Work Package 5
Report of analysis

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1 Introduction

The HECTOR project (**H**ydrog**E**n Waste **C**ollec**T**ion Vehicles in N**O**rth West Eu**R**ope) was initiated to demonstrate that fuel cell powered refuse collection vehicles (RCVs) provide an effective solution to reduce emissions from road transport. For this goal, seven fuel cell garbage trucks are deployed and tested in pilot sites across the north west Europe area:

- Aberdeen (Scotland),
- Groningen (Netherlands),
- Arnhem (Netherlands),
- Duisburg (Germany),
- Herten (Germany),
- Touraine Vallée de l'Indre (France),
- Brussels (Belgium).

The pilot sites cover a wide range of operational contexts; the various trucks operate in city centres and in rural areas, on fixed and flexible schedules, collecting municipal- and industrial waste.
HAN Automotive Research designed and carried out the research on the performance of the trucks in normal operating conditions as well as the social impact for the drivers.

PARTNER	**OPERATING AREA**	**CHASSIS**	**OUTPUT FUELCELL**	**BATTERY & OUTPUT**	**PRESSURE No of Tanks / Kg**
Aberdeen	City centre route, Municipal waste	**Mercedes**		45 kWh	*350 bar* *4 x 5 kg = 20 kg*
Groningen	City centre route, Municipal waste	**DAF**	1 x 40 kW	136 kWh	*350 bar* *15kg*
Arnhem	City centre route, Municipal waste	**DAF**	1 x 40 kW	136 kWh	*350 bar* *15kg*
Duisburg	Fixed schedule Industrial waste	**Mercedes**	3 x 30 kW	85 kWh	*350 bar* *4 x 5 kg = 20 kg*
Brussels	City centre route, Municipal waste	**Mercedes**			
Touraine	Rural area	**Mercedes**	2 x 30 kW	85 /112 kWh	710 bar 4 x 5 kg = 20 kg
Herten	Waste in containers / fixed schedule	**DAF**	1 x 30 kW	1 x 136 kWh	*350 bar* *4 x 5 kg = 20 kg*

This report reflects the research design and the results of the analysis.

2 Background

Today, transport emissions represent around 25% of the EU's total GHG emissions[1] and in 2020, road transport alone contributed to 77% of EU transport emissions[2]. About 25% of total road transport

emissions come from heavy-duty vehicles[3]. Despite being a niche market in heavy-duty vehicles, the emission contribution of refuse collection vehicles (RCVs) may usually be higher in comparison to other heavy-duty vehicles due to their higher curb weight and prolonged urban operation.
Having zero-emission RCVs may have a considerable impact on the reduction of road emissions. Among the zero-emission technologies currently available, fuel cell electric vehicles appeared to be the most adapted ones for RCVs due to their refuelling, range, and zero tank-to-wheel (T2W) emissions. When the hydrogen used for RCVs is green then they become zero-emission well-to-wheel (W2W). With this consideration, the HECTOR project aimed to deploy 7 fuel cell RCVs in 7 different cities over 5 countries in North-West Europe.

3 Research Design

3.1 Data analysis of the vehicle performance

The design of the data research is described in next documents which are appendices to this report:

- Monitoring plan; June 12th 2019
- What, How, Why – Analysis plan; June 17th 2020

Above documents are shared with and presented to the consortium partners during several plenary and bilateral consultations. These meetings were focused on the required signals, initially to collect by an in-car datalogger f or transferring via the cloud. Along this process, some partners could not get the allowance from the truck manufacturer to connect with the CANbus in the truck and to share specific signals.

3.2 Driver survey social Impact

During the Hector project a driver survey was held, with the purpose of collecting relevant information to ascertain the efficacy of H2 electric refuse collection vehicles (RCV) over traditional diesel vehicles. A questionnaire in local language was spread out to the consortium partners for gathering experiences and opinions, valuable for determining these vehicles' practical effectiveness. See appendix A: Driver survey .

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4 Data reception and processing

As mentioned earlier, while the project application envisioned an entire data pipeline from dataloggers on the vehicle, through processing and to storage, this was not allowed by the vehicle manufacturers. As there was no provision for this level of data sharing in the vehicle purchase contracts, the project partners who ordered the vehicles could only encourage the manufacturers to share data, so the data used for analysis here is limited to what they allow. These manufacturers are not partners and therefore have no concern over the success of the project, so have little interest in the incentives presented and therefore no reason to share more than they want.

4.1 Data reception

The data that has been received during the project time is limited to what was provided by two truck manufacturers:

- E-Trucks for Arnhem and Herten
- FAUN (at project start, now Enginius) for Duisburg

Additionally, a very limited dataset is available from FAUN for the SEMAT vehicle in France, but analysis was not included due to the limited dataset. No data was shared by FAUN for the vehicle in Brussels and was therefore not included. The E-Trucks vehicle intended for Groningen and Holthausen vehicle for Aberdeen have not yet been active to provide data. The Kirchhoff Group in Germany decides data sharing policy for the subsidiary companies SEMAT and Enginius. Therefore Enginius provides the data for the three vehicles provided by Kirchoff Group subsidiaries.
The project data made available by the manufacturers is as follows:

Table 1: Data availability

Data provider	City	Country	Analysis time (days)	Data access	Data start	Data end
E-Trucks	Arnhem	NL	33	Yes	2022/10/19	2023/06/13
E-Trucks	Herten	DE	80	Yes	2022/09/12	2023/05/05
E-Trucks	Groningen	NL	-	No	-	-
Enginius	Duisburg	DE	108	Yes	2021/04/23	2023/08/01
Enginius	Brussels	BE	-	No	2023/11/01	-
Enginius	Indre-et-Loire	FR	-	Yes	2023/08/01	-
Holthausen	Aberdeen	UK	-	No	-	-

For the purposes of finalising analysis it was decided to not utilise any data on or after 2023/08/01, but breakdowns of vehicles such as Herten result in the end of the data period being earlier. The vehicles purchased in this project were some of the first of their kind and as such it is important to keep track of the operability of these vehicles.

4.1.1 E-Trucks

The data provided by E-Trucks for Arnhem and Herten is made available through an online dashboard, from where it is manually downloaded in CSV format. The data is presented as "reports", in the form of a table with daily aggregated values for a number of basic vehicle signals and fuel cell signals.

Specifically, the signals are as follows:

Signal	**Unit**	**Aggregation**	**Description**
Day Start/End Time	-	None	Start and End time for data collection
Refill	#	Sum	Number of times refuelled
H2 Used	kg	Sum	Daily H2 used
Distance	km	Sum	Daily distance driven
Consumption	kg/100km	Average	Average hydrogen consumption over a day
Min/max Odo	km	None	Minimum and maximum odometer readings
Fc Hours	Hours	None	Total fuel cell operating time
Fc Energy	kWh	Sum	Daily energy produce by Fuel Cell
Wall Energy	kWh	None	Total wall energy
Wall Energy Per Day	kWh	Sum	Daily energy charged from charging station
Speed	km/h	Average	Average vehicle speed over a day
Temperature	°C	Average	External temperature

This data has limitations such as: "Consumption is only calculated when the trip distance was more than 30km. If the trip distance was lower the consumption is displayed as 0."; the temperature signal is almost always 0.0 so is too unreliable to consider; and there are many days of data to be discarded as they represent days during testing for vehicle repairs. Additionally, there is no wall energy data for the vehicle in Herten operated by AGR-DAR.

To extend the analysis possible, AGR-DAR in Herten has shared their own dataset based on the E-Trucks dashboard, but with additional information. This dataset splits the days of data into individual routes and provides additional information about both the volume and weight of the refuse collected. Specifically, the additional signals in this dataset are:

Signal	**Unit**	**Aggregation**	**Description**
Vehicle type	-	None	Front loader RCV type for all entries
Route designation	-	None	Name of specified collection route
Volume	m^3	Sum	Volume of refuse collected on route
Tonnage	ton	Sum	Weight of refuse collected on route

Both AGR-DAR Herten and PreZero Arnhem have provided a list of the operational days of data available for their vehicle. Using this the non-operational data (such as data recorded during repair or testing of the vehicle) is removed. All values and graphs have been created based on this cleaned dataset. The metrics for operation have variances and the possible causes of these variances are examined from the two perspectives. The operational variance over different calendar months is considered separately from the variations that can be shown as a result of the various routes driven. Some additional data was provided by PreZero Arnhem with information about refuse density, but unfortunately too late to be integrated.

4.1.2 FAUN/Enginius

Provides data for Duisburg in the form of high frequency data with many signals from different subsystems. Data format has changed throughout the project as and when issues were discovered/resolved.
Final format has 41 signals where samples are recorded when the value changes, up to a sample rate of 4Hz.

Measurement group	Imported Signal	Units	Explanation
GPS	latitude	°	GPS latitude in XX.xxxx°
	longitude	°	GPS longitude in XX.xxxx°
	altitude	m	GPS altitude in m
Vehicle	distance	m	Odometer reading
	totalAxleLoad	kg	Total axle load
	rearAxle1Load	kg	First rear axle load
	rearAxle2Load	kg	Second rear axle load
	frontAxleLoad	kg	Front axle load
Fuel Cell.	totalCurrent	A	Output current of the Fuel Cell
	totalVoltage	V	Output voltage of the Fuel Cell
Stack.	outputCoolantTemp	°C	Coolant temperature at outlet to fuel cell
	airFlow	slpm	Airflow into the fuel cell
Hydrogen.	tankTemp	°C	Temperature in H2 tank 1
	tankPressure	bar	Pressure in H2 tank
	storageLevel	%	Fuel storage level in %
	fuelMass	g	Fuel storage level in g
Inputs.	brakePedal	%	Distance brake pedal is pressed
	throttlePedal	%	Amount of throttle command
	statusHVAC	0/1	Active when status is on
	currentHVAC	mA	HVAC system current draw
	emergencySwitch	0/1	Activation of emergency stop button
Motor.	motorSpeed	rpm	Rpm of the motor
	motorTorque	Nm	Motor torque in Nm
	motorTemp	°C	Temperature of drive motor
	motorCurrent	A	Current use of the drive motor in A?
Power.	currentBattDC	A	Output current of the drive battery
	voltageBattDC	V	Output voltage of the drive battery
	minChangeV	V	The lowest of all cell voltages from the drive battery
	maxChangeV	V	The highest of all cell voltages from the drive battery
	stateOfCharge	%	State of charge of drive battery
	auxBattVoltage	mV	Voltage of the "24 volt" battery
Compactor	activation	0/1	Activation of garbage compactor
	powerUse	*10 W	Power use of the compactor system

4.2 Operability

The operability (or utility) of different vehicles can be seen by plotting the monthly average utility percentage, along with the corresponding number of days of operation in the month. This is defined as the number of days of actual operation in a period divided by the number intended days of operation and scaled to give a value from 0-100%. For example a vehicle intended to collect refuse 5 days in a week but due to repairs the vehicle was only collecting refuse for 4 days, the operability would be 4/5*100 = 80%.

The operability ratings as considered by calculating the number of weekdays in the operation window and recording how many of these days within which the vehicle is active. Specifically this percentage is the number of days of operation in a month divided by the number of weekdays (i.e. not Saturday or Sunday) in the month, scaled to percentage.

$$Operability\ [\%] = \frac{monthly\ active\ days}{weekdays\ in\ month} \times 100$$

For the vehicle in Herten, the testing done before operation causes the low utility in September 2022, while an motor replacement at the end of December 2022 is largely responsible for the low utility in January 2023, as seen in Figure 1.

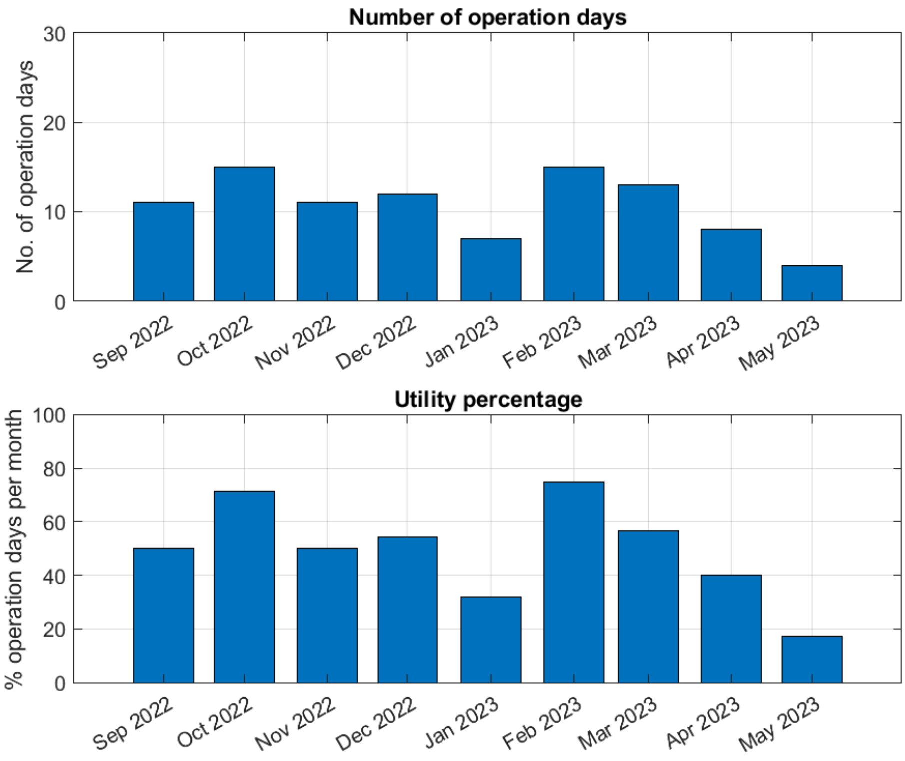


Figure 1: Monthly number of operation days and operability percent for AGR-DAR Herten, E-Trucks

The utility can be quite high as seen by the 71% and 75% utility in October and February respectively. According to project partners, typical diesel RCVs can have a utility/availability of approximately 85%. As can be seen, all months have less than 85% utility is caused by maintenance or repairs needed to get the vehicle back into operation.

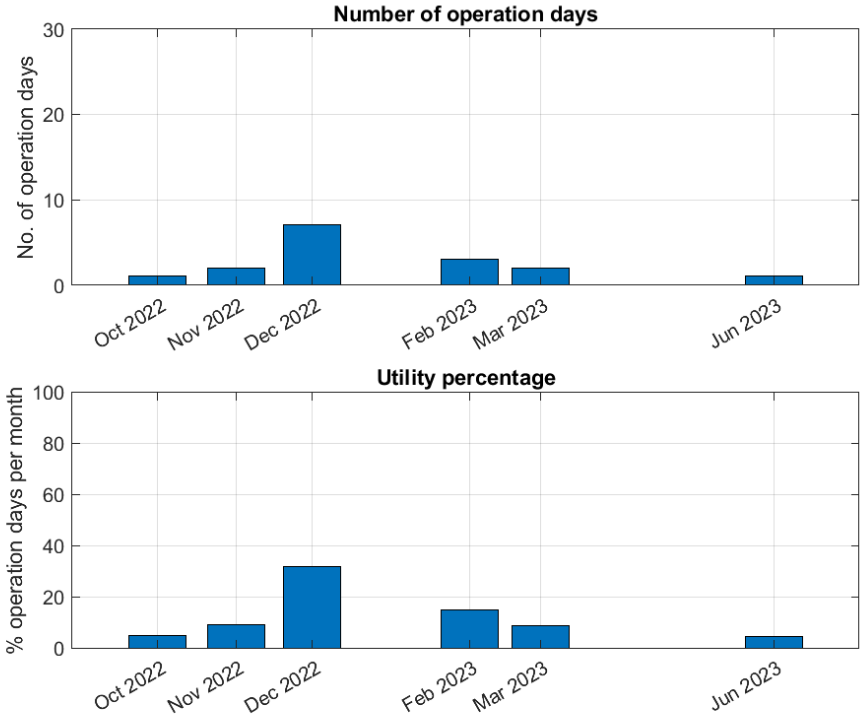


Figure 2: Monthly number of operation days and operability percent for PreZero Arnhem, E-Trucks

It can then be clearly seen in that the E-trucks vehicle delivered to PreZero in Arnhem has a much lower operability (it must be mentioned that there is some E-trucks testing data included in this dataset, which can cause problems unless eliminated). There is not a single month where the vehicle exceeds 40% utility, with the highest being December 2022 with 32% utility.

In contrast it can be seen that the WB-Duisburg vehicle is more reliable, with 91% utility in August, October 2022, and July 2023.

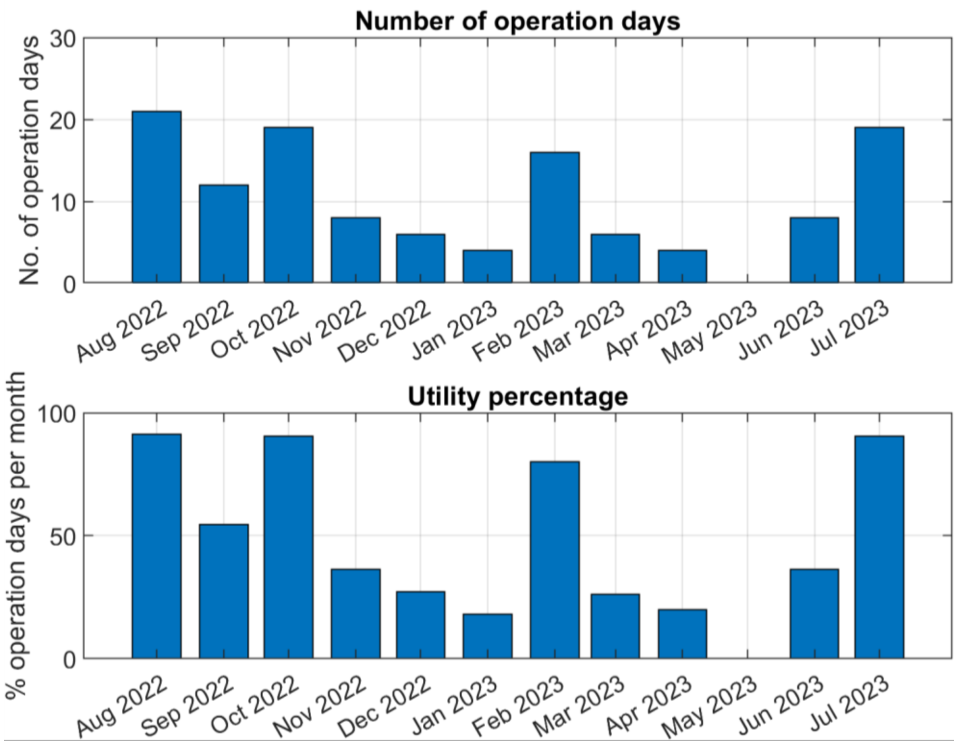


Figure 3: Monthly number of operation days and operability percent for WB Duisburg, Enginius

4.3 Processing

The data provided by both companies included issues which required processing to eliminate. For E-Trucks the issues present as 0 values; such as 0 consumption for trips under 30km. These entire days of data are therefore deleted before proceeding with analysis.

The processing needed for the Enginius data are issues that had intended to be avoided by installing our own datalogger. These are typically related to timestamps of the data. The initial data provided contained no millisecond precise timestamps despite the signals being recorded at higher than 1Hz (meaning that there were multiple unique data samples with the exact same timestamp). Additionally, many of the signals have obvious outlier values that need to be removed such as vehicle weight of 0 ton.

5 Analysis

In this section we describe the analysis of the data. The analysis is limited to the available data, provided by the manufacturers.

5.1 Arnhem and Herten, E-Trucks

As the data provided by E-Trucks is limited to daily aggregated data, the analysis is limited inspecting the provided statistics. The daily aggregated data is further aggregated to give the monthly variation, but this is limited by the limited amount of months that these vehicles were functioning.

The additional data provided by AGR-DAR for Herten that includes refuse weight allows for some further analysis relating the refuse collection and hydrogen consumption. The truck used in Herten was assembled by E-Trucks and is used for the purpose of collecting (primarily) industrial waste, using a front loading arm to collect refuse from dumpsters.
The truck used in Arnhem was assembled by E-Trucks and is used for the purpose of collecting household waste, using a lifting and manoeuvring arm.

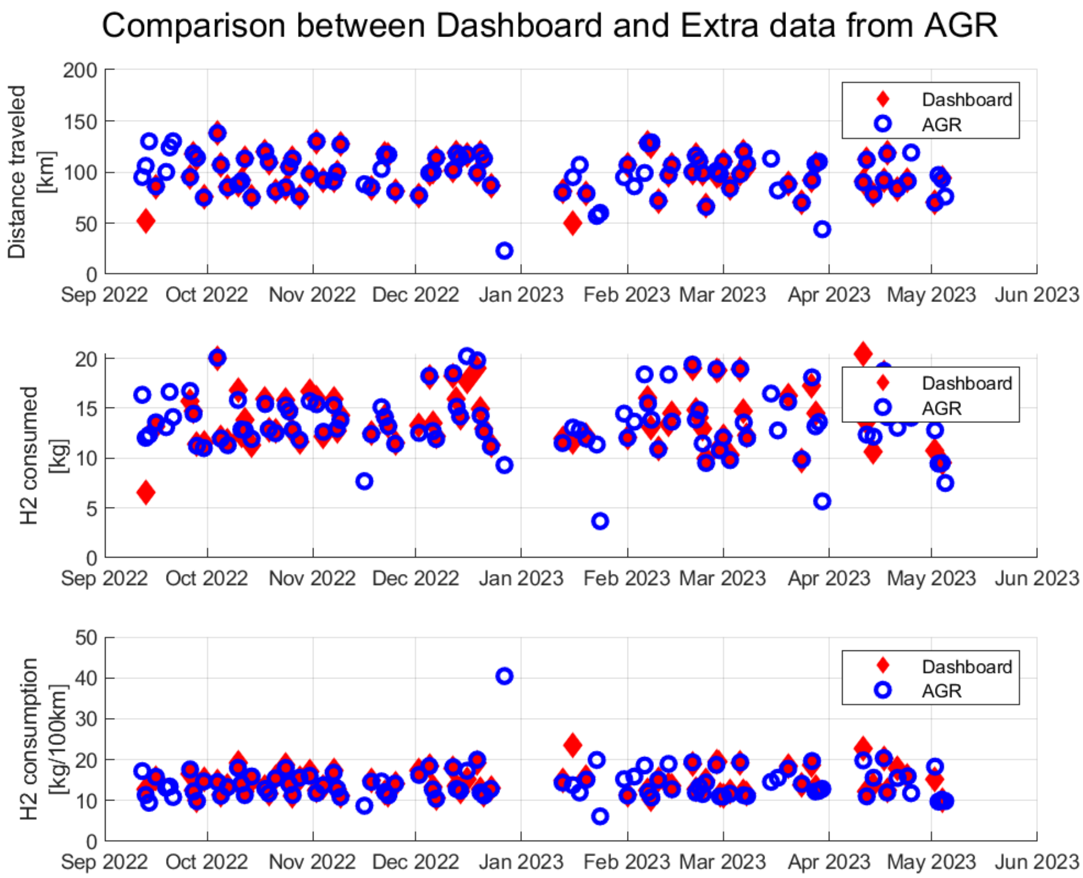


Figure 4: Comparison between E-Trucks dashboard data and data from AGR-DAR Herten

Due to issues observed in the dashboard data for some days (possibly due to issues with aggregation or development of the dashboard) it was decided to use the AGR-DAR data from Herten as this data has been checked by the vehicle operator and is therefore more reliable. The alignment between the two data sources can be confirmed with FIGURE, by comparing the distance travelled, hydrogen consumed, and the consumption rate calculated from these. For the distance, the error between the sets is within 1km for approximately 85% of the days; and for the hydrogen consumed, the error between the sets is within 0.5kg for approximately 68% of the days.

5.2 Duisburg, FAUN/Enginius

For the analysis done for Duisburg RCV is the provided data rich enough to understand and elaborate upon the basic operation of the RCV and associated energy/fuel requirement of the RCV.

5.2.1 Segmentation, duty cycle and daily operation

On a daily basis, the RCV may perform the three main activities: (1) Refuse-collection; (2) Refuse-disposal; and (3) Refuelling. Among the three, the refuse-collection is the most energy demanding activity. However, the most significant energy demand of the RCV comes from its driving to and from these activity locations. Therefore, to better understand the energy demand of the RCV, we first divide the daily operation into the four following segments:

1. **S1. Refuse-collection:** This segment is defined by identifying consecutive low-speed stops during which weight of the RCV increases. We assume this segment is central in defining the duty cycle and daily operation of the RCV. There can be multiple refuse-collection stops in a day, as shown in Figure 5.

2. **S2. Refuse-disposal:** This segment is defined by identifying the period during which the weight of the RCV sharply decreased while being stationary, as shown in Figure 1.
3. **S3. Refuelling:** This segment is defined by identifying the period during which the fuel level of the tank increases while RCV is stationary, as shown in Figure 1.
4. **Drive2 segments**: These segments represent the high-speed driving segments in between the above three segments and the base location. Thus, they are further defined as four types:
    a. **Drive2RefuseCollection (D2s1):** This segment represents the driving segment that terminates at S1 or Refuse-collection.
    b. **Drive2RefuseDisposal (D2s2):** This segment represents the driving segment that terminates at S2 or Refuse-disposal.
    c. **Drive2Refueling (D2s3):** This segment represents the driving segment that terminates at the S3 or refuelling station.
    d. **Drive2BaseLocation (D2s4):** This segment represents the driving segment that terminates at the base location. This segment typically represents the end of the daily operation.

All the Drive2 segments may have three variations depending on the start location of the segment. For example, a D2C segment may start from the base-location, refuse-disposal, and refuelling station and may influence the energy demand of the segment.

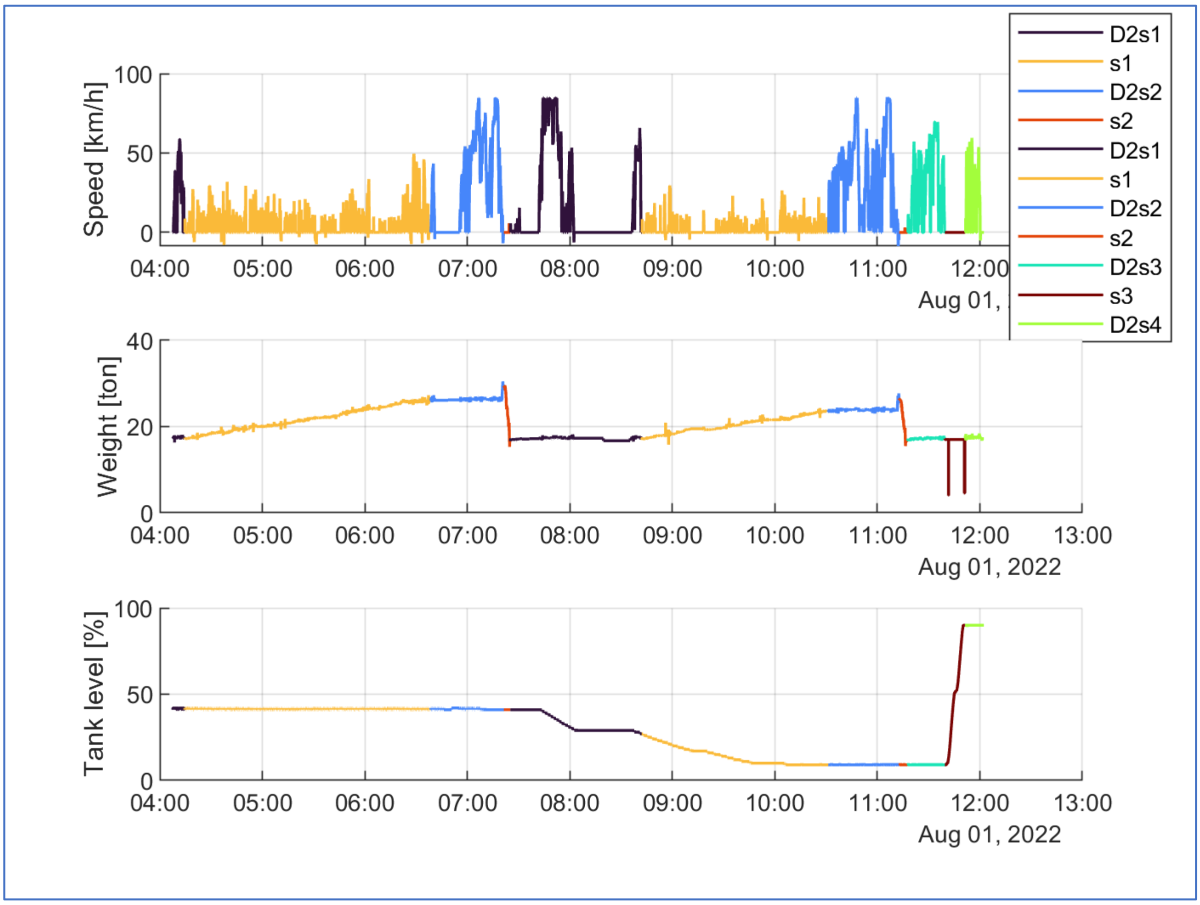


Figure 5: Segmentation example of RCV daily operation

It may be observed from the Figure 5 that RCV can perform multiple refuse collections in a day which could lead to a complex representation and many variations of daily operation. A plausible scheme for representing daily operation is presented in Figure 6.

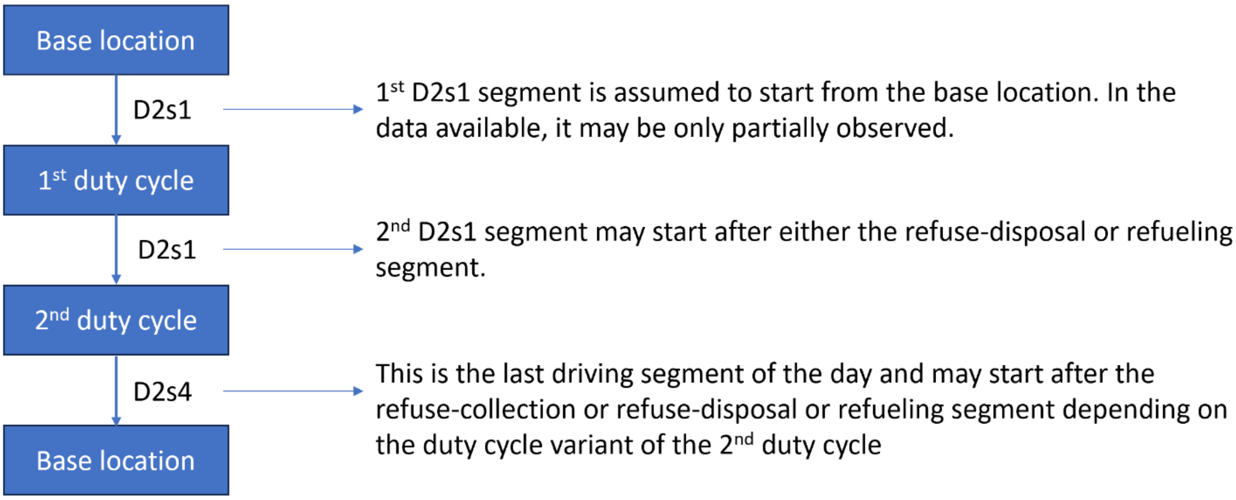


Figure 6: Schematic representation of RCV daily operation

The duty cycle may be represented by considering the main operational activities (i.e., refuse-collection, refuse-disposal and refueling) and their sequence. We consider the refuse-collection as the central activity and thus, each duty cycle starts with refuse-collection segment. The five duty

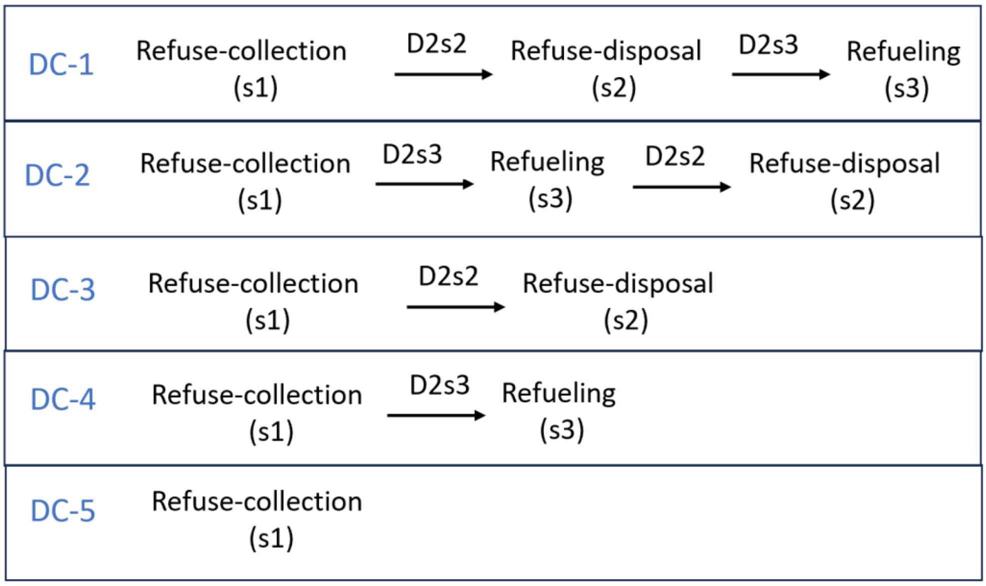


Figure 7: Duty cycle (DC) variants

cycle variants are shown in Figure 7. DC-5 is only considered a variant for 2nd duty cycle and not for the 1st one. In the cases when there is only one refuse-collection segment, then we ignore the 1st duty cycle and only consider the 2nd duty cycle to represent the respective day operation.

Using the above, the daily operation of the RCV can be represented in a generic sense, see Table 1.

Table 2: A few examples of daily operation of RCV representation

Date	Daily operation
1 august 2022	D2s1 -> DC-3 -> D2s1 -> DC-1 -> D2s4
2 august 2022	D2s1 -> DC-3 -> D2s1 -> DC-3 -> D2s4
3 august 2022	D2s1 -> DC-2 -> D2s1 -> DC-3 -> D2s4
4 august 2022	D2s1 -> DC-3 -> D2s1 -> DC-2 -> D2s4

5.2.2 Segment characterization

In order to understand the daily energy demand of RCV, we focus on characterizing the segments by quantifying them and we start from duty cycles. For different duty cycles as shown in Figure 7, refuse-collection, drive to refuse-disposal and drive to refueling segments are the most energy significant part of the daily operation. Energy requirement of the refuse-disposal may be considered very low compared to the other three segments. Refueling, itself, has no energy demand. We quantify the characteristic variables for segments as shown in Table 2.

Refuse may be collected over fixed or varying routes with in a specific area. The energy requirement of refuse-collection segment may depend on the no. of refuse collection stops, collection distance, and collected refuse weight. Since refuse-collection is a low-speed operation, therefore, we do not use speed as a characteristic variable for the refuse-collection segment.

The energy requirement of refuse-disposal segment may only depend on the disposed refuse weight and time duration.

All drive2 segments represent the driving from one location to another. Depending on the start and end locations of the segments, the weight of the RCV may vary due to the refuse weight besides the driving distance and speed during these segments. Therefore, the energy requirement of all drive2 segments may vary according to the average refuse weight, speed, and distance of the segment.

Table 3: Segments and respective characteristic variables

Segments	Characteristic variables
Refuse-collection	No. of refuse collection stops Total collected refuse weight Total collection distance Time duration
Refuse-disposal	Total disposed refuse weight Time duration
Drive2 segments	Average refuse weight Driving distance Average speed Time duration

6 Results and discussion

In this section, we examine the performance and energy demand of the trucks from E-Trucks in Arnhem and Herten and from FAUN in Duisburg.

6.1 E-Trucks vehicles in Arnhem and Herten

The box plots represent the median with a red line, non-outlier maximum and minimums with black whiskers, outliers with red, and the 25th and 75th percentiles of data with the box extents.

6.1.1 Arnhem, NL

The performance of the vehicle is evaluated based on distance driven and H_2 usage. The provided daily cumulative values were grouped according to month. Monthly aggregation could potentially show the influence of seasonality, if the utility of the vehicle was more consistent than shown in Figure 2. However it does provide insights into the monthly operational variances. The limited number of days of operation causes inconsistent results.

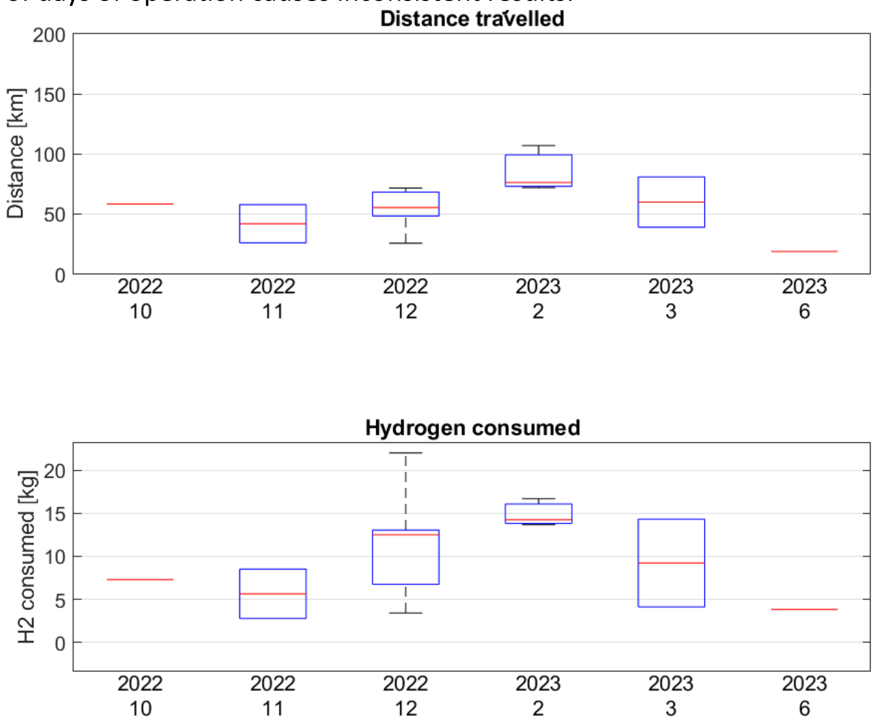


Figure 8: Distance travelled and hydrogen consumed for PreZero Arnhem, E-Trucks

The median distance travelled is less than for Herten which also results in lower amounts of hydrogen consumed per day as seen in Figure 8. The difference between hydrogen consumed (Figure 8) as recorded by the vehicle and hydrogen refuelled (Figure 9) as recorded by the fuel station, highlights the inconsistency seen in the dataset.

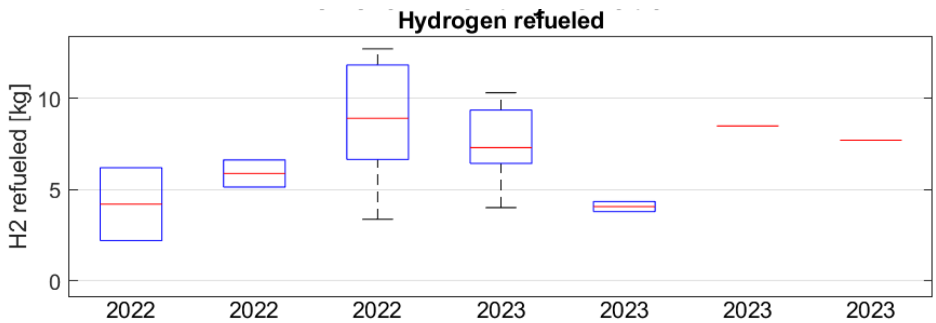


Figure 9: Hydrogen refuelled at station for PreZero Arnhem

The hydrogen consumption can be seen in Figure 10 along with the energy consumption that is based on the fuel cell and charging energy recorded.

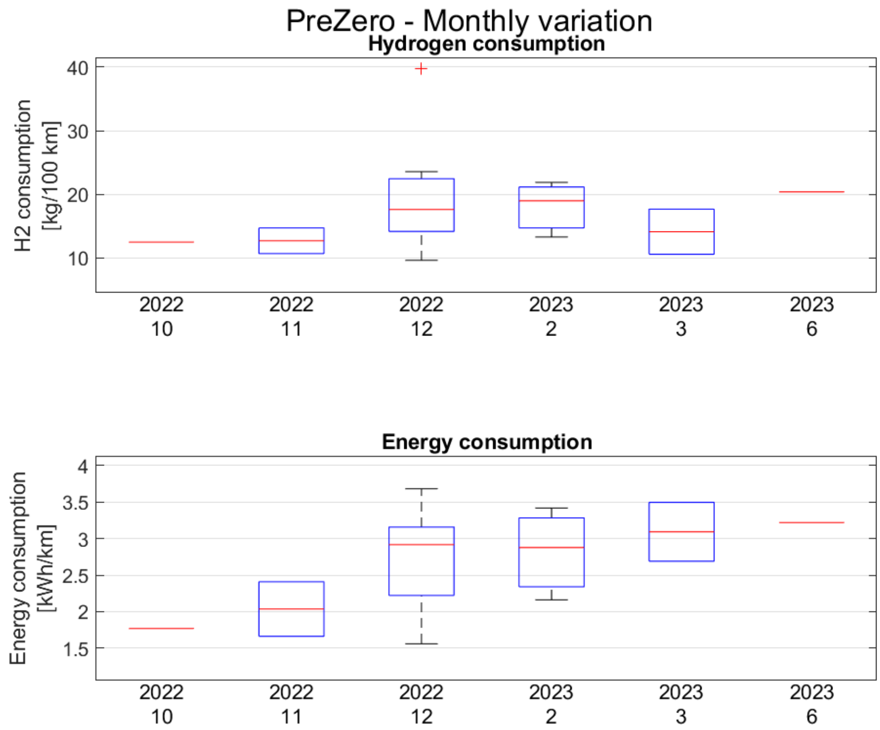


Figure 10: Monthly hydrogen consumption and energy consumption for PreZero Arnhem

The PreZero vehicle in Arnhem refuels twice in a day for half the data and once a day for the other half. Only two months show more than two refuels total as seen in Figure 11.

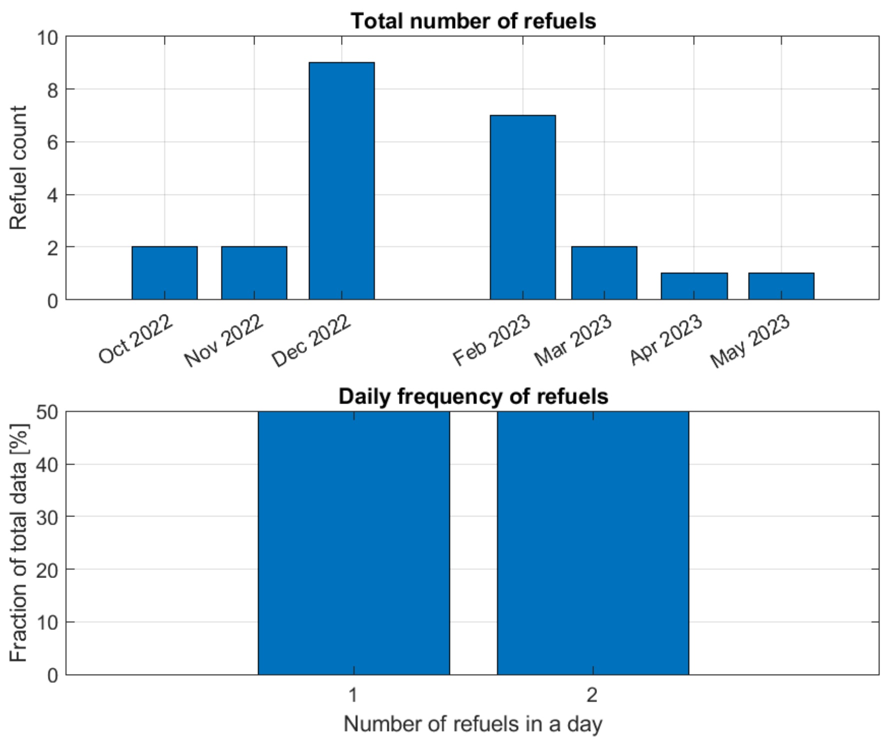


Figure 11: Monthly count of refuels and daily frequency of refuels, for PreZero Arnhem

6.1.2 Herten, DE

The performance of the vehicle is evaluated based on distance driven, H_2 usage and weight of refuse collected. The provided daily cumulative values were grouped according to month and also per route variation. Monthly aggregation could potentially show the influence of seasonality, if the utility of the vehicle was more consistent than shown in Figure 1. It does show the operational variations over the months.

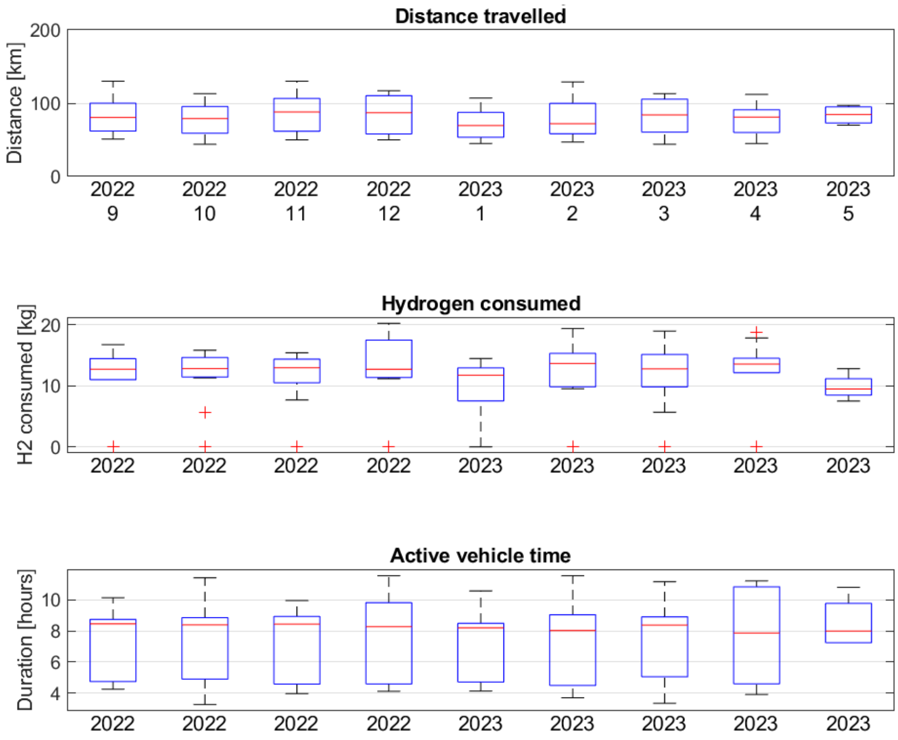


Figure 12: Monthly distance travelled, hydrogen consumed and active vehicle time for AGR-DAR Herten

The median distance travelled is approximately 81km, with the repair month of January 2023 having the lowest median value of 69.5km. The hydrogen consumed can be observed to be typically 12.7kg per day, with some outliers at 0 where there has been a problem with the data. The median active vehicle time per day is 8 hours which could indicate that the days with values outside of this median are days when the vehicle has not been fully operational.

As can be seen in Figure 12 and Figure 13, the low utility of 17.4% in May 2023 (see Figure 1) reflects where the vehicle and fuel cell stopped working early in the month.

The additional data provided by AGR-DAR Herten allows the hydrogen consumption to be calculated for not only distance, but also ton of refuse collected. Discounting the May 2023 values with low distance consumption of 10.04 kg/100km and high weight consumption of 3.38 kg/ton, the median distance consumption ranges from 13.72 to 16.25 kg/100km, while the median weight consumption ranges from 1.77 to 2.35 kg/ton.

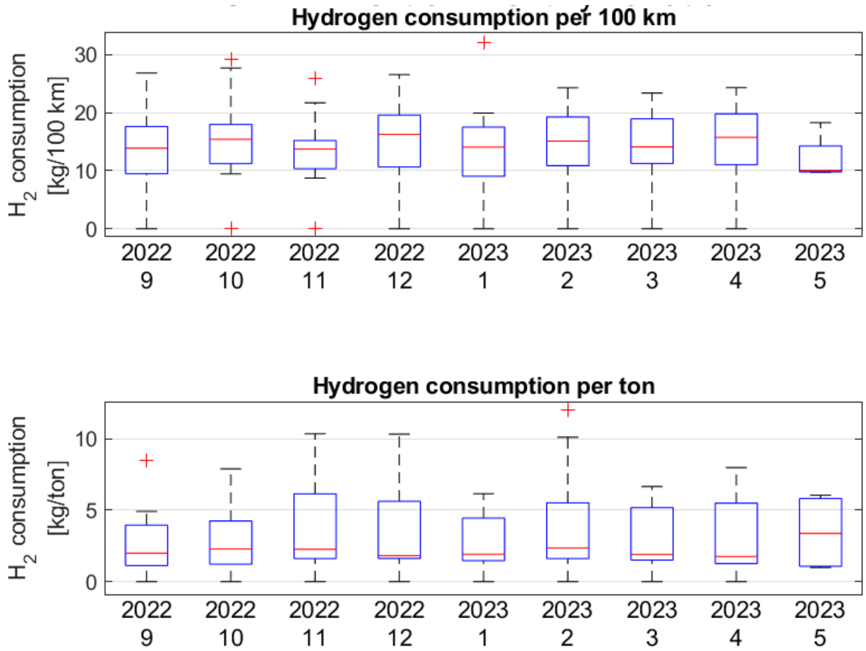


Figure 13: Monthly hydrogen consumption per distance and per refuse weight for AGR-DAR Herten

The median values for refuse weight and volume are consistent except for January where the vehicle was under repair. The refuse collected is close to 5 tons, steadily increasing in 2023 as the operators became more comfortable with the vehicle. Despite these consistent values, the range is relatively wide for the 25th and 75th percentiles, possibly due to the variety of the collection routes performed by the vehicle and the different refuse types collected therein.

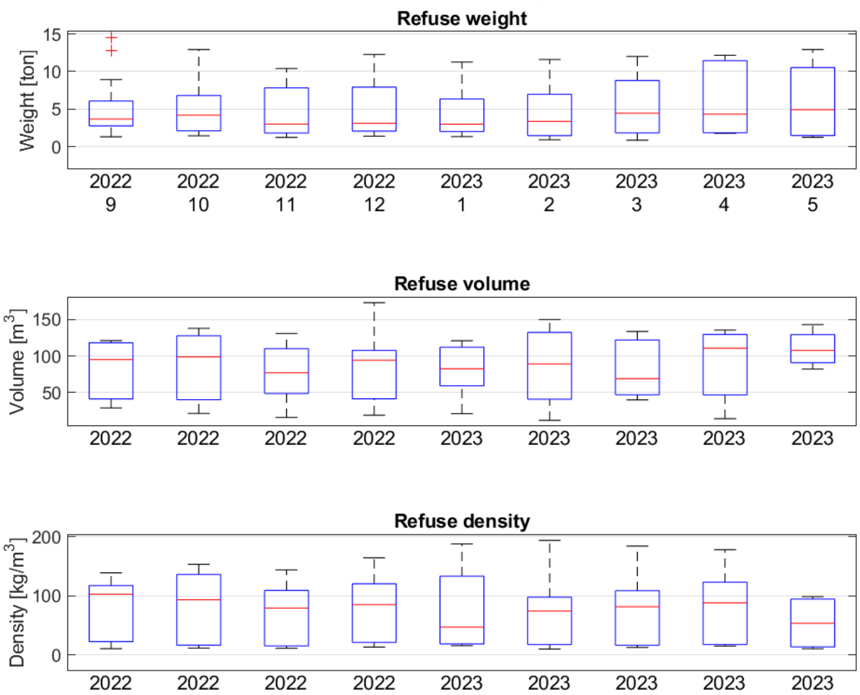


Figure 14: Monthly refuse weight, volume and density for AGR-DAR Herten

Most of the time the vehicle is refuelled once per day, with 16.22% of days having 2 refuels and only 1.35% of days (1 day in March 2023) had 3 refuels, as seen in Figure 15.

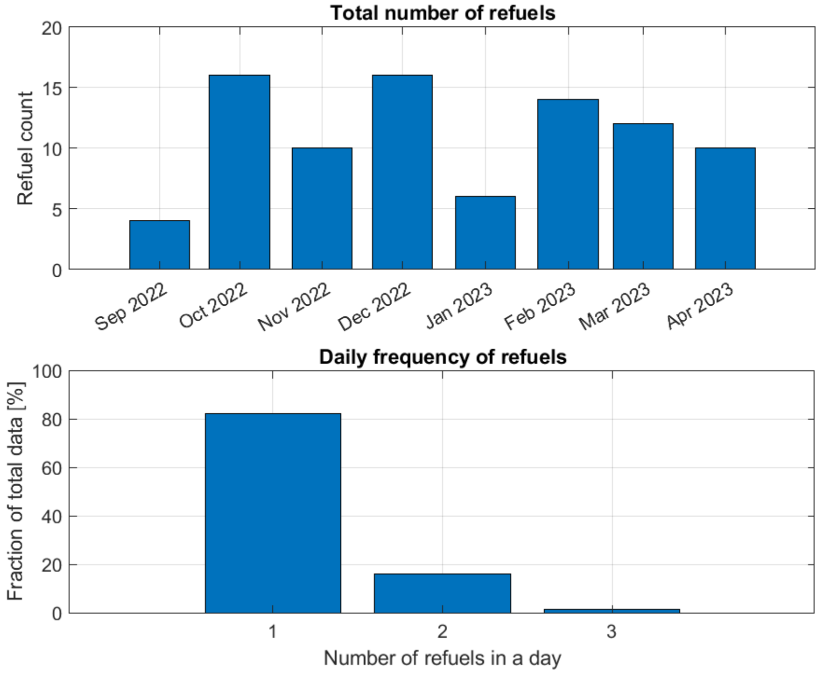


Figure 15: Monthly count of refuels and daily frequency of refuels, for AGR-DAR Herten

The RCV is refuelled between 10 and 15 kg, averaging around 13 kg per refuel, except for March 2023 (10.1 kg) and February 2023 (7.2kg). Refuelling time has improved over the months from 15 minutes per refuel to around 6 minutes per refuel.

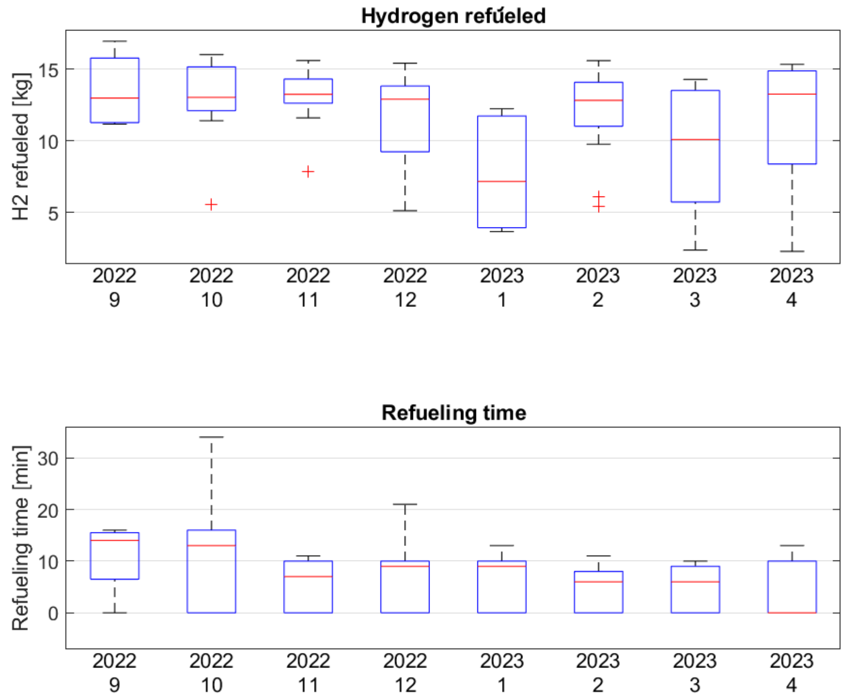


Figure 16: Monthly hydrogen refuelled and time spent refuelling for AGR-DAR Herten

The variation seen in the above monthly data can be primarily explained by the use of different routes by the truck. This vehicle in Herten is operated by AGR-DAR on 9 different routes which have varying distances, H_2 use, and different refuse weight and densities.

Routes 1 and 7-9 consist of mixed refuse collection, routes 2-4 are paper collection whilst 5 and 6 are low density foil refuse. There are over 20 trips available for Routes 3, 6, 7 and 9, with only 1 trip for routes 1, 2 and 4.

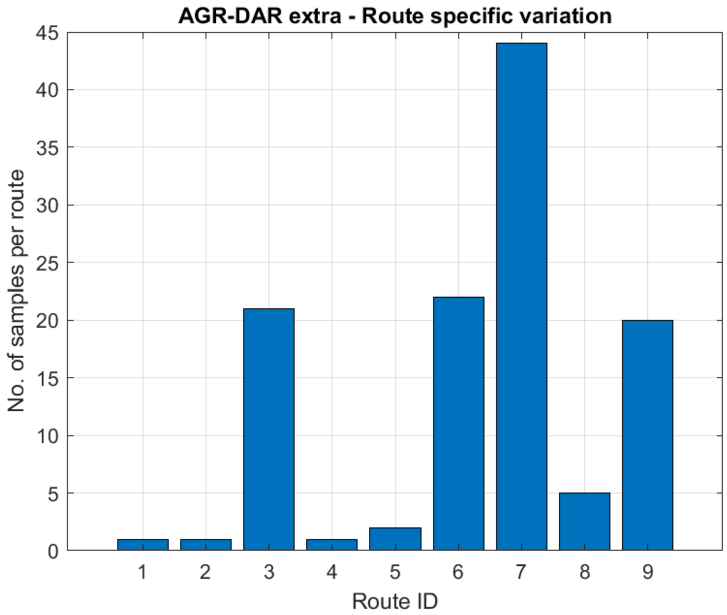


Figure 17: Number of trips per unique route for AGR-DAR Herten

On 2/3 of the routes, the average distance travelled is around 100 km. The shortest distance travelled corresponds to Route 3, at around 50 km. Highest H2 is consumed over Routes 8 and 9 (around 15 kg) while the least H2 is consumed over Route 3 (around 6 kg). For remaining routes, H2 consumed varies between 10 to 12 kg. Routes 8 and 9 have the largest operation hours (> 10 hours) while the smallest operation hours correspond to Route 3 (approx. 4,5 hours).

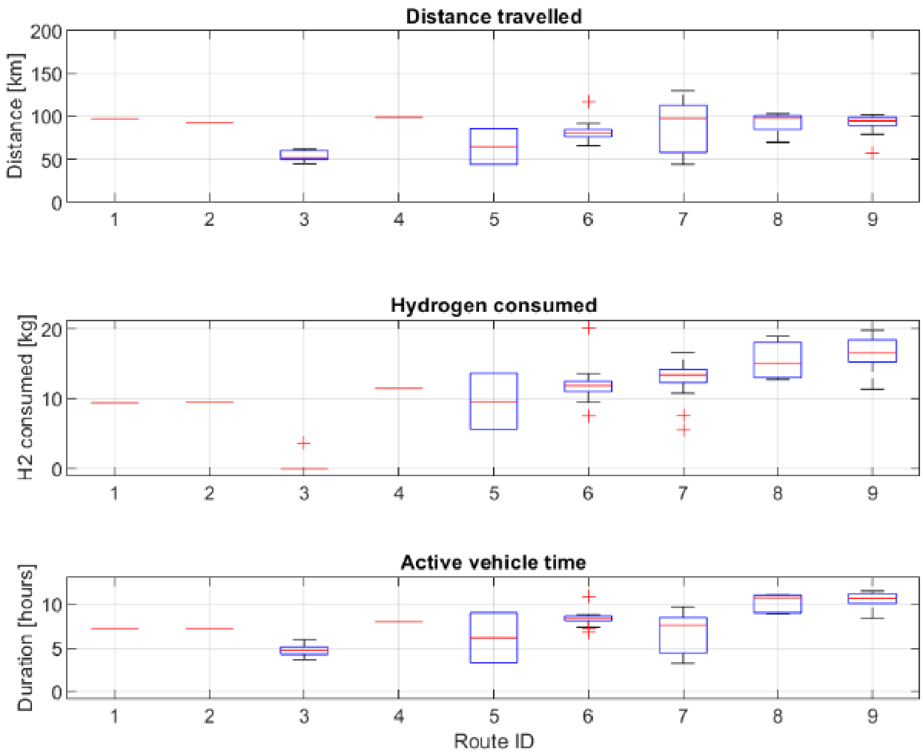


Figure 18: Per route distance travelled, hydrogen consumed and active vehicle time for AGR-DAR Herten

Average refuse collected over Routes 2 to 6 is around 2-3 tons (due to low-density refuse collection). Highest amount of refuse is collected over Routes 8 and 9 (> 10 tons), having a density close to 100 kg/m^3 and the largest density variation is associated with Route 7 (100 to 150 kg/m^3).

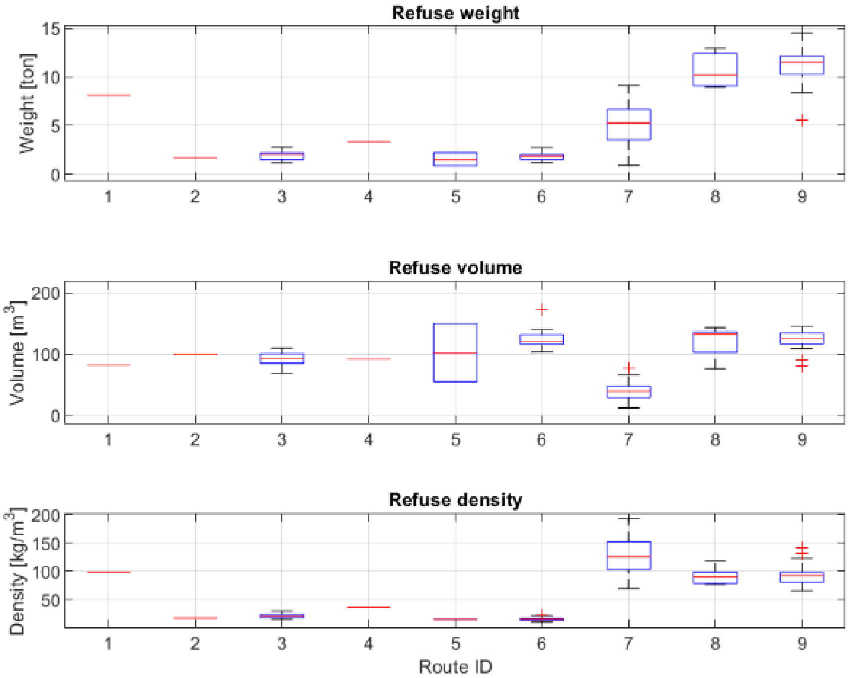


Figure 19: Per route refuse weight, volume and density for AGR-DAR Herten

Routes 3 and 6 are both low-density refuse collection routes, with comparable densities, and average refuse amount. Route 6 is comparatively longer than 3 and consumed more H2 thus higher consumption for Route 6 compared to 3.

Routes 1, 7, 8, and 9 are associated with high-density refuse, thus their consumption per ton of refuse is smaller than the other routes.

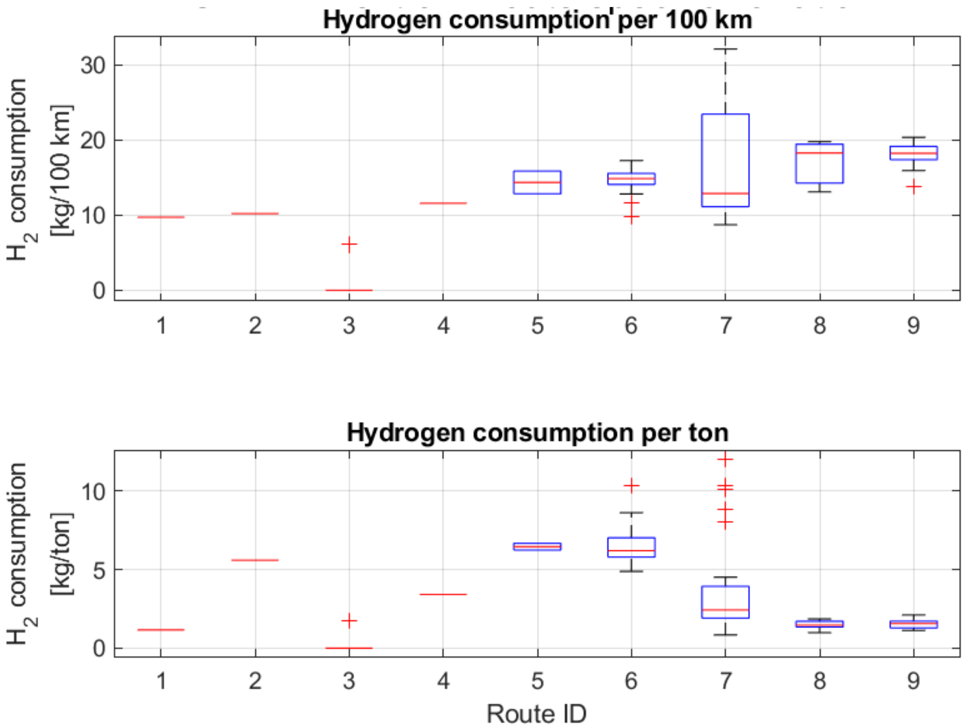


Figure 20: Per route hydrogen consumption measured per distance or weight of refuse for AGR-DAR Herten

6.2 FAUN Duisburg

6.2.1 Energy demand of operational segments

First, we analyse the energy demand of the segments.

6.2.1.1 Refuse-collection (s1)

Over the period of 01-08-2022 to 01-08-2023, the RCV has performed more than 200 refuse-collection trips. In this segment, the total energy demand can be divided into two parts: energy needed for driving during this segment and energy needed for handling and collecting the refuse. From Figure 4 (top figure), it may be observed that around 60-70% (i.e., 25-40 kWh) of total segment energy is needed for refuse handling activity.

Figure 4 (bottom figure) presents the hydrogen consumed during this segment. As seen, the hydrogen can be used for two purposes: (1) to charge the battery; (2) to meet the necessary energy demand of the segment. A few following observations:

- when H2 is not used for battery charging, the hydrogen demand for the majority of refuse-collection stays below 2 kg.
- In recent months (June-July 2023) or last trips (120+), use of fuel cell during this segment is decreasing in comparison to the starting trips.

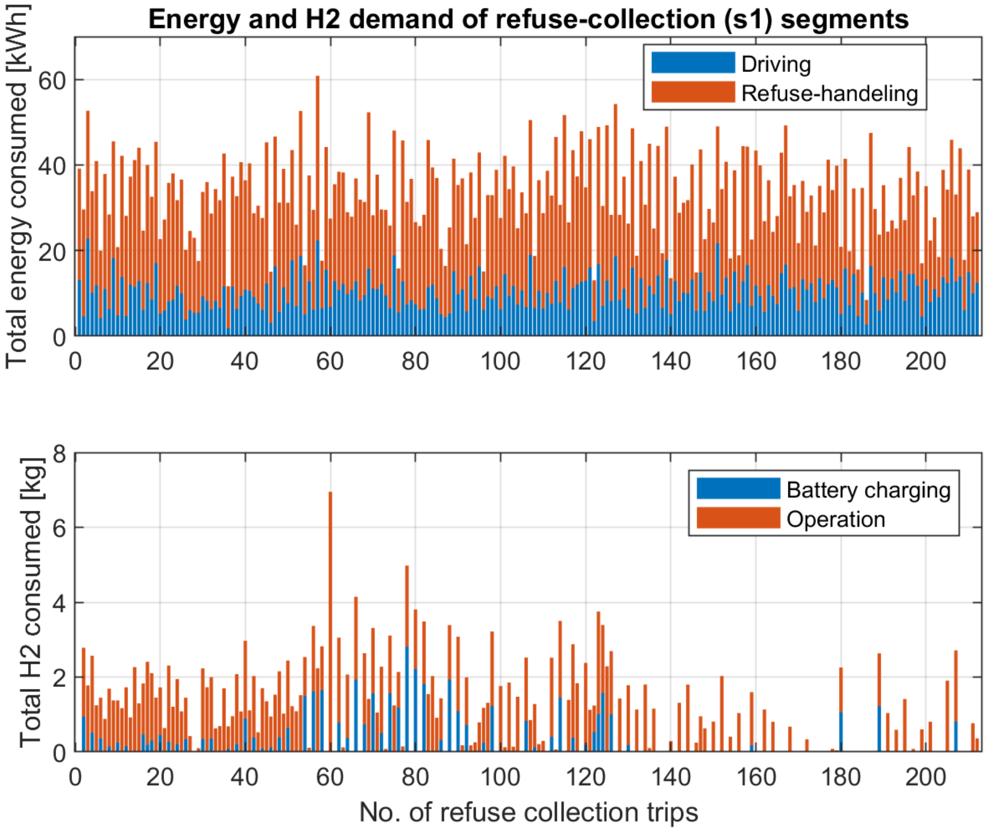


Figure 21: Energy and hydrogen demand of refuse-collection segments

To further understand the variables affecting the energy demand of RCV in s1 segments, we present energy consumption per km for driving related energy, and energy consumption per ton for refuse handling related energy in Figure 22 and Figure 23, respectively.

It may be observed in Figure 22 that the energy consumption per km stays within 1-2 kWh/km for s1 segments. The variation could mainly arise from topology of different collection routes but we have not analysed the routes. Higher average speeds tend to favour lower energy consumption whereas higher refuse weight tend to favour higher energy consumption.

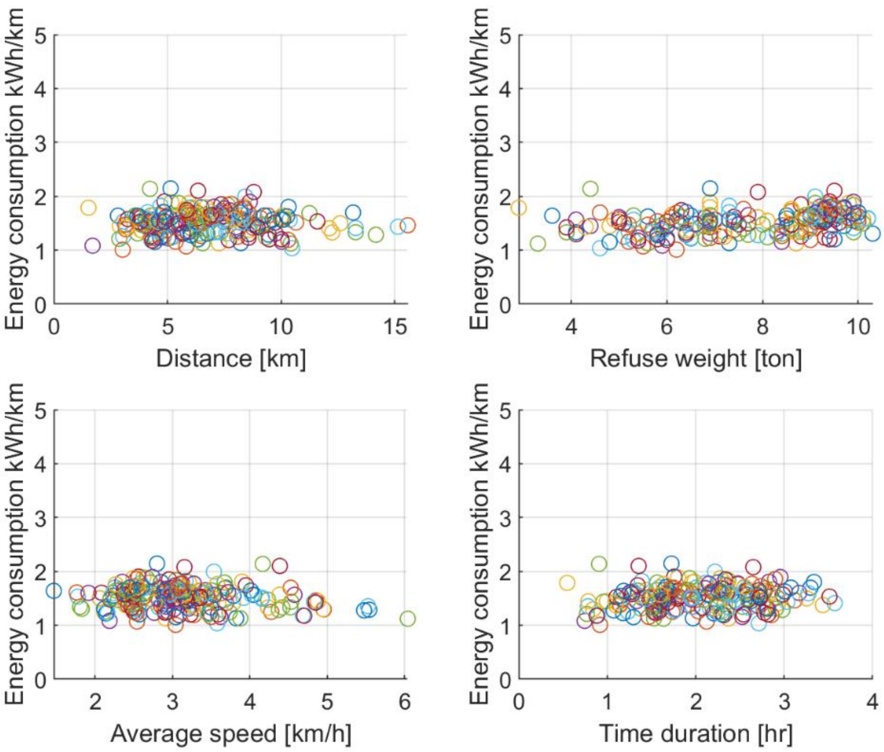


Figure 22: Energy consumption per km of s1 segments due to distance, refuse weight, average speed and time duration

It may be observed in Figure 23 that the energy consumption per ton varies within 0.75 to 2.75 kWh/ton for s1 segments. The bottom right figure shows that as the no. of collection stops increases, the energy consumption per ton also increases and may also be considered the most influencing variable for the energy related to refuse handling. The collection stops may vary in terms of the no. of bins collected, no. of lifts per bin, and the weight of the bins, which, in turn, will influence of energy consumption but we have not analyzed that.

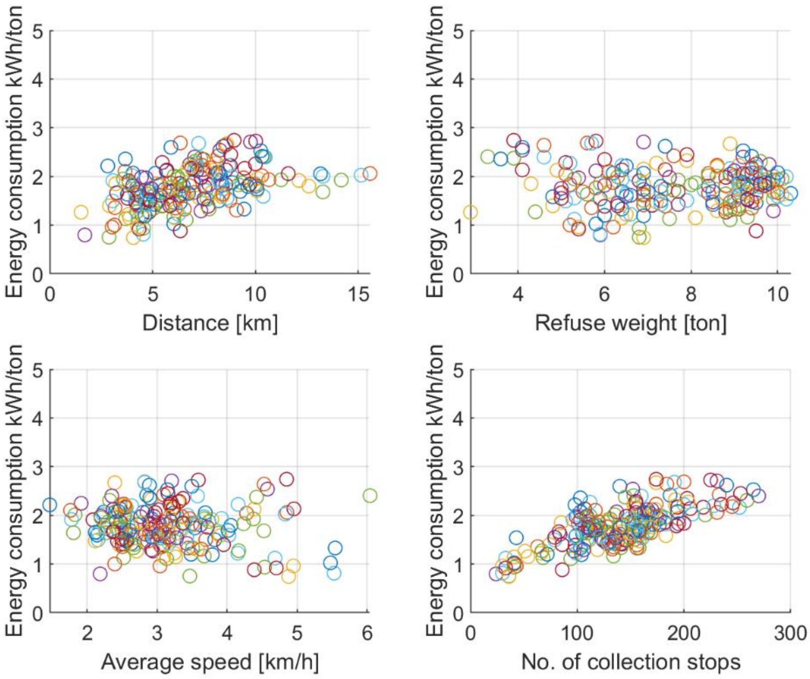


Figure 23: Energy consumption per ton variations of s1 segments due to distance, refuse weight, average speed and no. of collection stops

6.2.1.2 Refuse-disposal (s2)

Figure 24 presented the total energy and hydrogen consumed during refuse-disposal trips. It may be observed from the top figure that the energy related to driving is negligible for majority of the trips in comparison to energy related to refuse handling. In contrast to s1, hydrogen is used for battery charging in the majority of s2 segments, mainly because the power and energy demand of this section is very low in comparison to s1 segments. In general, this segment is a low-speed (< 1km/h) and low distance (around 10-20m) so we ignore the influences due to distances and speeds.

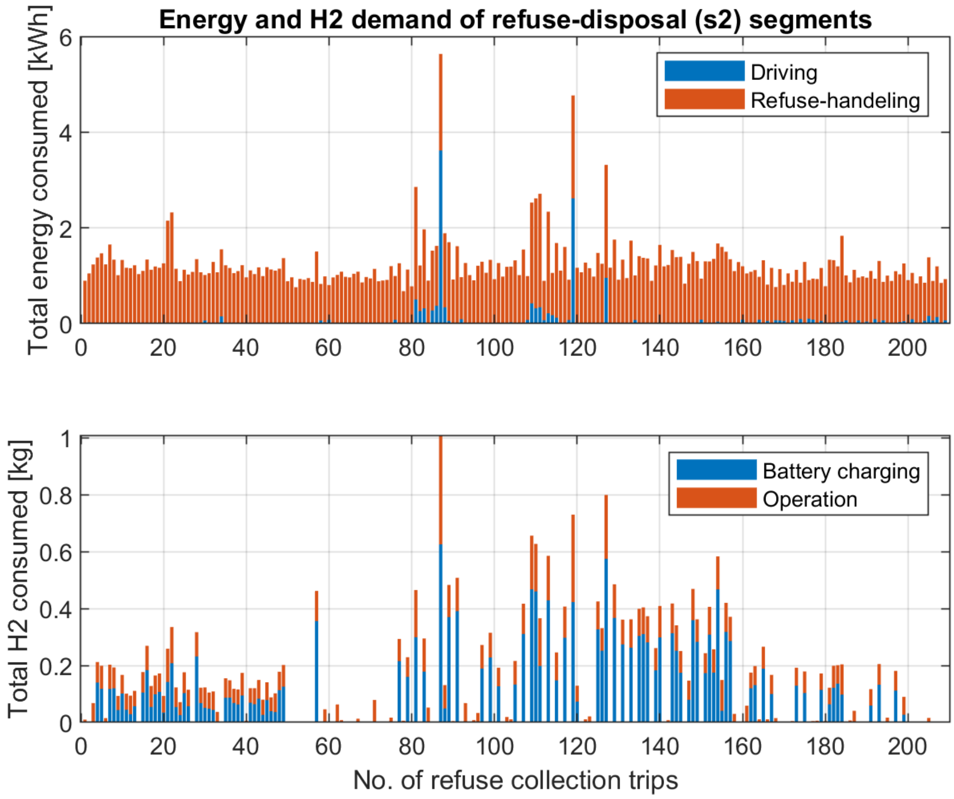


Figure 24: Energy and hydrogen demand of refuse-disposal segments

Figure 25 presents the refuse handling energy variations of s2 segments due to refuse weight and time duration. It may be observed from the top figure that energy demand increases with increasing refuse weight. The variations could be related to no. of tipping required during the refuse disposals but we have not examined that. From the bottom figure, it may be observed that generally, refuse disposal activity irrespective of refuse weight takes around 3 to 6 minutes and also indicates that higher time duration favors higher energy demand.

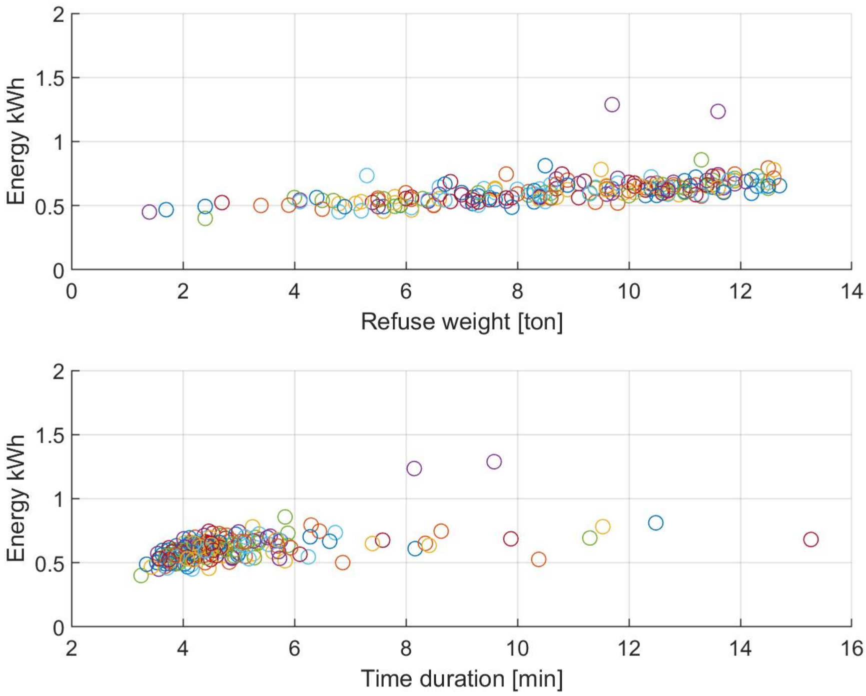


Figure 25: Refuse handling energy demand variations of s2 segments due to refuse weight and time duration

6.2.1.3 Refuelling (s3)

There is no energy demand of this segment but to depict the process and its variations, we present hydrogen refueled for its trip with respect to time taken for refueling in Figure 26. It may be observed that the refueled hydrogen varies from 4 to 15 kg per refueling and generally takes between 8 to 15 minutes. It may also be observed that increasing amount of hydrogen refueled increases time taken for refueling.

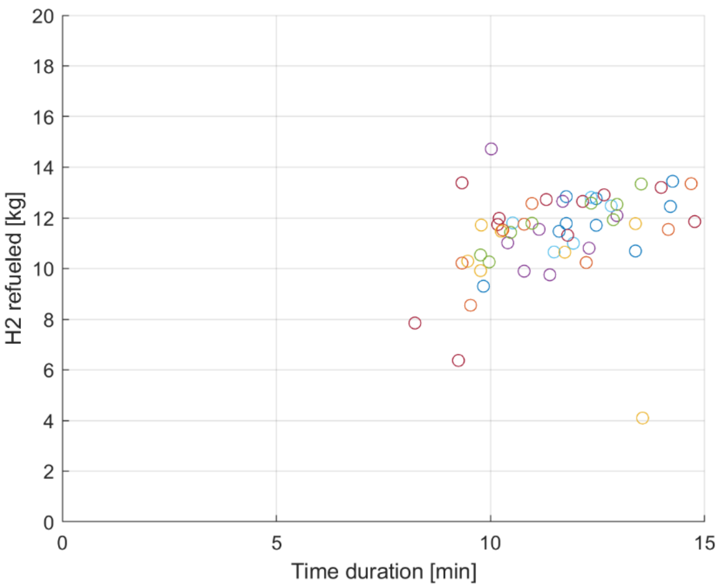


Figure 26: Hydrogen refuelled during s3 segments and respective refuelling time

6.2.1.4 Drive2RefuseCollection (D2s1)

Figure 27 shows the energy and hydrogen demand of the Drive2RefuseCollection segments. As seen, total energy demand may vary from 4 to 20 kWh and hydrogen demand may rise up to 3kg during these segments. The variation occurs mainly due to the start location of this segment, which could be base location, refuelling station or disposal site.

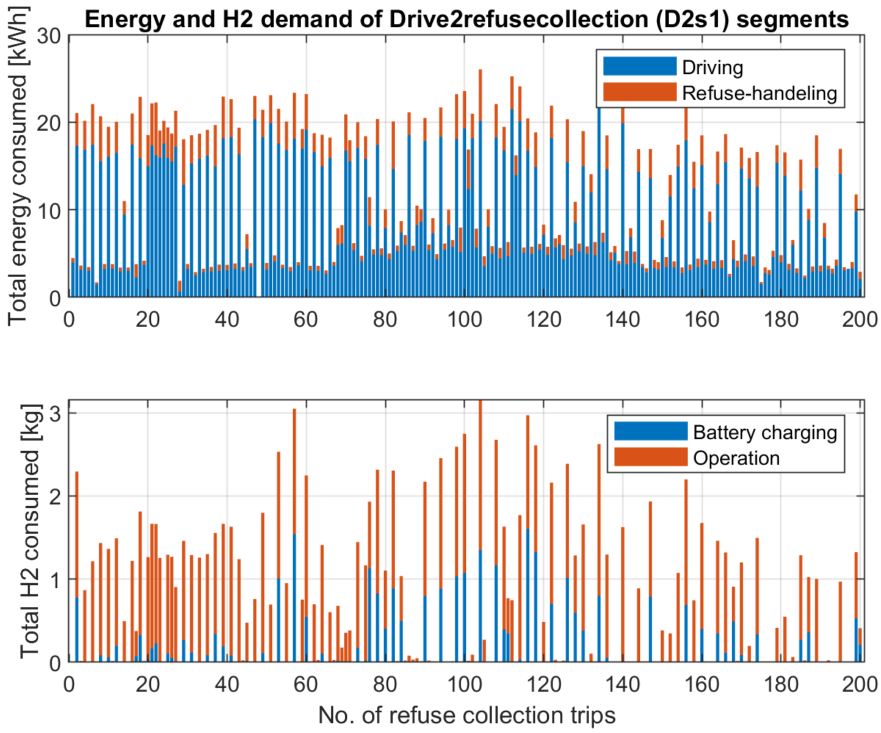


Figure 27: Energy and hydrogen demand of D2s1 segments

This can be seen in distances in Figure 28 (top left). Segments starting from base location and refuelling sites are performed, generally, at lower but varying average speeds, thus, the energy consumption per km may vary between 0,7 to 1,6 kWh/km. Whereas the segment trips starting from disposal site are usually performed with higher average speed and thus favour lower energy consumption per km varying between 0,7 to 1 kWh/km. No influence of refuse weight as they are performed with unladen weight of RCV (Figure 28, top right).

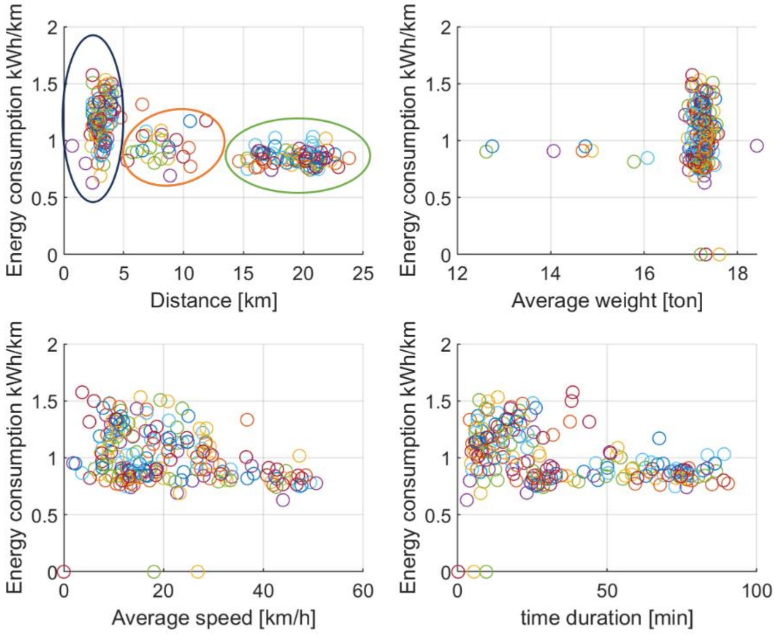


Figure 28: Energy consumption per km of D2s1 segments due to distance, average weight, average speed and time duration. Black eclipse -> Base location or disposal to collection area 2. Orange eclipse -> refuelling site. Green eclipse -> Disposal site (top left)

6.2.1.5 Drive2RefuseDisposal (D2s2)

Figure 29 shows the energy and hydrogen demand of the Drive2RefuseDisposal segments. As seen, total energy demand may vary from 8 to 30 kWh and hydrogen demand may rise up to 2kg during these segments. The variation occurs mainly due to the start location of this segment, which could be collection areas or refuelling site.

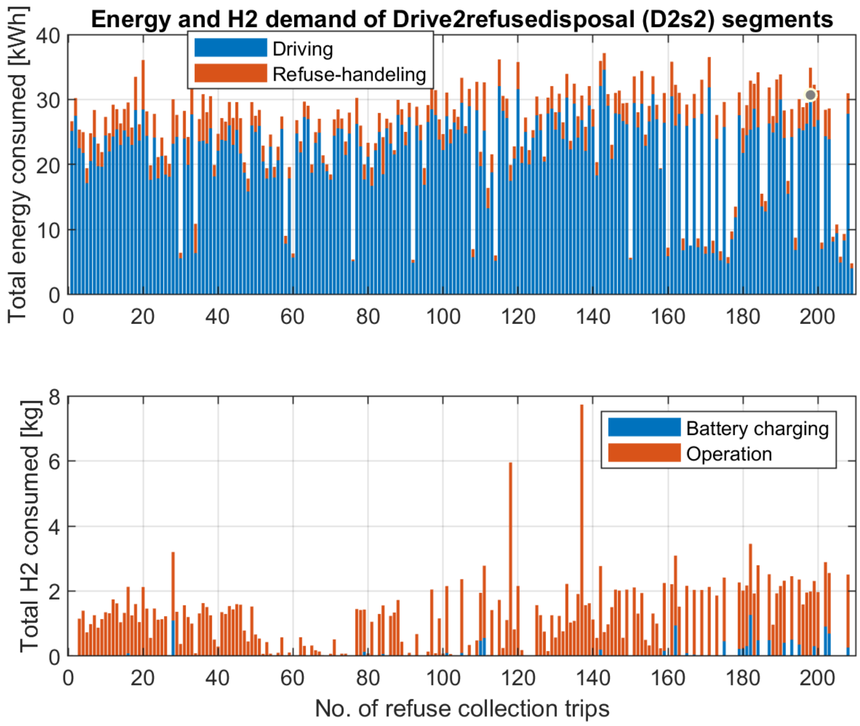


Figure 29: Energy and hydrogen demand of D2s2 segments

This can be seen in distances in Figure 30 (top left). These segments are performed, generally, at higher average speeds, thus, the energy consumption per km may vary between 1.0 to 1,6 kWh/km. There is also a slight increase in energy consumption with increase in average weight of the RCV as shown in Figure 30, top right.

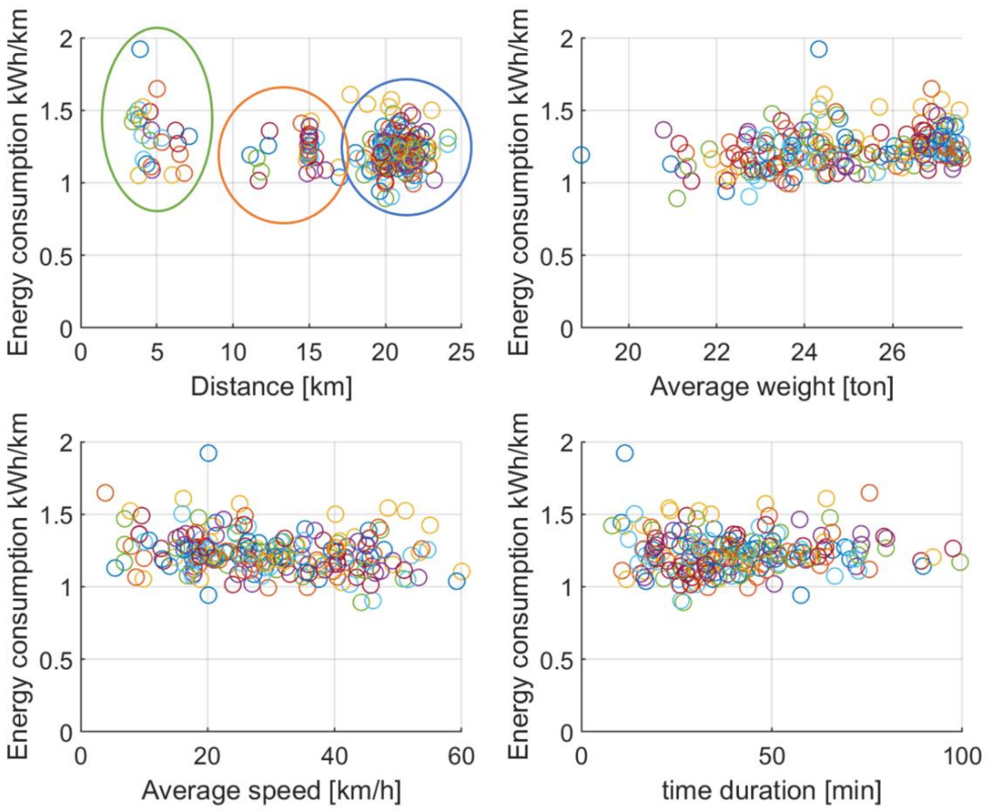


Figure 30: Energy consumption per km of D2s2 segments due to distance, average weight, average speed and time duration. Green eclipse -> Collection area 2, Orange eclipse -> refuelling station, blue eclipse -> Collection area 1 (top left)

6.2.1.6 Drive2Refueling (D2s3)

Figure 31 shows the energy and hydrogen demand of the Drive2Refueling segments. As seen, total energy demand may vary from 10 to 20 kWh and hydrogen demand may rise up to 2kg during these segments. The variation occurs mainly due to the start location of this segment, which could be collection areas or disposal site.

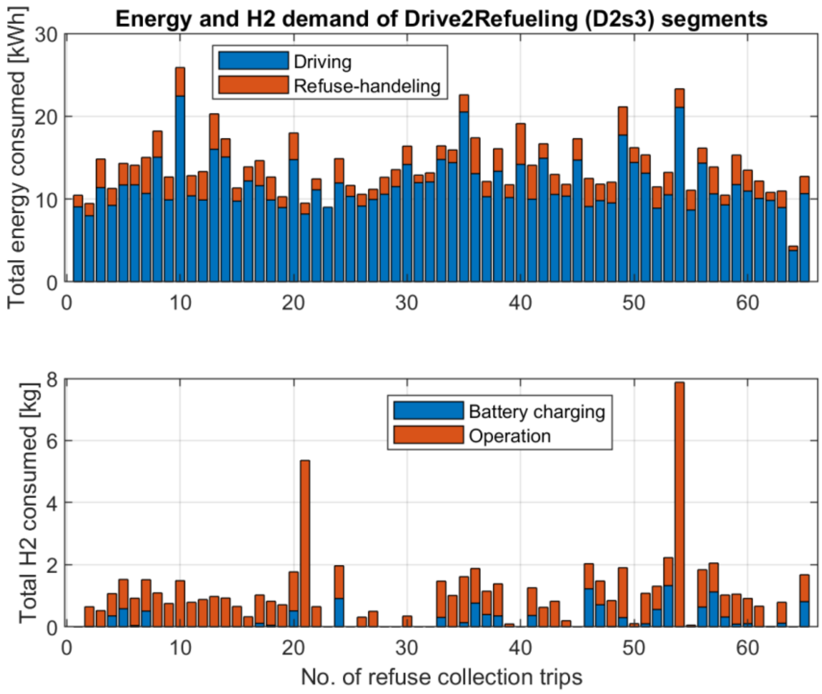


Figure 31: Energy and hydrogen demand of D2s3 segments

This can be seen in distances and average weight in Figure 32 (top left and top right, respectively). The segment trips starting from collection area are usually performed with higher average weight due to the collected refuse and thus consume higher energy per km, varying between 1 to 1,8 kWh/km. Whereas the segment trips starting from disposal site are usually performed unladen and thus consume less energy per km, varying between 0,7 to 1 kWh/km.

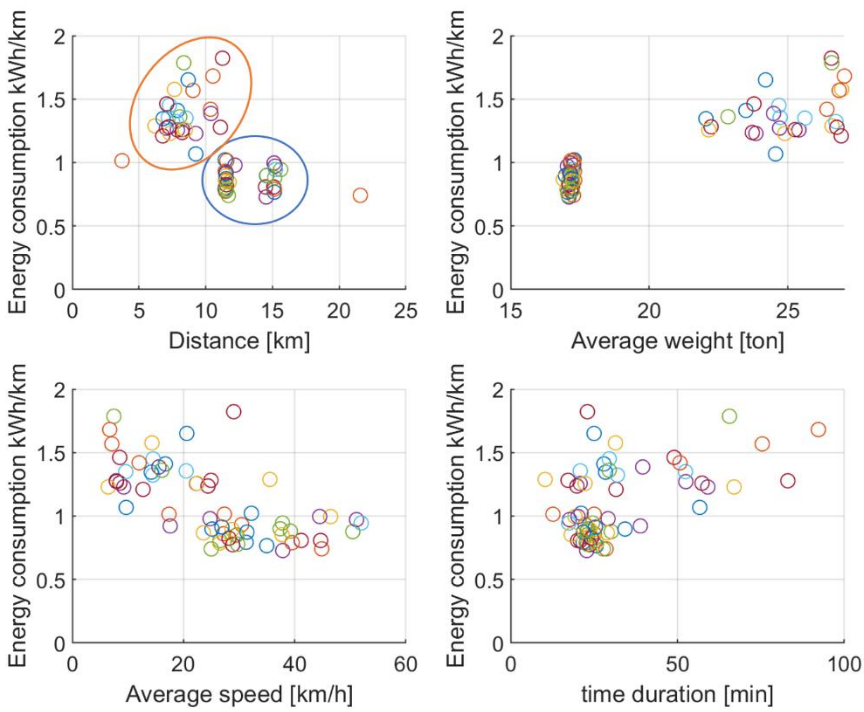


Figure 32: Energy consumption per km of D2s3 segments due to distance, average weight, average speed and time duration. Blue eclipse -> disposal site, orange eclipse -> collection area (top left)

6.2.1.7 Drive2Baselocation (D2s4)

Figure 33 shows the energy and hydrogen demand of the Drive2Baselocation segments. As seen, total energy demand may vary from 4 to 10 kWh and hydrogen demand may rise up to 2kg during these segments. However, in the majority of these segments, fuel cell is not active. The variation occurs mainly due to the start location of this segment, which could be collection areas, refuelling station or disposal site.

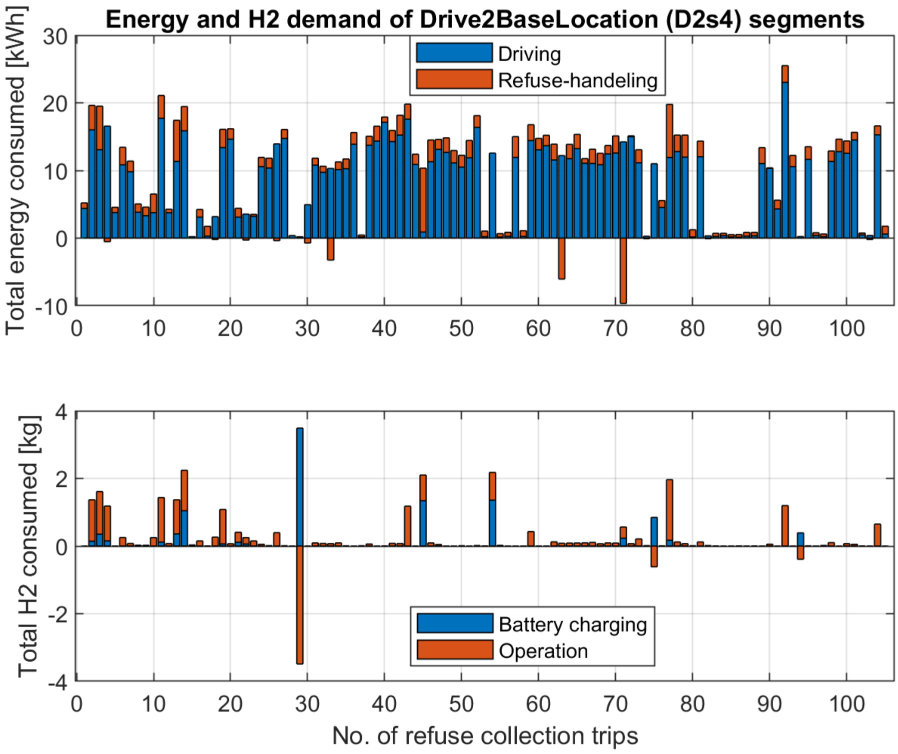


Figure 33: Energy and hydrogen demand of D2s4 segments

This can be seen in distances in Figure 34 (top left). The segments starting from refuelling station or collection area are performed at lower speeds whereas at higher speeds from disposal site and thus, the energy consumption per km can vary between 0,7 to 1,5 kWh/km.

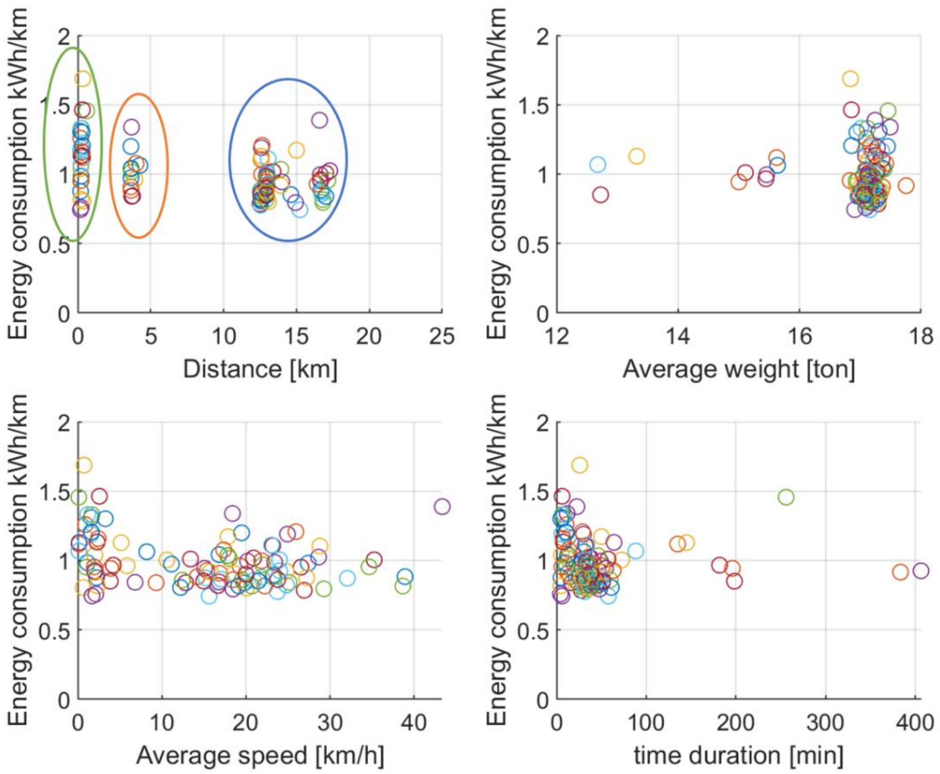


Figure 34: Energy consumption per km of D2s4 segments due to distance, average weight, average speed and time duration. Green eclipse -> collection area, orange eclipse -> refuelling station, and blue eclipse -> disposal site (top left)

6.2.2 Duty cycles and daily operation

In Figure 7, we presented 5 duty cycle variants that could be used to combine the operational segments and present the daily operation of RCV in a generic manner. Figure 35 presents the comparison between different duty cycles with respect to their energy and hydrogen demand, distance and average weight. It may be observed that the duty cycle type 4 (DC-4) is not observed at all while DC-5 only has a few trips. DC-1, 2 and 3 are the three variants that are generally performed by the RCV.

Comparison DC-2 and 3:

DC-3 has no refuelling in comparison to DC-1 and 2 which indicates 1 less drive2segment in DC-3 but the median of distances travelled are almost same for DC-2 and DC-3, as shown in Figure 35 (bottom left). This is because the D2s2 trips in DC-3 are longer than in DC-2 (see Figure 30 top left blue and orange eclipse) and the difference variation between them might be accounted by the D2s3 trips in DC-2 (see also Figure 32 top left orange eclipse). The median of average RCV weight is higher for DC-2 in comparison to DC-3 (Figure 35 bottom right) which leads to the higher energy and hydrogen demand of DC-2 compared to DC-3 (Figure 35 top left and right, respectively).

Comparison DC-1 and 3:

Both DC-1 and 3 may have some variations in D2s2 segments but DC-1 has an additional D2s3 segment compared to DC-3 (see Figure 32 top left blue eclipse) which makes the DC-1 longer than both DC-2 and 3 with respect to the distance which should also indicate higher energy and hydrogen demand for DC-1 compared to the other two. However, the average weight of the RCV is comparatively lower than the other ones which is why the energy and hydrogen demand is higher for DC-1.

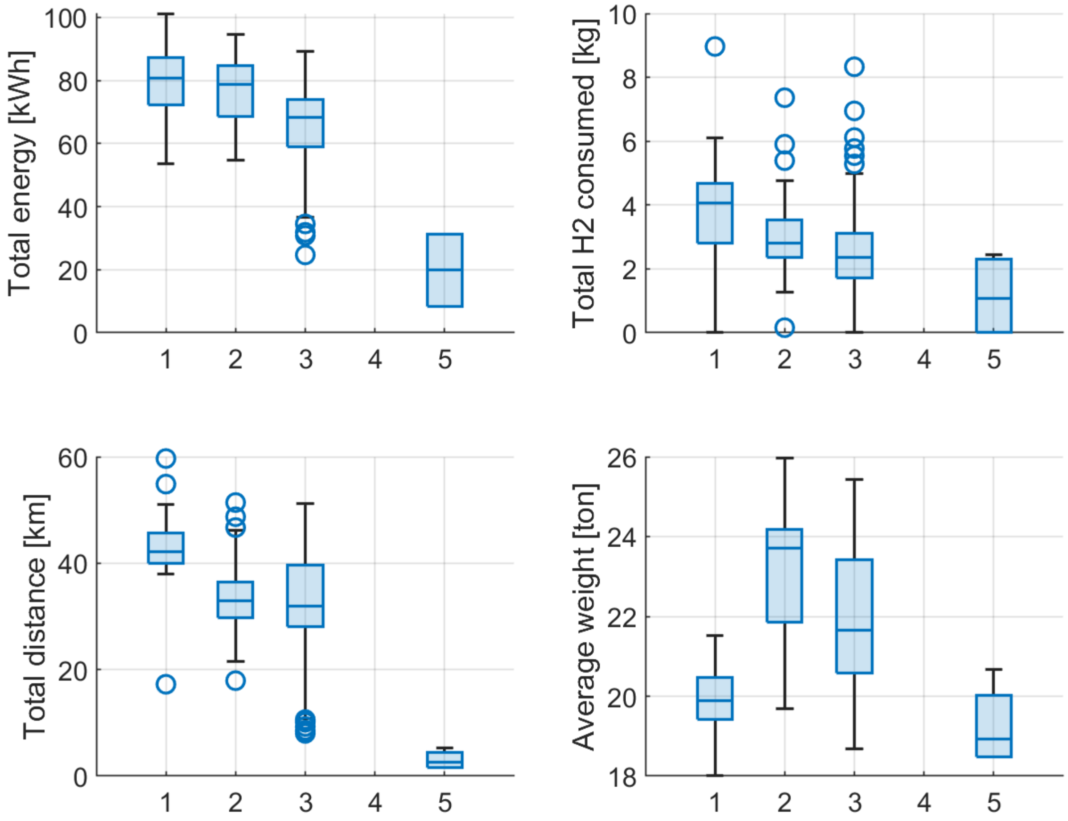


Figure 35: Energy and hydrogen demand of the duty cycles

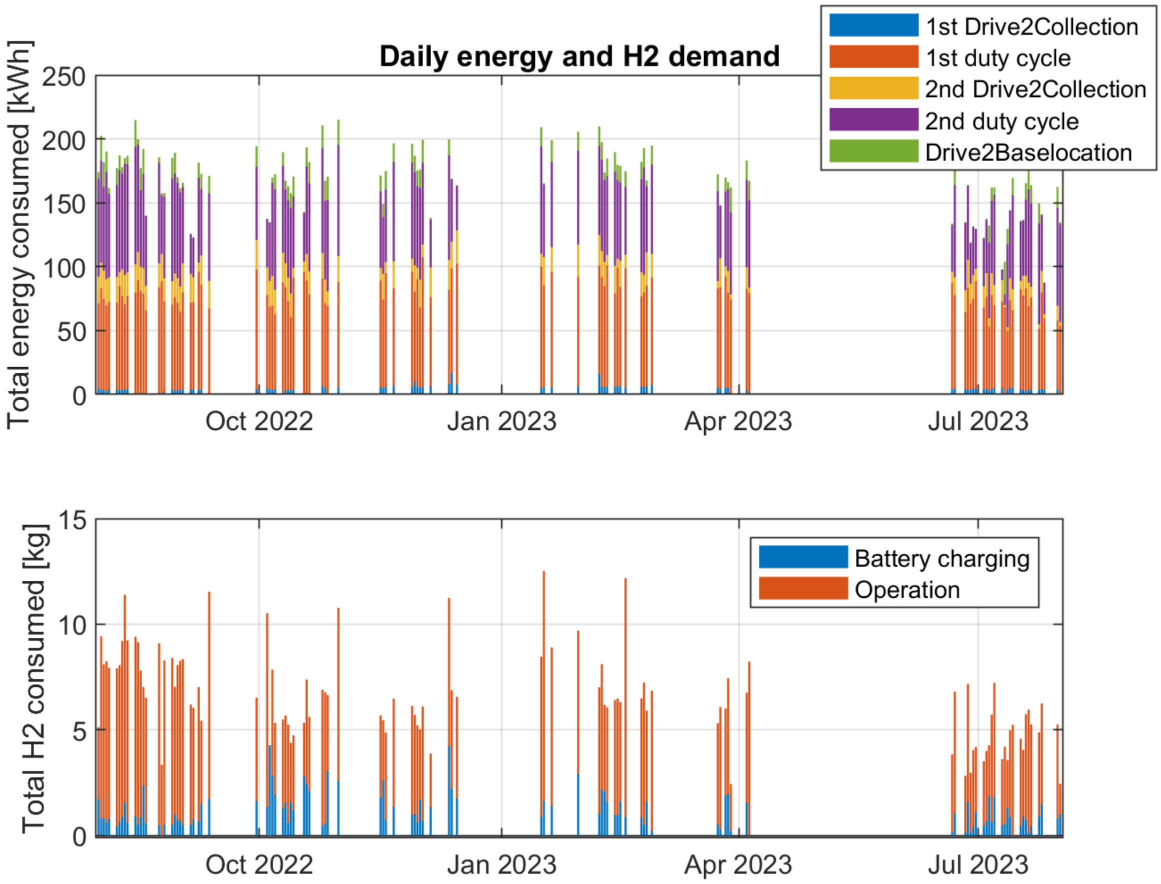
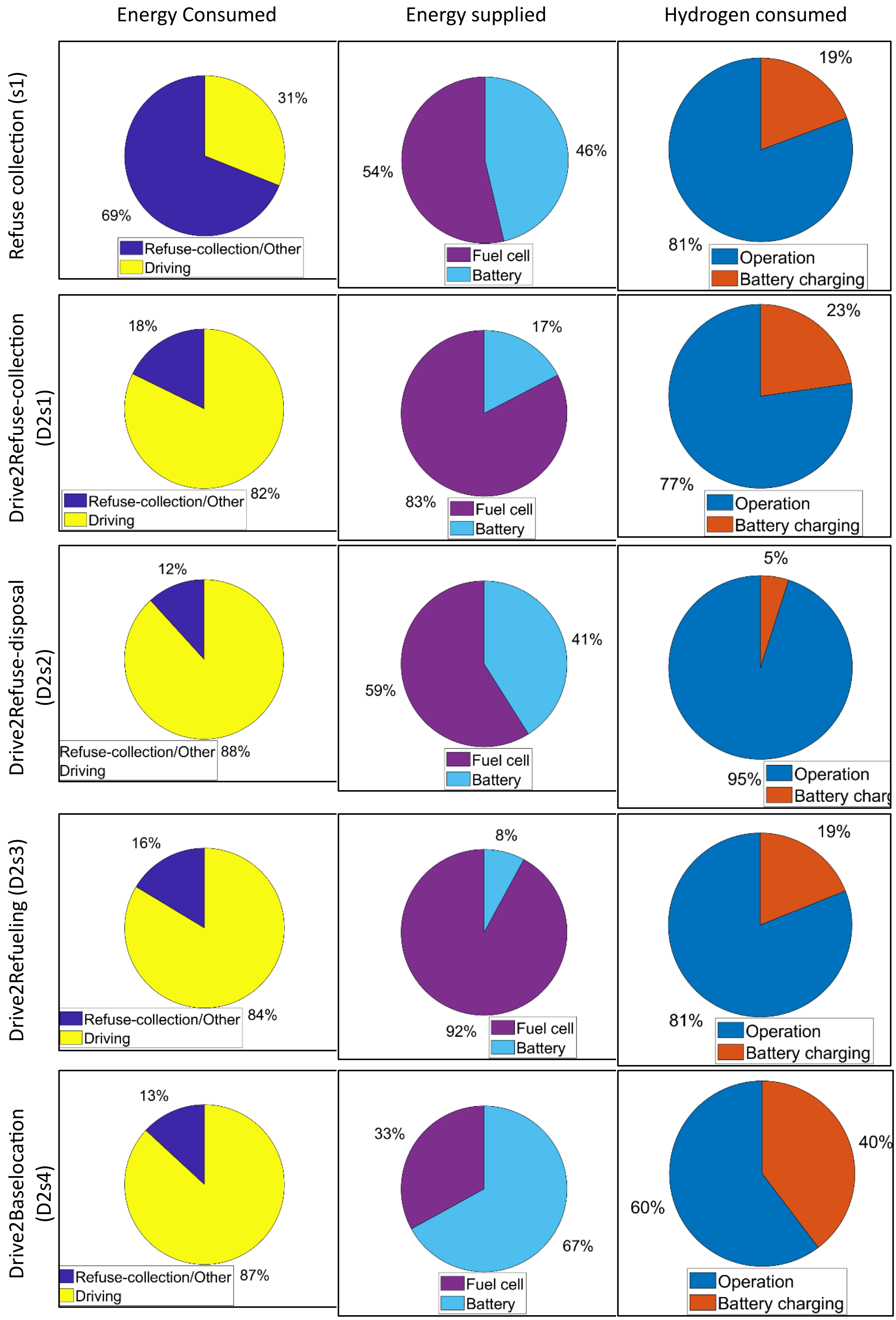


Figure 36: : Daily energy and hydrogen demand variation

By utilizing the duty cycles and the scheme for a day as shown in Figure 2, the daily energy and hydrogen demand can be calculated as shown in Figure 36 from 1st August 2022 to 1st August 2023.

The overall summary of energy and hydrogen usage per segment can be seen in the figures contained in Table 4.

Table 4: Summary figures of energy and hydrogen consumed by Duisburg vehicle



6.3 Results combined

At the end, the results are based on an extensive data collection from the truck in Duisburg, supplemented with data from Herten and Arnhem.

Due to differences in the vehicles themselves, operating profiles and data collection methods, they can't be directly compared. (see below table). Nothing can be inferred from the differences between the metrics from the vehicles shown in the table.
The vehicle in Duisburg uses a rotary refuse compactor which uses less power than the plate compactor of Arnhem and Herten. While Arnhem has a crane to lift large containers over the top of the vehicle to dump their contents and Herten uses large arms to deposit dumpster refuse into the top of the vehicle, Duisburg uses small arms that dumps refuse into the rear of the truck. These differences in vehicles likely influence the differences between the vehicles, but there is insufficient data to quantify this.
It has been observed in the Duisburg data that not every day has a refuel, which could be why there is a discrepancy between hydrogen use (per day) and refuelled (per refuel) averages.

Category	Metric	Arnhem, NL	Duisburg, DE	Herten, DE
Time	*Total operation days*	16	107	96
Distance [km]	*Daily average*	57.72	83.07	81.06
	Total	923.5	8639.83	9484
Speed (Km/h)	*Daily average*	24.17		28.11
Duration (hr)	*Daily average*			7.45
H_2 Use [kg]	*Daily average*	10.21	6.52	11.16
	Total	136.37	698.09	1306.17
Collected refuse (ton)	*Daily average* *Total*			5.08 593.84
Collected refuse (m3)	*Daily average*			84.67
Collected refuse (kg/m3)				59.95
H_2 Consumption [kg/100km]	*Daily average*	17.53	7.56	14.45
Energy efficiency	*Energy consumption [kWh/km]*	2.68	1.85	2.02
	FC Efficiency [kWh/kg]	16.30		14.07
H_2 Refuel	*Average per [kg]*	7.43	11.32	11.57
	Total [kg]	178.31	724.48	1018.19
	Number [#]	24	64	88
	Average time [min]	3.88	12.57	6.77

7 Emissions

Figure 37 is extracted from the supplement working paper of the International Council on Clean Transportation (ICCT)[4] and shows the average emissions produced by heavy-duty vehicles in relation to their curb weight. The data (blue points) comes from the monitored heavy-duty vehicles (mainly freight transport) under the scope of the regulation (EU) 2018/956[5] and using a linear fit through the data, RCV emissions are projected (orange point).

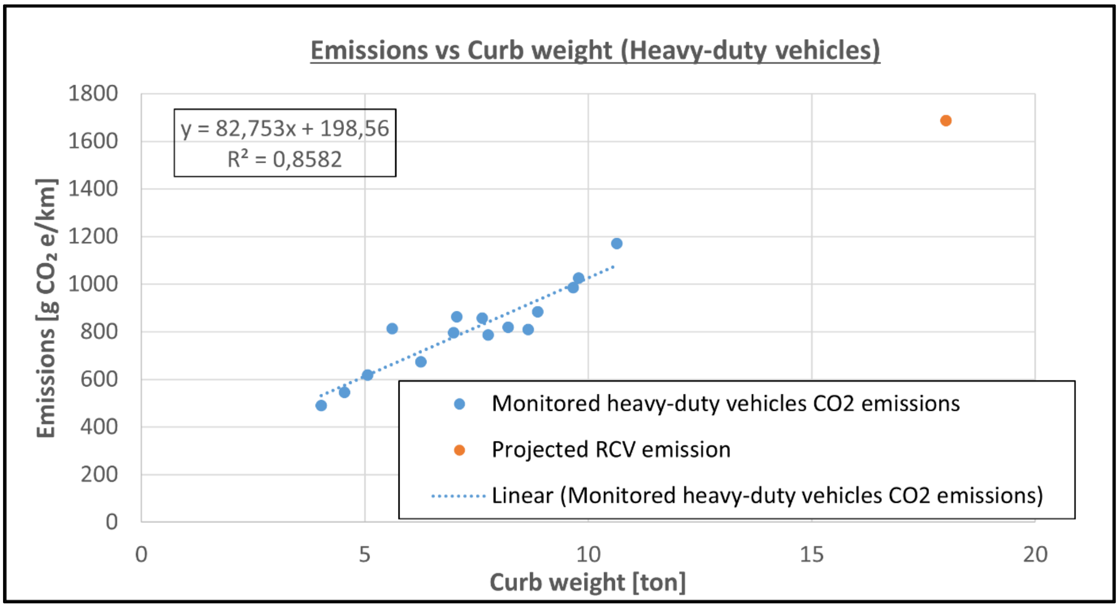


Figure 37: Monitored CO2 emissions of heavy-duty vehicles in the EU vs. their curb weight

In order to calculate the emission savings of fuel cell RCVs, we refer to the emission factors presented in the White Paper[1] published by the ICCT in February 2023, where the life-cycle GHG emissions of Euro VI diesel, compressed or liquified natural gas, battery electric, and hydrogen fuel cell electric heavy-duty vehicles are estimated. The scope of their life cycle analysis and constituents are presented in Figure 38.

[1] The International Council on Clean Transport (ICCT) White Paper: A comparison of the life-cycle greenhouse gas emissions of European heavy-duty vehicles and fuels, 06 February 2023. Online available at https://theicct.org/publication/lca-ghg-emissions-hdv-fuels-europe-feb23/, accessed on 04 August 2023.

Fossil fuels	• Crude oil/natural gas extraction (including flaring), processing and transport, and fuel refining and distribution; all including methane leakage • CO_2, methane, and nitrous oxide (N_2O) emissions of fuel consumption
Biofuels	• Plant cultivation/waste collection, processing and transport, and fuel production and distribution • Indirect land use change GHG emissions of plant cultivation • Methane and N_2O emissions of fuel consumption
Electricity	• GHG emissions of electricity generation, including new power plant infrastructure for renewable energy, transmission, distribution, and charging losses
Hydrogen	• For electrolysis-based hydrogen: GHG emissions of electricity, adjusted by energy losses during electrolysis and hydrogen compression or liquefaction • For natural gas-based hydrogen: natural gas extraction, processing, and transport; steam reforming and hydrogen compression; all including methane leakage • *Not included:* Long-distance hydrogen transport

Figure 38: Scope of GHG emissions considered in the fuel life cycle analysis, as mentioned in the ICCT's White Paper

The emission factor in the White Paper is presented in an equivalent amount of CO_2 (CO_2 e) to consider the non-CO_2 emissions like methane, NOx, and PM. as presented in Table 3. These emissions factors are comparable to the emission factors reported by the Joint Research Centre (JRC), the European Commission's Science and Knowledge Service in their W2W analysis[2], e.g., diesel 91.9 g CO_2 e/MJ (W2T: 18.9 g CO_2 e/MJ and T2W: 73 g CO_2 e/MJ), hydrogen from natural gas 480 g CO_2 e/kWh, and renewable hydrogen is 41 g CO_2 e/kWh.

Table 5: Emission factors for the fuel, as mentioned in the ICCT's White Paper.

Fuel	Emission factor
Hydrogen from natural gas	410 [g CO_2 e/kWh]
Renewable hydrogen	39 [g CO_2 e/kWh]
Diesel	97.5 [g CO_2 e/MJ]

Using Table 33, emissions for fuel cell RCVs and their diesel counterparts can be estimated by multiplying their energy or fuel consumption with the respective emission factor. Additionally, for diesel RCVs, it is convenient to convert the emission factor into g CO_2 e/l as their fuel consumption is usually represented in litres (l) per 100 km. For such, we use the net calorific value of 42.7[3] MJ/kg and density of 0.85 kg/l and the emission factor for diesel becomes 3538.7 g CO_2 e/l.

Table 4 summarizes the operation of fuel cell RCVs within the HECTOR project. Due to technical and regulatory issues, four out of seven RCVs aimed to be deployed within the project are not operational until the present moment, therefore, we only calculate the emissions and emission savings for the three operational RCVs. Figure 39 shows the emissions produced by the fuel cell RCVs in relation to their diesel counterpart. Even if the hydrogen comes from natural gas, the fuel cell RCVs have the

[2] JEC Well-To-Wheels report v5. EUR 30284 EN, Publication Office of the European Union, Luxembourg, 2020. Online available at https://publications.jrc.ec.europa.eu/repository/handle/JRC121213, accessed on 04 August 2023.

[3] European Commission. Regulation (EU) 2017/2400. Online available at https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32017R2400, accessed on 04 August 2023.

potential to reduce emissions by approx. 60% in relation to their diesel counterparts. And if the hydrogen is produced from a renewable energy, the emission reduction potential of fuel cell RCVs further increases to approx. 95% compared to their diesel counterparts. Since the average energy consumption of Duisburg RCV is the highest among the three thus the emissions produced by the Duisburg RCV is also the highest.

Table 6: Summary of operational fuel cell RCVs during the analysis period

RCV location	Arnhem, Netherlands	Herten, Germany	Duisburg, Germany
Average distance travelled per day [km]	58,04	81,73	82,51
Total distance travelled [km]	1.857,40	8.010,00	8.663,5
Average energy consumption of fuel cell RCV [kWh/km]	1,71	1,75	1,86
Average fuel consumption of diesel RCV [l/100 km]	51,28	60,75	60,00

Figure 40 shows the energy savings for the analysis period. The least emission savings may be expected for fuel cell RCV in Arnhem, Netherlands, ranging between 2 to 3,5 metric tons due to its lowest travelled distance during the analysis period. For fuel cell RCV in Herten, Germany, the emission savings may be in the range of 11 to 17 metric tons. The largest emissions savings may be expected for fuel cell RCV in Duisburg, Germany may be in the range of 13 to 19 metric tons during the analysis period. The emission savings for the Duisburg RCV will be higher for entire operational period as only half of the operational period is analysed.

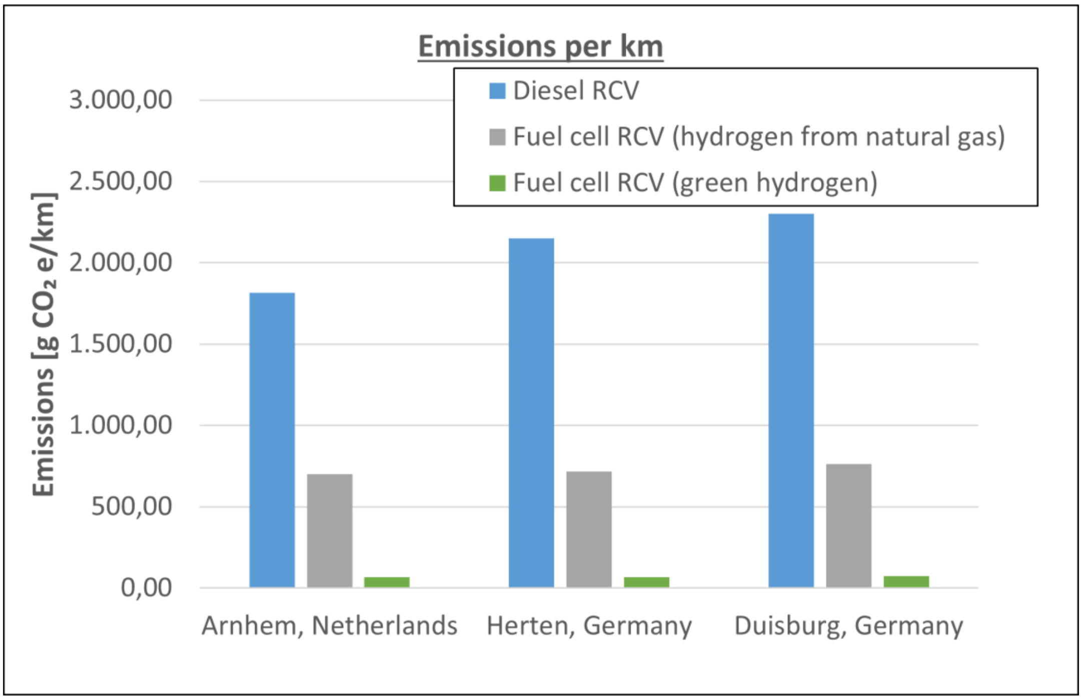


Figure 39: Emissions produced by the diesel RCV in comparison to fuel cell RCVs

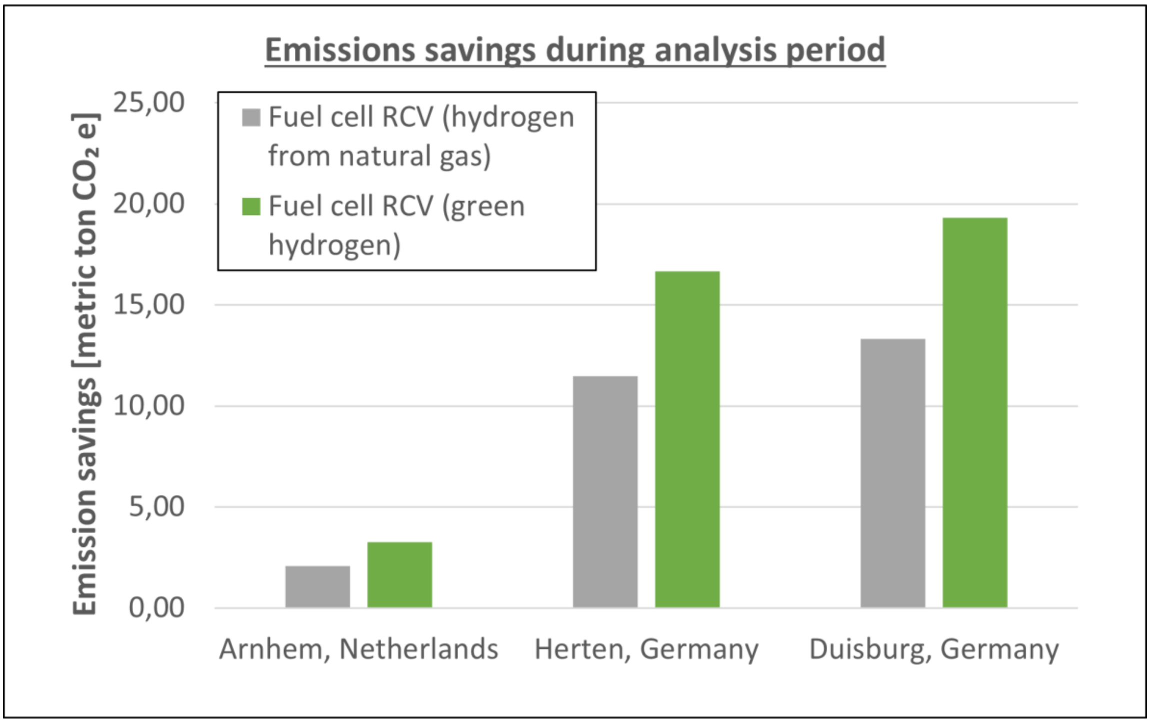


Figure 40: Emissions savings of HECTOR fuel cell RCVs during the analysis period

In conclusion, the HECTOR project shows the potential for emission savings of deploying fuel cell RCVs over conventional diesel RCVs. It also shows the importance of addressing challenges (technical and regulatory) to fully realize the emission reduction potential of zero-emission technologies such as fuel-cell electric vehicles. By leveraging green hydrogen production and reliable vehicle operation, zero-emission RCVs can help meet emission targets.

8 Social impact drivers

During the Hector project a driver survey was held, with the purpose of collecting relevant information to ascertain the efficacy of H2 electric refuse collection vehicles (RCV) over traditional diesel vehicles.

8.1 Driver Survey observations

In total 5 responses were received from drivers from the following companies:

Driver	Company
1	Wirtschaftsbetriebe Duisburg
2	AGR-DAR
3	AGR DAR
4	AGR-DAR
5	Prezero Duiven

The observations are summarized below.

- Driver 5 indicates that he has not yet driven the vehicle
- Five drivers have more than 5 years of driving experience on an RCV, but driving a H2 vehicle does not exceed ½ year.
- For four drivers the H2 vehicle experience is limited to 6 weeks (Question 4, Q5).
- Five drivers prefer their diesel vehicle over the hydrogen vehicle. (Q7).
- Two drivers indicate that range anxiety played a role during their trips (Q9).
- The driving performance of the hydrogen vehicle is perceived on average as less good as compared to the diesel counterpart (Q21).
- Lack of power and insufficient refuelling possibilities are mentioned as main drawbacks of the H2 vehicle, whereas low noise level is judged positively (Q23, Q25, Q28, Q30).
- Three drivers indicate that they like the fact that he can drive a new truck that is a Zero-Emissions Vehicle (Q40).

8.2 Driver survey conclusions

It can be concluded from the driver survey that 3 to 4 drivers are quite enthusiastic about the H2-RCV, especially regarding their potential to reduce harmful emissions.
On the other hand, we must conclude that lack of power is regarded as a negative aspect, that needs attention from the OEM's.

Appendix

This contains additional work done that is not part of the main report, such as the questions used to come to the driver survey conclusions.

A. Driver Survey Questions

Driver Survey

5	18:51	Active
Responses	Average time to complete	Status

1. How can we identify you?

0
Responses

Latest Responses

2. At which company do you work?

5
Responses

Latest Responses

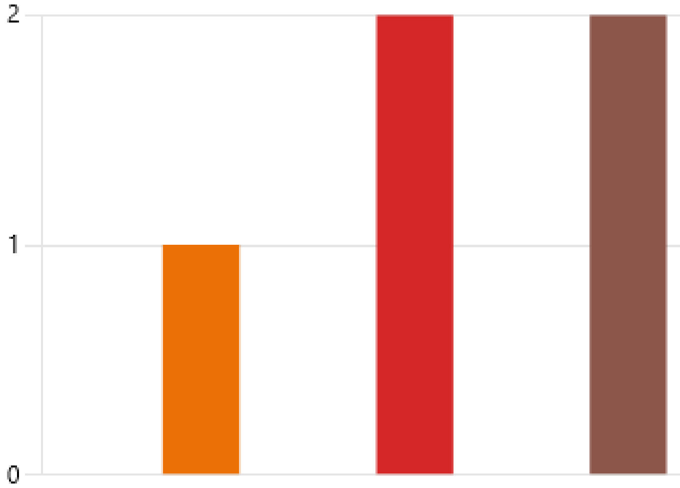
"Prezero Duiven"

"AGR-DAR"

"AGR DAR"

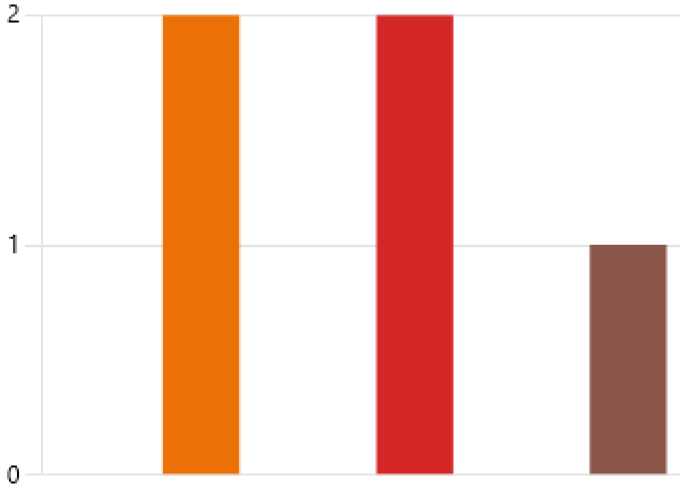
3. How many years have you had a C licence?

0-5 years	0
6-10 years	1
11-15 years	0
16-20 years	2
21-25 years	0
More than 25 years	2



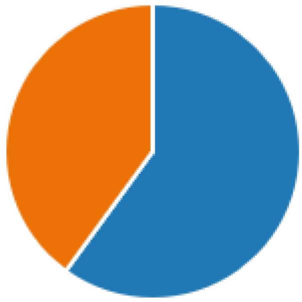
4. How many years of work experience do you have as a Refuse Collection Vehicle (RCV) driver?

0-5 years	0
6-10 years	2
11-15 years	0
16-20 years	2
21-25 years	0
More than 25 years	1



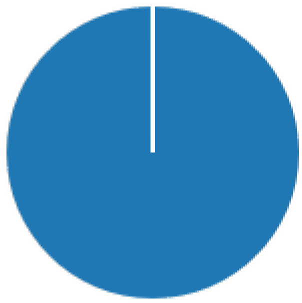
5. How many weeks/years' experience do you have with a H2 electric RCV?

0-6 weeks	3
6 weeks to 1/2 a year	2
1/2 a year to 1 year	0
1 year to 2 years	0
More than 2 years	0

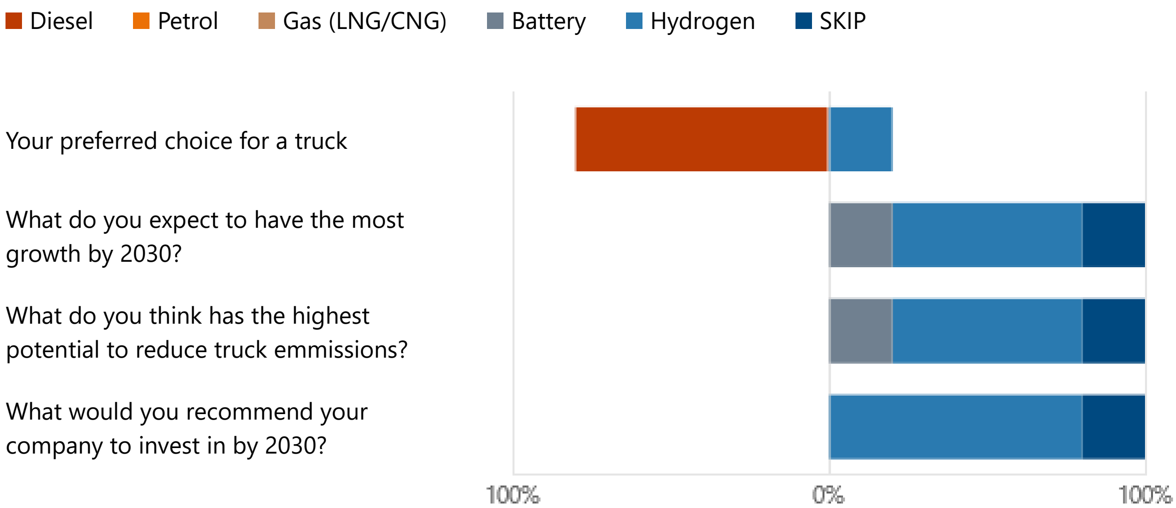


6. What was the fuel type used by the truck you drove before this H2 electric RCV?

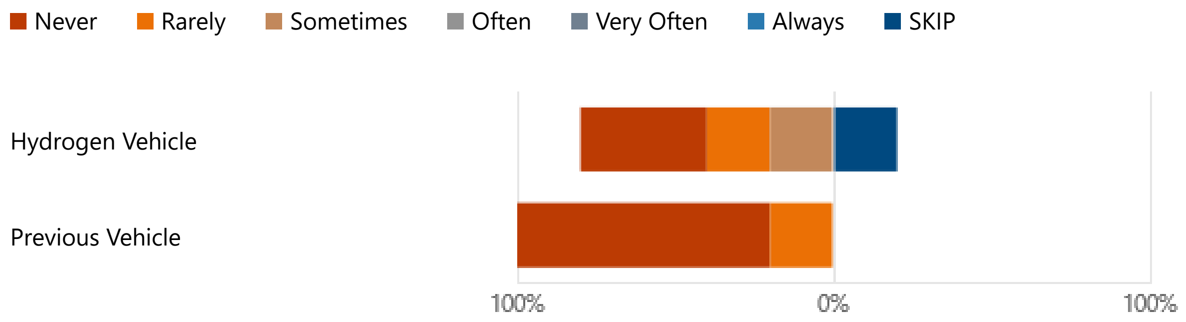
Diesel	5
Petrol	0
Gas (LNG/CNG)	0
Battery	0
Hydrogen	0



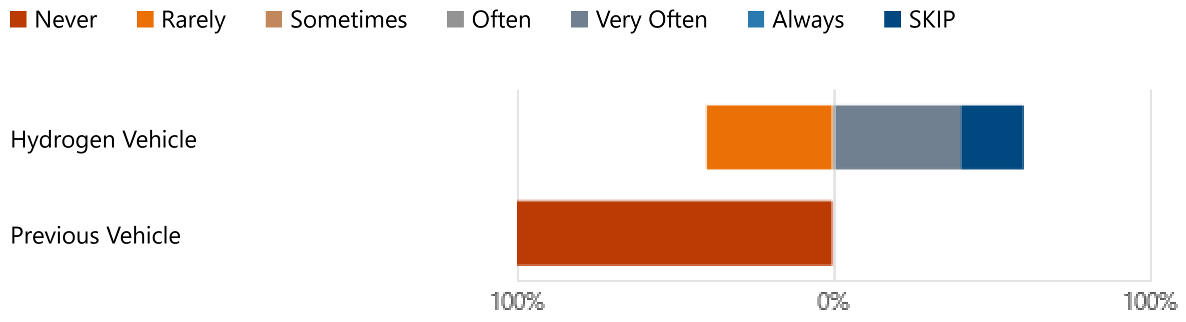
7. Please consider the power/energy source for the following statements



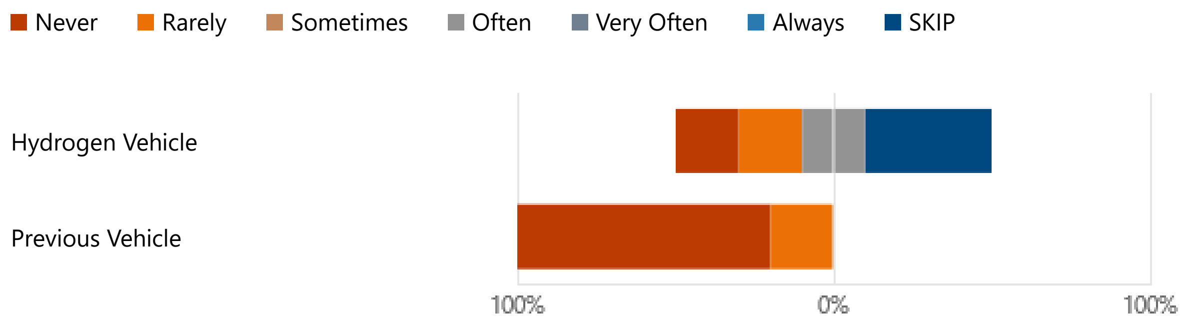
8. I'm concerned about safety while driving



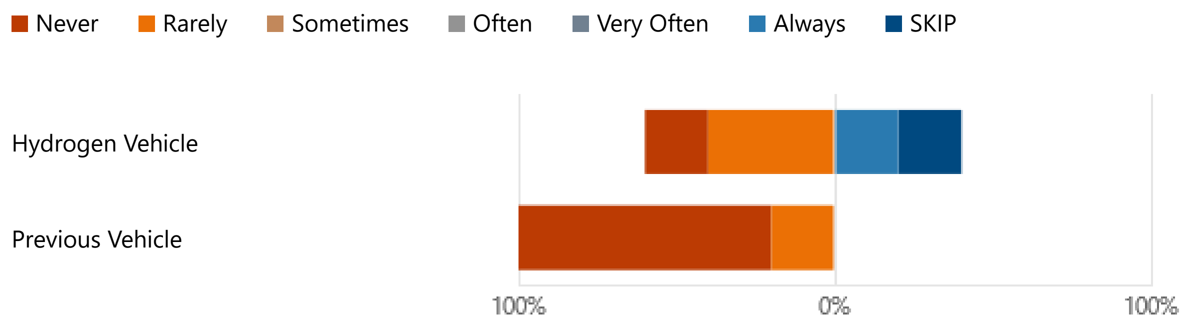
9. I'm concerned about the driving range



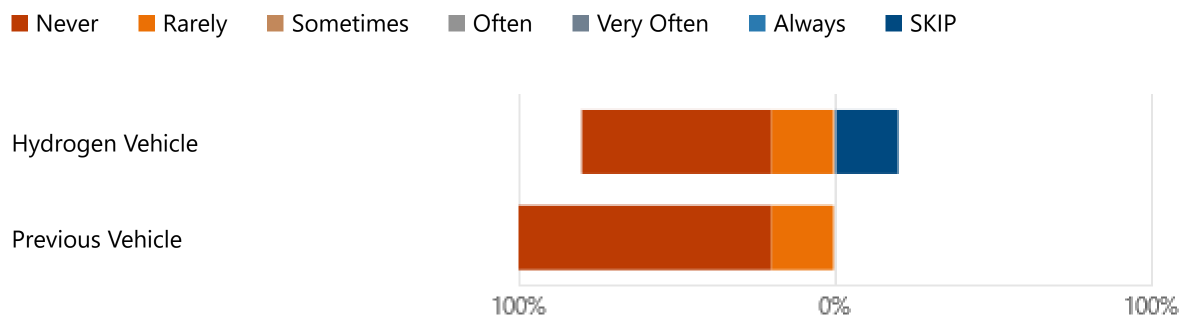
10. I'm concerned about the impact on the vehicle range when using auxiliary systems like A/C



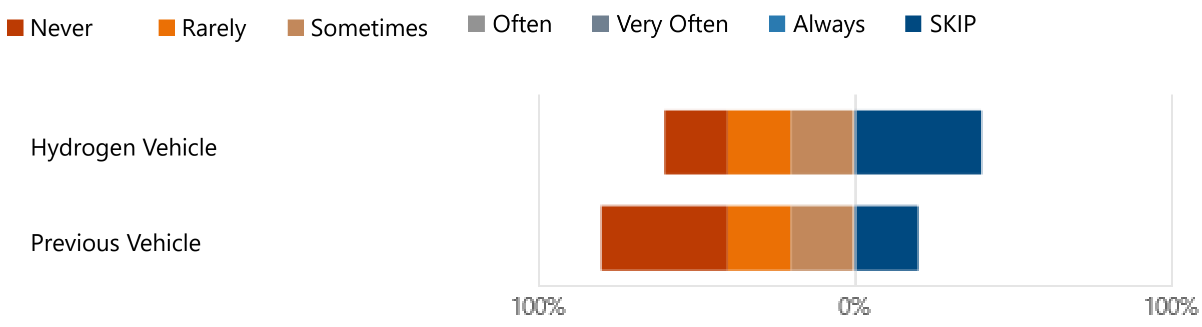
11. I'm concerned about the acceleration



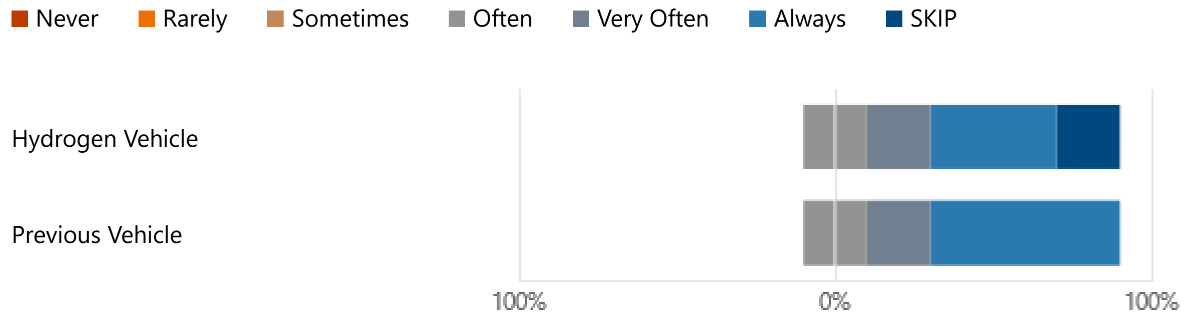
12. I'm concerned about the responsiveness of the brakes



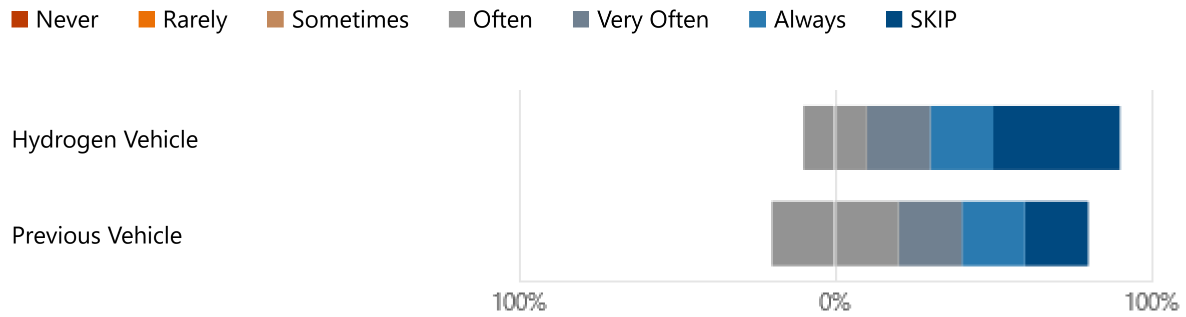
13. I'm concerned about distraction due to the monitoring of dashboard systems



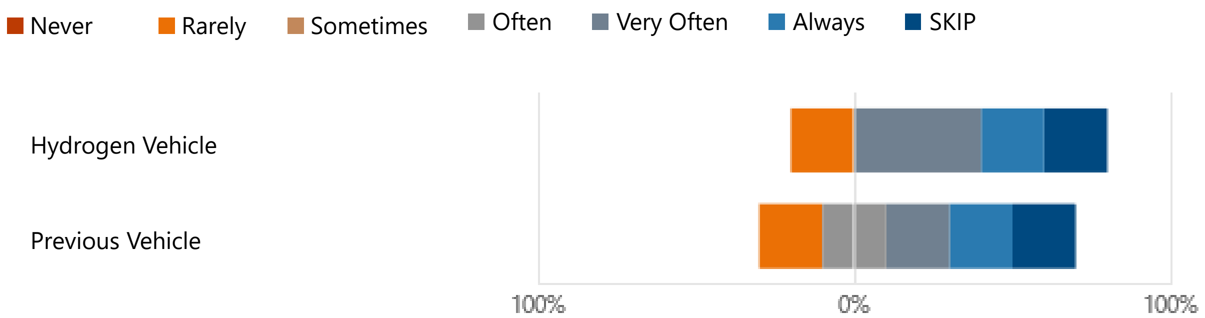
14. I try to take pre-emptive actions based on my knowledge of the operating route



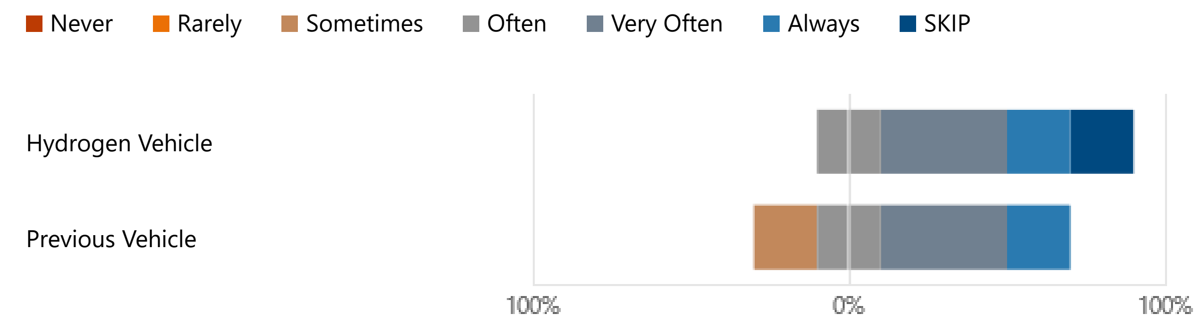
15. I try to anticipate the traffic to avoid harsh braking and accelerating



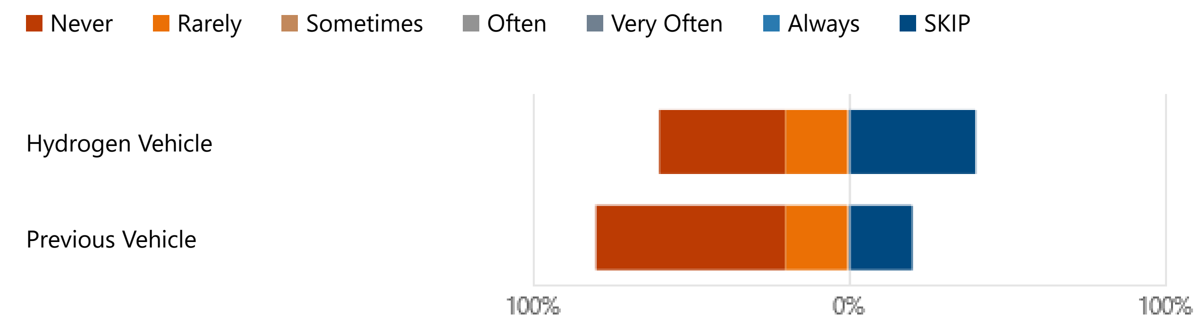
16. I try to optimize my route considering the differences in the driveability



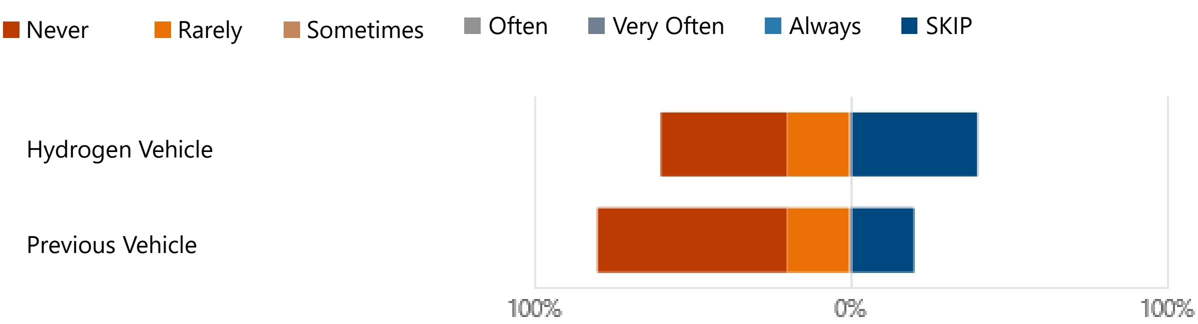
17. I try to drive economically



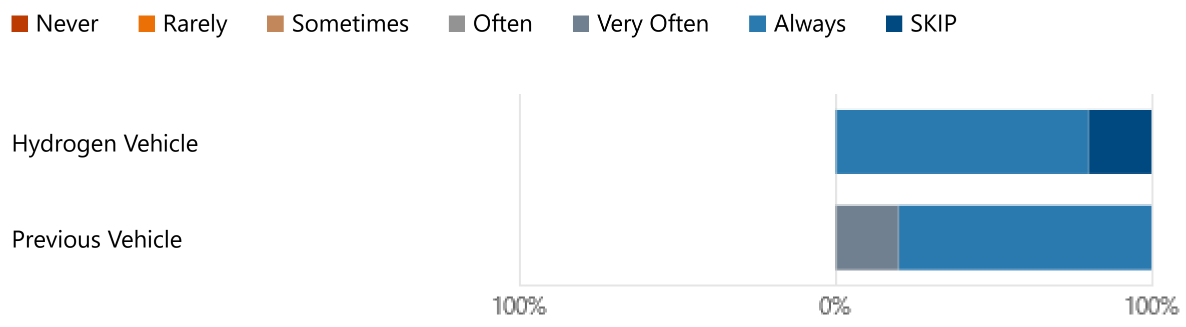
18. I find difficulty in accurately stopping for garbage collection



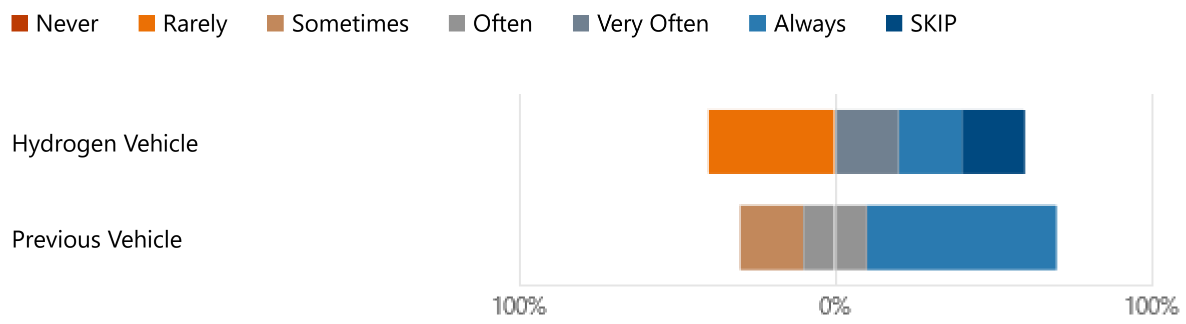
19. I find difficulty while cornering, changing lanes and reversing



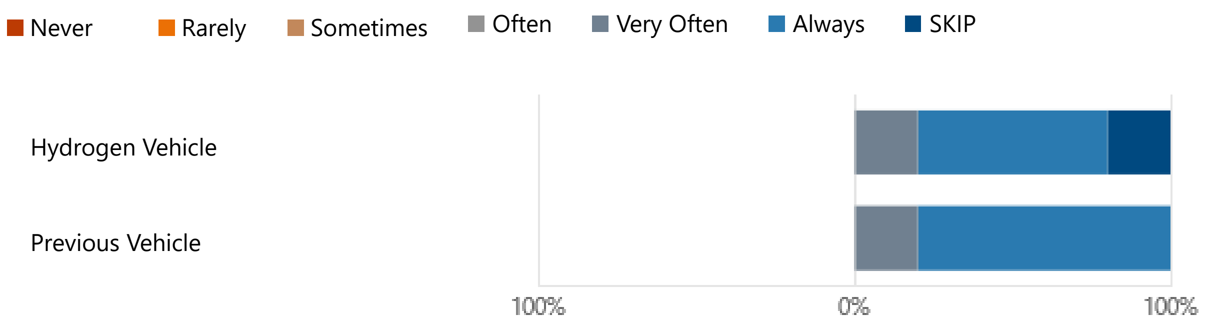
20. I feel I have control over the truck



21. I feel the driving performance is good



22. Overall, I enjoy driving a RCV



23. Considering your answer to the previous question, what do you like and dislike about the H2 electric RCV?

Latest Responses

5

Responses

"Op dit moment nog niet mee gereden"

"Mir gefällt: sehr leise, umweltfreundlich Mir gefällt nicht: geri...

"LKW ist leise. Das Vermogen der Presse reicht noch nicht aus."

24. If you have any additional remarks about the driveability of the H2 electric garbage truck, please mention them below and describe your experience briefly.

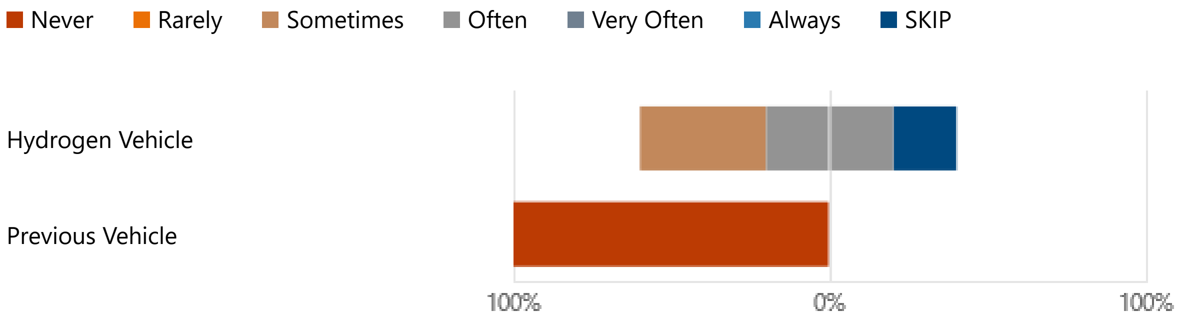
2

Responses

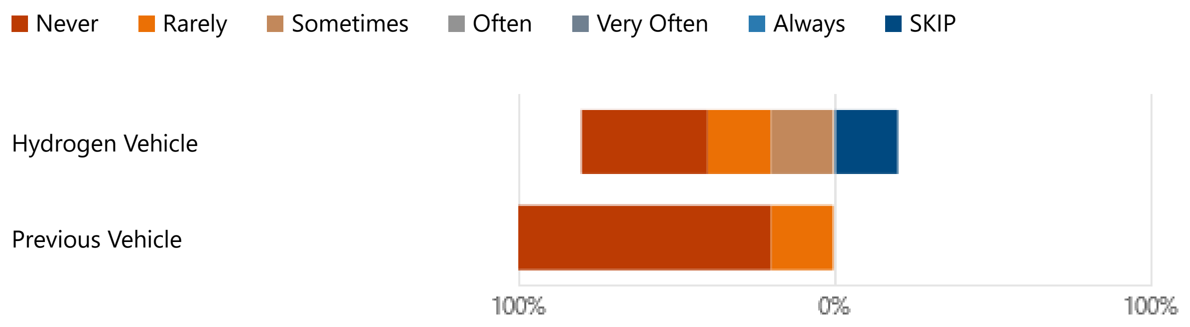
Latest Responses

"Zie bovenstaande"

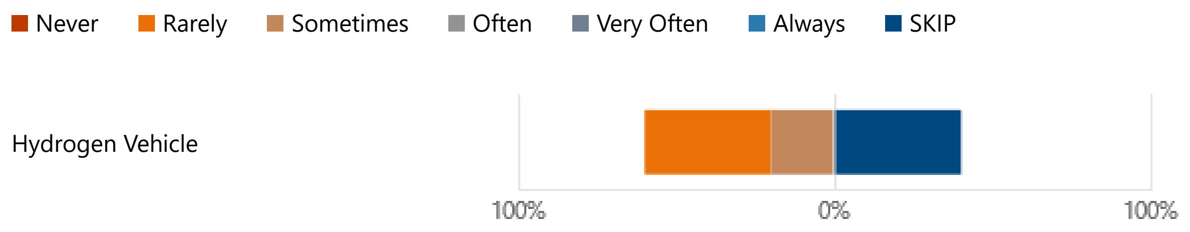
25. I'm concerned about the refueling possibilities



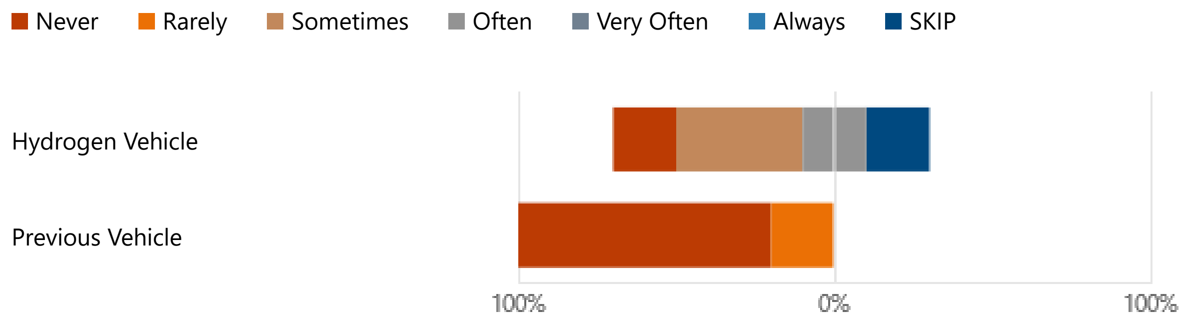
26. I'm concerned about the safety while refueling



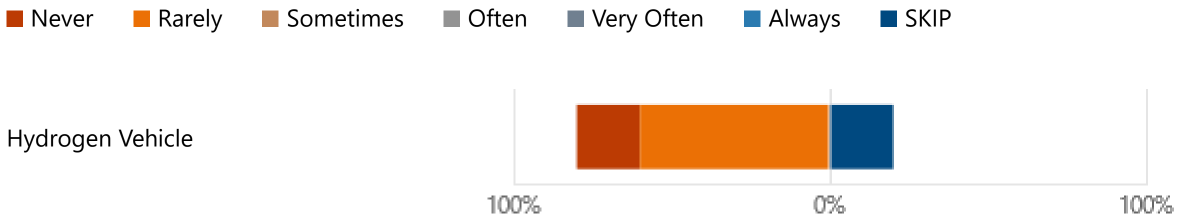
27. I'm concerned about the reliability of the hydrogen system



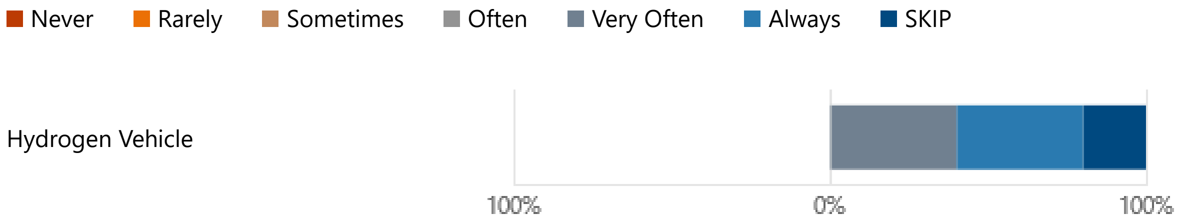
28. I'm concerned about the required power for garbage collection and compression



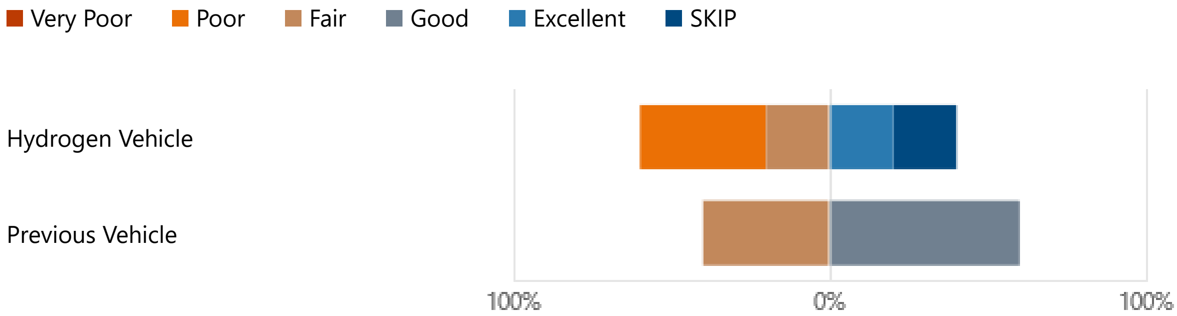
29. I'm annoyed or often distracted by dashboard warnings (such as lights or sounds)



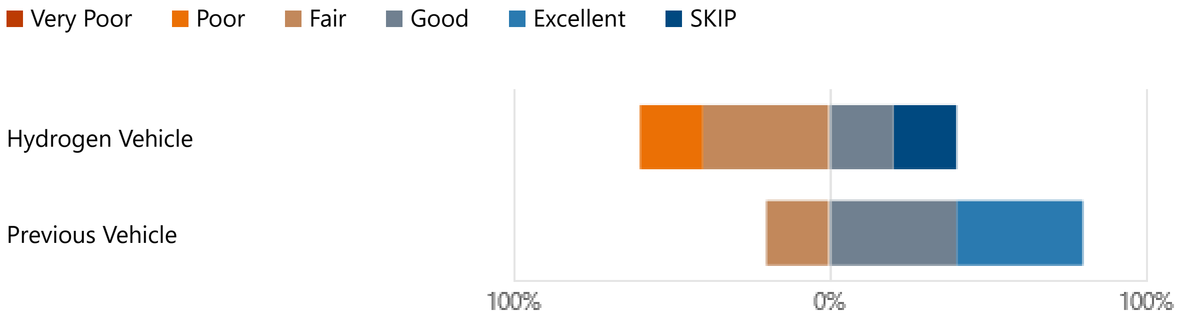
30. I feel that the noise produced is less while driving, garbage collection and compression compared to my previous truck



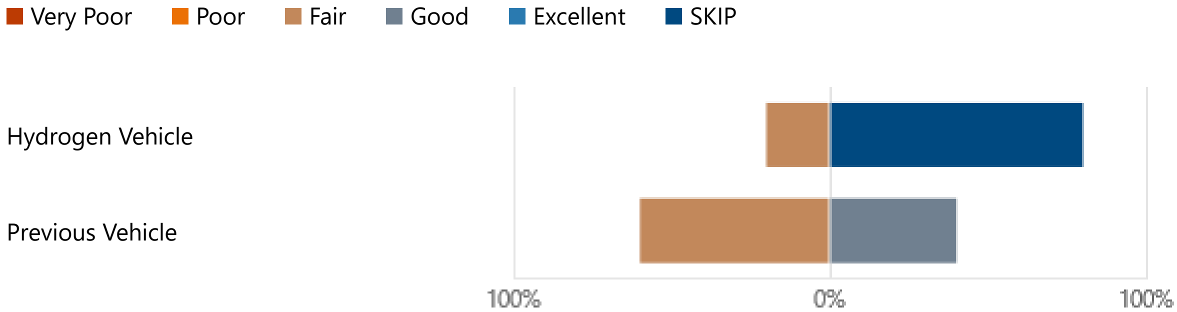
31. I feel the operational efficiency is



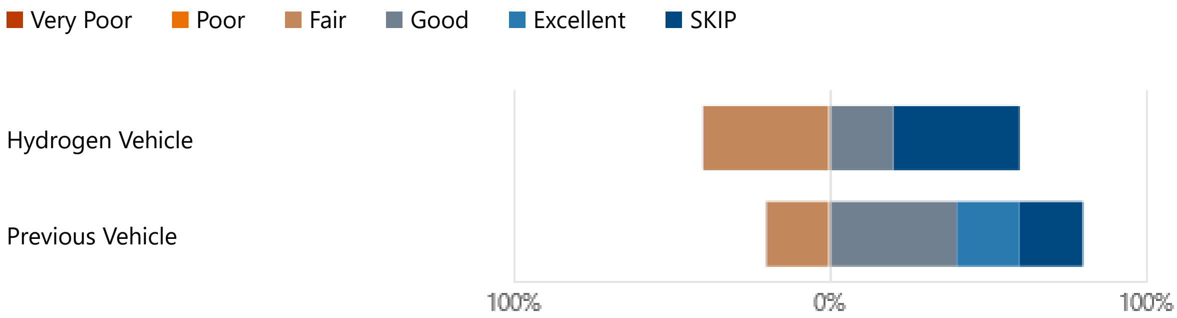
32. Time taken for refuelling is



33. The amount of maintenance and operational downtime is



34. The time taken for garbage collection and compression is

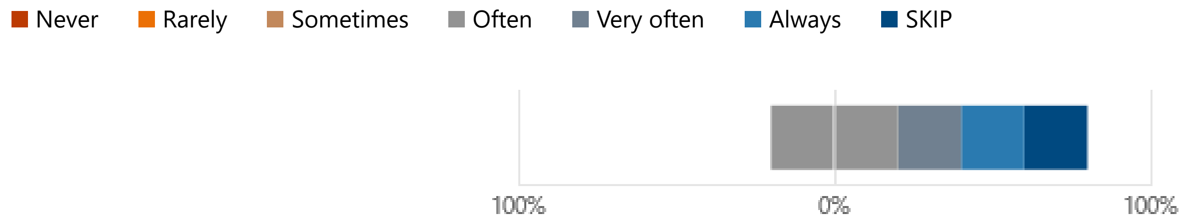


35. If you have any additional remarks about the operability (everyday use) of the H2 electric garbage truck, please mention them below and describe your experience briefly.

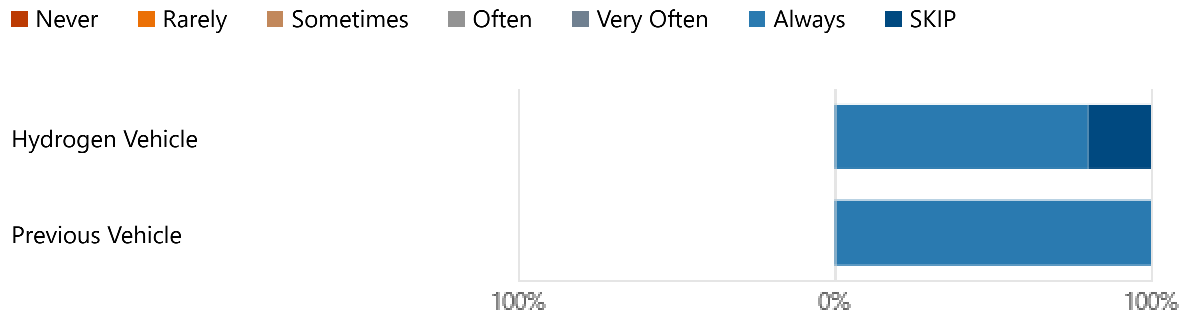
2 Latest Responses

Responses *"Nog niet mee gereden"*

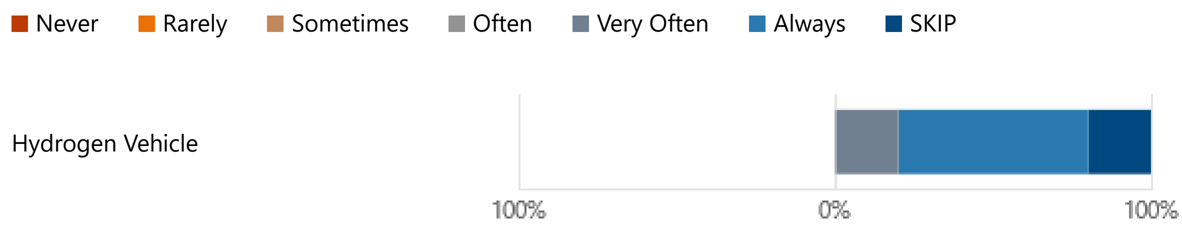
36. I drive more economically by primarily adjusting the speed using the accelerator pedal instead of using the brakes first



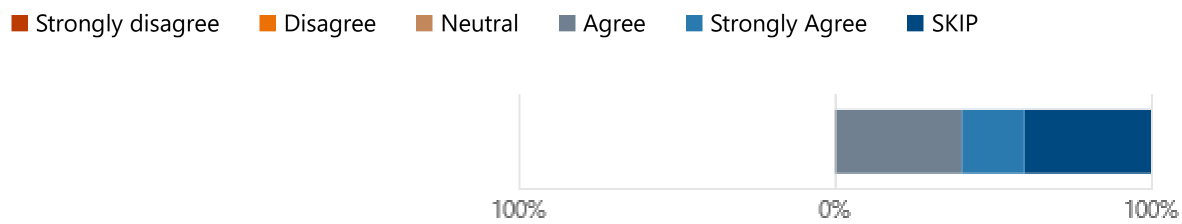
37. I perform safety checks before starting the trip



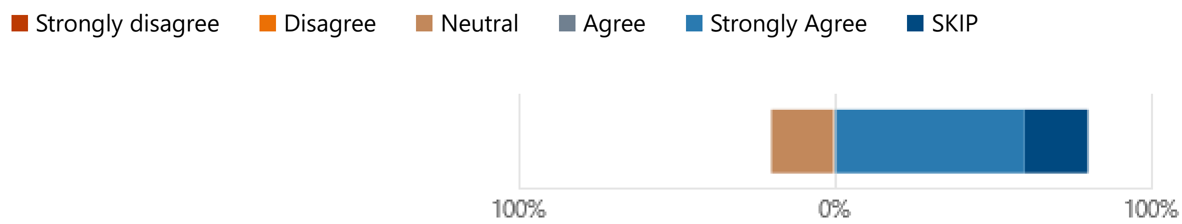
38. I continuously monitor the safety systems and act according to the warnings



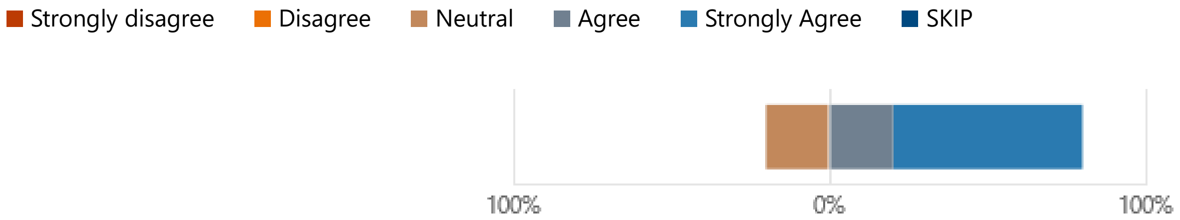
39. I feel that I have better knowledge about the functioning and operation of a H2 RCV,having driven one



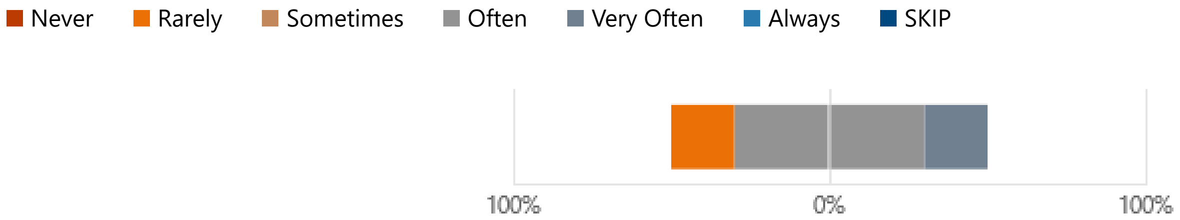
40. I like the fact that I am able to drive a new truck that is a Zero-Emissions Vehicle(ZEV)



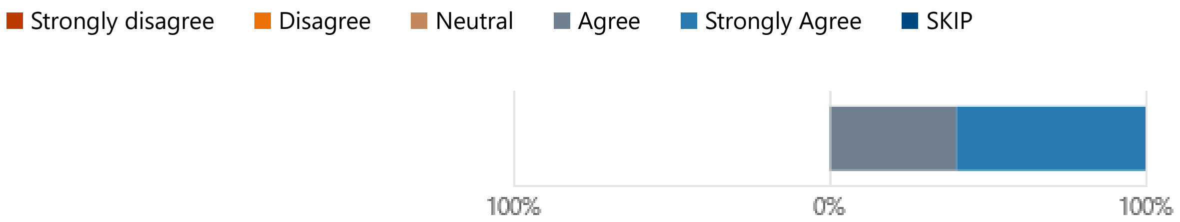
41. I like that fact that my employer wants to reduce the emissions of the fleet



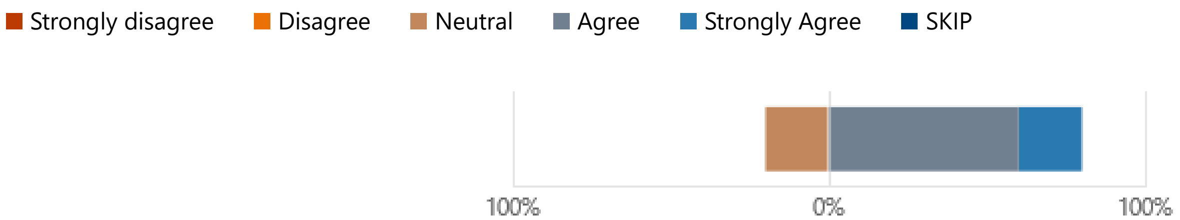
42. I also drive my personal vehicle economically



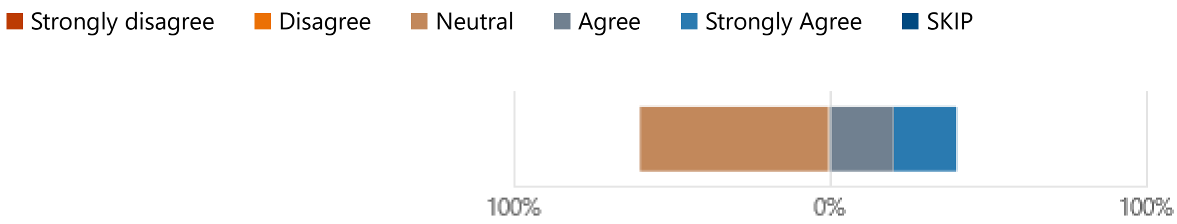
43. I think it is important to reduce harmful vehicle emissions



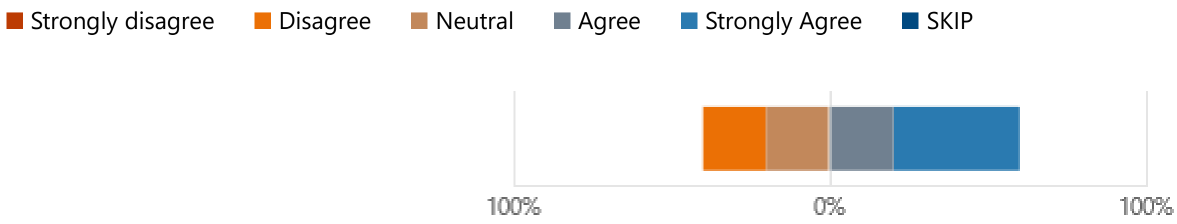
44. I want to contribute to reducing harmful vehicle emissions



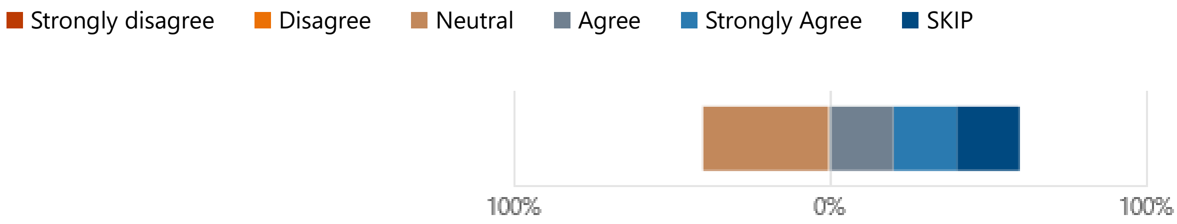
45. I fully support the move away from fossil fuels



46. If money was no object, I would choose an H2 electric or battery electric personal vehicle



47. I would recommend H2 electric vehicles to my colleagues, friends and family



48. If you have any additional remarks about your attitude and behavioural changes that occurred because of using the H2 electric RCV, please mention them below and describe your experience briefly.

0

Responses

Latest Responses

B. What, How, Why – Analysis plan

Interreg North-West Europe HECTOR
European Regional Development Fund
EUROPEAN UNION

'What', 'Why' and 'How' of collecting data for H2-garbage truck MONITORING

Version 1.0

HAN AUTOMOTIVE RESEARCH_

17 June 2020

HAN Automotive Research

1. Introduction

The HECTOR project is moving forward; the trucks are in production, and the first brand new one will be delivered soon. According to the HECTOR application, the HAN is responsible for collecting, checking and storing all project data for the technical analysis of vehicles and the assessment of societal impact.

This monitoring task of the HAN meets a critical phase: now, we need to make sure that all necessary data will be available for reporting the relevant aspects of operating their H2-garbage trucks to all partners. For which, combined efforts from all the partners, project leader and their truck suppliers are essential.

The remaining part of this document is organized as follows: first, the types of reports and the associated requirements are presented; then, which data is required to do what analysis is presented; then, how the required data can be collected, is presented, and finally, a confidentiality agreement is proposed.

2. Monitoring reports and required objects

Monitoring and analysis activities are described in WP. T3 of the HECTOR application. The results of monitoring and analysis activities will be documented and reported to the partners, facilitating a comparison between H2 and other technologies, leading to a potential Roll Out Strategy. HAN will provide the following reports:

A. Technical report – This report will address the following aspects:
    1. Operational performance of the H2-trucks;
    2. Safety incidents, and maintenance and failures;
    3. Technical specifications of the H2-trucks.
B. Socio-economic report – This report will address the following aspects:
    1. The total cost of ownership (TCO) for the H2-trucks. It will include capital investment, maintenance, downtime, and residual value;
    2. TCO comparison with other technologies;
    3. GHG emissions (CO2, NOx, PM) savings per year in comparison with other technologies;
    4. The behavioral change observed in the driver with experience.

The above two reports will be submitted at the end of the project. Additionally, HAN will provide small monthly operational reports (updates) to each of the partners customized to their points of interest. In order to provide these reports, HAN requires appropriate information, which has to be either collected and provided by partners or measured in real-time. For this, an overview is presented in Table 1:

Table 7: Overview of the required information (i.e., objects) for the reports, at which intervals they need to be provided (i.e., Regularity) and who needs to provide them (i.e., Provider)

Report	Objects	Regularity	Provider
Technical report	Operational performance	Real-time	Measured by HAN
	Safety incidents	When occurred	Relevant partner
	Maintenance (time and cost)	When occurred	Relevant partner
	Failures	When occurred	Relevant partner
	Fuelling station (downtime)	When occurred	Relevant partner link

	Technical specification	One-time after purchase	Relevant partner
Socio-economic report	Costs component-wise (capital investment, life span, residual value)	One-time after purchase	Relevant partner, literature
	Costs component-wise (other technology)	One-time	Relevant partner (past experience)
	GHG emissions (other technology)	One-time	Relevant partner (past experience)
	Driver surveys	Two-times per year	Relevant partner

3. Performance analysis and required data

One of the key performance indicator is the fuel consumption, which can be measured using two quantities: fuel used (kg) and distance travelled (km). However, with only these two signals, the fuel/energy required for waste collection and compression cannot be distinguished from fuel/energy required for driving. The following question, Q1, can be answered if the data variables presented in Table 2 are measured:

Q1: "How much is the fuel/energy consumption of waste collection and compression in comparison with driving? And how does it vary during the week (or specific period) of operation?"

Table 8: Data variables required for answering question Q1

Data variable	Unit
Distance	km
Fuel mass	kg
Loader activation signal	Boolean
Loader voltage	V
Loader current	A
Compactor activation signal	Boolean
Compactor voltage	V
Compactor current	A

Even the fuel/energy consumption due to driving depends on various factors, such as axle loads and route (length and elevation) and auxiliary units consumption. The fuel/energy consumption due to auxiliary units like wiper, head lights and dashboard are marginal and typically supplied through an on-board small (auxiliary) battery. However, fuel/energy consumption due to AC and heater are substantial, which depends on external temperature, and can account for approx. 20-40% of the total fuel/energy consumption due to driving. An effective planning and management can be done by knowing these influences. The following question Q2 can be answered, if the data variables presented in Table 3 (in addition to Table 2) are measured:

Q2: "How much do the aforementioned factors contribute to the fuel/energy consumption due to driving? And how do they vary during the week (or specific period) of operation?"

Table 9: Data variables requried for answering question Q2

Data variable	Unit
GPS longitude	DMS
GPS latitude	DMS

GPS time	UTC
Speed	km/h
Acceleration	m/s^2
External temperature	°C
Front axle load	N
Rear axle load	N
Auxiliary battery voltage	V
Auxiliary battery current	A
AC activation signal	Boolean
AC voltage	V
AC current	A
Heater activation signal	Boolean
Heater voltage	V
Heater current	A

Another key performance indicator is the tank to wheel (T2W) efficiency of H2-garbage trucks, which simply indicates how much fuel energy reaches the wheels and drives the truck. It includes the efficiencies of fuel-cell, battery, inverters and converters, electric motor and gearbox. The T2W efficiency together with the fuel consumption will provide a rather direct comparison of overall energy efficiency of H2-garbage trucks with other technologies. Additionally, whenever there are multiple energy sources, energy balancing and optimization is always of interest. Such a function is performed by a energy management system and by understanding its strategies (with respect to operation), potential scope for optimization can be determined. This insight will not only help respective partners in proposing requirements for their next set of trucks but also help their suppliers in developing optimal solutions. The following questions Q3 and Q4 can be answered, if the data variables presented in Table 4 (in addition to Table 2 and 3) are measured:

Q3: "What is the tank to wheel (T2W) efficiency of H2-garbage trucks? And how does it vary during the week (or specific period) of operation?"

Q4: "How does energy management system (EMS) affect the overall fuel/energy consumption of the H2-garbage trucks? And how can it be further optimized?"

Table 10: Data varaibles required for answering questions Q3 and Q4

Data variable	**Unit**
Fuel-cell voltage	V
Fuel-cell current	A
Fuel-cell temperature	°C
Battery voltage	V
Battery current	A
Battery temperature	°C
Battery state-of-charge (SOC)	%
Electric motor voltage	V
Electric motor current	A
Electric motor temperature	°C
Electric motor speed	rpm
Electric motor torque	Nm

It is foreseeable that with the experience, the opinions and attitudes of drivers towards H2-garbage truck will change, which will be reflected in the conducted surveys. It is also possible to quantify this changing behaviour using variables, besides their subjective opinions, to reflect upon the drivability and comfort of H2-garbage trucks. The following question Q5 can be answered, if the data variables presented in Table 5 (additional to Table 2, 3 and 4) are measured:

Q5: "How can the changing driver behaviour be quantified using measured data? And how long does it take for a driver to completely adapt his behaviour (i.e., stablized behavior) to the new technology?"

Table 11: Data varaibles required for answering questions Q5

Data variable	Unit
Steering wheel angle	°
Steering wheel torque	Nm
Throttle pedal	%
Brake	%
Lateral acceleration	m/s^2
Vertical acceleration	m/s^2
Yaw rate	°/s
Pitch rate	°/s
Roll rate	°/s

Furthermore, it is also possible to develop a H2-garbage truck model, which can be validated using the data variales presented in Table 2-5. The model could be used by the partners for their own developments, when the HECTOR project is completed.

Safety and reliability of H2-garbage trucks are an important aspect of the operation. If these aspects can be monitored then not only plausible incidents can be prevented but also appropriate and timely measures can be opted for maintenance and reliability. The following question Q6 can be answered, if the data variables presented in Table 6 are measured:

Q6: "How can the safety of H2-garbage trucks be ensured? And how can a potential failure or maintenance be predicted in advance?"

Table 12: Data variables required for answering questions Q6

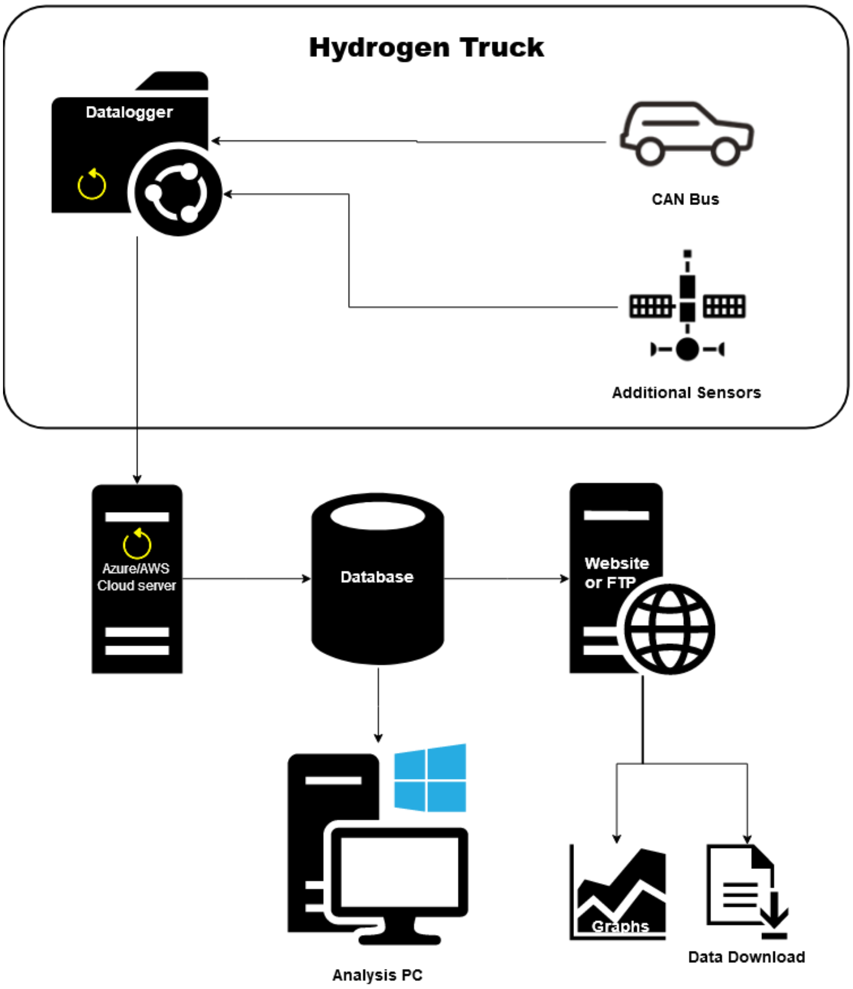
Data variable	Unit
H2 tank temperature	°C
H2 tank pressure	bar
H2 tank capacity	Kg
Fuel-cell Cell voltage (minimum voltage)	V
Fuel-cell Cell number (minimum voltage)	#
Fuel-cell Cell voltage (maximum voltage)	V
Fuel-cell Cell number (maximum voltage)	#
Battery Cell voltage (minimum voltage)	V
Battery Cell number (minimum voltage)	#
Battery Cell voltage (maximum voltage)	V
Battery Cell number (maximum voltage)	#

4. Data collection

Most truck owners work with a fleet Management system. Such system brings the most relevant data to the fleet manager for an efficient (daily) operation. For the Monitoring, according to the Interreg application for HECTOR, the fleet management system information is unfortunately insufficient since that brings up around 15% of the needed data from the truck.
This collection will happen in the truck and transferred to the cloud during operation, via 3G or 4G, or via Wi-Fi once per day when the truck is in the garage.

For collecting the data at the truck, the HAN setup a Datalogger to install in the trucks. This unit collects and transfers the data to the Database of the HAN. Although the Datalogger is equipped with some sensors, for most data a direct connection with the CAN bus is needed. All of this data is timestamped and collected into a single MQTT message (a machine-to-machine connectivity protocol).
The MQTT messages are transmitted via Wi-Fi if available. Otherwise the messages are buffered if no connection is available at all, to transfer to the HAN database later.

Below scheme shows the intended flow of data in the project.



5. Confidentiality

Sharing data is directly related to confidentiality. For this, data will be secured to avoid unauthorized used by others. Confidentiality concerns the protection of personal information as well as potentially sensitive commercial information.

Private information

The raw data the HAN collect will not be published to any third party, including the HECTOR partners, if it includes privacy related data. Before publishing, eventually, the privacy related data is made anonymous by changing it to dummy data and/or aggregate the data to such a level that the published data cannot lead to an individual. Regarding the aggregation of data, context matter; in a small company, data can be lead back to an individual. In a company with a hundred truckdrivers or more, this could not be an issue at all.

Commercial information

The HAN recognizes the potentially sensitive commercial nature of the data requested. The HAN also recognizes that the partner company will be owner of the data at all times.

For this reason, each deliverable will be defined by its level of dissemination (public, restricted or confidential). The levels of confidentiality will be agreed with the partners. This will allow maximum flexibility in ensuring that commercially sensitive data is protected. The final level of dissemination of data (PU, RE, CO) remains to be agreed by the project consortium. The decision to create any contract is up to the partner company.

Pre-requisites

The first edition of HECTOR Monitoring plan was presented in June 2019. To stress the essentiality of cooperation, please see again below the pre-requisites for the HAN Monitoring tasks.

a. All partners commit to cooperate on the development and exploring the data collection during the full project under the acceptance of changing data needs, eventually.
b. 'One-off' vehicle data (e.g., coefficient of drag) are collected from the vehicle manufacturers.
c. All runtime monitoring data to be collected from the vehicles will be made available on a CAN bus (partially) used for monitoring by the manufacturers.
d. The CAN bus monitoring data will be made available in industry standard formats J1939 and/or CANopen, or will be available in the form of raw CAN bus messages
e. Sensors are fitted by vehicle manufacturers to collect data for WP T3. Sensor data is made available on a CAN bus for monitoring this data
f. Data must be gathered for identical vehicle classes with standard diesel/gasoline/hybrid drive trains and battery electric where available. Data must be provided in an appropriate format (tbd) by the involved partners.
g. Data is regularly (weekly) uploaded by the vehicle operators to a data portal, automatically if possible.
h. Other data, such as vehicle down time and driver experience, is collected and regularly uploaded by operators to a data portal. Preferably connected to the same database where the technical data is collected.

i. 'One-off' station and infrastructure specification data are collected from the hydrogen infrastructure builders/operators.
j. Station and infrastructure performance data is regularly uploaded by the station operators to a data portal.
k. Other data, such as system down time, is collected and regularly uploaded by the station operators to a data portal.

6. Next step

This document is set up with specific focus on 'what', 'why' and 'how' data collection from the truck should happen. This process needs cooperation with all partners including their manufacturers. The HAN is available for further information and open for sharing considerations.

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C. Draft monitoring plan

Interreg North-West Europe HECTOR
EUROPEAN UNION
European Regional Development Fund

WP T3

MONITORING

DRAFT

12 June 2019

HAN AUTOMOTIVE RESEARCH

HAN_UNIVERSITY
OF APPLIED SCIENCES

HAN AUTOMOTIVE
RESEARCH_

1. Purpose

This document provides the proposed data protocols for Work Package T3 (WPT3) of the HECTOR project. It provides a template for discussion with vehicle manufacturers and vehicle owners on the data to be provided for analysis during the HECTOR project.

The document is 'live' and may be updated throughout the project as new vehicles are deployed which may have different data acquisition needs and capabilities.

The data protocols are based on those employed in other vehicle monitoring projects, such as the Cenex SmartMove electric vehicle trials and those recommended for hydrogen vehicle projects in the HyLights Monitoring and Assessment Framework.

2. WP T3 roles and responsibilities

- HAN, WP T3 leader.

Responsible for: collecting, checking and storing all project data; technical analysis of vehicle data; driver societal impact assessment; lead on project reporting.

WP T3 directly involved partners:

- Aberdeen City Council, ACC. Role: PP
- Municipality of Groningen, GRO. Role: PP
- SUEZ recycling and recovery Netherlands, SUEZ. Role: PP
- Publicly owned venture of the municipality of Duisburg, WBD. Role: PP
- ARP-GAN, ARP-GAN. Role: PP
- Touraine Vallee de l'Indre Municipalities , CCTVI. Role: PP
- AGR Waste Management Services , AGR. Role: PP

3. Pre-requisites

HECTOR Tasks for WP T3 requires that:

l. All partners commit to cooperate on the development and exploring the data collection during the full project under the acceptance of changing data needs, eventually.
m. 'One-off' vehicle data (e.g., coefficient of drag) are collected from the vehicle manufacturers.
n. All runtime monitoring data to be collected from the vehicles will be made available on a CAN bus (partially) used for monitoring by the manufacturers.
o. The CAN bus monitoring data will be made available in industry standard formats J1939 and/or CANopen, or will be available in the form of raw CAN bus messages
p. Sensors are fitted by vehicle manufacturers to collect data for WP T3. Sensor data is made available on a CAN bus for monitoring this data
q. Data must be gathered for identical vehicle classes with standard diesel/gasoline/hybrid drive trains and battery electric where available. Data must be provided in an appropriate format (tbd) by the involved partners.
r. Data is regularly (weekly) uploaded by the vehicle operators to a data portal, automatically if possible.
s. Other data, such as vehicle down time and driver experience, is collected and regularly uploaded by operators to a data portal. Preferably connected to the same database where the technical data is collected.
t. 'One-off' station and infrastructure specification data are collected from the hydrogen infrastructure builders/operators.
u. Station and infrastructure performance data is regularly uploaded by the station operators to a data portal.
v. Other data, such as system down time, is collected and regularly uploaded by the station operators to a data portal.

4. Report deliverables and confidentiality

Deliverables and levels of confidentiality associated with WP T3 will be agreed with the partners and listed in the final Monitoring plan.
The WP T3 participants recognize the potentially sensitive commercial nature of some of the data requested and will work with manufacturers and data providers to ensure that agreed levels of confidentiality is maintained, whilst ensuring that the analysis, agreed in the HECTOR project description, is still possible.
Each deliverable will be defined by its level of dissemination (public, restricted or confidential). This will allow maximum flexibility in ensuring that commercially sensitive data is protected. The final level of dissemination of data (PU, RE, CO) remains to be agreed by the project consortium.

5. Data inputs and outputs

The WP T3 description in the HECTOR Project description) details 'one-off' and on-going data to be collected, as reproduced below. These high-level data points are expanded on in the sections below, following detailed discussions with the data analysis partners

6. Data requirements for vehicles

This section details the list of data requested for WP T3, to carry out the full operational analyses of the vehicles and infrastructure and the TCO analysis of the vehicles. This list will be used in discussions with infrastructure and vehicle partners to agree on the final data protocols for WP T3.

6.1 Production phase

6.1.1 General vehicle data

Data to be provided as one electronic file per vehicle containing the following fields at the start of the vehicle deployment. The mechanism of data upload is to be agreed, but is likely to be via secure FTP or email. Data fields are described below:

6.1.1 General vehicle data		
Data	**Unit**	**Additional information (if needed)**
Completed by	Text	Name of person submitting data
Contact details	Text	Contact details (email, telephone) of person submitting data
Date	Alphanumeric	Date submitted
General		
Vehicle operator	Alphanumeric	Unique identifier for vehicle telemetry which also relates to hydrogen refuelling data
Vehicle identification number (vehicle_id)	Alphanumeric	Unique identifier for vehicle which also relates to telemetry and hydrogen refuelling data
Vehicle type	Alphanumeric	Segment of vehicle. Allowed values: A,B,C,D,E,F
Garbage operating system type	Text	eg. Crane, compression
Vehicle manufacturer	Alphanumeric	
Model and variant name	Alphanumeric	
Model year	Integer	
First time on the road as certified vehicle	Alphanumeric	

Odometer reading at project beginning	km	
Vehicle operating hours at project beginning	Integer	
Propulsion system	Text	For example, FC, FC hybrid
Propulsion system manufacturer	Text	
Gear box	Text	specs
Block scheme of main power generating and consuming components and their specs.	graphic/list	
Block scheme of main Electrical and hydraulic systems and their specs.	graphic/list	
Fuel		
Fuel	Text	For example, hydrogen
Fuel standard	Text	Needed to calculate fuel consumption and efficiency
Fuel purity requirements	Text	
Vehicle dimensions		
Length	m	
Width	m	
Height	m	
Wheel base	m	
number of drive axels		
Number of seats	Integer	
Unladen weight	kg	
Gross vehicle weight	kg	
loading capacity container weight	kg	per container
loading capacity container volume	ltrs?	per container
Static axle load front	kg	empty weight
Static axle load rear	kg	empty weight
Coefficient of drag		

6.1.2 Vehicle technical specification

Data to be provided as one electronic file per vehicle containing the following fields at the start of the vehicle deployment. The mechanism of data upload is to be agreed, but is likely to be via secure FTP or email. Data fields are described below):

6.1.2 Vehicle technical specification		
Data	**Unit**	**Additional information (if needed)**
Completed by	Text	Name of person submitting data
Contact details	Text	Contact details (email, telephone) of person submitting data
Date	Alphanumeric	Date submitted
Vehicle		

Vehicle_id	Alphanumeric	Unique identifier for vehicle which also relates to telemetry and hydrogen refuelling data
Maximum constant speed	km/h, decimal, 2 decimal places	
Acceleration (0-50km/h)	s, decimal, 2 decimal places	
Acceleration (0-100km/h)	s, decimal, 2 decimal places	
Elasticity (80-120km/h)	s, decimal, 2 decimal places	
Range	km, integer	
Drive cycle for assessing performance	?	e.g. NEDC and respective performance
Drivetrain		
Volumetric power density	l/kW, decimal, 2 decimal places	
Gravimetric power density	kg/kW, decimal, 2 decimal places	
Ambient temperature limits for vehicle operation	min (°C), max (°C), integer	
Hydrogen storage		
Hydrogen storage capacity of vehicle	kg of H_2, decimal, 2 decimal places	
Energy density of hydrogen storage system	w% and kg/l, decimal, 2 decimal places	
Fuel purity requirements	Text	

6.1.3 Vehicle materials mix for vehicle Life Cycle Analysis

All materials which are needed during the vehicle production should be quantified to guarantee a high-quality LCA. This material data should be based on the bill of materials of the vehicles. The focus of the assessment of the vehicle production phase will be on the comparison of drive trains. Special attention for rare/expensive metals like lithium, cobalt, platinum, etc. Therefore it is important to have a detailed database of fuel cell drive trains used in HECTOR and the alternative standard ICE drive trains. Data will be treated with strict confidentiality and should be provided as one electronic file per vehicle type containing the following fields at the start of the vehicle deployment. The mechanism of data upload is to be agreed, but is likely to be via secure FTP or email. Data fields are described below:

6.1.3 Vehicle materials mix for vehicle Life Cycle Analysis		
Data	**Unit**	**Additional information (if needed)**

Simplified bill of materials of vehicle production according to function groups	kg	Platform, tyres, power train, interior, body, etc.
Material mix of the different function groups		Separate into steel, aluminium, PA, PP, PE, PU etc.
Assembly and production processes		Statement on relevant production processes

6.1.4 Vehicle emissions of ICE drive trains for vehicle Life Cycle Analysis
Emission profiles (of the conventional drive trains) are necessary for the comparison of the environmental impacts of fuel cell drive trains with standard diesel/gasoline/hybrid drive trains. All emission profiles must be based on representative drive cycles or drive patterns (e.g. NEDC), which can be compared with drive patterns of the fuel cell vehicles in HECTOR. Data should be provided as one electronic file per vehicle type containing the following fields at the start of the vehicle deployment. The mechanism of data upload is to be agreed, but is likely to be via secure FTP or email. Data fields are described below:

6.1.4 Vehicle emissions of ICE drive trains for vehicle Life Cycle Analysis		
Data	**Unit**	**Additional information (if needed)**
Gasoline/diesel	l/km	Fuel consumption over the representative drive cycle
CO	g/km	Based on representative drive cycle/pattern
HC (CH4, NMHC, benzene, toluene, xylene)	g/km	Based on representative drive cycle/pattern
CO2	g/km	Based on representative drive cycle/pattern
NH3	g/km	Based on representative drive cycle/pattern
N2O	g/km	Based on representative drive cycle/pattern
NO	g/km	Based on representative drive cycle/pattern
NO2	g/km	Based on representative drive cycle/pattern
PN	g/km	Based on representative drive cycle/pattern
PM	g/km	Based on representative drive cycle/pattern

6.1.5 Vehicle lifetime and cost data for Life Cycle Cost analysis
A task of the HECTOR project will produce a life cycle cost analysis of the vehicles deployed in the project, as well looking at the cost trajectory for these vehicles as they move towards commercialization.
As part of this, it is important that we understand the capital and operating costs of the vehicles through time. An ideal cost breakdown for the vehicles is illustrated below. However, we recognize the sensitive commercial nature of some of the cost data requested and will work with manufacturers to ensure that confidentiality is maintained, whilst ensuring that the analysis is still possible.

Data to be provided as one electronic file per vehicle type containing the following fields at the start of the vehicle deployment. The mechanism of data upload is to be agreed, but is likely to be via secure FTP or email. Data fields are described below:

6.1.5 Vehicle lifetime and cost data for Life Cycle Cost analysis		
Data	**Unit**	**Additional information (if needed)**
General		
Completed by	Text	Name of person submitting data
Contact details	Text	Contact details (email, telephone) of person submitting data
Date	Alphanumeric	Date submitted
Vehicle type	Alphanumeric	Type of vehicle within the HECTOR project
Vehicle hydrogen capacity	Kg	
Range of vehicle	Km	Range on standard drive cycle
Fuel consumption	gH_2/km	
CO_2 emissions	g/km	For societal impact costs
Capital cost data for hydrogen vehicles		
Cost of chassis, body and standard interior components	Euros of capital cost	Values provided for 2012-2014, 2015-2017, 2018-2020, 2021-2023, 2024-2026, 2027-2029
Fuel cell system costs (including cooling system)	Euros of capital cost	Values provided for 2012-2014, 2015-2017, 2018-2020, 2021-2023, 2024-2026, 2027-2029Size of fuel cell in kW required, cost per kW where possible
Stack warranty cost	Euros of capital cost	Values provided for 2012-2014, 2015-2017, 2018-2020, 2021-2023, 2024-2026, 2027-2029
Stack replacement cost	% of fuel cell system costs	Values provided for 2012-2014, 2015-2017, 2018-2020, 2021-2023, 2024-2026, 2027-2029
Energy storage system cost	Euros of capital cost	Values provided for 2012-2014, 2015-2017, 2018-2020, 2021-2023, 2024-2026, 2027-2029 Size of energy storage system in kWh required, cost per kWh where possible
Hydrogen storage system cost	Euros of capital cost	Values provided for 2012-2014, 2015-2017, 2018-2020, 2021-2023, 2024-2026, 2027-2029
Power electronics and electric motor costs	Euros of capital cost	Values provided for 2012-2014, 2015-2017, 2018-2020, 2021-2023, 2024-2026, 2027-2029
Cost of labour for drivetrain integration	Euros of labour cost per vehicle over	Values provided for 2012-2014, 2015-2017, 2018-2020, 2021-2023, 2024-2026, 2027-2029

	and above standard drivetrain costs	
NRE costs	Euros of capital cost	Cost of developing commercial-ready version of vehicles
Capital cost data for conventional fuel incumbents		
Cost of chassis, body and standard interior components	Euros of capital cost	Values provided for 2012-2014, 2015-2017, 2018-2020, 2021-2023, 2024-2026, 2027-2029
Standard drivetrain costs	Euros of capital cost	Values provided for 2012-2014, 2015-2017, 2018-2020, 2021-2023, 2024-2026, 2027-2029
Lifetime data		
Standard vehicle lifetime	Thousands of hours operation	Values provided for 2012-2014, 2015-2017, 2018-2020, 2021-2023, 2024-2026, 2027-2029
Stack lifetime	Thousands of hours operation	Values provided for 2012-2014, 2015-2017, 2018-2020, 2021-2023, 2024-2026, 2027-2029
Fuel cell system lifetime	Thousands of hours operation	Values provided for 2012-2014, 2015-2017, 2018-2020, 2021-2023, 2024-2026, 2027-2029

6.2 Monitoring phase

6.2.1 Vehicle telemetry data

Data to be provided in Format (to be determined) and certain Speed (to be determined) containing the following fields. Data will be treated with strict confidentiality. In the case of positional (latitude/longitude/height) information which is important to fully characterize vehicle duty cycles data will only be recorded and analysed with the vehicle operator's consent. Data to be uploaded at least monthly. The mechanism of data upload is to be agreed, but is likely to be via secure FTP. Data fields are described below:

6.2.1 Vehicle telemetry data				
Measurement group	**Imported Signal**	**Units**	**Rate [Hz]**	**Explanation**
GPS	latitude	°	1	GPS latitude in XX.xxxx°
	longitude	°	1	GPS longitude in XX.xxxx°
	height	m	1	GPS height, seems incorrect compared to other sources
	speed	km/h	1	GPS speed. Smoother than attitude speed signal. Both match pretty closely

	numSatellites	#	1	Number of satellites the GPS unit is connected to
	time	usec	5	GPS time should theoretically be more accurate that the system clock
	quality	-	1	Rating calculated by GPS unit - can just indication lock type GPS/GALILEO / GPS/DGPS/RTKGPS
	course	°	1	Heading of vehicle
	HDOP	-	1	Horizontal dilution of precision - GPS system should provide this
Vehicle	latitude	g	5	Lateral acceleration
	longitude	g	5	Longitudinal acceleration
	vertical	g	5	For completeness
	yaw	°/s	5	Rate of vehicle yaw
	pitch	°/s	5	Vehicle incline
	roll	°/s	5	Vehicle dynamics are interesting!
	speed	km/h	5	Vehicle speed
	distance	km	1	Calculated measure
	rearAxleLoad	kg	1	Very useful for eliminating/identifying influence of load on efficiency
	frontAxleLoad	kg	1	See above, to a lesser extent
	externalTemp	°C	1	Air temperature outside the vehicle
Fuel Cell.	totalCurrent	V	5	Output current of the Fuel Cell
	totalVoltage	V	5	Output voltage of the Fuel Cell
	minChangeV	V	1	The lowest of all cell voltages from the Fuel Cell
	maxChangeV	V	1	The highest of all cell voltages from the Fuel Cell
	minVchangeNum	#	1	The cell number which has lowest voltage
	maxVchangeNum	#	1	The cell number which has highest voltage
Stack.	inletAirTemp	°C	1	Air temp at inlet to stack
	exhaustAirTemp	°C	1	Air temp at exhaust of stack
	inputCoolantTemp	°C	1	Coolant temperature at inlet to fuel cell
	outputCoolantTemp	°C	1	Coolant temperature at outlet to fuel cell
	inputCoolantPressure	kPa	1	Coolant pressure at inlet to fuel cell
	coolantPumpRPM	rpm	1	RPM of the coolant pump
	inputHydrogenPressure	kPa	1	Pressure of H2 at stack inlet
	outputHydrogenPressure	kPa	1	Pressure of excess H2 at stack outlet
	anodeBlower	rpm	1	RPM of the pump for anode H2 supply
	MAP	kPa	1	Manifold Absolute Pressure
	intakeAirTemp	°C	1	Temperature of airflow into the fuelcell
	airFlow	kg/h	1	Airflow into the fuel cell
	compressorPower	W	1	Power use of air compressor
Hydrogen.	tankTemp	°C	1	Temperature in H2 tank 1
	numRefuelTank	#	1	Number of times vehicle refueled

	tankPressure	kPa	1	Pressure in H2 tank
	storageLevel	%	1	Fuel storage level in %
	fuelMass	kg	1	Fuel storage level in KG [Calculated]
	flowOut	g/s?	1	Don't know the cost of a CAN gas flow meter, or if it exists?
Inputs.	steeringAngle	°	5	Angle of steering wheel
	brakePedal	mm	5	Distance brake pedal is pressed
	throttlePedal	%	5	Amount of throttle command
	shiftMode	enum	1	Any drive mode that's selectable Like economy mode)
	shiftLever	enum	1	P/R/N/D
	statusAC	0/1	1	Active when status is on
	ignitionState	0/1	1	Active when ignition is on
	wiperPower	W	1	Power use of windscreen wiper motors
	lightsPower	W	1	Power use of lights/headlights/working lights
	emergencySwitch	0/1	1	Activation of emergency stop button
	controlType	enum	1	Driver/ADAS control of vehicle
Motor.	rotorSpeed	rpm	5	Rpm of the motor
	torqueCommand	Nm	5	Motor torque in Nm
	torqueReference	%	5	Motor torque in %
	motorTemp	°C	1	Temperature of drive motor
	inverterTemp	°C	1	Temperature of drive motor inverter
	motorVoltage	V	5	Voltage use of the drive motor/s
	motorCurrent	A	5	Current use of the drive motor/s
Power.	currentBattDC	A	1	Output current of the drive battery
	voltageBattDC	V	1	Output voltage of the drive battery
	minChangeV	V	1	The lowest of all cell voltages from the drive battery
	maxChangeV	V	1	The highest of all cell voltages from the drive battery
	minVchangeNum	#	1	The cell number which has lowest voltage
	maxVchangeNum	#	1	The cell number which has highest voltage
	stateOfCharge	%	1	State of charge of drive battery
	auxBattVoltage	V	1	Voltage of the "12 volt" battery
	accumDischargeCurrent	Ah	1	Drive battery discharge current
	accumDischargePower	kWh	1	Drive battery discharge power
	accumOpTime	s	1	Drive battery operation time
	accumChargeCurrent	A	1	Drive battery charge current
	accumChargePower	W	1	Drive battery charge power
Loader.	activation	0/1	1	Activation of garbage collector
	voltageUse	V	1	Voltage use of the loading system
	currentUse	A	1	Current use of the loading system (incl. hydraulic pump etc.)

	extension	m? %?	1	How far the pickup arm? Has been extended
Compactor	activation	0/1	1	Activation of garbage compactor
	voltageUse	V	1	Voltage use of the compactor system
	currentUse	A	1	Current use of the compactor system (incl. hydraulic pump etc.)
	extension	m	1	How far the compacting arm? Has been extended
Processed data structure		**Information**		

6.2.2 Vehicle incident/availability data

Data to be provided as Excel or CSV (comma-separated value) file with one row of data per vehicle scheduled/unscheduled event, or safety incident. The mechanism of data upload is to be agreed, but is likely to be via secure FTP. Data fields are described below:

6.2.2 Vehicle incident/availability data		
Data	**Unit**	**Additional information (if needed)**
Vehicle_id	Alphanumeric	Unique identifier for vehicle which also relates to telemetry and hydrogen refueling data
Driver_id		
Time_out	DD/MM/YY HH:Mi:SS	Time taken out of operation
Odometer_out of operation	Km	Odometer reading when taken out of operation
Time_in	DD/MM/YY HH:Mi:SS	
Odometer_in	Km	Odometer reading when back in operation
Event		
Event_code	Alphanumeric	Allowed values: 0: scheduled maintenance A: stack B: balance of plant C: electrical system D: H_2 storage E: high-voltage battery F: other technical failures (describe in text Event_comment)
Event_comment	Text	Free text comment.
repair_labour		costs
repair_parts		costs
Safety incident		
Safety_code	Decimal	If needed for a safety incident. Allowed values: 0: not a safety incident 1: vehicle incident with injury. H_2 released 2: vehicle incident with injury. No H_2 released 3: vehicle incident without injury. H_2 released 4: vehicle incident without injury. No H_2

		released 5: other (see text field below)
Safety_comment	Text	Free text comment if safety incident occurred

6.2.3 Other data required from environment and local society
Data to collect from internet sources and local society

6.2.3 Other data required from environment and local society		
Data	**Unit**	**Additional information (if needed)**
Weather conditions		
Time	DD/MM/YY HH:Mi:SS	
Temp_outside	C	
Wind	m/s	
rain	mm	
road conditions		
track conditions		flat, slopes,..
pavement		
local effects society		
health		
sound		
smell		
social impact		
public support		
branding/image waste collecting service		

6.2.4 Vehicle operating cost data for Life Cycle Cost analysis
A task of the HECTOR project will produce a life cycle cost analysis of the vehicles deployed in the project, as well looking at the cost trajectory for these vehicles as they move towards commercialisation.
As part of this, it is important that we understand the operating costs of the vehicles. We recognise the sensitive commercial nature of some of the cost data requested and will work with manufacturers to ensure that confidentiality is maintained, whilst ensuring that the analysis is still possible.
Data should be provided as one electronic file per vehicle type containing the following fields at a frequency to be agreed. The mechanism of data upload is to be agreed, but is likely to be via secure FTP or email. Data fields are described below:

6.2.4 Vehicle operating cost data for Life Cycle Cost analysis		
Data	**Unit**	**Additional information (if needed)**
Cost of hydrogen	Euros per Kg	
Maintenance costs	Euros/hour of operation	Additional cost over maintenance of standard vehicle, not including stack replacement costs

Costs of alterations to maintenance facilities	Euros of capital cost	

Data requirements for infrastructure

7.1 Production/installation phase

7.1.1 General hydrogen refuelling station data

Data to be provided as one electronic file per station containing the following fields on completion of station commissioning. The mechanism of data upload is to be agreed, but is likely to be via secure FTP or email. Data fields are described below:

7.1.1 General hydrogen refuelling station data		
Data	**Unit**	**Additional information (if needed)**
Completed by	Text	Name of person submitting data
Contact details	Text	Contact details (email, telephone) of person submitting data
Date	Alphanumeric	Date submitted
General		
Fuelling station operator	Alphanumeric	
Fuelling station location	Text	
Station_id	Alphanumeric	
Date of first operation	Integer	
Fuelling station details		
Total number of hydrogen dispensing units	Integer	
Total number of hydrogen refueling nozzles	Integer	
Dispensing capacity	kg/day, decimal, 2 decimal places	
Station footprint	m^2	
Type of station (hydrogen only or mixed)	Text	
Accessibility		
Refuelling operation	Alphanumeric	Allowed values: self-service/assisted/operator only
Public access/restricted use	Alphanumeric	Allowed values: public (by appointment)/restricted access
Opening hours	Alphanumeric	Daily/weekly opening hours
Station components		
Hydrogen station supplier	Text	
Hydrogen storage type on site	Text	Allowed values: CH2/LH2/both
Hydrogen manufacture	Text	Allowed values: onsite/offsite
On-site hydrogen storage capacity	kg H2, integer	

7.2 Monitoring phase

7.2.1 Hydrogen refuelling facility data

Data to be provided as Excel or CSV (comma-separated value) file with one row of data per vehicle fill or scheduled/unscheduled event as described in the acquisition frequency column below. The mechanism of data upload is to be agreed, but is likely to be via secure FTP. Data fields are described below:

7.2.1 Hydrogen refuelling facility data			
Data	**Unit**	**Acquisition frequency**	**Additional information (if needed)**
Station_id	Alphanumeric		Unique identifier for the hydrogen station unit
Station_address			
Vehicle_id	Alphanumeric		Unique identifier for vehicle. Fuelcardid is acceptable provided a unique fuel card is assigned to each vehicle
Date	DD/MM/YY HH:Mi		Date and time of vehicle fill
Filling_pressure	Bar		
Vehicle_pressure_start	Bar	For each filling	Needed for calculations of energy and efficiency
Vehicle_pressure_end	Bar	For each filling	Needed for calculations of energy and efficiency
Hydrogen_mass_transferrred	kg	For each filling	Needed for calculations of energy and efficiency
Filling_duration	HH:MM:SS	For each filling steps of 15 seconds	Needed for calculations of energy and efficiency
Total_hydrogen_transferred	kg	Daily total	For closing the mass balance
Electricity_consumed	kWh	Daily	Consumption of the station unit only
Downtime_hours	Hours	Daily	
Downtime_reason	Integer		Station unit downtime category codes. Allowed values are: 0. Failure – Hydrogen storage 1. Failure - Hydrogen compressors. 2. Failure – Dispensing equipment 3. Failure - Control or electronics. 4. Failure - Alarms, H2 leaks, safety devices 5. Failure – Production Unit 6. Failure – external H2 delivery 7. Safety issues 8. External reasons (e.g. power outage). 9. Other.