handled at docks/ terminals when autonomous vehicles execute the last mile.
- **Sustainable long haul transport.** The development towards sustainable (electric) first/last mile transport to, from and at yards is expected to be an incentive for stronger and faster development of electric driving for the related long haul transport.

Next to that, yards at (air) port and business park areas face high unpredictability of the arrival and departure of trucks. This unpredictability leads to high inefficiencies and congestion problems. Van Kempen and Van Meijeren (2022) describe that CAT might also contribute to alleviating these congestion problems.

In order to assess the sustainability and efficiency potential of the above it is necessary to make a comparison with current emissions and congestion at yards. However, to date, it seems that *estimates* (rather than real-world data) for terminal tractor emission factors are used (e.g., Yu, et al., 2017) or relatively outdated information is used (e.g. the emission factors of the Californian Environmental Protection Agency (Soriano, 2006; Oonk, 2006)). By combining the above we aim to provide an outlook on the sustainability impact of automated vehicles or smart dollies when implemented at logistics yards.

We believe this links clearly to the developments regarding digitization and automation and the sustainability targets from the national and international climate agreements.

1.2 The YES Project in a nutshell

Identifying impact of Connected and Automated Transport on reduction of emissions for freight transport to, from yards

Given the context described in section 1.1, the following main research question is identified:

What is the impact of connected and automated transport on reduction of emissions (both CO_2 and pollutants) for freight transport to, from and at yards, including reduction of congestion and development towards electric driving?

Thus, the main goal of the YES project is to answer this research question, including the following sub-goals (SGs)

SG1. To analyse whether and why automated transport and electric driving go hand in hand (reported in (Gerritse & Van Kempen, 2022)).
SG2. To monitor real-world operation and emissions of terminal tractors.
SG3. To estimate the impact of clean, connected and automated transport to, from and at yards on reduction of emissions by analysing current levels of congestion of truck-trailer combinations at (air) port yards.
SG4. To give an outlook on the development of clean, connected and automated transport at yards.

The YES project is a top-up project of the CATALYST Living Lab. This Living Lab is aimed at developing and accelerating Connected Automated Transport innovations for efficient, safe and sustainable heavy-duty road transport (see www.catalystlab.nl). In the research line 'smart yards' in CATALYST it is examined through simulation whether and how autonomous vehicles, combined with logistics concepts – such as decoupling points – impact logistics at yards and the first/ last-mile towards these yards. The CATALYST simulations mainly aim to uncover which scenarios lead to reduced congestion of inbound and outbound transport of yards and improved efficiency and reliability of the first and last mile. The analysis that is conducted in YES will be a valuable addition in order to provide better insights with respect to the *sustainability* impacts of the various simulated scenarios.

YES is part of the research programme Sustainable Living Labs, which is co-financed by the Dutch Research Council (NWO), the Ministry of Infrastructure and Water Management, Taskforce for Applied Research (SIA) and the Top Sector Logistics. TKI Dinalog monitors the progress and the relation to the content of the innovation agenda of the Top Sector Logistics.

1.3 Aim of this report and reading guide

This report aims to provide insight in current baseline logistics operations and related real-world emissions of both terminal tractors and trucks travelling on and towards yards (Ch2-Ch3). Furthermore, in Ch4 we provide an outlook on what these real-world measurements mean compared to regular truck long-haul operations (see Figure 1). Chapter 5 provides the overall conclusions and recommendations for further research.

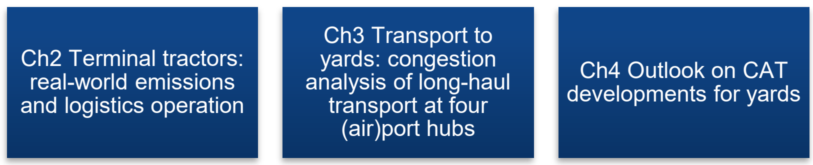

Figure 1: Reading guide

2 Terminal tractors: real-world emissions and logistics operations

2.1 Introduction and research aim

As outlined in section 1.1, there is a need to investigate the real-world emissions of terminal tractors in order to get a baseline measurement for establishing the sustainability potential at yards.

In this chapter we aim to answer the following research questions:

- *What are the emissions (CO_2, NO_x, PM10) of terminal tractors at logistics yards?*
- *What is the operational use of terminal tractors at logistics yards in terms of movements, load and workload (i.e. idling)?*

First, before we answer the research questions, we outline the methods in section 2.2. Subsequently we present the analysis for a terminal tractor at a logistics yard in section 2.3. This is followed in section 2.4 by the analysis for a terminal tractor that is used in an industrial (port) area. Results are summarized in section 2.5.

2.2 Methods

For gathering the data that is required for answering the research questions we use the Smart Emissions Measurement System (SEMS) (see Figure 2). This system was developed by TNO for the purpose of logging real-world emissions, that is vehicles in natural driving conditions (as opposed to a controlled, laboratory environment) (Vermeulen et al., 2014; Spreen et al., 2016). SEMS allows for monitoring vehicles in their day-to-day logistics and engine operations in order to retrieve realistic emission profiles.

SEMS gathers amongst others CAN-bus data (RPM, mass air flow, engine load, fuel rate) and sensor data (GPS-location, exhaust gas temperature, NO_x and PM concentration).

Figure 2: Example of the system installed on the vehicle. On the left, the SEMS central unit where the data is gathered and stored. On the right: the welding of the sensors on the exhaust.

For the current study, the SEMS was installed in two terminal tractors: a terminal tractor operating mainly on-site of a logistics service provider and a terminal tractor operating in the industrial port area of Moerdijk and thus travelling between different logistics locations.

The vehicles are chosen in agreement with the logistics service providers. For the purposes of our research (and especially as input for the outlook in Chapter 4), the vehicles are representative for the fleet of the specific logistics service providers.

2.3 Terminal tractor on-site

2.3.1 General vehicle characteristics and monitoring period

Table 1 summarizes the general vehicle characteristics of the terminal tractor that operates mainly on-site of a logistics service provider. The terminal tractor is monitored in real-world operations for a period of 18 weeks.

Table 1: Vehicle characteristics on-site terminal tractor

	
Vehicle	Kamag PM (WBH 25-E5)
Engine	Deutz TCD 4.1 L4
Emission legislation	Stage V
Weight	18.000 kg
Power (rated)	115 kW
Engine speed (rated)	2.300 rpm
Torque max (at 1500 rpm)	610 Nm
Speed limit [km/h]	25
Fuel	Diesel
Swept volume	4.038 L
# of cylinders	4
Exhaust gas aftertreatment	Exhaust Gas Recirculation Diesel Oxidation Catalyst Diesel Particulate Filter Selective Catalytic Reduction system
VIN	W09WB1003LUKB3175
Year of manufacturing	2019
Measurement period	27 Oct ‘21 – 4 Mar ’22 (18 weeks; 14 weeks data because of 4 week maintenance period 11 jan-10 feb)
Distance	5949 km
Total time	1242 h
Fuel used	4541 L

2.3.2 *Logistics operations*

Figure 3 presents the location history and speed of the on-site terminal tractor. It can be seen that the speed of the vehicle is higher (+- 20 km/h) when driving on the terrain (e.g., northside of the site). Vehicle speed is lower (0-5 km/h) when manoeuvring to the docks (majority of manoeuvres are performed at the southside docks of the site).

Specifically, it can be observed that the vehicle is typically waiting at three locations:

1. Docks near the employee parking deck (15% of all samples)
2. Parking space opposite of Westfield dock (16% of all samples)
3. The entire dock on the Westfields side (58% of all samples)

The remaining 11% of samples the vehicle is driving on other parts of the terrain and not at locations 1,2, or 3.

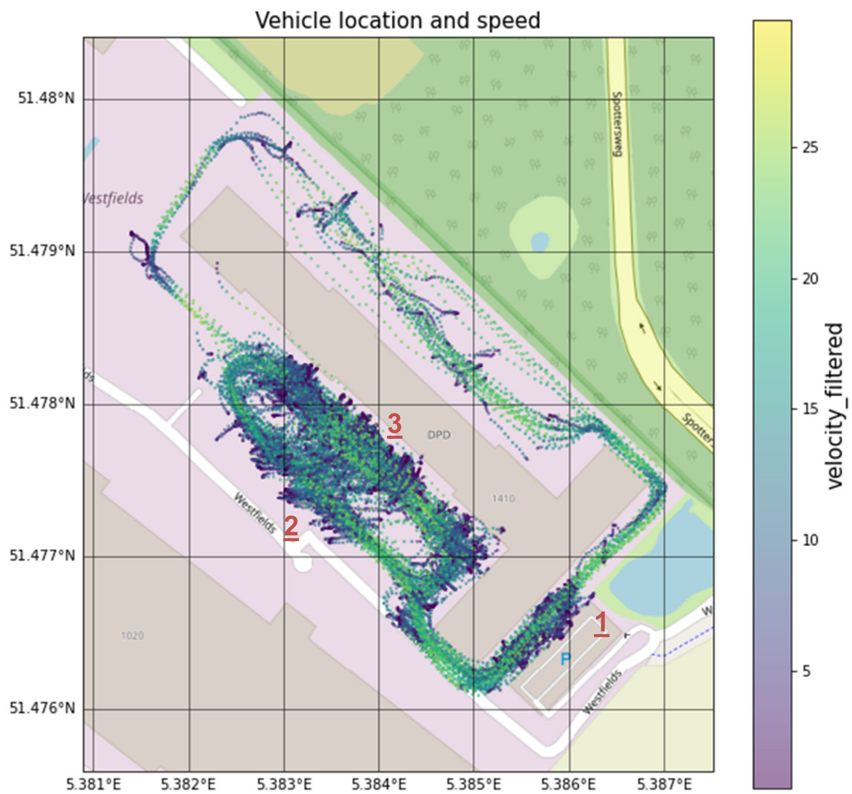

Figure 3: Location history and speed of the on-site terminal tractor (KAMAG). For the sake of clarity, data shown corresponds to the period of one week only. Each point denotes the location of the vehicle with a 1 s sample rate whereas the colour denotes the instantaneous speed of the vehicle in [km/h] coded following the colour map on the right.

We observe the daily activity in terms of duration and number of trips, based on the ignition. In general, the daily activity is consistent between weeks in terms of hours of activity and number of trips: low activity during the weekends and progressive increase throughout the week (see Figure 4). The average daily active time is 13 hours.

In the period of 17th of January until 11th of February the vehicle was under maintenance and thus low activity was reported. We excluded this period from the consecutive analysis.

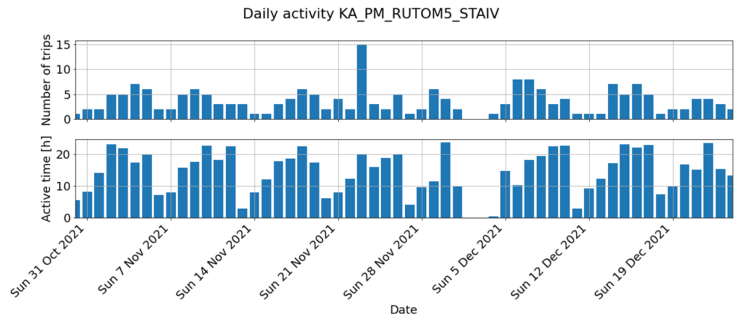

Figure 4: Daily activity if the Kamag vehicle. On top: the number of trips per day along the monitored period. Below: the cumulative active time through each day. The number of trips is based on the ignition. The maintenance period 17 January – 11 February is out of scope and thus excluded from the figure.

We can also observe at the overall distribution the velocity, the trip duration and trip distance. The most frequent speeds are those around zero. Furthermore, the mean speed of 11 km/h seems to indicate that the vehicle spends a considerable amount of time without moving (see Figure 5).

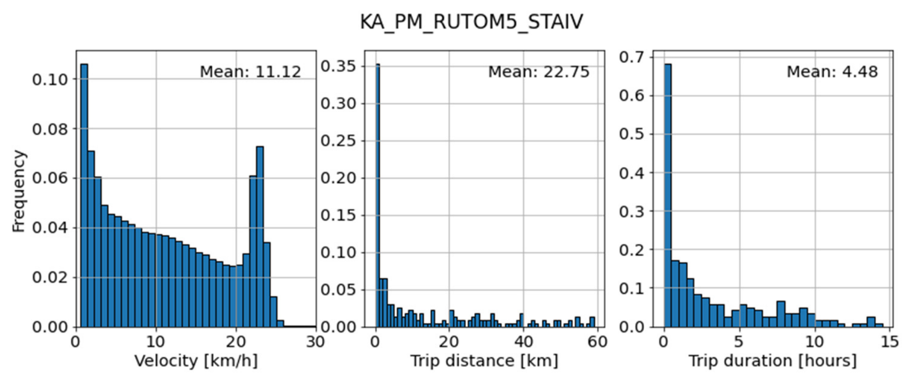

Figure 5: Statistics of the Kamag vehicle. From left to right, distribution of velocity, trip duration and trip distance.

Based on the vehicle usage (Figure 4), we can derive that the duration of daily activity is relatively long (i.e., on average 13 hours), while majority of trips (+- 70% is about 30 minutes). It is worth investigating how much of this time is the vehicle performing actual operation and how long is idling. To do so, we first determined a criterion to identify the idling periods based on the engine speed (RPM), the instantaneous torque and the vehicle speed (see Figure 6 and Appendix A).

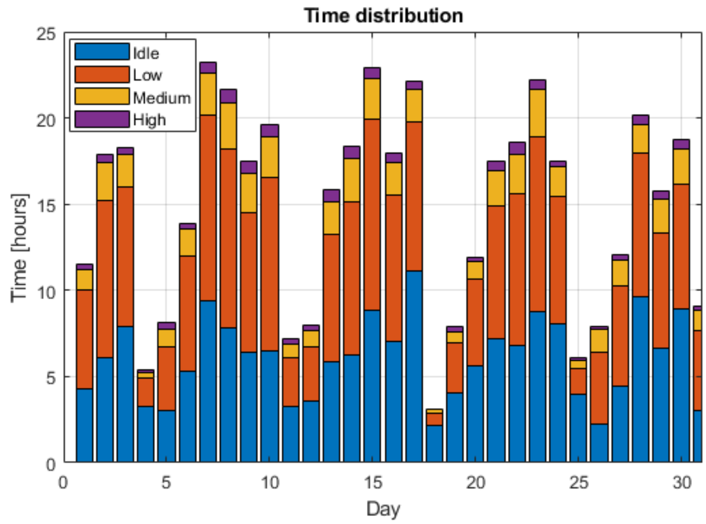

Figure 6: Activity distribution based on engine load for a typical month.
The load is defined as:

Idle	850 < Engine speed < 950 RPM and engine torque < 81 Nm and speed < 1 km/h
Low	81 < Engine torque < 150 Nm
Medium	150 < Engine torque < 340 Nm
High	Engine torque > 340 Nm

From Figure 6 it can be derived that a relatively small amount of time the vehicle engine load is medium-high in a typical month. A considerable amount of time is spend idling or with low engine load (blue and purple bars respectively). Therefore we take a closer look at the idling periods by determining the duration of consecutive idling.

Figure 7 shows the distribution of waiting time in bins of 5 minutes

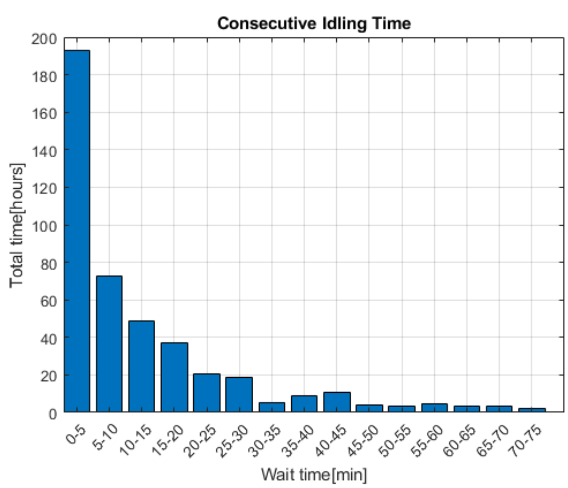

Figure 7: Distribution of idling time (in bins of 5 minutes; limited to 75 minutes), plotted against total idle time (hours)

The total idling time during the monitoring period is 447 hours which amounts to 36% of the total logged time. In 43% of the total idling time, the consecutive idling time is within 5 minutes. These short periods of idling can be caused by decelerating, manoeuvring and swapping containers. On the whole dataset these short instances lead to the large amount of idling time (about 192 hours as derived from Figure 7).

Figure 8 shows the distribution of waiting time for the idling periods that are longer than 5 minutes (i.e. for 2% of the whole dataset). When looking at the extreme cases (n=10 in the sample, 0.8% of all data; 1,8% of all idle samples) when consecutive idling is longer than 30 minutes, it can be observed in Figure 9 that the position of the idling vehicle is not at the docks but at the parking spots. This might be an indication that idling can be avoided in these instances.

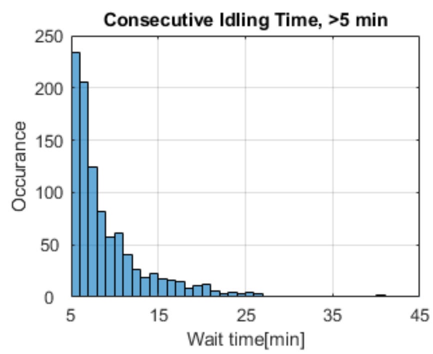

Figure 8: Occurrences of consecutive idling time longer than 5 min

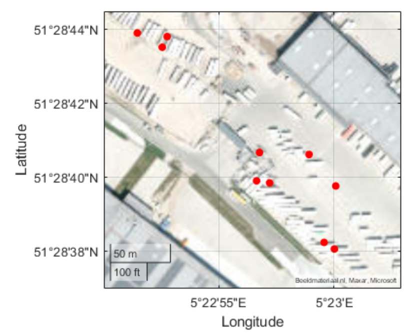

Figure 9: Positions of terminal tractor when idling more than 30 minutes

2.3.3 *Real-world emissions*

The overall emissions for the entire monitored period are shown in Table 2.

Table 2: Average emission rate per unit of time for the Kamag vehicle

Average emission rate on-site terminal tractor		
CO_2	[g/h]	9694
NO_x	[mg/h]	81589
NO_x/Fuel	[mg/L]	21982

In order to have a reference to estimate the emissions in relation to the regulations (European Parliament, 2016), we also compute the overall average emissions per power output, see Table 3. In order to make fair comparisons with the regulatory limit, this can only be done for the periods in which the vehicle's power output is above 20% of the rated power, which limits the analysis to only 7% of the data.
It can be observed that the vehicle performs outside regulatory limits. However this does not mean that the vehicle does not comply with the Stage V type approval since the type approval emission test consists of other engine load distributions compared to the engine load distribution of this particular daily operation.

Table 3: Average emission rate per power output in comparison with regulatory limit of 20% minimal engine power demand

Average emission rate on-site terminal tractor			Regulatory limit Stage V
CO_2	[g/kWh]	737	n/a
NO_x	[mg/kWh]	6023	400
NO_x/Fuel	[mg/L]	21982	n/a

As stated in paragraph 2.3.2, we can identify idling periods based on the engine speed (RPM), the instantaneous torque and the vehicle speed.
Based on this definition we can split the active time in idling and not idling and furthermore, we can compute the fuel consumption and the emissions for either case which results in the fractions shown in Figure 10.

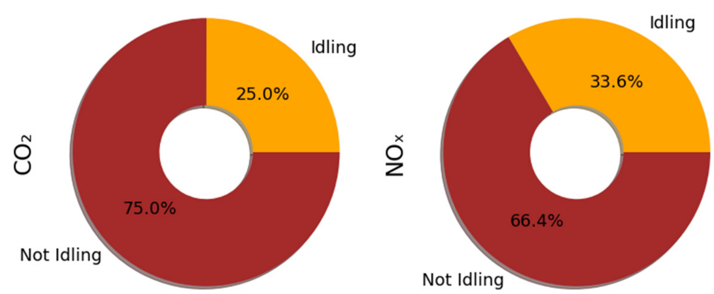

Figure 10: Emissions for the Kamag tractor while idling and while active. From left to right, CO_2, NO_x.

The CO_2 is proportional to the fuel consumed, hence the first panel in Figure 10 is also valid for the fuel fractions. The most outstanding result from this figure, seems to be the 33.4% of NO_x emitted during idling. This might be due to the low load usage of the vehicle (see section 2.3.2). As can be seen in Appendix A, the vehicle spends most of the time on a low temperature, where the NO_x emissions are higher. As can be inferred from the NH_3 levels, this might be caused by the inactive SCR[1].

The Stage V engine is equipped with a Diesel Particle Filter (DPF) to meet the particle number emission standard. The particulate matter (PM) emissions are therefore expected to be very low, close to the detection limit and therefore, these emissions are not further investigated and reported.

For further research it remains relevant to analyse the functioning and performance of the DPF and the resulting emissions for this vehicle. Given that this terminal tractor operates on low load, the regeneration cycles might have a lower frequency than the ones needed for the DPF to operate properly, negatively impacting the engine's efficiency. Such analysis would require to measure the pressure gradient across the DPF for which additional sensors need to be installed.

[1] Selective Catalytic Reduction (SCR) is an advanced active emissions control technology system that reduces tailpipe emissions of nitrogen oxides (NO_x).

2.3.3.1 *Mitigating measures on NO_x emissions*

The emission results of this terminal tractor were discussed with the manufacturer KAMAG. The following possible mitigating measures were identified:

- For the on-site terminal tractor, the increased NO_x emission is mainly caused by an inactive SCR system due to too low exhaust gas temperatures. By an appropriate thermal engine management, with slightly increasing the injected fuel (~2%), the exhaust gas temperature can rise significantly. This adaptation of the engine control is expected to result up to a tenfold decrease in NO_x emission. This option requires a change in the motor management software which can be executed by the manufacturer.
- Another option, which is already accounted for according to the manufacturer, is the positioning of the SCR catalyst. The closer the catalyst is positioned to the engine exhaust port, the higher the exhaust gas temperature is. This will help to get the SCR catalyst at operating temperature of 200°C or more.

2.4 Terminal tractor: industrial area

2.4.1 *General vehicle characteristics and monitoring period*

Table 4 summarizes the general vehicle characteristics of the terminal tractor that operates in an industrial port area. The terminal tractor is monitored in real-world operations for a period of 13 weeks.

Table 4: Vehicle characteristics industrial area terminal tractor

Vehicle	Terberg YT182
Engine	Cummins QSB6.7-173
Emission legislation	Tier 3 (Stage IIIa)
Weight	35.000 kg
Power (rated)	129 kW
Engine speed (rated)	2.500 rpm
Torque max (at 1500 rpm)	800 Nm
Fuel	Diesel
Swept volume	6.7 l
# of cylinders	6
Exhaust gas aftertreatment	None
VIN	XLWYT182X76246684
Year of manufacturing	2007
Measurement period	30 Sep '21– 28 Dec '21 (13 weeks)
Distance	3530 km
Total time	520 h
Fuel used	1253 l

2.4.2 *Logistics operations*

Figure 11 presents the location history and speed of the industrial terminal tractor. It can be seen that the speed of the vehicle is higher (25-30 km/h) when driving on the public road between the logistics centres and container terminal in the port area. Vehicle speed is lower (0-5 km/h) when manoeuvring on the sites of these logistics centres (e.g. 1, 2 and 3) or container terminals (see 4).

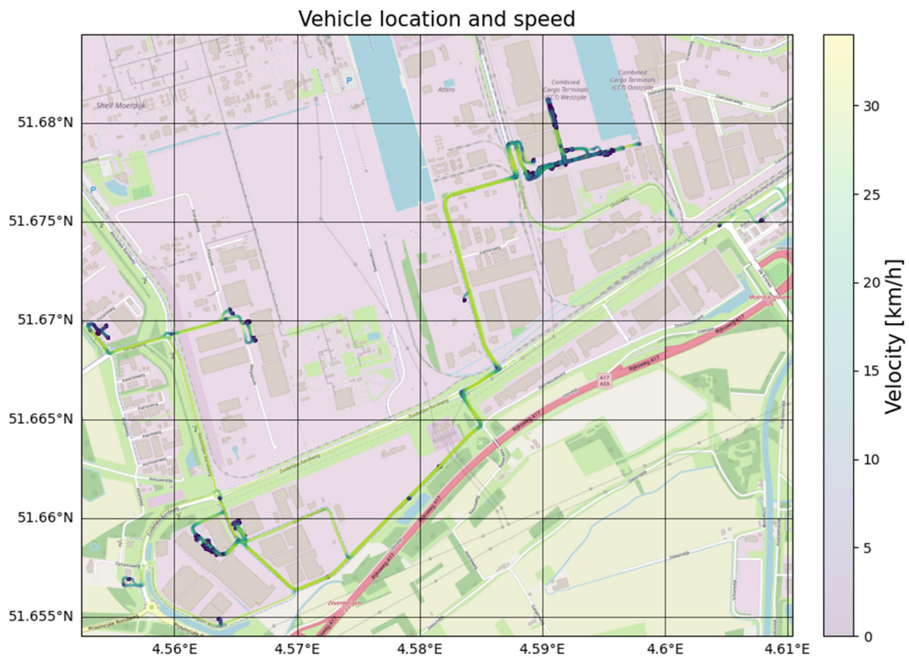

Figure 11: Location history and speed of the industrial area terminal tractor (Terberg). For the sake of clarity, data shown corresponds to the period of one week only. Each point denotes the location of the vehicle with a 1 s sample rate whereas the colour denotes the instantaneous speed of the vehicle in [km/h] coded following the colour map on the right.

We observe the daily activity in terms of time and number of trips, based on the ignition (see Figure 12). In general, in the beginning of the monitoring period, in October, the hours active time per day and the number of trips is fluctuating. From 25th of October onwards daily activity is consistent between the weeks (with an exception from 10-22nd of November where no data was recorded). The average daily active time is 9.90 hours.

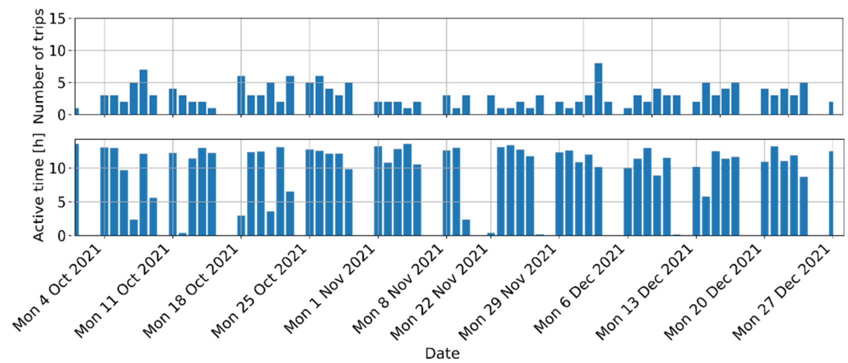

Figure 12: Daily activity of the Terberg vehicle. On top, the number of trips per day, on the bottom, the time in which the vehicle is active per day, in hours. Note that no data was recorded 10-22nd of November.

We can also observe at the overall distribution the velocity, the trip duration and trip distance. The most frequent speeds are those around 30 km/h and 0-5 km/h. Trip duration, based on ignition, is about an hour on average (see Figure 13).

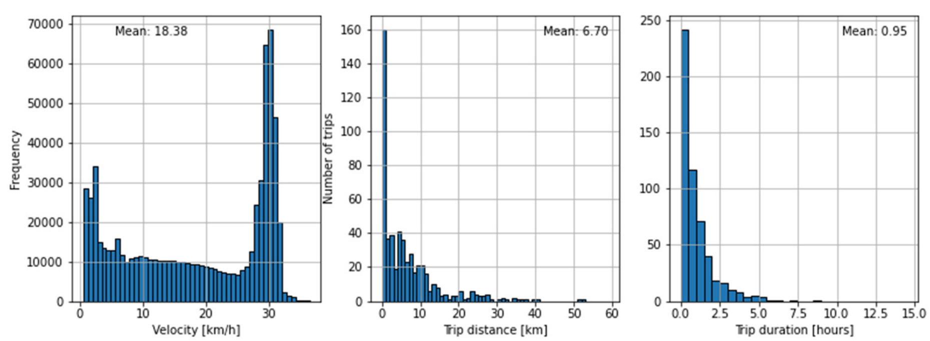

Figure 13: Statistics of the Terberg vehicle. From left to right: the distribution of velocity, trip distance and trip duration.

Based on the vehicle usage Figure 12, we can derive that the duration of daily activity is relatively long (i.e., on average 9.90 hours). It is worth investigating how much of this time is the vehicle performing actual operation and how long is idling. To do so, we first determined a criterion to identify the idling periods based on the engine speed (RPM), the instantaneous torque and the vehicle speed (see Figure 14 and Appendix A for details). Based on this definition we can split the active time in idling and not idling.

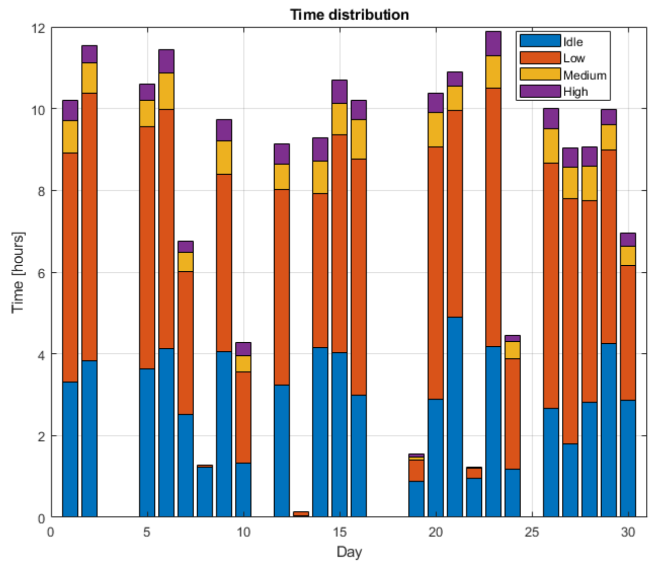

Figure 14: Activity distribution based on engine load for a typical month.
The load is defined as:
Idle 600 < Engine speed < 775 RPM and engine torque < 78 Nm and speed < 1 km/h
Low 78 < Engine torque < 200 Nm
Medium 200 < Engine torque < 450 Nm
High Engine torque > 450Nm

From Figure 14 it can be derived that a relatively small amount of time the vehicle engine load is medium-high in a typical month. A considerable amount of time is spend idling or with low engine load (blue and orange bars respectively). Therefore, we take a closer look at the idling periods by determining the duration of consecutive idling.

Figure 15 shows the distribution of waiting time in bins of 5 minutes.

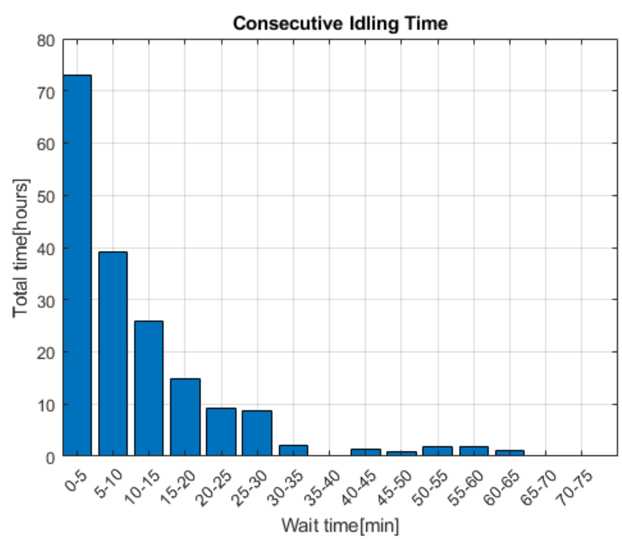

Figure 15: Distribution of idling time (in bins of 5 minutes; limited to 75 minutes), plotted against total idle time (hours)

The total idling time during the monitoring period is 179 hours, which is 34% of the total logged time. In 41% of the total idling time, the idling duration was shorter than 5 minutes. These short periods of idling can be caused by decelerating, manoeuvring and loading containers and are necessary for the logistic process. On the whole dataset this leads to the large amounts of idling time (about 74 hours as derived from Figure 15).

Figure 16 shows the distribution of waiting time for the idling periods that are longer than 5 minutes (i.e., for 9% of the whole dataset). When looking at the extreme cases (n=13 in the sample, 2.3% of all data; 6.5% of all idle samples) when consecutive idling is longer than 30 minutes, it can be observed in Figure 17 that the position of the idling vehicle is mostly at the container terminal (top-right from the middle of the figure). It is worthwhile investigating whether idling can be avoided in these instances.

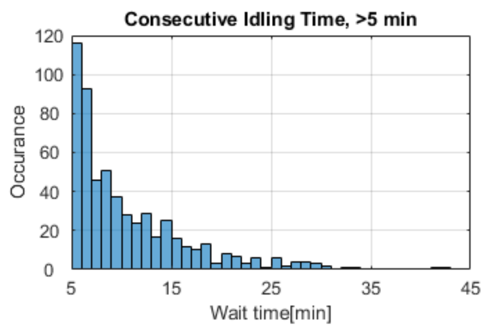

Figure 16: Occurrences of consecutive idling time longer than 5 min

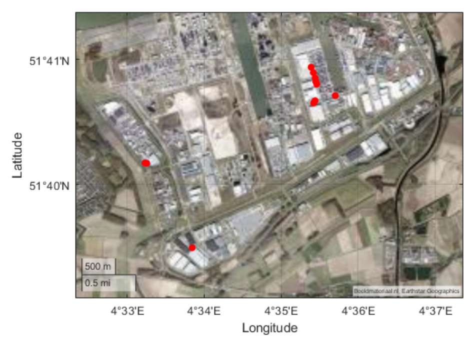

Figure 17: Positions of terminal tractor when idling more than 30 minutes

2.4.3 *Real-world emissions*

The overall emissions for the entire monitored period are shown in Table 5.

Table 5: Average emission rate per unit of time for the Terberg vehicle

Average emission rate industrial area terminal tractor		
CO_2	[g/h]	18125
NO_x	[mg/h]	32576
NO_x/Fuel	[mg/L]	4763

In order to have a reference to estimate the emissions in relation to the regulations (European Parliament, 2004), we also compute the overall average emissions per power output, see Table 6. In order to make fair comparisons with the regulatory limit, this can only be done for the periods in which the vehicle's power output is above 20% of the rated power, which limits the analysis to only 16% of the data. Although there is no specific NO_x limit for Stage IIIa engines (only a combination of hydrocarbons (HC) and NO_x), it can be observed that the vehicle performs within regulatory limits.

Table 6: Average emission rate per power output for Terberg vehicle in comparison with regulatory limit, for 16% of the time the engine power demand is above 20% of the rated power

Average emission rate industrial area terminal tractor			Regulatory limit Stage IIIa
CO_2	[g/kWh]	1194	n/a
NO_x	[mg/kWh]	2146	4000 g/kWh (HC + NO_x)
NO_x/Fuel	[mg/L]	4763	n/a

We compute the fuel consumption and the emissions for both idling and non-idling which results in the fractions shown in Figure 18. The CO_2 is proportional to the fuel consumed, hence the first panel in Figure 18 is also valid for the fuel fractions.
The most outstanding result from this figure, seems to be the 35.9% of NO_x emitted during idling. This indicates that the NO_x emissions for this vehicle are relatively stable with load demand, at least for this low range of operation and the emissions during idling are of the same order of those during operations.

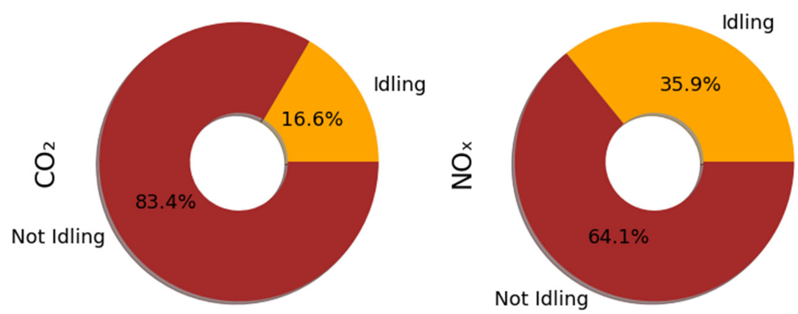

Figure 18: Emissions for the Terberg tractor while idling and while active.
From left to right: CO_2, NO_x

The level of emissions of particulate matter was also measured and the results are displayed in Table 7 together with the EU emission standards. It is relevant to note that PM emissions of diesel engines are typically smaller than 0.2 µm, and therefore it contributes to the different standards PM10, PM2.5 and PM1. Provided that only 12% of the monitored time the vehicle's power demand was higher than 20%, it is expected that the emissions of particulate matter are lower than the standards since they are positively correlated to engine load.

Table 7: Average emissions of particulate matter during the monitored period for the Terberg vehicle. On the right the EU standard is shown for reference for the case of emissions per unit of energy.

Average emission rate industrial area terminal tractor			Regulatory limit Stage IIIa
PM10	[g/km]	0.43	n/a
PM10	[g/kWh]	0.13	0.3

The PM emission limit of Stage IIIA (from 2007) of 0.3 g/kWh is high compared to the Euro-IV limit (from 2006) of 0.03 g/kWh. Although the engine complies to the limit in normal use, the emission levels are high.

2.5 Conclusions

This chapter presents:

- That real-world logistics operations and emissions of both on-site terminal tractors and terminal tractors active in an industrial port area can be monitored by using the Smart Emissions Measurement System (SEMS);
- Characteristics of on-site terminal tractor operations:
  - Long working days (about 13 hours on average) with lots of short trips (about 70% is less than 30 minutes);
  - Vehicle operation is often low speed manoeuvring at the docks;
  - Most of the time the vehicle is idling or operating with low engine load. Although a lot of idling is observed, 98% of instances idling is shorter than 5 minutes and hence might be difficult to avoid;
  - Idling accounts for a relatively large proportion of CO_2 (25%, which relates to fuel) and NO_x (33.6%) emissions;
  - With respect to NO_x (mg/kWh) emission regulations, the Stage V vehicle performs beyond regulatory limits during ‘normal’ operation.
  - Especially NO_x emissions are higher than expected, which can be explained by the fact that operational use is as such (low speed, low engine load) that the SCR light-off does not take place due to too low exhaust gas temperature.
- Characteristics of industrial area terminal tractor operations:
  - Working days (9.90), with trips between logistics centres and container terminal in the port area that are on about an hour average;
  - Vehicle operation is a mix between driving on open road (30 km/h) and load speed manoeuvring on sites (0-5 km/h);
  - Most of the time the vehicle is idling or operating with low engine load. Although a lot of idling is observed, 91% of instances idling is shorter than 5 minutes and hence might be difficult to avoid;
  - With respect to NO_x (mg/kWh) emission regulations, The Stage IIIa vehicle performs within the regulatory emission limits.
  - The PM10 emissions are low compared to the limit, since the engine load is low. Particulate matter emissions are generally related to high engine load.

Next to these observations, in order of impact, we summarize the mitigating measures that are proposed for reducing NO_x emissions of the on-site terminal tractor (2.3.3.1):

- Increase fuel injection via the motor management system.
- Position the SCR catalyst as close as possible to the engine exhaust ports.

To conclude, transporters can use the presented emission factors for assessing their own operation. Of course, one has to be cautious when operations are not comparable or a different vehicle/ engine/ fuel type is used. Then these results cannot be transferred directly.

3 Transport near yards: congestion and emission analysis

3.1 Introduction and research aim

As outlined in section 1.1, there is a need to acquire **detailed and fact-based insight in the last mile vehicle operation towards (smart) yards.** In the sector, congestion near ports is regularly reported (e.g. Mackor, 2021; Transport Online, 2021). However, detailed insight in the magnitude of these congestions is lacking and can be investigated in more detail. This allows us to better substantiate possible organizational and technical innovations (such as new logistics concepts combined with Connected Automated Transport) to reduce emissions and improve efficiency (Van Kempen & Van Meijeren, 2022). In this chapter we aim to shed light on the current situation (as a baseline measurement) in order to gain better insights on the improvement potential with respect to efficiency and sustainability at yards such as (air)port terminals and logistics hubs.

In this chapter we aim to answer the following research questions:

- *To what extent are trucks congested at yards?*
  - *At what daily pattern do trucks arrive at the yard? And what kind of spread across the various access roads can be observed?*
  - *How much time do the vehicles spend at the yard, how do these times develop over a longer period and how much variation is visible?*
  - *What factors are relevant for the duration of a yard visit, e.g. resting times, other activities?*
  - *To what extent are trucks idling near yards?*
- *What are the emissions - related to congestion - of trucks at yards?*
  - *How much fuel did the vehicles consume at the yard and how many emissions (CO_2 and pollutants) were expelled?*

First, before we answer the research questions, we outline the methods in section 3.2. Subsequently we present the main observations and findings, first from a broader method view and then specifically on the different yards. This chapter will conclude with some conclusions and recommendations

3.2 Methods

The general steps followed for data collection and data analysis are presented in Figure 19. The subsequent paragraphs discuss the data collection (3.2.1) and data analysis (3.2.2) steps in more detail.

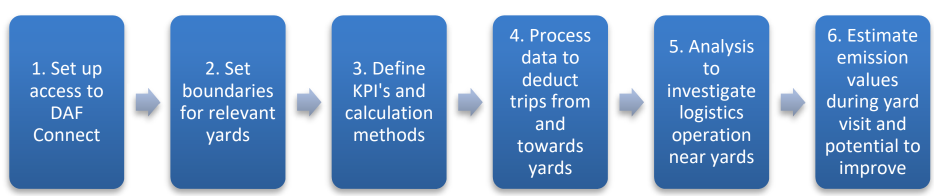

Figure 19: Method steps for data collection (step 1) and congestion analysis (steps 2-6)

The analysis is focused on five yards which are aligned with the CATALYST Living Lab: Port of Moerdijk, North Sea Port (Vlissingen), Port of Rotterdam, Schiphol Airport and DPD Oirschot (Van Kempen & Van Meijeren, 2022). As part of this report the more detailed results for the Port of Rotterdam will be provided. In order to enhance the readability of the main report, the results for the other yards are summarized in a general comparison in section 3.4. If required, the additional statistics and figures are available upon request.

3.2.1 *Data collection*

As part of a joint session with DAF, Vepco and TNO, it was investigated from different viewpoints (vehicle manufacturer, logistics service provider, mobility expert and logistics expert) what expectations exists regarding the occurrence of congestion on yards and how these can subsequently be made measurable. E.g. observations that companies (such as Vepco) both deploy dedicated vehicles (that drive back and forth between the terminals and depots) and are supplemented with vehicles that focus on the long-haul transport between terminals and customers were of added value to define and scope the intended data analysis. Other topics that came up were specific filtering on long-term parking facilities (e.g. Maasvlakte Plaza near the Maasvlakte) and the relevance to filter vehicles that only visited the yard for the pick-up and/or drop-off of a container as part of a long-haul trip from vehicles that visit other companies at the Maasvlakte.

Based on these discussions, TNO subsequently prepared a proposal of the data attributes that were requested from DAF Connect, subsequently it was jointly decided to select the second half of 2021 as the intended research period. Lastly this request was processed by DAF and the resulting dataset was exchanged.

3.2.1.1 *Set up access to DAF Connect and data characteristics*

In order to assess to what extent trucks are congested at yards, DAF Connect data is used. DAF Connect is a telematics platform that provides data and information services to transporters and fleet owners. Connectivity via the DAF Connect platform was offered as an option on the previous generation trucks and is ‘standard’ on the New Generation XF, XG and XG+. Vehicles equipped with the DAF Connect platform have on-board equipment to periodically (both event and time-based) collect and process status messages. These messages are subsequently transmitted to the DAF backend database servers.

As part of this yard congestion analysis the following data was utilized:

- Every 5 minutes a vehicle provides a heartbeat status message with the GPS location and general vehicle information;
- As part of heartbeat message also additional engine parameters are collected with a higher resolution (1 min). This data can be utilized to gain insight in the engine usage across the duration of the status message.

All measurements are ‘instantaneous’, it provides the values and status for that specific variable at that specific ‘moment’ in time.

For the purpose of this research DAF has provided an export of a subset of the DAF Connect dataset that contained specific attributes that were requested by TNO, a non-exhaustive list of the data attributes is given in Table 8.

The data export contained status messages for a period of 6 months between July 1st 2021 and December 31 2021. Individual drivers and underlying logistical operators cannot be identified in the dataset provided by DAF and as such, the data is considered to be anonymous.

Table 8: DAF Connect data attributes of the dataset that has been processed as part of the congestion and emission analysis. All measures are instantaneous.

Data attribute	**Description**	**Units**	**Time resolution**
unixTimestamp	Date and time of the measurement	Seconds from 1970	5 min
tripID	Identification number of the trip	#	5 min
GPSLatitude	Latitude in WGS84	degree	5 min
GPSLongitude	Longitude in WGS84	degree	5 min
totalDistance	Distance travelled by the vehicle	M	5 min
GPSAltitude	Altitude in WGS84	M	5 min
GPSHeading	Direction angle w.r.t WGS84	degree	5 min
fuelLevel	Fuel level	%	1 min
grossCombinationWeight	Vehicle + load mass	Kg	5 min
wheelbasedSpeed	Speed measured based on the wheel	km/h	1 min
tachographSpeed	Speed measured from the CAN bus	km/h	1 min
GPSSpeed	Speed measured from the GPS	km/h	1 min
AmbiantAirTemperature	Outside air temperature	°C	5 min
engineCoolantTemperature	Coolant temperature	°C	5 min
GPSHDOP	GPS accuracy	#	5 min
acceleration	Vehicle acceleration	m/s	5 min
engineLoad	Engine torque	%	1 min
engineSpeed	Speed of the engine	RPM	1 min
gearCurrent	Current gear	#	5 min

Representativeness of dataset
Given that not all DAF vehicles are equipped with DAF Connect and that DAF is only one of several truck manufacturers it is important to understand to what extend the sample is representative for the total fleet of Heavy Goods Vehicles in The Netherlands. As part of the EU funded project ENSEMBLE an earlier analysis was conducted in which DAF Connect data was employed (Lützner et al., 2021)[2]. As part of these activities also an elaborate analysis was performed that compared the DAF Connect vehicle trajectories with measurements that were derived from roadside sensors (induction loops) that continuously monitors the number of vehicles that pass his sensor and the corresponding vehicle categories.

[2] This analysis is documented as part of Ensemble deliverable D4.2 (section 3.4.5) which can be accessed here.

The analysis in ENSEMBLE was performed (in Q1 2021) on data recorded in September 2020. Given that this analysis contains the most recent insights and that the (re)evaluation of the current dataset does not necessarily contribute to the primary objective of this congestion analysis, we base the representativeness of our data on this study.

The ENSEMBLE results show that in The Netherlands, the average market share of DAF Connect is 3.6%. The patterns (e.g., variations in intensities throughout the day) are consistent in both space and time.

3.2.2 Data analysis

3.2.2.1 Set boundaries for relevant yards

As the second step of the methodology, the intended yards were examined in terms of geographical location, the distribution of functions (roads, parking areas, terminals, generic (logistical) companies) and the access & egress routes. Based on this analysis, the yards were defined as polygons that depict the edges of the yards as line segments that are connected to each other end to end. A similar procedure was followed to define the areas for the terminals, long term parking facilities and logistic areas.

The boundaries for the various yards are visualized in Figure 20, including the areas and/or locations that were used for filtering (parking areas, terminals and logistics hubs).

As mentioned, the locations and the surrounding road network of the yards are important factors that delineate when and where vehicles towards the yard can be registered. For example the Maasvlakte area with the N15 as dedicated access road is different than the Moerdijk area where multiple inbound and outbound routes and where the A17 lies very close the yard area. Given that traffic with an origin and destination outside the area should not be included in the analysis the yard surface for the Moerdijk area is relatively smaller.

Visualization of the yards included in the analysis
The yards that are include in the analysis are linked to the yards under analysis in the CATALYST Living Lab (Van Kempen & Van Meijeren, 2022). The analysis includes: 3 port areas with their terminals (Port of Rotterdam, Port of Moerdijk, North Sea Port), one airport area with its ground handlers (Schiphol Airport) and one logistics distribution centre (DPD Oirschot).

Port of Rotterdam - Maasvlakte

Vehicles are detected from the A15 onwards. This yard includes the Maasvlakte Plaza as 'long term' parking area and the various terminals in the area. Lastly the logistical distribution parks are included for filtering purposes.

Port of Moerdijk

Vehicles are detected when they leave the A17. Includes the CCT terminal and no parking areas, terminals or distribution parks.

North Sea Port – Vlissingen

Vehicles are detected when the leave the N254 road. Does not include any filtering locations such as parking areas, terminals or distribution parks.

Schiphol Zuidoost

The ground handlers north and south of the Kaagbaan are included.

DPD Oirschot

Includes the full DPD yard. Vehicles are detected as soon as they enter the DPD yard area.

Figure 20: Visualization of the yards included in the analysis

3.2.2.2 *Define KPI's and calculation methods*

After the areas were defined, the focus shifted to defining the indicators and making these measurable. In the text below the indicators for the yard congestion and engine behaviour are described.

Yard congestion and turnaround times
From the perspective of yard congestion, it was decided to mainly focus on the turnaround times as primary key performance indicator. This turnaround time is defined as the time between the first GPS measurement of the vehicle trajectory that falls within yard polygon and the last GPS measurement that falls within the defined area. This implies that this turnaround time also includes part of the journey of each of the vehicles that travels from and towards the yard. Moreover, given that vehicles only provide 1 GPS signal every 5 minutes, vehicles are not detected at the same point when they cut through the bounding box when entering and exiting the area. In practice this means that the first and last point often are located in an region around the outer edge of the polygon that represents a travel time of 5 minutes.

Investigating engine behaviour and identifying idling periods
To examine the engine usage statistics during each of the registered yard visits the data parameters that represent the engine utilization (engine speed, engine torque and engine load) are linked to the yard visits. Given that these measurements have a higher sample rate and are not synchronized, a filtering was implemented. For example some measurements overlap and also some measurements are missing when the engine has completely been shut down. An idle engine measurement is defined as a measurement in which the datapoints fulfil three requirements; 1) the engine speed (RPM) is higher than 0 RPM and less than 600 revolutions per minute; 2) the engine load is <10%; and 3) the speed of the vehicle is <10 km/h.

Measurements in which the engine RPM values were equal to 0 due to the start-stop vehicle functionalities were disregarded. The definition of idling and corresponding cut-off values are selected based on expert judgement and by looking at the histograms of specific data signals. Particularly when analysing and interpreting the engine idling it is important to understand the fact that the measurements are ‘instantaneous’. E.g. when a vehicle at the time of the measurement is waiting for an intersection that full minute is assumed to be an idle period.

Translating idling behaviour to fuel consumption and CO_2 emissions
To translate the idle periods to a corresponding fuel consumption and associated CO_2 emissions, this project has repurposed a dataset that was collected within the Integrator Connected Truck Trials project (van Kempen, et al., 2021). As part of this project 9 DAF vehicles were monitored with the SEMS emissions measurements system (similarly to the method, described in section 2.2 of this report) in real-world logistics operations for a period of 15 weeks. To reconstruct an average idle fuel consumption, all measurements of the vehicles are binned that meet the previous definition of idling. Based on the readings of the exhaust sensors, an average fuel consumption of 2,561 litre per hour was deducted. Given that 1 litre of fuel produces 2630 grams of CO_2 when burned, this translates to 6,789 kg of CO_2 per hour when idling (De Ruiter, Van Gijlswijk, & Ligterink, 2019).

Scale up fuel consumption on yard level to total fuel consumption on journey
Lastly, the idling statistics were related to the total fuel consumption that is representative for an ‘average’ trip from and towards the yard area. For this, a trip recognition algorithm was implemented that selects the subset of points where the vehicle is on the road with finite speed between an origin and destination.

A trip is then the set of timeseries between origin and destination where the vehicle's speed is higher than zero[3]. Based on the origins and destinations of the trips, origin-destination (OD) matrices were produced that include the average distance per trip per OD relation. The OD matrices that describe the average trip distance between the various regions and which includes the region 'Rest Nederland' are added to appendix B of this final report.

3.2.2.3 *Process data to deduct trips from and towards yards*

As part of the description of the KPI and calculation methods, the relevant processing steps were already described. As part of this step the actual analysis was performed which resulted in a database of yard visits that were deducted from the DAF Connect dataset. As part of the activities, it was important to make algorithms efficient in order to limit the processing time and required computing power.

3.2.2.4 *Analysis to investigate logistics operation near yards*

In this step, the results from the individual yard visits were aggregated to statistics on the yard level. As part of this analysis a flexible method was applied that allows to select different cross sections of the data.

The following filters are applied:

- Which yard has been visited
- Time of day (weekdays, weekends & specific time windows)
- Visit of specific terminals, and whether 1 or multiple terminals have been visited.
- Stay at long term parking facility
- Visit of other logistical distribution centres within yard

The resulting statistics were exported as tables and visualized by figures. These can include scatter plots, box-plots and/or histograms.

As part of the analysis also a case study was performed for a specific day at the Maasvlakte when extreme congestion occurred due to demonstrations (18th November 2021). As part of this use case it becomes possible to investigate individual trajectories and to investigate how the individual yard visits and turnaround times are affected by these external circumstances.

3.2.2.5 *Estimate emission values during yard visit and determine improvement potential*

As a final step, it is important to put the results of this work package in perspective and relate it to the image that that emerges from the various partners of the YES consortium (internal) but also the initiatives that are relevant outside the consortium. Ultimately this last step enables the translation of the statistics towards an action perspective to potentially improve efficiency and the air quality at (smart) yard areas.

As part of the activities of this step, the results were presented and discussed as part of a YES consortium meeting. The results were also discussed with other stakeholders (such as the Port of Rotterdam). The aim is to validate the storyline that emerged from the results and to define possible steps for follow-up research.

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[3] The minimum requirements for a single trip are: a). that the vehicle drove with a speed 10 km/h for 5 consecutive minutes; and b) that the trip ends when the vehicle was stationary for a minimum of 15 minutes.

3.2.3 *Observations from implementing the methodology*

As part of the data processing, a number of observations can be made that reflect on the process and lessons learned. Given that these are not directly related to answering the research questions, it these are incorporated below as part of the methods section.

Iteration cycles needed for making optimal use of dataset
In this work package of YES a large-scale dataset from an OEM was applied in which vehicles movements in and around yards can be deducted. This dataset contains detailed vehicle parameters that are collected at a relatively high refresh rate. Processing such datasets naturally brings challenges in terms of computationally efficiency and required processing power. The challenge with these type of analysis is, on the one hand, to retain as much 'raw' information to perform underlying detailed analysis and, on the other hand, to collect aggregated statics on the yard-level visit. In order to find this balance, it was necessary to iterate in terms of data structures and processing methodologies during the course of this project. In a logistics environment, in which the increasing digitalization is clearly recognizable, such lessons are valuable for future follow-up projects.

Validation of individual dataset parameters
As part of the data processing activities also certain aspects from the data became apparent which required further clarification and interpretation. For example, originally it was intended to use the fuel level as one of indicators for the fuel consumption. However when analysing the individual measured values it seemed that the fuel level fluctuated during the yard visit and also that vehicles often departed from the yard with a small amount additional fuel. Given that the difference was often low (for example 1 or 2%) it was highly unlikely that vehicles would have refuelled. In consultation with DAF it became apparent that the fuel levels can be affected by the ride height and angle of the vehicle as a result of the (additional) weight from loading. The weight of the payload mainly presses on the rear axle which affects the measurements of the fuel level that is derived from a floating sensor in the fuel tank. For example these observations emphasize the importance of data verification.

Validation of dataset through descriptive statistics
As part of the validation and interpretation of the analysis a number of general statistics were retrieved and visualized per yard. The main aim was to verify whether the recognizable general trends appear. For example Figure 21 depicts the normalized distribution of vehicles arriving and departing from the Maasvlakte during the day. What becomes clear, is that the pattern of arriving vehicles starts early in the morning and that the flow of departing vehicles will start to increase between one and two hours later. Similarly Figure 22 depicts the distribution of gross combination weights (sum weight of truck, trailer and payload); given that the distribution shifts right when comparing the outbound (red) and inbound (blue) vehicles it becomes apparent that the outbound vehicles are heavier. These statistics and underlying patterns, and a number of other analyses performed in the background that are not included in this report, gave confidence that more complex analyses could be performed.

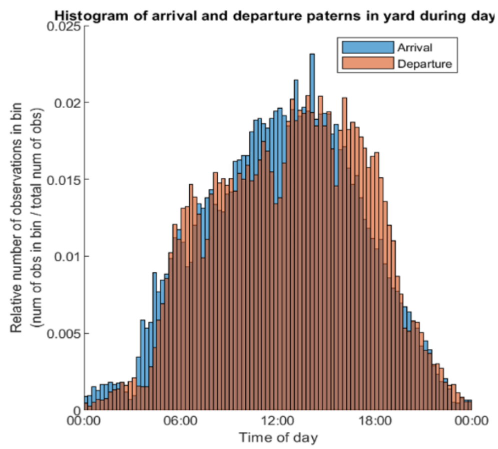

Figure 21: Distribution of arriving and departing vehicles across the day from the Rotterdam Maasvlakte

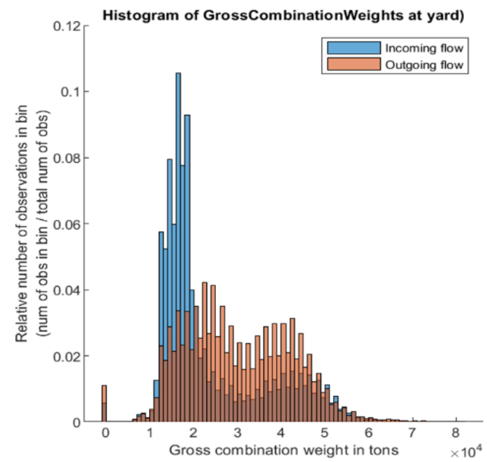

Figure 22: Distribution of the weight of vehicles arriving and departing from the Rotterdam Maasvlakte,

3.3 Results

Section 3.3.1 presents an overview of the main results. The specific results regarding congestion and fuel consumption and emissions are reported in sections 3.3.2 and 3.3.3 respectively. Lastly, the observations per yard are summarized in section 3.3.4. Overall, it is possible to use DAF Connect data to derive yard visits and turnaround times of trucks. Also, it is possible to estimate fuel consumption and CO_2 emissions from *idling* at yards. It turned out that estimating pollutant emissions (NO_x, NH_3) and emissions from *transport movements* at yards was not possible.

3.3.1 General results and observations

The main results in terms of number of visits, turnaround times and idling percentages are depicted below in Table 9. Turnaround time of trucks yards varies, which can be explained by the different ways the yards are operating. Also the percentage of time that trucks are idling during a yard visit, is yard specific.

Table 9: Results analysis of yard visits and idling behaviour for the various yards.

	Average number of yard visits per day		**Average turnaround time in minutes**		**Average idle percentage (time) at yard**	**Fuel consumption during idling in litres**	**CO_2 emissions in kg's while idling**
	Weekday	Weekend	Weekday	Weekend			
Maasvlakte	211,8	16,1	86,5	92,9	24%	0,84	2,2
Moerdijk	25,6	1,4	180,1	168,5	29%	1,48	3,9
Vlissingen	70,4	5,7	191,5	245,2	20%	0,81	2,1
Schiphol terminal	66,0	38,5	113,3	136,9	19%	0,41	1,7
DPD Oirschot	36,5	8,6	58,6	54,1	36%	0,64	1,7

As part of Table 11, the fuel consumption by idling is related to the total fuel consumption of the total journey as a fraction (excluding fuel consumption of yard transport).
The fraction of fuel consumed at a yard when idling is relatively low compared to the fuel consumed for the long-distance transport from/to the yard (1-5%). The results will be further analysed in the next two sections of this chapter.

Table 10: Results for fuel consumption and CO2 emissions while idling for various yards.

	Average idle percentage (time) at yard	Fuel consumption during idling in litres	CO_2 emissions in kg's while idling	Average distance as origin in km's	Average distance as destination in km's	Total journey distance in km's	Total fuel usage in litres for journey and idling	Fraction fuel consumption in relation to the total fuel usage
Maasvlakte	**24%**	**0,84**	**2,2**	**64,2**	**73,7**	**137,9**	**39,7**	**2%**
Moerdijk	**29%**	**1,48**	**3,9**	**49,6**	**50,0**	**99,6**	**29,6**	**5%**
Vlissingen	**20%**	**0,81**	**2,1**	**69,3**	**64,8**	**134,2**	**38,6**	**2%**
Schiphol terminal	**19%**	**0,41**	**1,7**	**53,1**	**61,2**	**114,4**	**32,1**	**1%**
DPD Oirschot	**36%**	**0,64**	**1,7**	**94,0**	**86,4**	**180,4**	**32,9**	**2%**

3.3.2 *Main observations in regard to yard congestion*

In relation to the aim of this work package to gain insight in the yard congestion it appears that, based on the DAF Connect vehicle information, it is possible to deduct vehicle movements during yard visits and to gain a better operational picture of the logistics process. In particular, the general intermediate steps are easy to trace, for example and how many terminals have been visited by the vehicle. In order to put these results into perspective and context, it is important to be able to filter on certain parameters such as long term parking of vehicles during resting periods and vehicles that visits specific logistical locations that are not directly related to the loading and unloading at the major terminals.

The main results in terms of turnaround time per yard are depicted in Table 9, e.g. the results show that:

- The average turnaround time (87 minutes during weekdays) of the Maasvlakte yard is significantly different to the turnaround time of the Moerdijk area (180 minutes during weekdays);
- The average number of yard visits per weekday (e.g. 212 visits for the Maasvlakte) clearly differs to the average number of visits on weekend days (15 for the Maasvlakte).

The large difference between weekdays and weekends can also clearly be observed from the visualization below (Figure 23) in which the turnaround time per day for the Maasvlakte is depicted on the upper figure and the number of yard visits per day on the lower picture. What becomes apparent is that far fewer equipped vehicles with DAF Connect visit the Maasvlakte during weekends. In terms of the turnaround times it becomes apparent that, although the average duration during the weekend is slightly higher the error (standard deviation) is also significantly higher.

When looking at the individual visits it becomes apparent that some very short turnaround times are registered but also some very long, the latter might be a result from drivers that take a long break during the weekends and have not used the Maasvlakte Plaza.

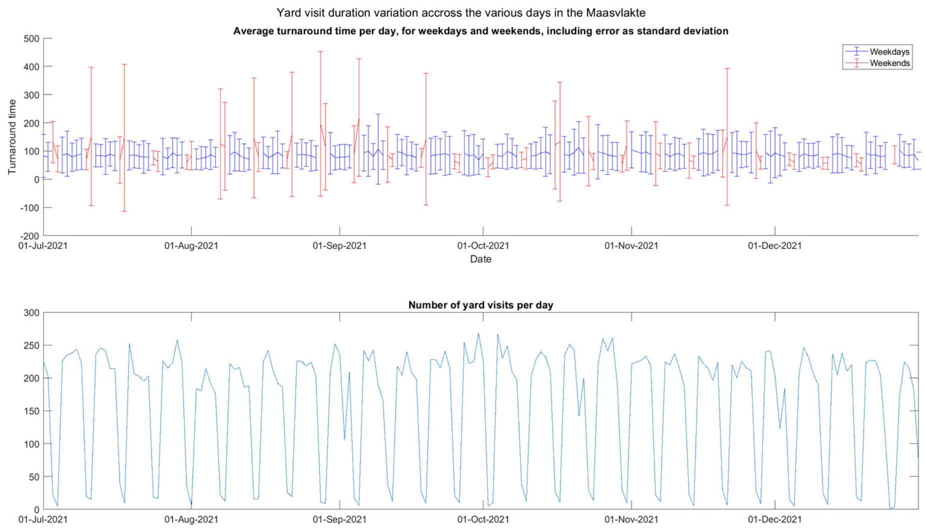

Figure 23: Turnaround time and number of yard visits per day 01 July 2021 - 31 December 2021

When individual terminals can be unambiguously indicated as a (closed area) polygon as part of the yard area, it is possible to gain insight into the yard visit statistics of individual terminals. The spatial design of the respective yard is an important factor to enable such analysis. The Maasvlakte, where the private terminal areas are located significantly further away from the public roads and where the terminal areas are relatively large, is an example where such an analysis can be performed. Figure 24 shows the density of registered GPS points of vehicles that were registered as part of a Maasvlakte visit, the various terminals and other relevant locations are clearly depicted as ‘hotspots’.

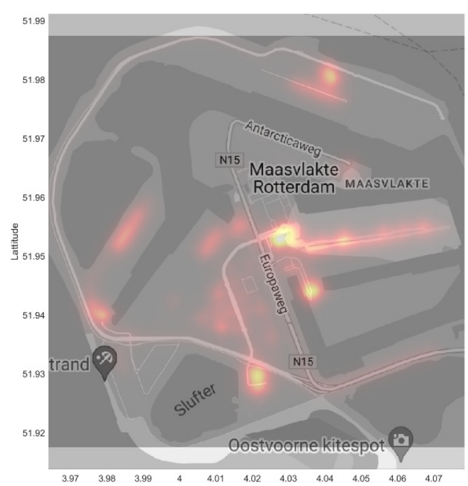

Figure 24: Visualisation of GPS points that were registered as part of visits of the Maasvlakte area

In principle, the data and forthcoming indicators allow to make comparisons between different periods, months and time-of-day; for example to study the turnaround times over the various months of the year. Due to the large number of connected vehicles as part of the DAF Connect platform, the sample for various cross-sections remains sufficiently large to provide reliable insights into differences. Although it was originally expected that the turnaround times would differ, especially during the day and also during the months, the current results do not indicate such differences and variations. For example Figure 25 visualizes the normalized distribution of turnaround times at the Maasvlakte between July 2021 and December 2021. As can be seen, variance between the different months is limited. Figure 27 depicts a stacked bar-chart that shows the distribution of turnaround times across the various periods during the day (nighttime, morning peak, day and evening peak). Also the distributions in this plot show a similar pattern without large difference between the time-of-day, the peak of the distribution lies consistently near 85 minutes.

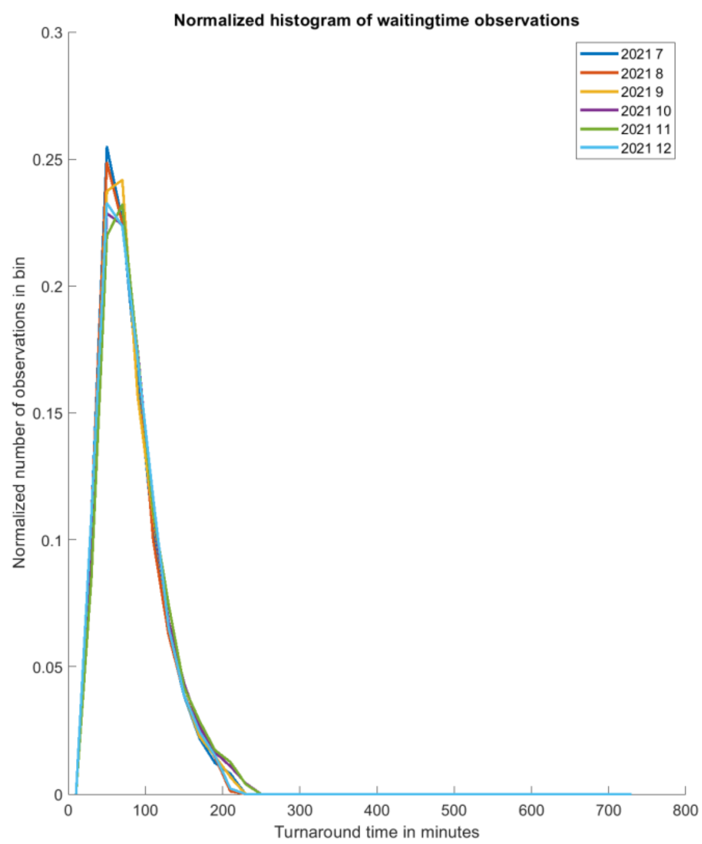

Figure 25: Normalized turnaround times at the Rotterdam Maasvlakte area

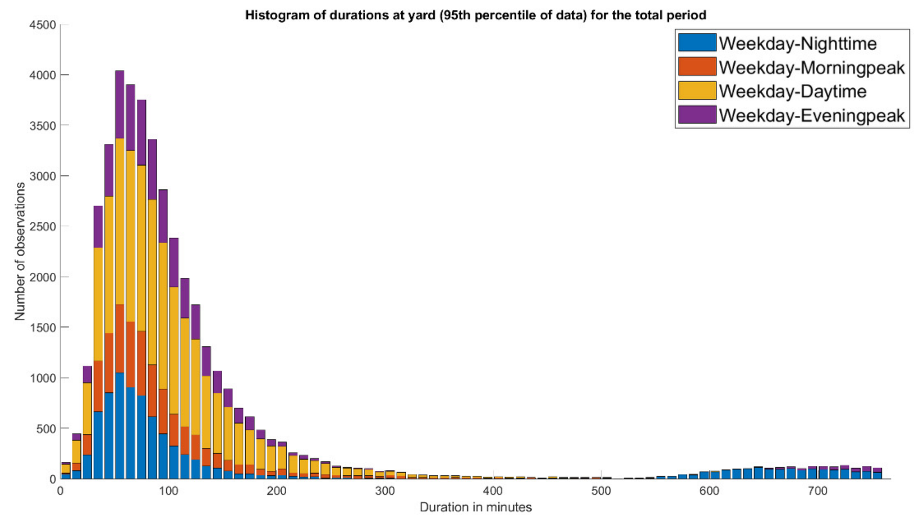

Figure 26: Histogram of turnaround times for the Rotterdam Maasvlakte for various time of days. Morning period: 07:00 to 09:00 CET, daytime: 09:00 to 16:00 CET, evening peak 16:00 to 18:00 CET and night-time 18:00 to 07:00 CET.

At this moment, the results (i.e. lack of variation in turnaround times) are not fully recognized by logistic operators. Factors that might contribute to the observations are:

- Given the 5 minute refresh interval for GPS points and the fact that data is not logged while the engine is off, fairly large time steps can arise when little data is available.
- Additionally, all measurements are instantaneous, meaning that only the measurements of that specific point in time are logged. This in practice means that every five minutes a GPS points is available but that it is unclear where the vehicle travelled in the intermediate minutes.
- Partly in combination with the chosen filtering (to disregard/include vehicles that visited specific locations) some behaviors are less reflected. For example vehicles that turn around in extreme circumstances such as incidents are disregarded because they turn around without visiting any of the terminal locations.

The points above imply that better understanding is required to investigate specific cases of congestion. Further research is recommended and advised to better understand the factors that contribute to discrepancy between the observations in this analysis and the experiences from logistics operators in the sector.

3.3.3 *Main observations in regard to fuel consumption and emissions during yard visits*

As part of Table 10, the results of the fuel consumption and CO_2 emission analysis are depicted for various yards. This table firstly describes the idling behavior which was deducted from the yard visits and subsequently relates these to an average vehicle visits (in terms of full round-trip journey).

Compared to the congestion analysis, which is mainly dependent of the 5 minute GPS measurements, the engine behavior (a.o. idling) can be more reliably researched due to the increased sampling rate of the engine parameters. Based on the data points that are considered as idling (RPM equal or less than 600 RPM, an engine load of <10% and a speed of 0 km/h), it appears that on average, vehicles at the Maasvlakte idle for 24% of the time in which these vehicles are registered on the yard area. For the other yards this percentage various between 19% for the Schiphol terminal area and 36% for DPD Oirschot.

When one looks at the figures in detail and when comparing the results for the various yards, especially the difference in idle fuel use between Moerdijk and the Maasvlakte becomes apparent (0,84 litres per visit for the Maasvlakte versus 1,48 litres per visit for Moerdijk). The higher amount of fuel burnt during idling at Moerdijk results from a reinforcing effect between the larger turnaround time and the larger idling percentage as compared to the Maasvlakte. However it should be noted that the sample size for the Moerdijk yard is significantly smaller (26 visits per working day on average for the Moerdijk area versus 211 visits for the Maasvlakte).

Also the occurrence and length of the idling behavior was analyzed. As depicted in Figure 27, it appears that as part of an average trip often multiple idling periods are found and range between 0 and 28 occurrences with an average of 6,3 idle periods. Of these idle periods 10,6% of the occurrences had a duration above 10 minutes.

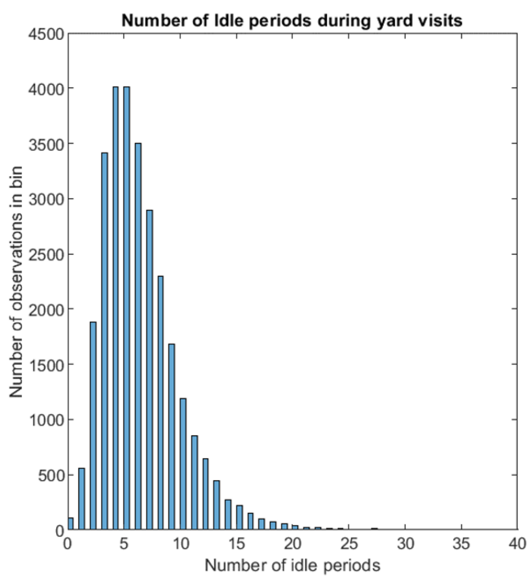

Figure 27: Distribution of number of idling periods for Maasvlakte area for period between Jul 2021 and Dec 2021.

To translate the idle durations to a fuel consumption value and forthcoming emissions, an earlier dataset was repurposed from the Integrator Connected Truck Trial Project in which SEMS data from 9 DAF trucks was collected. Based on real-world measurements (during 15 weeks), the average fuel consumption of 2,561 liter per hour was deducted while idling, which translates to 6,789 kg of CO_2 per hour. Based on these assumptions, the revealed fuel consumption per visit while idling is derived. Across the various yards, the fuel consumption per visit ranges between 0,41l. per visit for the Schiphol Terminal and 0,84l for the Maasvlakte yard.

The fuel consumption while idling at Moerdijk is relatively higher with 1,48l per visit. Partly this higher number is a result of the longer average turnaround time, but also the percentage of time idling at this yard is relatively high with 29%. These two factors together amplify the difference between Moerdijk and the other yard areas.

This research has specifically focussed on the fuel consumption when idling. The main reason for this demarcation is that the DAF Connect export dataset does not contain cumulative fuel consumption statistics from the on-board computer. Also, the vehicle fuel level measurements varied due to the vehicle weights (as denoted in section 3.2.3 of this report). When idling, variables like vehicle weight, road conditions, driving behaviour and elevation profiles all remain stable. When driving, all these factors dynamically change and the current data sample rate of 1 minute is not sufficient to reliably estimate the fuel consumption.

A similar reasoning applies to the measurement of additional pollutants such as NH_3 and NO_x. As seen in Chapter 2, the emission of such pollutants is dependent more on other factors such as engine temperature and the status of the use of after-treatments technologies such as the exhaust gas recirculation (EGR) and selective catalytic reduction (SRC). These parameters are not available in the current dataset.

3.3.4 *Brief elaboration of the observations per yard*

Where the previous results have mainly emphasized the overarching results and observations, this specific section will indicate the most important findings per yard.

3.3.4.1 *Port of Rotterdam - Maasvlakte*

- Given the geographical location and distribution of various functions across the area, the Maasvlakte is considered a very useful proofing ground to implement certain filters, validate the performance and then to translate these to the other yards.
- The filtering that was applied for the Maasvlakte was the most extensive; for example the Maasvlakte contained multiple container terminals which were identified individually.
- On average we have detected 211 yard visits per working day, with an average turnaround time of 86 minutes.
- This average turnaround time includes the travel time from and towards the N15, so the actual time at the terminals is shorter.
- During weekends the turnaround time increases slightly, however the sample size of the yard visits during weekends is significantly lower which hampers the representativeness of this indicator (16 vehicle visits per day). Moreover the data shows more extreme values that express themselves in both short and very long turnaround times. The latter category is most likely related to drivers that take a longer rest period.
- On average, vehicles are idling for 24% of the total yard visit which translates to an average idle fuel consumption of 0.84L
- Both across the months, days and terminals the turnaround time remain relatively stable, e.g. clear peak congestion is not observed.
- Based on the data it is possible to ‘detect’ anomalies in terms of extreme yard congestions but not the extend/severity. For example on November 18th 2021 there as a major strike which blocked one and/or multiple access routes to and from the Maasvlakte, and traffic jams were reported (Branse, 2021).

From the results and turnaround times an anomaly becomes apparent that less vehicles arrive but the turnaround times before, during and after the event do not show a clear increase in turnaround time as a result of the congestion.

3.3.4.2 *Port of Moerdijk*

- Compared to the Maasvlakte, the observed turnaround times for Moerdijk are clearly higher. With an average of 26 visits per working day an average turnaround time of 180 minutes is observed.
- The percentage of time which vehicles idle is also relatively higher for the Moerdijk area (29% of the duration of the visit).
- The longer turnaround time and higher idling percentage together result in a higher idling fuel consumption. On average for Moerdijk 1,48l of fuel is used per visit while idling.
- Compared to the Maasvlakte, vehicles arriving and departing from Port of Moerdijk travel a shorter average distance, possibly because Moerdijk fulfils a more regional role. This means that the fuel consumed during idling makes up a relatively larger part of the total journey fuel consumption.

3.3.4.3 *North Sea Port - Vlissingen*

- The observed average turnaround time for Vlissingen was 191,5 minutes for an average weekday. On average 70 vehicles per working day have been registered.
- As part of the Vlissingen area it was perceived to be more challenging to identify whether trucks visited the dedicated logistics centres within the port area as most logistics hubs are located very close to the public road which hamper the filtering in combination with possible GPS inaccuracies.
- Due to the limited filtering the observed yard visit may include other logistical activities than only the loading and unloading of containers (as specifically researched for the Maasvlakte and Moerdijk).
- The observed average idling percentage of vehicles was 20% of the total yard visit time which translates to 0,81l of fuel and 2,1kg of CO_2.

3.3.4.4 *Ground handlers at Schiphol airport*

- The observed average turnaround time for the Schiphol Cargo terminals was 113,3 minutes for an average weekday. On average 66 vehicles per working day have been registered that visit the terminal area.
- As part of the Schiphol area there are multiple dedicated parking areas, vehicles from-and-to these facilities were filtered out during the calculation of the average turnaround time.
- Given the compact area structure it was not possible to filter on specific ground handler areas. Most ground handlers are located very close to the public road which hamper the filtering in combination with possible GPS inaccuracies.
- The observed average idling percentage of vehicles was 19% of the total yard visit time which translates to 0,41l of fuel and 1,7kg of CO_2.

3.3.4.5 *DPD Oirschot*

- The observed average turnaround time for the DPD Oirschot terminal was 58,6 minutes for an average weekday. On average 36 vehicles per working day have been registered that visit the DPD yard.
- Given the specific characteristics of this yard, no filtering was applied for parking areas or other logistics hubs; the yard only covers the DPD area.

Vehicles visiting the DPD area are registered when they arrive and depart through the main gate.

- The highest idling percentage was observed at the DPD yard, but given that the observed vehicles drive long haul trips (average journey distance is 180 kilometres) the percentage idling in relation to the total fuel consumed during the journey is limited (2%).

3.4 Conclusions

As part of YES we researched the real-world operation and forthcoming CO_2 emissions of heavy duty vehicles in the first and last mile towards (smart) yards. This chapter demonstrates the added value of high-quality vehicle information from OEM based cloud solutions, whereby it is possible to investigate how this information can be used to improve efficiency in the supply chain, to limit fuel consumption and to reduce emissions. The extensive dataset makes it possible to investigate at vehicle level at what time and place the vehicle arrived, how much time it spent at the yard and when it left again. Given the availability of engine parameters, it is possible to look at the engine behavior at an aggregated level and to utilize this information to estimate the fuel consumption and CO_2 emissions while idling.

This brings us to the following conclusions:

Yard congestion

- With the DAF Connect data it was possible to derive turnaround times and variation in these times for the different yards are observed;
- Within the yards, however, the expected variations in turnaround times and peak hours are not observed. Surprisingly, this does not reflect the experiences in the sector (as resulting from consortium discussions, sector publications, and other initiatives that aim to tackle congestion near port terminals). We have not (yet) found a single unambiguous explanation for this discrepancy. Most likely it is a combination of (smaller) factors that add up which results in less apparent patterns in terms of yard congestions.
- Efforts are ongoing to validate the observed results. As part of these activities a meeting took place with the Port of Rotterdam. During this meeting it became apparent that the port authority recognizes the potential added value of high-resolution and large scale OEM based telematics data and the relevance of the analyses that have been conducted. The Port of Rotterdam does not recognize the limited variation in terms of the turnaround times and suggests that additional cross-sections and filtering may be valuable to include the processes at the terminals (e.g. gate procedures and seaside operation). In addition to the ongoing contact with the port authority of Rotterdam, it is recommended to engage with stakeholders from the other yards as well, to explore the results in more depth.

Emissions of trucks idling at yards

- With the DAF Connect data it was possible to derive estimated CO_2 emissions from trucks *idling* at yards. Because of a lack of data on specific vehicle characteristics (e.g. on the presence of after-treatments technologies), deriving local pollutant emissions (NO_x, NH_3) in a reliable way was not possible;

- It was not possible to derive fuel and emission statistics from trucks *driving* at yards. The DAF Connect export dataset does not contain cumulative fuel consumption statistics from the on-board computer. Also, the vehicle fuel level measurements varied due to the vehicle weights (as denoted in section 3.2.3 of this report);
- In relation to total fuel consumption of an average trip from/ to the specific yards, a marginal percentage of fuel consumption can be attributed to idling at the yard (1-5%, depending on the specific yard that is visited).
  - As seen from a transporter's perspective, the potential fuel saving potential related to idling at yards is limited. However, on a fleet level and annual basis the potential fuel saving is of relevance for transporters.
  - It should be noted that the labour costs of waiting during idling have not been taken into account in this analysis. Given that the labour cost constitute a larger share of the operational costs of transporters, this is will be a bigger trigger (compared to fuel consumption) for transporters to minimize waiting times at yards.
  - As seen from a port and terminal perspective, idling at yards (and the related emissions) is of relevance as well. Local emissions during idling are dense in terms of time and space. Moreover, as this dataset by estimate contains 3.4% of trucks, this is still of relevance for the local air quality of the port terminals and logistics hubs under consideration.
- It is recommended to explore in future research which idling can be prevented and which efficiency gains can be made.

To our knowledge, this is one of the first projects that explores the arrival and departure of heavy duty trucks at yards by using real-world and high definition vehicle based data.

4 Outlook on Connected Automated Transport development for yards

4.1 Introduction and approach

In order to put the results from the yard emission monitoring in perspective, we provide this outlook by answering the following questions:

- *What are annual emissions of a fleet of yard vehicles?*
- *How do emissions of yard vehicles relate to long-haul transport emissions?*
- *What are the implications of electrification of automated yard vehicles?*

The first two research questions are discussed in section 4.2. Section 4.3 covers an exploration of the implications when electrifying automated yard vehicles. Finally, we conclude in section 0 by providing further research possibilities.

4.2 Putting yard emissions into perspective

In order to get an understanding of the order of magnitude of the fuel consumption and related emissions at yards as analysed in Chapter 2, we engage in 2 activities:

a. We scale single terminal tractor emission numbers to the whole fleet of terminal tractors on a monthly and annual base. Since transporters indicated that the monthly data (the average pollutants expelled per litre fuel consumed as reported in Chapter 2) is representative, we simply multiply these by 12 in order to get the annual figures for the entire yard.
b. We compare these with fuel consumption and emissions of regular trucks that are used for medium to long-distance transport. We detail our approach in the next section (4.2.1).

4.2.1 Approach and analysis

As real-world monitoring of regular trucks was out of scope for this project, we asked the participating transporters to provide company measures on fuel consumption (tanked litres) and where available emission statistics. We acknowledge that this approach differs from the detailed real-world monitoring as we did in Chapter 2. However, this provides us with a best estimate for comparing order of magnitude.

Line haul transport

For the first transporter (DPD), CO_2 emission statistics from line haul services could be retrieved from DPD's quarterly emission report. The total amount of emissions is based on fuel consumption and emission factors (Base Carbone, see Appendix II). Line-haul trips are performed by subcontractors who provide transport between distribution hubs in the Netherlands and towards distribution hubs in Europe. As a result, it was not possible to derive tanked litres or kilometres driven for a daily, monthly or annual estimate. We incorporated the reported annual CO_2 emissions, and based on that, we derived the monthly emissions (reported annual emissions divided by 12) and we estimated the emissions for 1 truck for 1 day (monthly estimate, divided by 254 trucks, divided by 25 days).

Scale-up on-site terminal tractors
For the terminal tractors we retrieved the tanked litres for each quarter of 2021. In order to make the monthly estimate in Table 11, we divided the quarterly figures by 3. We used the TTW emission factor 2630 g CO_2/ litre (De Ruiter et al., 2019). For NO_x, we used the emission factors as presented in Table 2 (22363 mg NO_x/ litre).

Table 11: Comparison emissions line haul operations with on-site terminal tractor

	1 Line Haul truck DPD	**1 on-site terminal tractor**			**% emissions terminal tractor**
1 day operation	479 kg. CO_2 (Estimate)	63 km	126 kg CO_2	1.05 kg NO_x	16,7%
1 month estimate	**254 Line Haul vehicles DPD**	**12 on-site terminal tractors**			**% emissions terminal tractor**
	3041 ton CO_2	14.282,67 L	37.56 ton CO_2	319 kg. NO_x	1,24%
Annual figures	36.488 ton CO_2	176.419 L.	464 ton CO_2	3939 kg. NO_x	1,25%

When comparing emissions (in Table 11), from 1 on-site terminal tractor use with the emission estimate of 1 line-haul truck, we observe that the on-site terminal tractor accounts for approximately 16% of the combined (on-site and long-haul) emissions. If we make the comparison for the entire line-haul operations (254 trucks), this is only ~1%.

Long haul transport
For the second transporter (Vepco), we retrieved fuel consumption data (from CAN-bus) (January 2022) for their regular truck operations. Trucks are utilized in two different ways: either for short trips in the port area or for long-distance trips from customers to the port area. Furthermore some EcoCombi's are used. As trucks are not dedicated to one of these tasks, we could not filter out the non-long distance trips based on license plate. In consultation with Vepco, we included only the trips with a fuel consumption <40 L/100km. All fuel consumption above that threshold level can be attributed to either short trips in the port area or trips where an EcoCombi was used.

For the example of 1 long-distance Euro VI truck, we picked a truck (in consultation with Vepco) that drives 661 km with an average fuel consumption of 27,23 l/ 100 km (and total litres used for this trip: 179,99L). In order to convert this to CO_2, we used the TTW emission factor of 2630 Kg CO_2/litre (De Ruiter et al., 2019). In order to convert the fuel consumption to NO_x, we used the average NO_x emission factor for heavy transport on highways of ~0,55 g NO_x/ km (Ligterink, et al., 2019). For the Vepco long-distance truck this results in ~2,02 g NO_x/ litre. Note that we use an estimate here.

Scale-up of industrial area terminal tractors
For the terminal tractors we retrieved the tanked litres for one month. For both the trucks and the terminal tractors only monthly data was available.

In order to make the annual estimate in We used the TTW emission factor 2630 g CO_2/ litre (De Ruiter et al., 2019). For NO_x, we used the emission factors as presented in Table 5 (4763 mg NO_x/ litre).
Table 12, we multiply the monthly fuel consumption (trucks) and tanked litres (terminal tractors) by 12, since it was indicated by Vepco that the reference month is representative for the rest of the year. We used the TTW emission factor 2630 g CO_2/ litre (De Ruiter et al., 2019). For NO_x, we used the emission factors as presented in Table 5 (4763 mg NO_x/ litre).

Table 12: Comparison emissions long-haul operations with industrial area terminal tractor

	1 long-distance truck Vepco (Euro VI)			**1 industrial area terminal tractor**			**% emissions terminal tractor**
1 day operation	661 km.	473 kg. CO_2	0.3635 kg. NO_x	49 Km.	133 kg. CO_2	0.24 kg. NO_x	22% CO_2 39,7% NO_x
	52 vehicles long-distance operations Vepco			**10 Terminal tractors**			**% emissions terminal tractor**
1 month	97.006, 992 L	255 ton CO_2	195 kg. NO_x	8.008,6 4 L.	21 ton CO_2	109 kg NO_x	8% CO_2 36% NO_x
Annual estimate	1.164.0 83,90 L	3061 ton CO_2	2351 kg. NO_x	96.103, 68 L.	253 ton CO_2	1305 kg NO_x	

When comparing the emissions from one industrial area terminal tractor use with one long-haul operations truck (Table 12), we observe that the industrial area terminal tractor accounts for 12% of the combined (industrial area and long-haul) CO_2 emissions and ~40% of the combined NO_x emissions. When looking at the kilometres driven, the terminal tractor only drives ~7% of the kilometres that the long-haul truck drives on one day. Thus, in this comparison emissions of the terminal tractor are relatively high and are mainly emitted in a dense local area.

4.3 Potential emission reduction by electrification of automated yard vehicles

Automated vehicles can be implemented with conventional or electric powertrains (Gerritse & Van Kempen, 2022). Electric powertrains are considered best from an environmental perspective as these do not have an exhaust with pollutant exhaust gas flow as their diesel counterparts. This paragraph quantifies the difference between these powertrains by calculating the CO_2 expelled in two steps. First, the Tank To Wheel (TTW) emissions are considered, then the Well To Wheel (WTW) are calculated.

Local Emissions versus total emissions

The local emissions, commonly referred to as TTW, are the emissions expelled by the vehicle on site by burning fuel. The total emissions, Well To Wheel (WTW), include the emission of producing and transporting the energy to the vehicle in addition to the TTW emissions. The diesel and electric powertrain TTW and WTW emissions are determined based on the scaled data, i.e.: for the entire fleet of terminal tractors for 1 year.

Diesel powertrain
The diesel powertrain expels emissions locally by burning fuel. One litre of diesel consumed expels 2630g CO_2 (De Ruiter et al., 2019). By combining this with the known fuel consumption, the TTW emissions can be calculated. When the production and transport of diesel is also included, the CO_2 emission is 3181g/l (Edwards et al., 2014). This results in the TTW and WTW as reported in Table 13.

Electric powertrain
The local emissions of electric vehicles are 0 as they do not burn fuel or emit pollutants via other means. However, they do consume energy which must be produced elsewhere. Pollutants are emitted in the power generation process (the WTW emissions). The electric energy emissions factors are described as the grid mix and are determined by CE Delft in 2020. To produce 1 kWh of electric energy 480 gram of CO_2 is emitted considering the current Dutch energy mix (Wielders & Nusselder, 2020). When considering WTW emissions, it can be seen that with the current energy mix, 24.7% of emissions can be reduced. It is expected that the share of renewable energy in the Dutch energy mix will increase. Thus it can be expected that the WTW savings of using an electric powertrain will increase as well.

Table 13: Comparison TTW and WTW emissions for on-site and industrial area terminal tractors with diesel and electric powertrain.

Terminal tractor	Diesel Powertrain	Electric Powertrain	CO_2 reduction
On-site WTW	561 ton CO_2	422 ton CO_2	24.7%
On-site TTW	464 ton CO_2	0	100 %
Industrial area WTW	305 ton CO_2	229.5 ton CO_2	24.7%
Industrial area TTW	253 ton CO_2	0	100%

4.3.1 Boundary conditions for electrification of automated yard vehicles given current operations

Using electric automated yard vehicles is different from using diesel powered vehicles. For electric vehicles, charging the battery is a key factor in successful deployment of these vehicles. Therefore, in this paragraph we *explore* the boundary conditions for electrification, given the current operations of the terminal tractors as described in Chapter 2. We looked at the operational use of the terminal tractors in a generic way in Chapter 2. Based on the current usage, current activities can be performed with electric yard vehicles.

The two investigated yards have different needs in terms of energy capacity and available charging time. The goal is not to fully design an electric powertrain, but to give a first estimation of the implications based on current operations. To be able to say something about charging strategies, we need to determine the required battery size(estimation). This is now done based on the fuel consumption and difference in powertrain efficiencies. Both applications are described in the following paragraphs.

On-site yard operations
In this yard the trucks operate 20 hours per day on a regular basis. This leaves very little time for charging the battery. Furthermore, most of the fleet will be charging their batteries simultaneous with high powered fast chargers, which puts a large load on the already overloaded electricity grid in this area. Several options can be considered to mitigate this problem.

Switching batteries or vehicles during the day is an option in this application. By this, the batteries can be charged over a longer period of time, reducing the required power of the chargers. Based on the daily fuel consumption and powertrain efficiencies, an estimate can be given for the required battery size (Liimatainen, van Vliet, & David, 2019), see Table 14.

Table 14: Battery capacity estimation derived from (Liimatainen, van Vliet, & David, 2019)

$$Battery\ Capacity[kWh] = \frac{B \cdot Lhv \cdot \eta diesel}{\eta electric \cdot 3.6}$$

Here, B is the maximum fuel consumed on a day [L]

L_{hv} is the lower heating value of diesel[MJ/L]

η_{diesel} is the diesel powertrain efficiency[-]

$\eta_{electric}$ is the electric powertrain efficiency[-]

For the on-site truck this yields a required battery capacity of 428kWh, as can be seen below.

$$Battery\ Capacity[kWh] = \frac{114.5 \cdot 35.9 \cdot 0.30}{0.8 \cdot 3.6} = 428kWh$$

For reference, the largest battery capacity available for the electric yard truck of Terberg's YT203 is 222kWh. The required capacity can be achieved by switching vehicles during the day. However, this would double the required fleet size.

Since these trucks operate on-site and not on the public road, the batteries can be charged during the day using inductive chargers or by implementing charging stations on parking spots. The batteries can then be charged while the truck is parked and waiting for the next trip. This would eliminate the need for oversized batteries and corresponding chargers, significantly reducing the costs.

Industrial area yard operations

The trucks operating in the industrial area are operated up to 12 hours per day, leaving sufficient time to charge their batteries. Furthermore, the daily fuel consumption is significantly lower than the on-site trucks. Based on the daily fuel consumption and estimated powertrain efficiencies, the required battery capacity for this application is 133kWh, as can be seen below.

$$Battery\ Capacity[kWh] = \frac{35.5 \cdot 35.9 \cdot 0.30}{0.8 \cdot 3.6} = 133kWh$$

This is well within the range of current available technology.

4.4 Conclusions

In this final chapter of the analyses, we strived to put the results of the real-world yard emission analysis in perspective.

- When comparing the emissions from one industrial area terminal tractor use with one long-haul operations truck (Table 12), we observe that the industrial area terminal tractor accounts for 12% of the combined (industrial area and long-haul) CO_2 emissions and ~40% of the combined NO_x emissions. When looking at the kilometres driven, the terminal tractor only drives ~7% of the kilometres that the long-haul truck drives on one day. Thus, in this comparison emissions of the terminal tractor are relatively high and are mainly emitted in a dense local area.

From earlier work in the YES project (Gerritse & Van Kempen, 2022), it can be derived that powertrains of autonomous yard vehicles can be electric. Therefore, we made first calculations on the sustainability impact of electrifying these autonomous yard vehicles.

- The annual estimated TTW savings are 464 tons and 253 tons CO_2 for the on-site and industrial area fleet of terminal tractors respectively. Given the current Dutch energy mix, ~25% of current WTW emissions can be reduced.
- It should be noted that the above mentioned energy and emissions savings potential is only due to an electric powertrain. Based on current operational data, it was not possible to analyse the potential to improve efficiency because of automation. Further research is needed to explore this in more detail.
- Based on current energy required for the transports to be done, it is estimated that current yard transport can be executed by electric (and autonomous) yard vehicles. Given current operations, the required battery capacity for the on-site terminal tractor does not fit current available battery sizes. Therefore, charging strategies have to be designed to make it fit in practice (or operations need to be adjusted). Given the operation of the industrial area yard tractor, the required battery capacity seems to fit the current use.

5 Conclusions and opportunities for further research

5.1 Conclusions

In YES the aim was to identify the potential impact of Connected and Automated Transport on reduction of emissions for freight transport to and from yards. By the conducted analyses we were able to contribute to this initial research aim by:

- Establishing a baseline measurement of real-world operational use and resulting emissions (CO_2, NO_x, PM10) of a terminal tractor operating in an industrial port area and a terminal tractor operating at a logistics site;
- Establishing a baseline measurement of freight transport to and from yards by the analysis of turnaround times of trucks and estimated CO_2 emissions while idling at logistics and (air)port yards, which are based on high definition vehicle data from an OEM's telematics platform (DAF Connect);
- Showing that emissions of a terminal tractor are relatively high compared to long haul transport and that these are mainly emitted in a dense local area.
- Providing first insights on the electrification potential of yard vehicles. Based on other research in YES (Gerritse & Van Kempen, 2022), it is expected that most autonomous yard vehicles will also be electric.

It is expected that by implementing Connected and Automated Transport at yards, current operations can be made more efficient. The available data and conducted analyses in YES leave room to further explore the potential efficiency gains that are expected to result from CAT (see section 5.2). Insight in this efficiency potential is needed to fully address the initial knowledge gap as presented in section 1.2.

All in all, this is a valuable study as it is the first one that reports real-world emission measurements on terminal tractors in their logistics operation. Also, it is rather unique how a OEM telematics platform (DAF Connect) was applied for analysis of trucks at yards. Both analyses were a first exploration regarding establishing a baseline measurement for logistics operations and emissions at yards.

5.2 Opportunities for further research

The analyses of YES can be used as input for further research as there are opportunities for answering follow-up questions related to scaled-up scenarios of the deployment of Connected Automated Transport at yards and its impact on emission reduction and efficiency improvement:

- *Emissions of yard vehicles* (such as terminal tractors). These types of vehicles are considered Non Mobile Road and Machinery (NMRM). Research on real-world emissions of NMRM vehicles has started to take off only recently. It is expected that insights regarding local emissions will become more relevant in the current air quality and NO_x discussions in the Netherlands. It would be interesting to expand the current research, and scale-up the results to get a better understanding of yard emissions in the Netherlands as a whole. It is expected that vehicles are relatively old and thus do not have the newest (and most energy efficient) technology. And our research on the on-site terminal tractor indicates that vehicles having the newest (SCR) technology, might not perform as intended with respect to local emissions;

- *Congestion in port areas using vehicle telematics data*. This research has shown that valuable insights can be retrieved from OEM telematics data. Regarding congestion analysis, there is untapped potential to refine the current analysis and go more in-depth to find congestion patterns. These can be of relevance for port authorities and local road authorities near logistics hubs for example, to determine current bottlenecks and improvement potential;
- *Efficiency savings because of automation*. In the current research it was out of scope to make a *detailed* analysis on the potential efficiency savings that might be made by CAT on yards. Given the operational data as described in Chapter 2, no analysis was performed on whether the terminal tractors were operated in the most efficient way. Because of that it was not possible to determine improvement potential. For advancing research on CAT, it is advisable to explore the magnitude of this potential in more detail.

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7 Signature

The Hague, 24 June 2022

TNO

Björn de Jong
Projectmanager

Elisah van Kempen
Author

A Idling definition and SCR behavior

Idling definition

For both vehicles analysed in Chapter 2, idling was defined based on a combination of criteria on RPM, actual torque, and vehicle speed. These criteria were determined on a data driven fashion, following the standby intervals. Figure 25 and Figure 26 illustrate with examples for the Kamag and the Terberg vehicles the definition of idling, respectively. On the bottom panel of both figures the load is also shown as reference and to indicate that idling and high load and independent criteria.

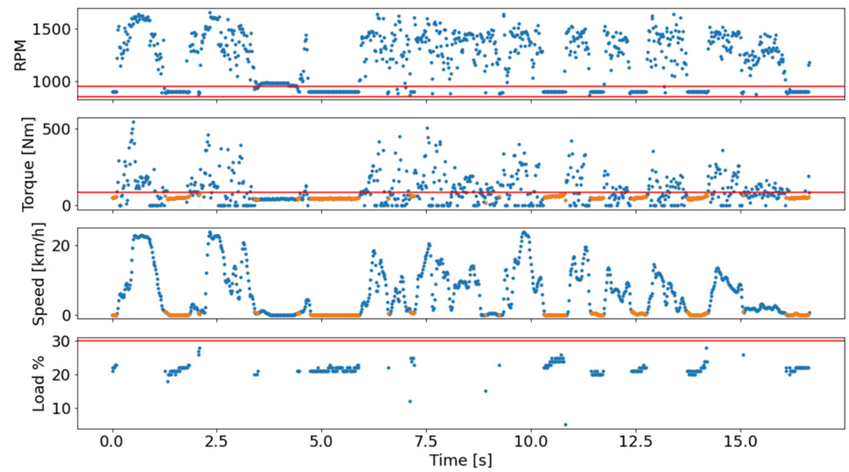

Figure 28: Example of the definition of idling on an arbitrary piece of signal of the Kamag vehicle. From top to bottom: RPM, Torque, Speed and Load. The red horizontal lines indicate the thresholds used as criteria for the RPM and Torque i.e., RPM is required to be bounded between both red lines (top plot) and torque below the threshold. The line on the bottom plot (Load) is just for reference for comparison with the load definition and does not act as a criteria.

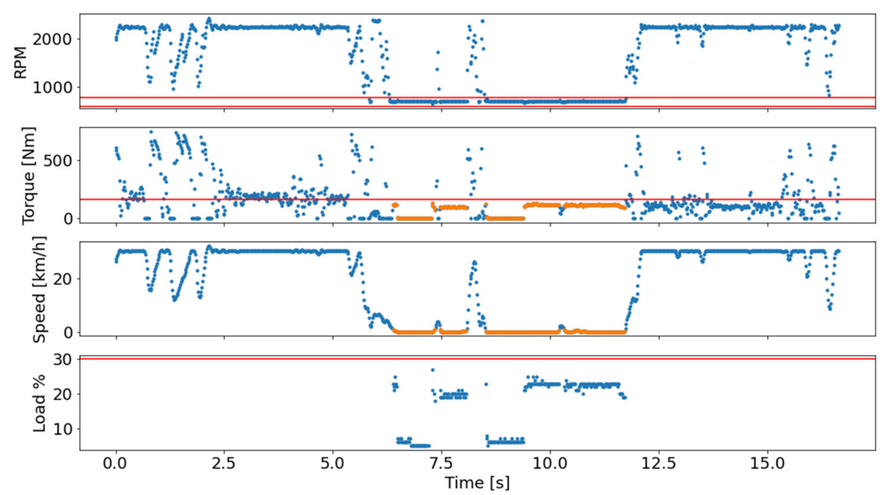

Figure 29: Example of the definition of idling on an arbitrary piece of signal of the Terberg vehicle. From top to bottom: RPM, Torque, Speed and Load. The red horizontal lines indicate the thresholds used as criteria for the RPM and Torque i.e., RPM is required to be bounded between both red lines (top plot) and torque below the threshold. The line on the bottom plot (Load) is just for reference for comparison with the load definition and does not act as a criteria

Table 15: Values used to define the period of idling. Only those datapoints that simultaneously fulfil all the conditions on the table are categorized as idling.

	Maximum torque [Nm]	Minimum engine speed [rpm]	Maximum engine speed [rpm]	Vehicle Maximum speed [km/h]
Kamag	81	850	950	1
Terberg	78	600	775	1

SCR behavior

To understand the level of emissions for the vehicles analyzed in Chapter 2, we analyze the dependence on the exhaust temperature. In the case of the Kamag, we use the NH_3 concentration as a proxy for the SCR[4] activation. In Figure 30 we show the NH_3 and NO_x emissions as a function of the exhaust gas temperature (EGT) together with the frequency of occurrence of such temperature. The significant decrease of the NO_x due to the injection of NH_3 starts at 200 C but the vehicle operates more than half of the time at lower temperatures. Because of the vehicle operating in low load, the engine is not hot enough for the SCR to function properly.

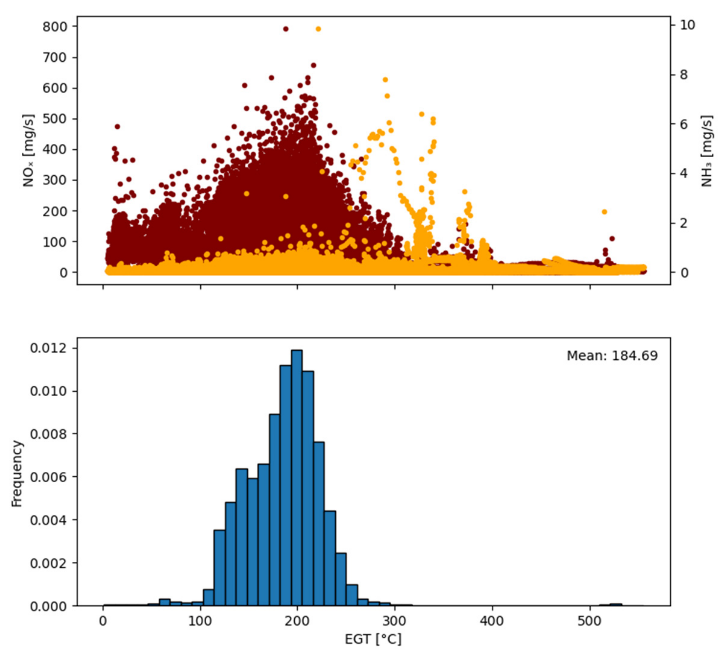

Figure 30: Illustration of the NO_x and NH_3 dependence on the Temperature. Top panel: on maroon, the NO_x and in yellow the NH_3, both as a function of the Exhaust gas temperature. On the bottom panel, the distribution of exhaust gas temperature.

There is no SCR installed in the Terberg vehicle, hence such analysis cannot be done. For completeness, we show the NO_x as a function of the EGT together with the temperature distribution.

[4] Selective Catalytic Reduction (SCR) is an advanced active emissions control technology system that reduces tailpipe emissions of nitrogen oxides (NO_x).

It can be seen that as with the Kamag the vehicle operates at low temperatures, and although the NO_x emissions increase with temperature, they remain lower than the values for the Kamag when the SCR is not operating but higher than those of the Kamag when the SCR is operating.

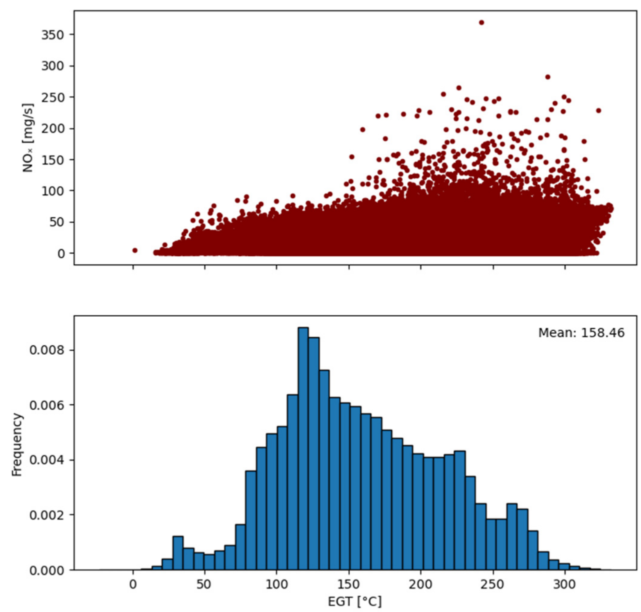

Figure 31 Illustration of the NO_x dependence on the Temperature. Top panel: on maroon, the NO_x, both as a function of the Exhaust gas temperature. On the bottom panel, the distribution of exhaust gas temperature.

B Trip recognition

Table 16: Number of trips resulting from the trip recognition, based on DAF data from Sept. 2020

OD relation		Destinations						
		Maasvlakte	Moerdijk	Vlissingen	Schiphol Terminals	Oirschot	Rest NL	Anders
Origin	Maasvlakte	826	64	0	0	3725	346	3725
	Moerdijk	64	90	4	8	1185	382	1185
	Vlissingen	17	10	0	0	235	183	235
	Schiphol Ground Handlers	1	0	37	0	224	107	224
	Oirschot	0	0	0	0	74	60	74
	Rest NL	3808	1459	428	150	222936	30011	222936
	Anders	333	339	123	32	29795	14491	29795

Table 17: Average distance per OD relation from the recognition, based on DAF Connect data from Sept. 2020

OD relation		Destinations						
		Maasvlakte	Moerdijk	Vlissingen	Schiphol Terminals	Oirschot	Rest NL	Anders
Origin	Maasvlakte	11,3	70,7	83,7			64,2	179,7
	Moerdijk	71,4	9,3	79,9	93,5	69,5	49,6	117,6
	Vlissingen	87,7	80,7	15,7			69,3	113,9
	Schiphol Ground handlers	96,4			6,2		53,1	213,3
	Oirschot						94,0	157,2
	Rest NL	73,7	50,0	64,8	61,2	86,4	47,4	121,9
	Anders	171,9	99,5	78,3	202,0	125,8	113,5	132,5

C Emission factors DPD

Emission factors (CO_2e) for GeoPost (Sources: Base Carbone® from June 2014 and La Poste Indicia 201

	Upstream phase[4]	Use phase[5]	Uncertainty	Source
		TRANSPORT		
Petrol	0,53 kg CO_2e/litre LVH	2,2637 kg CO_2e/litre LVH	10 %	Base Carbone®
Diesel	0,65 kg CO_2e/litre LVH	2,51113 kg CO_2e/litre LVH	10 %	Base Carbone®
LPG	0,249 kg CO_2e/litre LVH	1,59855 kg CO_2e/litre LVH	5 %	Base Carbone®
Natural Gas	0,64 kg CO_2e/kg	2,81 kg CO_2e/kg	5 %	Base Carbone®
Natural Gas – Specific Netherlands	0,35 kg CO_2e/kg	2,284 kg CO_2e/kg	5 %	CO2emissiefactoren
LNG	0,704 kg CO_2e/kg	2,81 kg CO_2e/kg		Base Carbone®