RESEARCH REPORT

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Operation of a Snow-Plough-Sweeper-Blower

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beyond the obvious

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Summary

The scope of this project is to perform a feasibility study on use of hydrogen in heavy airport snow equipment. The project describes the baseline on current technology and operational use of existing snow-plough-sweeper-blowers (PSBs) in order to form the basis for the piloting of similar equipment with a hydrogen engine.

From a technical perspective, when considering only the winter operation, Øveraasen seems to be the most capable machine for snow-clearing as it has the highest sweeping capacity by a large margin. If versatility is the key requirement, then Boschung would be the correct choice since it can be equipped with several additional devices for runway maintenance. All in all, the cost of the machine would determine in the end what would be the optimum solution for different airports and unfortunately the purchase price was not available for any of the machines.

The analysis of current use of PSBs shows how on challenging days the PSBs are used almost around the clock. On such days, the daily driven distances can reach almost 400 km. Of course, this also means that fuel consumption is high. The average daily consumption was 3.7 GJ for propulsion and 7.7 GJ for auxiliary engine. Correspondingly, the maximum values were 15.4 GJ and 37.4 GJ. Regarding the coming pilot PSB with a hydrogen-powered auxiliary engine, the average daily energy consumption of 7.7 GJ would correspond with approximately 64 kg of hydrogen, while the maximum consumption of 37.4 GJ would correspond with approximately 312 kg of hydrogen.

Regarding the KPIs for the pilot PSB the writers of this report would like to stress the importance of practicality, reliability and their relation to working efficiency and energy consumption. Reliable operation of a work machine is paramount as unscheduled but unavoidable maintenance breaks can easily disturb the operation of a whole team of machines. Energy consumption of a PSB on the other hand varies greatly depending on the weather conditions and the hardest working days of the winter season are sure to exceed the energy storage capacity of the pilot PSB's hydrogen tanks.

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Preface

The authors would like to acknowledge the assistance of Finavia personnel during the research work of the project. Without their professional assistance this research project would not have been successful.

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Contents

1. Introduction

As the Baltic Sea Region airports aim to facilitate the early adoption of gaseous hydrogen-powered aircraft there is a unique opportunity to expand the use of gaseous hydrogen at the airports to other airport equipment as well. Challenges to be addressed include determining the feasibility of such gaseous hydrogen powered equipment, as well as their development and testing along with procedures for refuelling and handling.

The scope of this project is to perform a feasibility study on use of hydrogen in heavy airport snow equipment. The project describes the baseline on current technology and operational use of existing snow-plough-sweeper-blowers (PSBs) in order to form the basis for the piloting of similar equipment with a hydrogen engine.

1.1 Introduction to snow-plough-sweeper-blowers

A PSB (Figure 1) is a heavy snow-removal work machine used at airports to clear snow off runways. As its name states, it has three main components, which are used to clear snow to the side of the machine: at the machine’s front there is a plough (Figure 2) that pushes the snow; at the machine’s mid there is a rotating broom (Figure 3) that sweeps the snow remaining after the plough; and at the machine’s rear there is a blower and air channels (Figure 4) that blows the final remaining snow. All of the components can be controlled from the driver’s cabin to adjust their function and to control to which side the cleared snow is directed.

Figure 1. A PSB without the plough (broom and blower arm not deployed)

Figure 2. A PSB's snow plough

Figure 3. A PSB's broom (not deployed)

Figure 4. A PSB's blower (blower arm not deployed)

PSBs can be used at airports to clear runways, taxiways, and the apron. When clearing runways, they are normally employed in large formations of up to ten machines formed up in a flying wedge to clear the whole runway in a single pass. As the lead machines at the front of the wedge push the snow from their way to the side, the next machine needs to push both the lead machine’s snow and the snow in their own way to the side and so on, ultimately leading to the last machine pushing the snows off five PSBs. Thus the load on the machines is not equal and is directly related to the machine’s position in the formation.

To see the PSBs in action the reader is directed to a video on Youtube by Helsinki Airport: https://youtu.be/xk1vwyQAC8k?si=0nNewLz5vc2Hmc2J

2. Goal

The project had two tasks:

Task 1 compares PSBs from different manufacturers in terms of technical specifications and cost of ownership. The aim is to present information on differences in technical features, investment costs and common operational costs, and how the technical features of the different machines impact operation. It produces an illustrative comparison of PSBs from different manufacturers. Comparison includes main technical features of different PSBs and the differences in investment and operational costs of the machines. Level of detail of the comparison is limited due to the available information from the manufacturers.

Task 2 describes the operative work cycles, power output and the fuel consumption of the machines in operative work during a period of one winter. Special attention was paid to variation in the operative use of PSBs and the variation in fuel consumption (due to changes in snow conditions). It produces an overview of operative use of PSBs at Helsinki-Vantaa with use profile (hours, distances, power profiles), metered fuel consumption, deduced energy consumption and other parameters of engines, variation in operations, re-fuelling cycle in different operating conditions, and re-fuelling duration.

This report will provide key performance indicators (KPIs) taking into consideration both the technical and operative issues during the upcoming piloting phase of the project. Suggested KPIs aim to point out the key factors affecting the piloting in regard to successful operation of the hydrogen-powered PSB.

3. Task 1: Comparison of different PSBs

Four different manufacturers were selected for the comparison of airport runway surface maintenance machines. Since Vammas is currently the main supplier for runway snow-removal machine at Helsinki-Vantaa airport, its model PSB5500 was used a reference for the comparison as the operation of that machine is well known. Thus, PSB5500 was stated as a reference product for other manufacturers and manufacturers were requested to provide the relevant information from a machine with similar functionality than Vammas PSB5500. Manufacturers selected for the comparison are Vammas, Boschung, Aebi Schmidt and Øveraasen. A list of questions was sent to all manufacturers to collect the needed information but since there are only a handful of companies manufacturing this type of machines and competition in this industry segment is close, two manufacturers did not want to disclose any other information than what is publicly available on their website. Therefore, in the following chapters the specifications for machines manufactured by Øveraasen and Aebi Schmidt are missing information compared to Vammas and Boschung.

3.1 Main features and dimensions

Below is group of pictures which present the appearance of each machine: Vammas PSB 5500 on top left, Aebi Schmidt CJS-DI on top right, Øveraasen RS 600 on bottom left and Boschung Jetbroom 10000 on bottom right. As one can see, the machine manufactured by Vammas is the only one not based on a heavy-duty truck platform. Boschung's and Aebi's machines are categorised as compact PSBs since both machines are based on a custom built heavy-duty truck chassis, and thus the length of the machines corresponds to regular HD trucks.

Figure 5. PSBs selected for comparison.

First, the functionality of the machines is compared against each other. In Table 1 is shown functions which each machine can perform both in winter and in summer. All the machines perform the same basic functions during winter (ploughing, sweeping and blowing) but in addition to those, Aebi and Boschung machines can be equipped with optional sprayer or spreader for de-icing the runway simultaneously while removing snow. Boschung even provides an option to use a suction device instead of sprayer or spreader to remove excess of glycol around the aircrafts after de-icing procedure. This makes them both versatile machines and their use could potentially reduce the size of the fleet operating on airport surface maintenance thus lowering the total investment costs.

In the summer, all machines can use the broom and blower to remove water from the runway surface. In addition to sweeping and blowing, Boschung's machine can be equipped with multiple other tools such as magnetic bar to remove magnetic debris, suction device to vacuum all kinds of debris and simultaneously wash the runway or apron surfaces with a high-pressure washer. In terms of functionality, Boschung Jetbroom 10000 is clearly the most versatile machine, but all of the optional functions come with an extra cost.

Table 1. Main features of different PSBs

Manufacturer **Model**		**Vammas** **PSB 5500-4**	**Aebi Schmidt** **CJS-DI**	**Øveraasen** **RS 600**	**Boschung** **Jetbroom 10000**
Winter	Ploughing	x	x	x	x
	Sweeping	x	x	x	x
	Blowing	x	x	x	x
	Sprayer	-	o	-	o
	Spreader	-	o	-	o
	Vacuum	-	-	-	o
Summer	Sweeping	x	x	X	x
	Blowing	x	x	X	x
	Vacuum	-	-	-	o
	Magnetic bar	-	-	-	o
	High-pressure washer	-	-	-	o

”x” = function available
”o” = function optional
”-” = function not available

In Table 2 is presented the main dimensions and masses of the different machines. Here the working position corresponds to situation where the machine is equipped with a snowplough and the plough is positioned in a nominal working angle, usually between 30-35 degrees. As seen in the table, two machines stand out in length as already mentioned earlier in the report. Since Aebi Schmidt's and Boschung's chassis are directly based on commercially available HD trucks they are the shortest machines of the group. Usually longer vehicles have larger turning radius and since Vammas' and Øveraasen's machines are significantly longer than the other two, one could expect them to be inferior in agility. However, due to the steering solutions in Vammas and Øveraasen. they have only 1 – 1.5 meter larger turning radius. Vammas has a steering axle in the front and articulated steering at the back which leads to decreased turning radius. Since Øveraasen has basically a regular HD truck towing the sweeping/blowing unit, it has a steering axle in the front and the rear unit attaches to the tow vehicle with a fifth-wheel. This makes the combination almost as agile as the two compact PSBs. Surprisingly, despite Boschung's machine being the shortest one of the group and having a four-wheel steering system to enhance manoeuvrability, it does not have the smallest turning radius. This is due to it being the only machine with a four-wheel drive and this in turn increases the turning radius as the maximum rotation angle of front wheels is limited due to the drive-shafts.

Table 2. Basic dimensions and masses

Manufacturer	**Vammas**	**Aebi Schmidt**	**Øveraasen**	**Boschung**
Length in working position [m]	21,1	14	23	12,9
Width in working position [m]	7,5	4,75	8,1	7,12
Transport width [m]	2,6	NA	3,9	5,7
Height [m]	3,7	3,7	4	3,76
Broom diameter [mm]	1170	914	1170	1170
Wheelbase [m]	10,5	NA	NA	6,85
Turning radius [m]	10,6	9	9,75	9,48
Axle masses [t]	10,3/11,15/11,15	NA	NA	14/14/7
Total mass [t]	32,6	28	30	35

Looking at the working position widths in Table 2, Aebi Schmidt stands out as significantly narrower machine as the other three. This is due to narrower plough and broom which will be discussed further in the following chapters. The other three machines have quite similar widths in working position, but the transport widths vary greatly between the machines. Transport width is the width of the machine when plough is removed. Unfortunately, there is no information regarding the transport width for Aebi Schmidt but since both Boschung and Aebi Schmidt machines are both compact in nature, and for Boschung the transport width equals the working width of the broom, one could expect the same applies to Aebi Schmidt. Figure 6 illustrates the limited space under the body which inhibits swivelling the broom underneath the machine.

Figure 6. Limited space for broom in Aebi Schmidt (left picture) and Boschung

Vammas is the narrowest machine when it comes to non-operational transport of the machine. This is due to the length of the machine since the broom can be swivelled directly under the body (Figure 3) when not in use. Similarly, the broom in Øveraasen's machine can be positioned directly under the body but as can be seen in Figure 7, extra space is needed for the blower nozzles when they are not deployed. This increases the transport width by 1.3 metres compared to Vammas.

Figure 7. Øveraasen RS 600 with blower nozzles pulled to the sides.

3.2 PSB operation

Table 3 presents some of the key parameters affecting the efficiency of the machines. Except Øveraasen all the other machines can work at 60km/h speed when removing snow from the runway. Øveraasen has maximum speed of up to 65km/h which makes it the fastest machine of the group. Snow clearing width describes how wide area the plough and broom can clear in one pass. Here as well Øveraasen has the largest working area since both the ploughing and sweeping widths are the widest. Sweeping width is the most important parameter here as it determines how wide area is cleared to the tarmac from snow.

Table 3. Operational parameters

Manufacturer	**Vammas**	**Aebi Schmidt**	**Øveraasen**	**Boschung**
Maximum working speed [km/h]	60	60	65	60
Maximum structural speed [km/h]	80	80	80	80
Snow clearing width [m]				
plough	6,7	4,75	8,1	7,12
broom	5,5	3,56	7,5	5,7
Max sweeping capacity [m^2/h]	330000	213600	487500	342000
Blower fan capacity [m^3/h]	39600	NA	60000	50400
Maximum rated snow load				
Thickness of snow [m]	0,02	NA	NA	0,15
Density of snow [kg/m^3]	500	NA	NA	400
Drive speed @ max load [km/h]	37	NA	NA	40
Noise level [dB]				
In-cabin	75	NA	NA	85
External	105	NA	NA	118

Regarding sweeping width, Øveraasen has a two-meter advantage over Vammas and almost the same advantage over Boschung. Combining the sweeping width and maximum working speed of the machine, maximum sweeping capacity can be calculated. As Øveraasen has both higher maximum speed and wider sweeping area, the sweeping capacity is 40 to 50 percent higher compared to Vammas and Boschung. This means that the number of machines operating on the runway could be drastically decreased. To clear a 45-meter-wide runway it would require minimum of 9 PSBs from Vammas, 8 from Boschung but only 6 machines from Øveraasen. Since Aebi Schmidt has so narrow clearing width it would require 13 of their machines to perform the task.

Looking at the blower fan capacity, Øveraasen has the highest capacity followed by Boschung and then Vammas. It is assumed that the difference between Vammas and Øveraasen is caused by the larger snow clearance width as the blower needs to cover a larger area when operating with Øveraasen. The need for larger fan capacity in Boschung's machine can be explained due to different blowing nozzle arrangement. While Boschung has nozzles on both front and rear side of the broom, the other machines have nozzles only behind the broom. The main purpose of the blower is to remove the remaining loose snow from the surface after the plough and broom. However, Boschung is using the nozzles in front of the broom to propel swept snow to the side so that the angle of the broom does not need to be that aggressive. By doing this the clearance width of the broom is increased as illustrated in Figure 8.

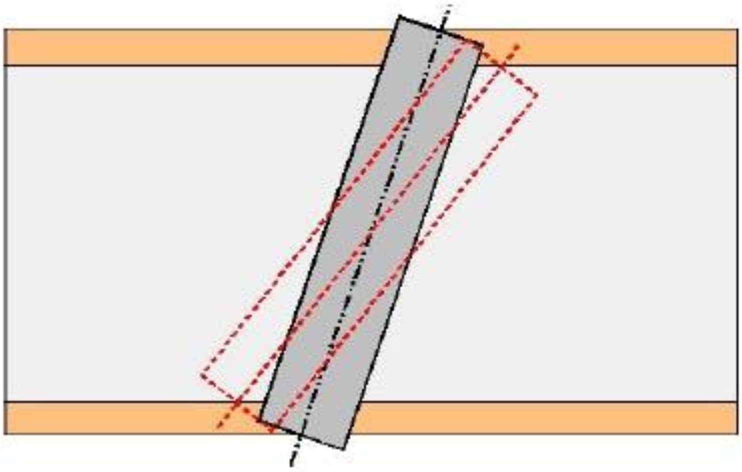

Figure 8. Reduced broom angle due to blower nozzle in front of the broom.

Only two of the manufactures, Vammas and Boschung, shared information regarding the maximum snow load under operation. Boschung seems a lot more capable than Vammas since it can plough significantly higher snow load and even at slightly higher speed. Since the difference is so large and the available engine power is similar between the two machines, it raises a question whether the manufacturers define the maximum load in same manner. For example, is the higher maximum load with Boschung defined as instantaneous load for short bursts or can the machine sustain that load for the length of the whole runway. Although, Boshung does have four-wheel drive in their machine so there is larger traction force which could then increase the maximum capacity.

In operator's perspective, it is vital to compare the noise levels of the machines as there are multiple elements producing loud sound. Noise levels were available only for Vammas and Boschung. The in-cabin noise of Boschung machine is significantly higher compared to Vammas which is believed to be caused by different layout of the machines. Vammas has a separate cabin away from the drive and auxiliary engines and all the auxiliary devices powering the broom and blower unit. In Boschung's machine the chassis is relatively short compared to Vammas, and especially the turbine for the blower is directly behind the cabin which increases the sound level in the cabin. In addition, since the fan capacity is higher for Boschung and there are more blowing nozzles in Boshung's machine, it is assumed that they produce higher overall sound level and thus both in-cabin and external noise levels are higher.

3.3 Engine performance and fuel economy

All of the machines have two separate engines: one is used for propulsion while the other one drives the auxiliary systems needed for producing the air flow and rotating the broom. In Table 4 is presented basic information of the powertrain for each machine. Some of the machines have the same manufacturer for both drive and auxiliary engine while others combine engines from different manufacturers. Naturally, for Aebi Schmidt, Øveraasen and Boschung the drive engine is from the same manufacturer as the truck chassis used. The least powerful machine is Aebi Schmidt which can be expected as it has significantly smaller snow clearance width and thus the need for power is lower. Following similar trend, the most powerful machine is Øveraasen since it has the largest snow clearance width by a large margin. However, Boschung's machine is equipped with smaller engines than Vammas' even though it has slightly greater snow clearance width and significantly higher blower fan capacity. Possible reasons for this could be that either Vammas has configured the machine conservatively with additional power reserve or Boschung is using more efficient auxiliary components for blower and sweeper. Either way, Boschung seems to be capable of performing the same task with less engine power.

Table 4. PSB powertrain information.

Manufacturer	Vammas	Aebi Schmidt	Øveraasen	Boschung
Engine manufacturers (drive/auxiliary)	Volvo Penta/ Volvo Penta	MAN/ Mercedes Benz	Mercedes Benz/ Volvo Penta	Mercedes Benz/ Mercedes Benz
Drive engine [kW]	345	235	390	330
Auxiliary engine [kW]	345	260	405	330
Fuel tank volume [l]	1160	600	1550	1000
Transmission type	Automatic	NA	Automatic	Automatic
Alternative fuels	HVO	NA	HVO	HVO

The size of the fuel tank is following same trend as maximum engine power, naturally. A simplified investigation of the machine efficiency can be performed by assuming that when the machine is working at the maximum working speed, both drive and auxiliary engines are operating at the maximum power. This is not necessary the case since it depends for example on snow load but gives a good estimation how the machines perform compared to each other. More accurate comparisons would require operational data from all of the machines and this kind of data is not available. Fuel consumption is assumed to be 200 g/kWh which is a suitable assumption for full load operation since typically the consumption varies between 190 to 200 g/kWh on full power. Naturally, the different engines here can vary in fuel efficiency but since that data was not available, a single value was used for all engines. Based on the full load power in Table 4 and using density of 0.832 kg/l for diesel, estimated maximum fuel consumption can be seen on first row in Table 5. The maximum fuel consumption if combined consumption for both drive and auxiliary engine and, as expected, highest power results in highest consumption per hour. That said, Øveraasen has the highest overall consumption but also the highest snow clearing capacity.

Table 5. Estimated maximum fuel consumption.

Manufacturer	Vammas	Aebi Schmidt	Øveraasen	Boschung
Maximum fuel consumption [l/h]	166	119	191	159
Refuelling interval @ max power [h]	7,0	5,0	8,1	6,3
Sweeping area per fuel litre [m^2]	1990	1795	2551	2156

Connecting the estimated maximum consumption with fuel tank volume, it is seen that despite Øveraasen having the highest consumption, it still has the longest refuelling interval. At maximum power, refuelling would be needed every 8 hours followed by Vammas with a 7-hour refuelling interval. More interestingly, using the maximum sweeping capacity together with the estimated fuel consumption, fuel consumption per sweeping area can be calculated. Looking at the bottom row of Table 5, it is seen that Øveraasen has the highest working efficiency by large margin as it has 20 to 30 percent larger sweeping area per fuel litre compared to Boschung and Vammas, respectively. Even though this efficiency illustration is assuming and simplifying many things, the efficiency of Øveraasen is nevertheless highest since the clearing area is over

40 percent larger and the fuel consumption will not be equally much higher. In low loaded cases the engine efficiency is most likely higher for Øveraasen since diesel engine efficiency is the highest slightly below maximum torque and efficiency deteriorates when approaching low load condition. Hence, the wider snow clearance area increases the engine load and fuel efficiency increases.

As alternative fuels are a topical subject, all the machines except Aebi Schmidt can be operated with renewable hydrotreated vegetable oil (HVO) as direct substitute for standard diesel. Most likely Aebi Schmidt can be operated with it as well but there was no information available regarding that. Vammas can be equipped even with a hydrogen engine and Boschung have performed a review of options to convert their machine to use hydrogen. Since Boschung manufactures their own chassis, it can be freely modified which in turn enables the option to use engines from different manufactures than stated in Table 4. Therefore, a hydrogen powered engine could be installed on their machine as well. Similarly, Aebi Schmidt manufactures their own chassis so they could possibly be able to convert their machine to use hydrogen as well but no official confirmation regarding this was received.

3.4 Investment and operational costs

Firstly, no actual acquisition prices were received due to the competition between different manufacturers. Based on the discussions with different manufacturers, there can be large differences in investment costs between the machines depending on the functionality of the machines. As mentioned in chapter 3.1, Boschung has the most versatile machine of the group and could possibly replace some other machines from service machine pool with its functionality. In terms of overall fleet acquisition costs, since Øveraasen can perform the runway cleaning task with 20 to 30 percent fewer machines compared to Vammas and Boschung, the fleet size could be reduced, which potentially reduces the overall investment costs. In direct relation to this, the labour costs would be decreased as well since fewer operators are needed. Since the nature of PSB machine usage is highly seasonal, in summertime there are only a handful of operators employed. Thus, to cover the high demand of operators in winter, a recruitment process is conducted to fill the required vacancies. With fewer operators, the recruitment process would be easier and in case of inexperienced operators are recruited, educating the new operators could be less demanding as there is potentially fewer completely inexperienced persons. Nevertheless, this all naturally depends on the price difference between Øveraasen and the other machines.

In terms of operational costs, the calculations performed in previous chapter regarding the fuel consumption would put Øveraasen on the top regarding fuel costs. However, it is necessary to remember that there would be fewer machines needed if the fleet consisted of machines from Øveraasen, and fuel costs would most likely be lower than with the other machines. Service costs were not available but service intervals for Vammas and Boschung were provided. Vammas has mostly a 1000-hour/12-month service interval for common service items whereas Boschung has a 500-hour/24-month service interval. If the operation hours are accumulated quickly, the service program for Vammas is more beneficial as hour-wise their machine is serviced more rarely. With fewer operation hours, Boschung would require less maintenance since the machine can be operated 24 months when the operation hours stay under 500 hours between the services. Discussion with manufacturers revealed that one of the single most expensive spare-part is the broom for sweeping unit since the cost is in the range of several thousands of euros. That said, the broom replacement cost for Øveraasen would most likely be significantly higher than for the rest of the machines as the broom is considerably wider compared to the other machines. On the contrary, due to narrower broom in Aebi Schmidht’s machine, the replacement cost for it would be then the lowest.

4. Task 2: Analysing the current use of PSBs at Helsinki-Vantaa airport based on historical data

This task describes the operative work cycles, power output, the fuel consumption and re-fuelling cycles of the PSBs in operative work during winter 2023-2034 (1.11.2023 – 30.4.2024) at Helsinki-Vantaa airport. The analysis of the current use of machines is based on historical data which were available on three datasets:

1. Operating data from 19 PSBs: H10-H14, H17-H21, H23-26, H32 and H35-H38. The dataset contain:
    I. Travel related parameters like distance travelled, speed, working hours.
    II. Measurements related to broom and blower like power and pressure.
    III. Fuel consumption for propulsion and for auxiliary systems (broom, blower). These are for H10, H11, H12-H14, H26 and H35-H38.
    IV. Some weather-related measurements like temperature and wind.
2. Fuel refuelling information from four PSBs (H35-H38).
3. Auxiliary engine data from H37.

Unfortunately, there were missing values in the datasets 1. and 3. The most important missing values were in fuel consumption data, of which about 87% sampling values were missing for H35-H38 and more than 90% for others. The only measurement that was close to perfect in some PSBs was speed in the dataset 1. Although it would theoretically be possible to calculate the distance travelled from the speed and the time spent, in practice this did not reach the same values as distance travelled measurement although different methods were used to estimate average speed over time span. Most likely this is due to its accuracy and precision (1 km). Because of this, ”distance travelled (km)” was used for calculations although its values contain only about 50 % of time samples.

Missing values made it difficult to get accurate results and led to the fact that it was necessary to interpolate data to get estimates for missing values. If the time interval and/or the distance travelled, for which there are no measurements, is long, linear interpolation gives greatly incorrect values. For this reason, an attempt was made to use traditional linear and robust regression to improve interpolation. These gave good results in most cases but failed completely in others. If regression is used, results should be verified one by one. Since there are several million samples of data, resulting in several thousand driving cycles, it was practically too time-consuming to check and then code exceptions for them all. For these reasons, it was decided to evaluate the reliability of the interpolation and accept the results based on reliability information. Some of the aforementioned issues are presented in Appendix A.

The period under study was 1.11.2023 – 30.4.2024 in datasets 1. and 2. whereas the dataset 3. was limited to the months of February 2024. The winter 2023-2024 was long and snowy. During the winter season there were 30 days with meetings about weather at the Helsinki-Vantaa airport. Some comments and graphs of weather are presented in Appendix B.

4.1 Use profiles (hours, distances, power profiles)

The challenges of estimating use profiles have been described in the paragraph above and in Appendix A. The hours and distances are based on work shifts on the runway, which are estimated from the speed of the PSBs. Under 10 minutes breaks are included to the work shifts. Due to the estimation method, it is possible that the values are underrated but they nevertheless give a good picture of the total usage. Also, the division into days does not give a real picture of usage, as the airport works continuously. For this reason, the corresponding values have been calculated starting with full hours. These values can be found in Appendix C. Calculated this way, the maximum working time may reach almost 22 hours.

Since every day is different, average and maximum day have been identified. The usage hours are shown in Table 6 with also duration of work shifts.

Table 6. The sum of daily work shift hours and duration of work shifts.

	Duration of work, daily (hh:mm)				**Duration of work shift (hh:mm)**			
ID	Mean	Median	Maximum	Date of max.	Mean	Median	Maximum	Start time of max.
H10	05:41	04:34	18:48	18.1.2024	01:31	01:20	11:40	18.1. 2:42
H11	05:15	04:30	15:21	3.4.2024	01:22	01:17	04:05	18.1. 10:26
H12	05:50	04:48	17:59	18.1.2024	01:27	01:15	08:50	22.12. 1:45
H13	05:30	04:35	17:36	18.1.2024	01:27	01:19	08:52	22.12. 1:44
H14	05:07	04:32	16:31	18.1.2024	01:25	01:16	08:50	22.12. 1:45
H17	04:43	03:29	13:57	18.1.2024	01:21	01:16	09:15	18.1. 3:06
H18	04:40	03:57	16:11	12.1.2024	01:32	01:26	11:57	12.1. 11:37
H19	05:27	04:01	13:56	18.1.2024	01:34	01:23	08:10	14.2. 6:23
H20	05:56	04:59	13:28	12.1.2024	01:36	01:23	05:07	18.1. 0:56
H21	05:06	04:06	17:19	18.1.2024	01:28	01:22	05:50	21.1. 11:36
H23	05:20	04:15	18:18	18.1.2024	01:37	01:19	09:36	14.2. 6:12
H24	05:09	04:41	13:45	3.4.2024	01:25	01:20	05:50	21.1. 11:37
H25	05:27	04:42	15:25	28.11.2023	01:28	01:20	07:34	22.12. 1:44
H26	05:43	04:19	16:29	18.1.2024	01:33	01:25	05:51	21.1. 11:37
H32	04:19	04:19	04:19	28.11.2023	02:09	02:09	02:57	28.11. 2:09
H35	05:30	04:34	16:21	22.12.2023	01:32	01:20	08:50	22.12. 1:45
H36	05:11	04:06	16:36	22.12.2023	01:34	01:26	14:37	14.2. 1:00
H37	05:19	04:10	19:13	18.1.2024	01:32	01:17	13:57	18.1. 6:07
H38	05:54	04:58	18:18	18.1.2024	01:34	01:21	13:54	18.1. 2:40

The distances are calculated from the first work shift to the end of the day or end of the last shift. The results of the travelled distances are in Table 7. As above, the table contains information about individual work shifts.

Table 7. Travelled distances.

	Distance, daily (km)				**Distance, work shift (km)**			
ID	Mean	Median	Maximum	Date of max.	Mean	Median	Maximum	Start time of max.
H10	113	94	374	18.1.2024	30	27	232	18.1. 2:42
H11	105	89	303	13.12.2023	27	25	84	12.1. 12:52
H12	115	92	385	18.1.2024	29	25	151	22.12. 1:45
H13	110	91	389	18.1.2024	29	27	154	22.12. 1:44
H14	105	89	357	18.1.2024	29	27	150	22.12. 1:45
H17	66	57	190	30.12.2023	19	18	107	18.1. 3:06
H18	67	59	184	14.2.2024	22	20	102	12.1. 11:37
H19	82	63	197	17.3.2024	24	21	95	14.2. 6:23
H20	91	76	266	12.1.2024	25	22	76	12.1. 12:53
H21	81	65	325	18.1.2024	23	22	116	21.1. 11:36
H23	104	84	387	18.1.2024	32	28	175	18.1. 6:07
H24	96	83	279	3.4.2024	27	24	141	21.1. 11:37
H25	87	72	254	28.11.2023	23	22	117	21.1. 11:37
H26	112	96	379	18.1.2024	30	28	136	21.1. 11:37
H32	55	55	55	28.11.2023	28	28	34	28.11. 2:09
H35	102	81	311	12.1.2024	29	25	151	22.12. 1:45
H36	84	73	289	14.2.2024	26	24	259	14.2. 1:00
H37	102	86	393	18.1.2024	30	26	284	18.1. 6:07
H38	114	94	357	18.1.2024	30	28	253	18.1. 2:40

Power profile was estimated from the dataset 3. It has auxiliary engine measurements from H37 and it covers a period from 29.1.2024 to 28.2.2024. During that period the estimated fuel consumption per work hour and kilometre during work shifts are presented in Figure 9.

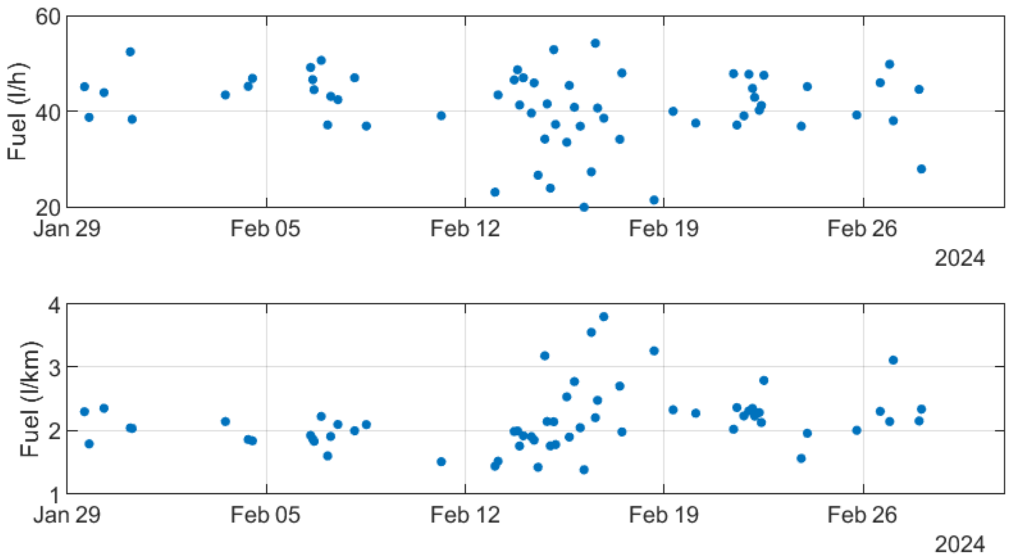

Figure 9. Estimated fuel consumption per work hour and kilometre.

The minimum and maximum consumption varied between 19.9 to 54.2 l/h and 1.4 to 3,8 l/km. The dates and times of those extreme values are shown in Table 8. It is interesting that the extreme values fall on the same day, which of course reduces the average consumption for that day.

Table 8. Extreme consumption values with timing.

		Date			**Date**	
	Minimum	Start	End	Maximum	Start	End
Litres per hour	19.9	16-Feb-2024 01:04	16-Feb-2024 04:16	54.2	16-Feb-2024 13:50	16-Feb-2024 15:07
Litres per kilometre	1.4	16-Feb-2024 01:04	16-Feb-2024 04:16	3.8	16-Feb-2024 20:58	16-Feb-2024 22:03

The power of the minimum case is presented in Figure 10. There are some time sections with low constant power. Even when running, the average power is under 100 kW.

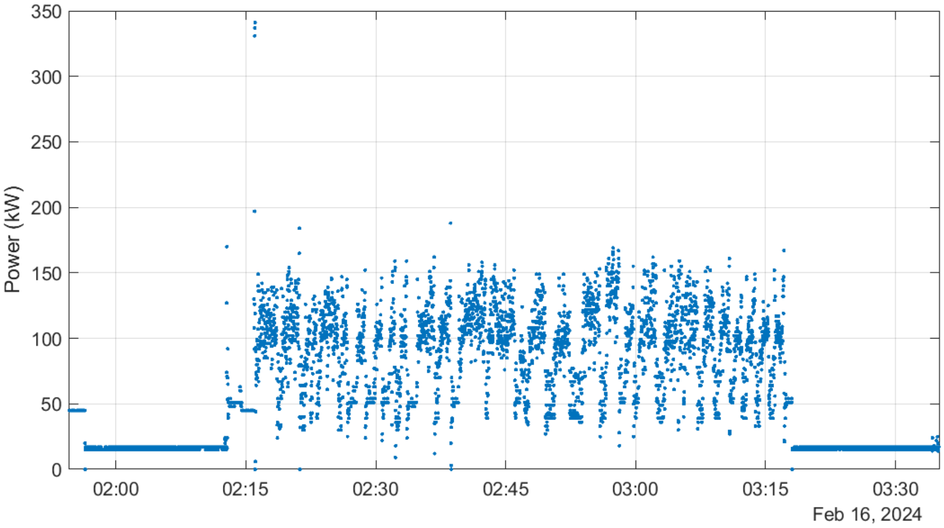

Figure 10. Power in low fuel consumption.

Figure 11 shows power in the maximum consumption case. It is possible to notice that the machine operates in two power ranges where the average power is 40 kW and 240 kW.

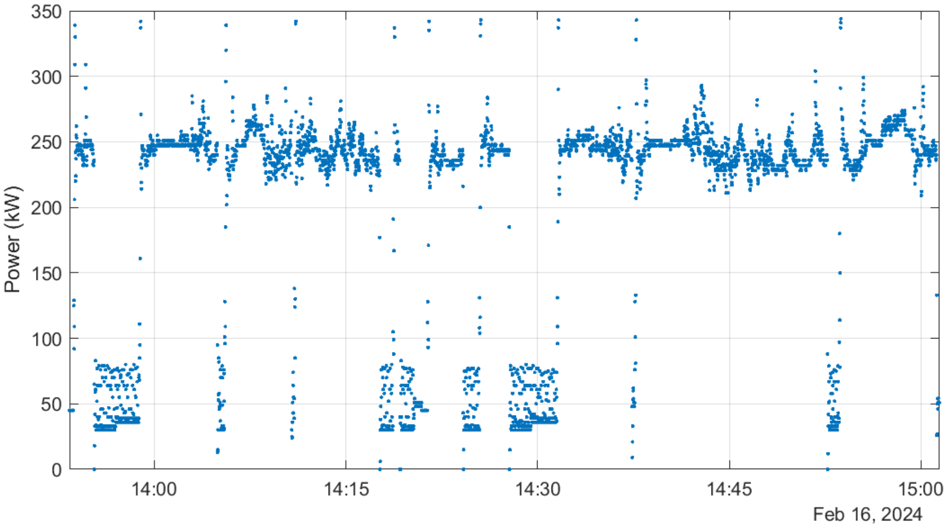

Figure 11. Power in high fuel consumption.

The power data also contains two constant values at 15 and 17 kW. If those mentioned above (under 20 kW power values) are removed, the histogram of the remaining values is in Figure 12. The distribution is clearly visible, and it can be stated that the machine operates largely in only two power ranges.

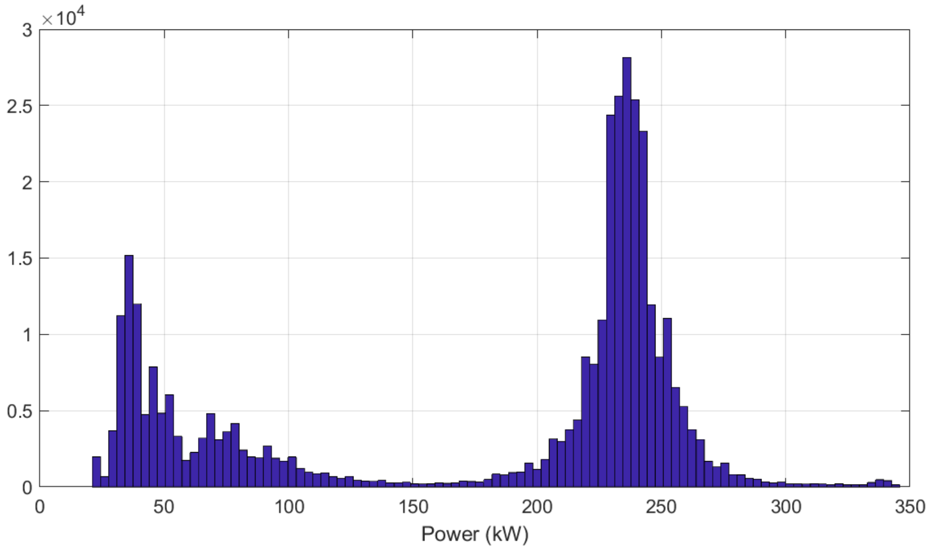

Figure 12. Histogram of power values.

4.2 Metered fuel consumption, deduced energy consumption and other parameters of engines

Fuel consumptions are estimated from dataset 1. It contains data for both fuel used for propulsion (DriveFuel) and fuel used for auxiliary systems (AggFuel). This data is available for ten PSBs. The daily mean, median and maximum usage of propulsion fuel is in Table 9. It has also respectively fuel consumption per kilometre and hour.

Table 9. Fuel used for propulsion in litres.

	Fuel daily usage (l)				**Fuel (l/km)**				**Fuel (l/h)**			
ID	Mean	Median	Maximum	Date of max.	Mean	Median	Maximum	Date of max.	Mean	Median	Maximum	Date of max.
H10	117	91	400	03-Apr	1.0	1.0	1.8	18-Feb	7.2	6.5	18.3	03-Apr
H11	107	89	424	03-Apr	1.0	1.0	1.9	18-Mar	6.6	5.8	19.4	03-Apr
H12	122	87	359	17-Jan	1.0	1.0	1.8	04-Dec	7.4	7.2	16.9	31-Dec
H13	90	72	328	22-Dec	1.1	1.1	2.1	18-Mar	6.3	4.5	22.1	27-Dec
H14	111	87	328	22-Dec	1.2	1.2	2.4	10-Dec	6.6	5.8	19.3	18-Jan
H26	94	72	329	23-Apr	1.1	1.2	1.9	18-Mar	6.1	4.0	19.9	17-Mar
H35	75	72	193	11-Jan	1.1	1.0	3.1	02-Jan	5.4	4.9	12.9	19-Nov
H36	93	71	277	13-Dec	1.2	1.2	3.4	11-Dec	5.5	4.5	14.7	12-Jan
H37	105	82	335	18-Jan	1.0	1.0	2.0	27-Feb	7.1	6.8	16.4	24-Apr
H38	113	95	337	03-Apr	1.0	1.0	1.6	03-Jan	7.3	7.2	15.4	03-Apr

Deduced energy consumption is in Table 10.

Table 10. Deduced energy consumption for propulsion.

	Fuel daily usage (GJ)				**Fuel (MJ/km)**				**Fuel (MJ/h)**			
ID	Mean	Median	Maximum	Date of max.	Mean	Median	Maximum	Date of max.	Mean	Median	Maximum	Date of max.
H10	4.3	3.3	14.6	03-Apr	35	35	67	18-Feb	260	240	670	03-Apr
H11	3.9	3.3	15.4	03-Apr	38	36	71	18-Mar	240	210	710	03-Apr
H12	4.5	3.2	13.1	17-Jan	37	36	64	04-Dec	270	260	620	31-Dec
H13	3.3	2.6	12.0	22-Dec	41	40	77	18-Mar	230	160	800	27-Dec
H14	4.0	3.2	11.9	22-Dec	45	42	89	10-Dec	240	210	700	18-Jan
H26	3.4	2.6	12.0	23-Apr	42	42	68	18-Mar	220	150	720	17-Mar
H35	2.7	2.6	7.0	11-Jan	40	38	113	02-Jan	200	180	470	19-Nov
H36	3.4	2.6	10.1	13-Dec	45	43	125	11-Dec	200	160	540	12-Jan
H37	3.8	3.0	12.2	18-Jan	36	35	73	27-Feb	260	250	600	24-Apr
H38	4.1	3.5	12.3	03-Apr	36	35	59	03-Jan	270	260	560	03-Apr

Fuel used for auxiliary systems is presented in Table 11 and respectively deduced energy in Table 12.

Table 11. Fuel used for auxiliary systems in litres.

	Fuel daily usage (l)				**Fuel (l/km)**				**Fuel (l/h)**			
ID	Mean	Median	Maximum	Date of max.	Mean	Median	Maximum	Date of max.	Mean	Median	Maximum	Date of max.
H10	257	209	1026	18-Jan	2.1	2.1	4.0	02-Feb	15.8	15.3	46.2	18-Jan
H11	225	181	800	28-Nov	2.1	2.2	3.2	26-Dec	13.7	11.7	34.4	08-Jan
H12	227	166	786	12-Dec	1.9	1.9	4.1	04-Dec	14.0	12.5	34.2	21-Dec
H13	172	142	685	18-Jan	2.1	2.1	4.2	16-Dec	12.3	9.2	51.5	27-Dec
H14	214	160	759	08-Jan	2.3	2.2	5.4	15-Dec	12.8	10.9	50.4	18-Jan
H26	165	132	416	23-Apr	2.2	2.0	3.0	22-Jan	11.0	8.2	33.2	17-Mar
H35	138	96	411	11-Jan	1.9	2.0	2.9	15-Dec	10.0	8.9	31.3	13-Dec
H36	186	164	585	28-Nov	2.4	2.5	3.8	16-Dec	10.8	9.7	26.8	23-Dec
H37	238	201	917	18-Jan	2.2	2.2	3.2	27-Feb	15.9	15.4	41.3	18-Jan
H38	274	235	891	18-Jan	2.4	2.3	3.4	28-Feb	17.7	17.6	40.1	18-Jan

Table 12. Deduced energy consumption for auxiliary systems.

	Fuel daily usage (GJ)				**Fuel (MJ/km)**				**Fuel (MJ/h)**			
ID	Mean	Median	Maximum	Date of max.	Mean	Median	Maximum	Date of max.	Mean	Median	Maximum	Date of max.
H10	9.4	7.6	37.4	18-Jan	76	77	145	02-Feb	580	560	1680	18-Jan
H11	8.2	6.6	29.2	28-Nov	76	79	118	26-Dec	500	430	1250	08-Jan
H12	8.3	6.1	28.6	12-Dec	68	69	150	04-Dec	510	450	1240	21-Dec
H13	6.3	5.2	25.0	18-Jan	76	78	152	16-Dec	450	340	1870	27-Dec
H14	7.8	5.8	27.6	08-Jan	84	81	196	15-Dec	470	400	1840	18-Jan
H26	6.0	4.8	15.2	23-Apr	79	74	108	22-Jan	400	300	1210	17-Mar
H35	5.0	3.5	15.0	11-Jan	68	73	105	15-Dec	360	320	1140	13-Dec
H36	6.8	6.0	21.3	28-Nov	89	92	139	16-Dec	390	350	980	23-Dec
H37	8.7	7.3	33.4	18-Jan	80	81	115	27-Feb	580	560	1500	18-Jan
H38	10.0	8.6	32.4	18-Jan	87	85	123	28-Feb	650	640	1460	18-Jan

Some graphs of fuel consumption related to other parameters are in Appendix D.

4.3 Re-fuelling

Re-fuelling information is in dataset 2. It contains data from four PSBs (H35-H38). Since it is not known how much fuel was in the tanks at the beginning of the review period, it is not possible to calculate how much fuel was left in tank at each moment. In any case Table 13 present fuel usage from the dataset 1 and total re-fuelling amounts.

Table 13. Re-fuelling amounts.

Unit	**Drive fuel (l)**	**Agg fuel (l)**	**Total fuel (l)**	**First refill**	**Last refill**	**Total refill amount (l)**
H35	10 704	19 111	29 815	18.11.2023 10:48	06.04.2024 16:06	28801
H36	8 736	18 196	26 932	05.11.2023 18:52	28.02.2024 19:59	27192
H37	12 096	26 578	38 674	02.11.2023 07:51	06.04.2024 04:31	37622
H38	13 355	32 033	45 387	02.11.2023 08:49	06.04.2024 16:09	44685

Typical re-fuelling amount was 250 litres and maximum 674 litres (H38, 25-Jan-2024 17:28). Respectively mean daily re-fuelling was 380 litres and maximum 1361 litres (H37, 18-Jan-2024). The number of daily re-fuelling events are in Table 14 with percentage of all days when re-fuelling has taken place. About half of the days can be completed with one re-fuelling, but there are days when re-fuelling is done even four or five times.

Table 14. Re-fuelling events.

	1 re-fuelling		**2 re-fuelling**		**3 re-fuelling**		**4 re-fuelling**		**5 re-fuelling**	
ID	#	%	#	%	#	%	#	%	#	%
H35	36	55	22	33	8	12	0	0	0	0
H36	41	61	17	25	8	12	1	1	0	0
H37	52	62	20	24	11	13	1	1	0	0
H38	42	45	29	31	12	13	9	10	1	1

Since the data had only the time when re-fuelling started, an attempt was made to estimate its duration based on the information in the dataset 1. It can be concluded that the re-fuelling has ended when the vehicle is in motion again at the latest. Re-fuelling durations obtained in this way varied greatly. The conclusion from them is that some of them have happened during a longer break while some of them have been completed as quickly as possible. The latter cases appear to have occurred on challenging days like 18-Jan-2024. In some cases, it was possible to deduce that from stop to start the re-fuelling rate was about 100 litres per minute. Appendix E contains some graphs of re-fuelling events with amounts and estimated durations for December 22nd and 23rd.

5. Conclusions

In task 1, the goal was to compare the different PSBs both in technical and economical perspective. However, the comparison in economical perspective was not possible to perform extensively since the manufacturers did not disclose the required information. In addition, two of the four manufacturers selected for this comparison, Aebi Schmidt and Øveraasen, did not provide any information other than which was already publicly available on their website.

Functionality-wise, the most versatile machine is manufactured by Boschung since it can be equipped with several additional devices for runway maintenance such as de-icer for winter and, for example, vacuuming and/or washing unit for summer. Such versatility would be beneficial if there is a need to renew other utility vehicles at the same time. Investment costs could be lower when purchasing one machine from Boschung carrying out all the needed maintenance functions instead of purchasing separate machines for different tasks. Vammas and Øveraasen are providing only the basic functionality for winter maintenance: ploughing, sweeping, and blowing. Aebi Schmidt also provides de-icing functionality for winter operation but looking at the dimensions of the machines, it has clearly the narrowest snow-clearing width of the group which makes it inefficient in terms of snow-clearing. The highest sweeping capacity by a large margin is with Øveraasen's machine followed by Boschung and Vammas. Keeping this in mind, machine fleet consisting only of Øveraasen PSBs would require 20 to 30 percent less machines operating on the runway compared to closest competitors Boschung and Vammas. Depending on the difference in purchase price of the different machines, the investment costs could potentially be reduced with fewer machines from Øveraasen.

Considering the dimensions, Aebi Schmidt's and Boschung's machines are so called compact PSBs which could enable using them also in other parts of the airport where space is limited. Despite the quite similar turning radius of all the machines, longer machines from Vammas and Øveraasen are not suitable for working in areas where high manoeuvrability is required. As an example, operation in the vicinity of the aircrafts would not be feasible. Here, the smaller machines from Aebi Schmidt and Boschung could lower the investment costs since, for example, the fleet size for apron maintenance could possibly be reduced. Regarding the costs, it was estimated that the fuel costs would be lower for Øveraasen since it has the highest sweeping capacity per fuel litre. On the other hand, Øveraasen would most likely have the highest maintenance costs since the broom is significantly longer than in the other machines, and as the cost for the broom is thousands of euros, it has a substantial impact on the overall maintenance costs.

As a summary, when considering only the winter operation, based on the information available Øveraasen seems to be the most capable machine for snow-clearing. If versatility is the key requirement, then Boschung would be the correct choice. All in all, the cost of the machine would determine in the end what would be the optimum solution for different airports and unfortunately the purchase price was not available for any of the machines.

In task 2, the analysis of current use of PSBs at Helsinki-Vantaa airport showed how on challenging days the PSBs are used almost around the clock - at least some of them. On such days, the daily driven distances can reach almost 400 km. Of course, this also means that fuel consumption is high. The average daily consumption was 3.7 GJ for propulsion and 7.7 GJ for auxiliary engine. Correspondingly, the maximum values were 15.4 GJ and 37.4 GJ. Standard deviation is much greater in auxiliary than in propulsion engine: 1.6 GJ versus 0.5 GJ. Typical daily refill was 380 litres per unit, but the maximum reached 1361 litres. Regarding the coming pilot PSB with a hydrogen-powered auxiliary engine, the average daily energy consumption of 7.7 GJ would correspond with approximately 64 kg of hydrogen, while the maximum consumption of 37.4 GJ would correspond with approximately 312 kg of hydrogen (assuming a similar engine efficiency as for the current diesel internal combustion engine).

Regarding the KPIs for the pilot PSB, which would be equipped with a hydrogen fuelled auxiliary internal combustion engine, the writers of this report would like to stress the importance of practicality, reliability and their relation to working efficiency and energy consumption. Reliable operation of a work machine is paramount as unscheduled but unavoidable maintenance breaks can easily disturb the operation of a whole team of machines. For example, because of certain technical issues, a whole PSB team might need to wait in stand-by while the malfunctioned PSB is taken to maintenance/service and a replacement is brought over. This is not to say that any time spent in maintenance is a problem, as scheduled maintenance can be easily considered and a less mature pilot PSB application is almost guaranteed to spend more time in maintenance compared to its extensively tested diesel fuelled siblings. Energy consumption of a PSB on the other hand varies greatly depending on the weather conditions and the hardest working days of the winter season are sure to exceed the energy storage capacity of the pilot PSB’s hydrogen tanks. As the hydrogen re-fuelling station will be deployed only for the benefit of the pilot, and their refuelling speeds vary greatly depending on the selected model, it’s not fair to compare the refuelling speed of the pilot machine to the others of the PSB fleet.

Proposed KPIs for the pilot PSB:

1. Number of un-scheduled maintenance breaks
    1. Number of un-scheduled maintenance breaks caused by issues related to the hydrogen engine.
    2. Number of un-scheduled maintenance breaks caused by issues related to the hydrogen energy storage and refuelling equipment/system.
2. Length of un-scheduled maintenance breaks
    1. Length of maintenance breaks caused by issues related to the hydrogen engine.
    2. Length of maintenance breaks caused by issues related to the hydrogen storage and refuelling systems.
3. Additional length of maintenance breaks due to hydrogen system safety requirements (flushing of hydrogen feeds etc.)
4. Number of operation days with a single hydrogen re-fuelling
5. Number of operation days with two hydrogen re-fuelling
6. Number of operation days with more than two hydrogen re-fuelling
7. Operation time [h] between two hydrogen re-fuelling
8. Hydrogen [kg] / energy [kWh] consumption per day of operation
9. Hydrogen [kg] fuelled per re-fuelling

Although not a KPI as such, piloting of a hydrogen powered PSB has special requirements related to its storage, refuelling and maintenance premises, and the additional costs (both financial and operational) associated with these requirements should be evaluated. These include:

1. Additional equipment costs for pilot PSB storage area, refuelling station and maintenance premises
2. Additional operational costs (e.g. additional distance from staff quarters due to safety distance requirements increases the time needed to start operations) for pilot PSB storage area
3. Additional operational costs (e.g. separate refuelling location for hydrogen requires two refuelling stops for pilot PSB) for pilot PSB refuelling station
4. Additional operational costs (e.g. separate premises with low utilisation rate can lead to lower availability of required tools, as the tools are moved to premises with higher utilisation rates) for pilot PSB maintenance premises

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Witness Events	Signature	Timestamp

Notary Events	Signature	Timestamp

Envelope Summary Events	Status	Timestamps
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Payment Events	Status	Timestamps

APPENDIXES

13.11.2024 / VTT-R-00625-24

Appendix A. Preprocessing of data

Typically, data processing begins with estimating its reliability. In this case, the first findings were that all data is not in chronological order, some outliers in fuel consumption measurements and many missing values. The first one was easy to fix since all data has timestamps. Also fixing outliers did not cause any problems as show in Figure 1.

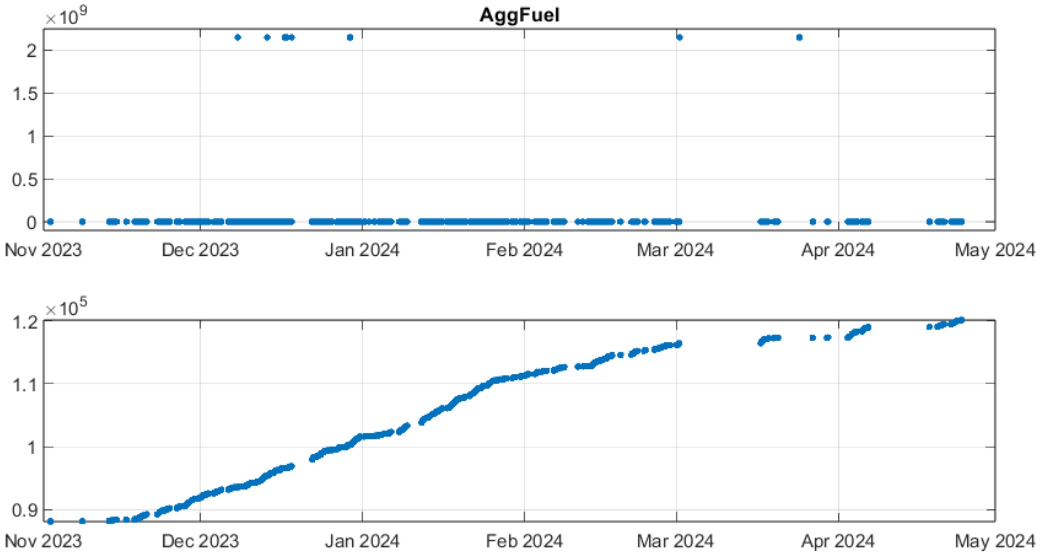

Figure 1. Aggregate fuel consumption: upper original – lower after removing outliers.

Instead, missing values caused difficulties. If the gap between samples is short, linear interpolation can replenish the values as shown in Figure 2. But if the interval without information is long or there is need to try to estimate the situation where the state changes, the analysis may end up with incorrect results. An example is in Figure 3, where linear interpolation can lead to the conclusion that the vehicle was moving slowly forward, although it is more likely that it has stopped. Nonlinear interpolation can correct estimation in this case as shown in the figure.

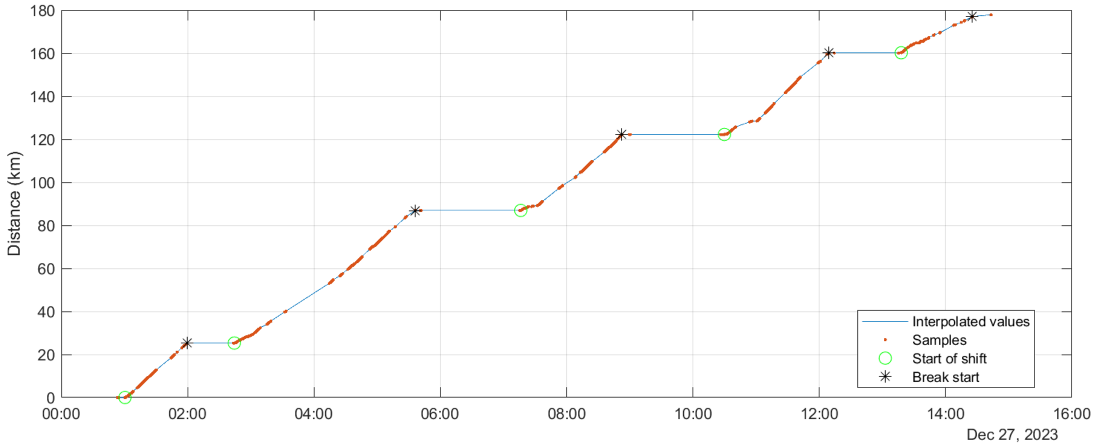

Figure 2. Linear interpolation.

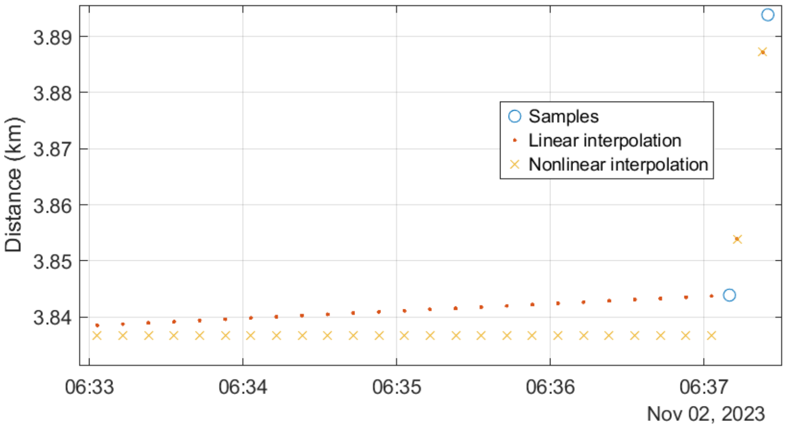

Figure 3. An example of nonlinear interpolation.

Another example of a problematic situation is in Figure 4, where linear interpolation does not take into account the probable break and gives 96 minutes longer work shift than estimation with robust regression.

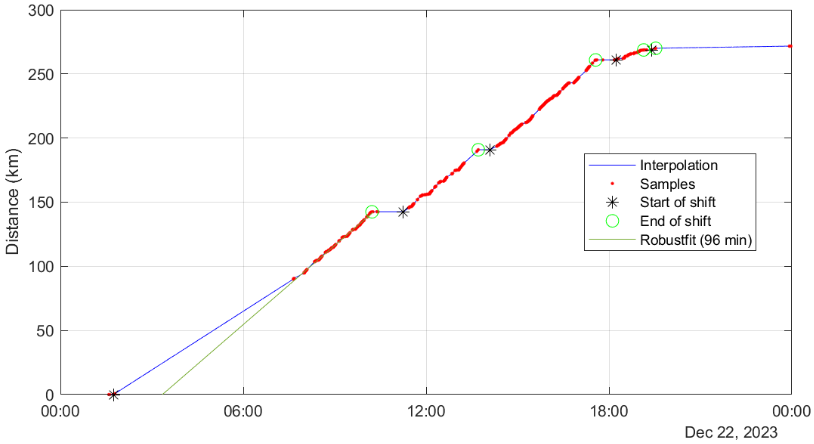

Figure 4. Comparison of linear interpolation and robust regression.

One possibility to replace the missing values is to estimate them from other values. However, this did not produce good results: either the necessary values were not available, or their accuracy was not sufficient. An example is in Figure 5 where distance was tried to estimate from duration and speed.

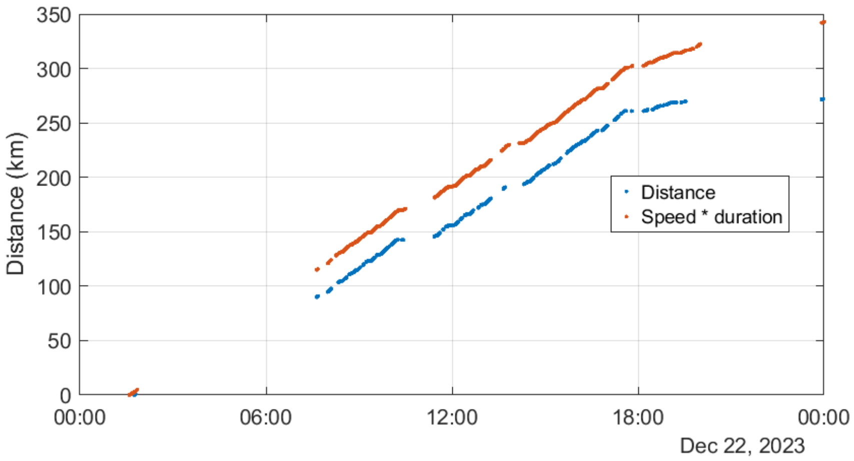

Figure 5. Distance estimation from other measurements.

Appendix B. Weather during winter 2023-2024

In Figure 6 and Figure 7 there are weather information at the Helsinki-Vantaa airport during the whole winter season and only February, respectively, with marked lines (red start and green end) when there were “weather meetings”. The meetings correlate well with snowing which was estimated from the temperature and precipitation.

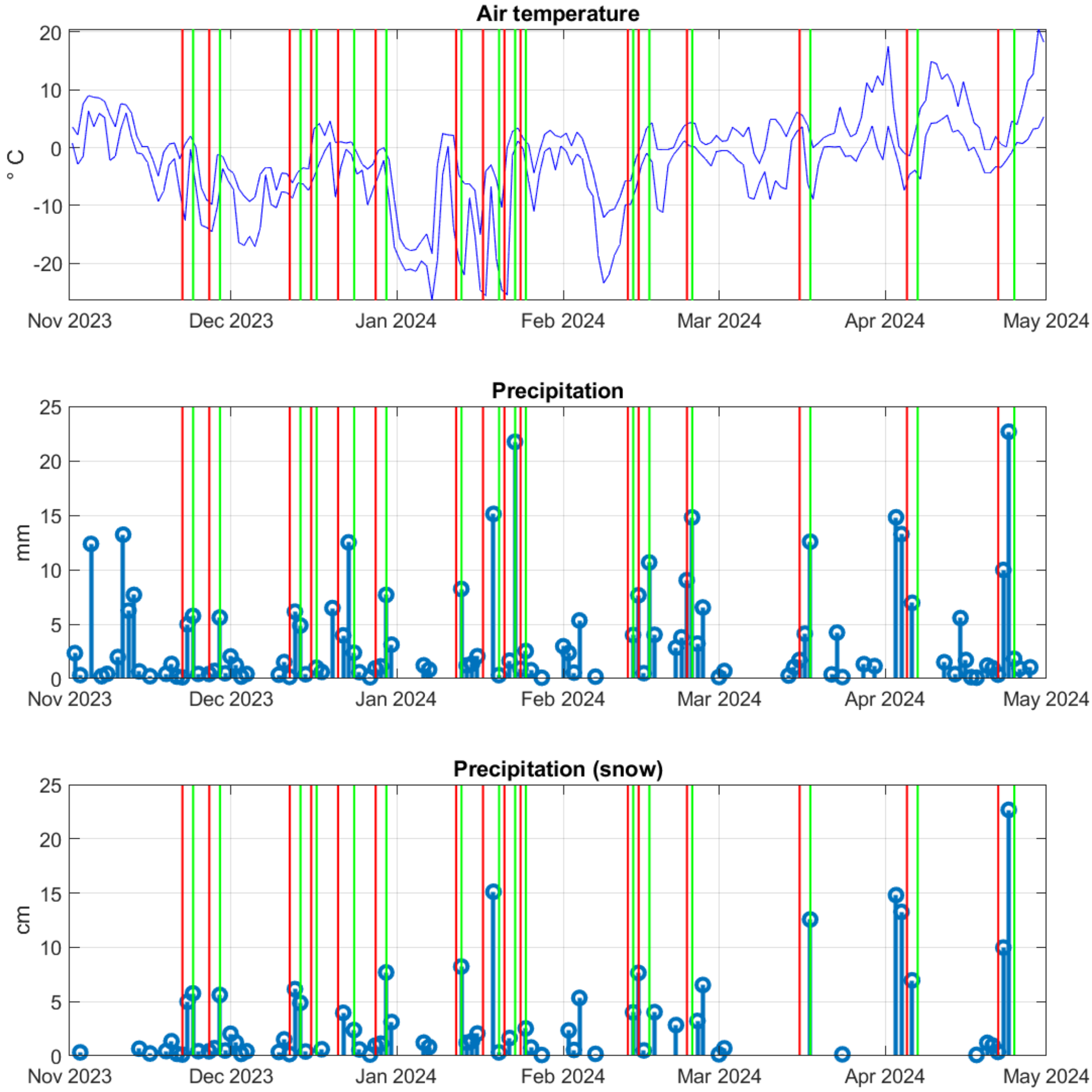

Figure 6. Air temperature and precipitation during winter 2023-2024.

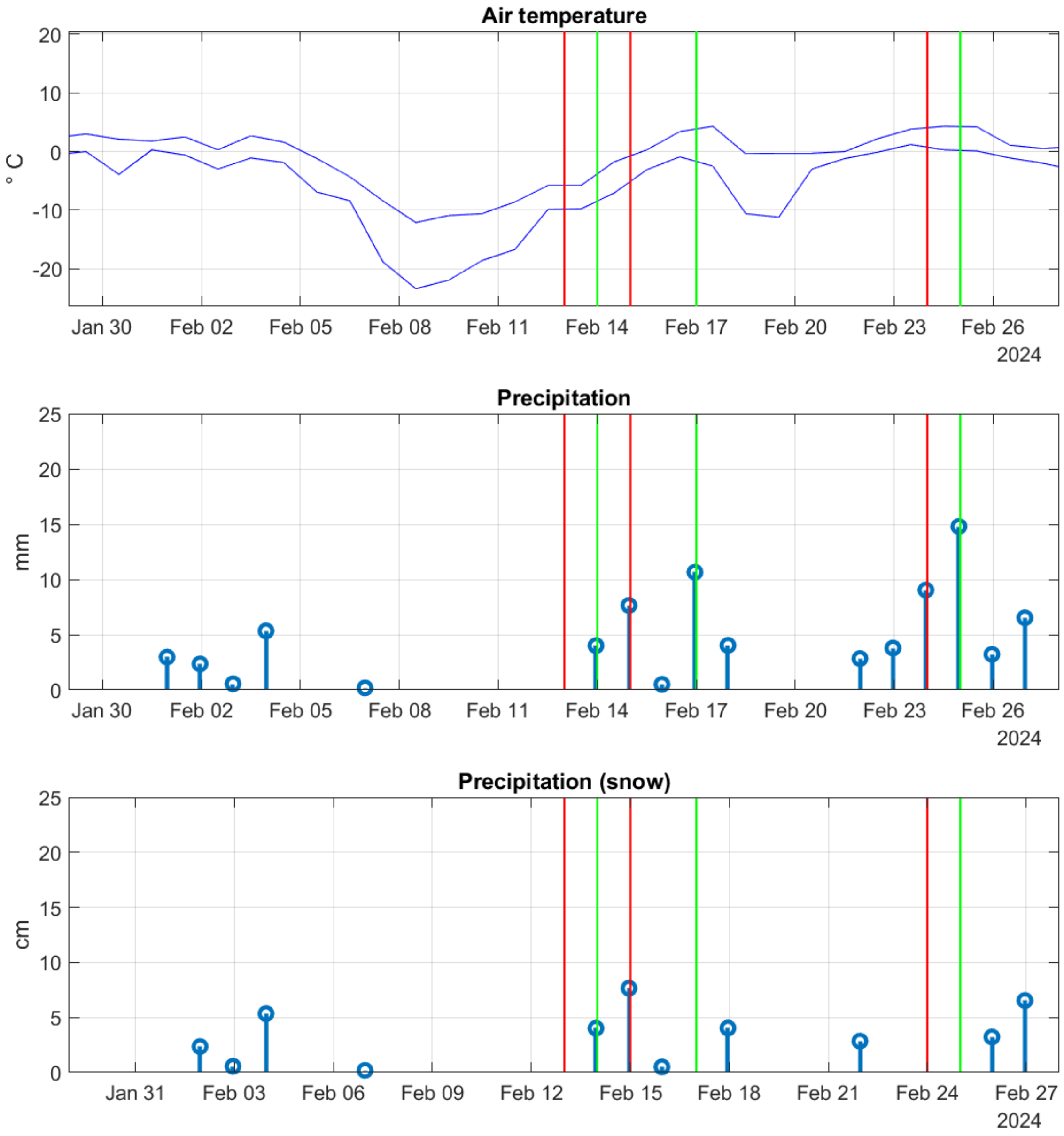

Figure 7. Weather of February 2024

Appendix C. Use profiles starting from full hours

The report presents daily working hours which does not give a true picture because the operation is continuous. For this reason, Table 1 and Table 2 give a more realistic picture of the situation.

Table 1. Work hours.

	Duration of work, daily (hh:mm)				**Duration of work shift (hh:mm)**			
ID	Mean	Median	Maximum	Date	Mean	Median	Maximum	Start time
H10	05:41	04:52	19:44	17.1.2024 22:49	01:30	01:20	11:40	18.1. 2:42
H11	05:13	04:28	16:08	12.12.2023 22:05	01:22	01:17	06:26	28.11. 22:30
H12	05:57	04:58	18:37	17.1.2024 18:14	01:30	01:16	14:25	20.12. 19:21
H13	05:35	04:42	18:39	22.1.2024 5:25	01:27	01:20	08:52	22.12. 1:44
H14	05:24	04:46	18:14	22.1.2024 6:06	01:27	01:17	08:50	22.12. 1:45
H17	05:00	04:03	15:56	28.11.2023 7:01	01:22	01:16	09:15	18.1. 3:06
H18	04:49	03:49	18:24	21.12.2023 21:03	01:34	01:26	12:16	21.12. 21:03
H19	05:40	04:47	18:48	13.2.2024 18:49	01:37	01:24	08:10	14.2. 6:23
H20	05:57	05:04	19:37	22.1.2024 6:24	01:38	01:23	11:46	22.1. 14:45
H21	05:07	03:59	17:19	18.1.2024 0:38	01:30	01:22	06:25	28.11. 22:30
H23	05:31	04:25	19:06	17.1.2024 18:15	01:38	01:20	09:36	14.2. 6:12
H24	05:13	04:39	17:09	22.1.2024 6:12	01:26	01:20	06:25	28.11. 22:30
H25	05:35	04:58	19:34	12.1.2024 12:53	01:30	01:20	12:59	12.1. 22:06
H26	05:27	04:18	19:22	18.1.2024 6:07	01:33	01:25	05:51	18.1. 21:09
H32	03:44	04:19	04:19	28.11.2023 0:10	02:07	01:22	02:57	28.11. 2:09
H35	05:24	04:37	17:48	12.12.2023 22:05	01:33	01:21	08:50	22.12. 1:45
H36	05:22	04:23	18:34	12.12.2023 18:23	01:35	01:27	14:37	14.2. 1:00
H37	05:24	04:17	19:13	18.1.2024 0:36	01:33	01:18	13:57	18.1. 6:07
H38	05:49	05:00	21:47	13.1.2024 23:42	01:34	01:20	13:54	18.1. 2:40

Table 2. Distances travelled.

	Distance, daily (km)				Distance, work shift (km)			
ID	Mean	Median	Maximum	Start time	Mean	Median	Maximum	Start time
H10	112	96	397	17.1.2024 22:49	30	27	232	18.1. 2:42
H11	104	86	363	17.1.2024 12:35	28	25	111	28.11. 22:30
H12	115	93	412	17.1.2024 18:14	29	25	158	20.12. 19:21
H13	111	94	407	17.1.2024 18:15	29	27	154	22.12. 1:44
H14	110	93	382	17.1.2024 18:04	30	27	150	22.12. 1:45
H17	69	57	218	28.11.2023 7:01	19	18	107	18.1. 3:06
H18	69	55	240	13.2.2024 18:50	22	20	102	12.1. 11:37
H19	84	80	237	13.2.2024 18:49	24	22	95	14.2. 6:23
H20	89	80	293	12.1.2024 6:10	25	22	108	22.1. 14:45
H21	80	60	330	17.1.2024 18:14	24	22	116	21.1. 11:36
H23	106	87	406	17.1.2024 18:15	31	28	175	18.1. 6:07
H24	97	83	300	13.12.2023 6:20	27	25	141	21.1. 11:37
H25	87	72	255	13.12.2023 6:20	23	22	117	21.1. 11:37
H26	104	85	402	17.1.2024 22:43	30	28	136	21.1. 11:37
H32	48	55	55	28.11.2023 0:10	27	21	34	28.11. 2:09
H35	99	81	357	12.12.2023 18:16	29	25	151	22.12. 1:45
H36	87	73	331	13.2.2024 17:16	26	24	259	14.2. 1:00
H37	103	86	393	18.1.2024 0:36	29	26	284	18.1. 6:07
H38	111	95	397	17.1.2024 18:07	30	27	253	18.1. 2:40

Appendix D. Fuel consumption related to other parameters

The propulsion fuel usage per kilometre is related to the average speed (Figure 8). The relation is not as clear for older machines.

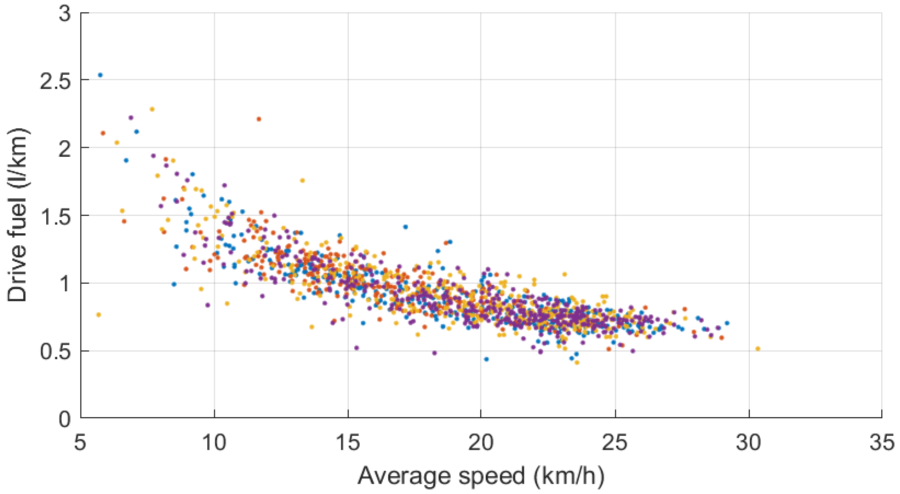

Figure 8. Fuel usage related to average speed (H35-H38)

The dataset 1 contains hydraulic pressure measurement. The auxiliary engine fuel consumption is correlated with its integral as shown in Figure 9.

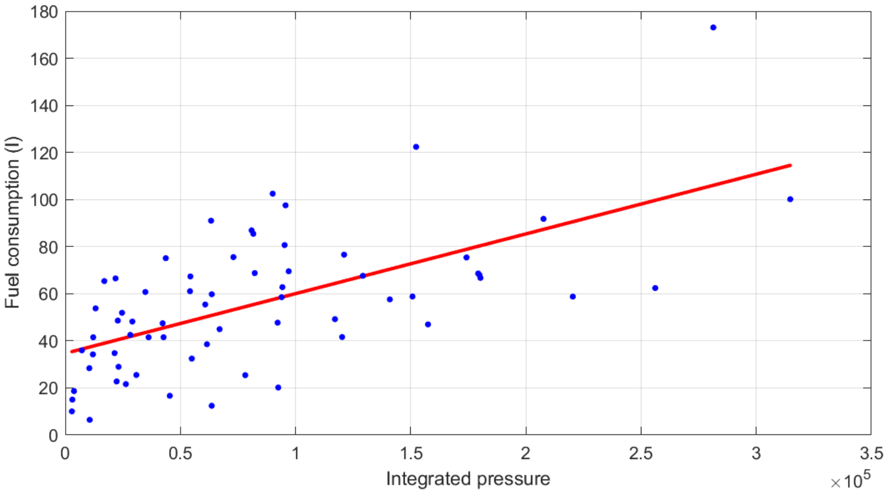

Figure 9. Fuel consumption related to the pressure integral.

Appendix E. Re-fuelling

Figure 10, Figure 11, Figure 12 and Figure 13 presents graphs of re-fuelling for December 22nd and 23rd. They contain also estimated duration and the amount of fuel taken. H35 had three re-fuelling on December 22nd with a total of 925 litres. H38 refuelled 487 litres in 6 minutes.

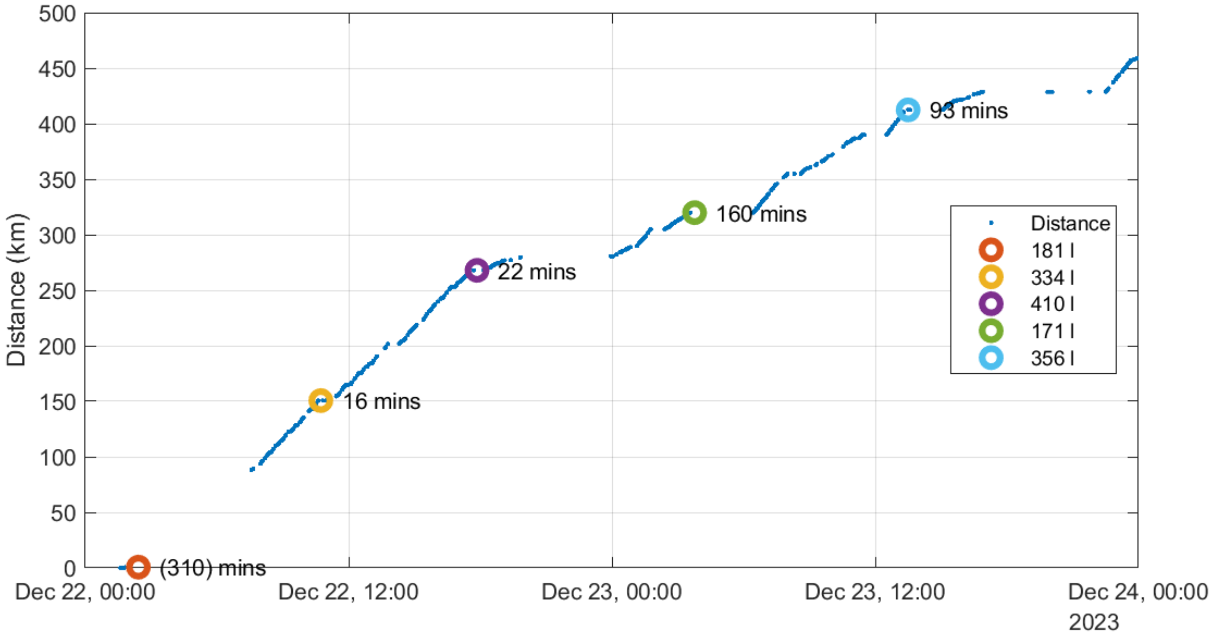

Figure 10. Re-fuelling of H35.

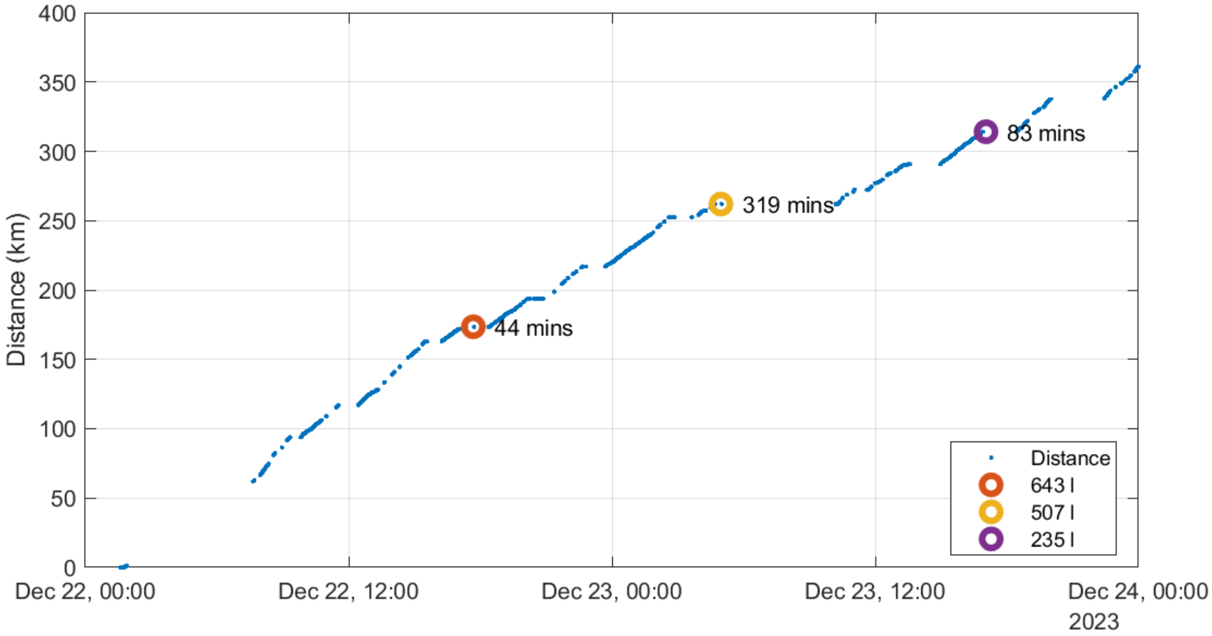

Figure 11. Re-fuelling of H36.

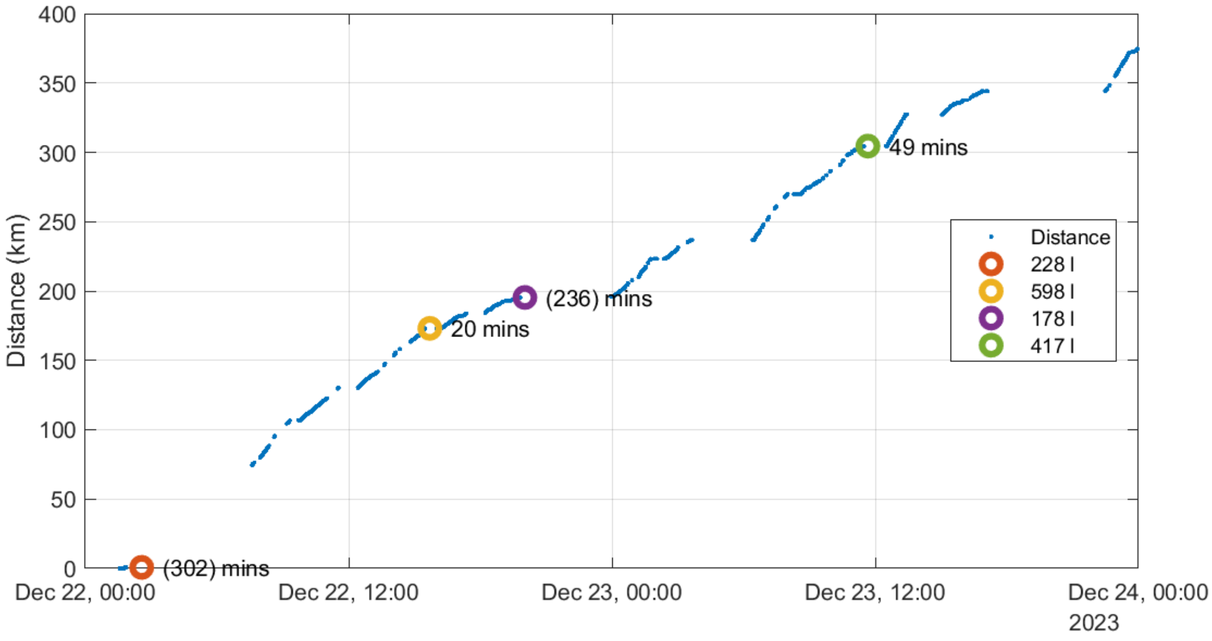

Figure 12. Re-fuelling of H37.

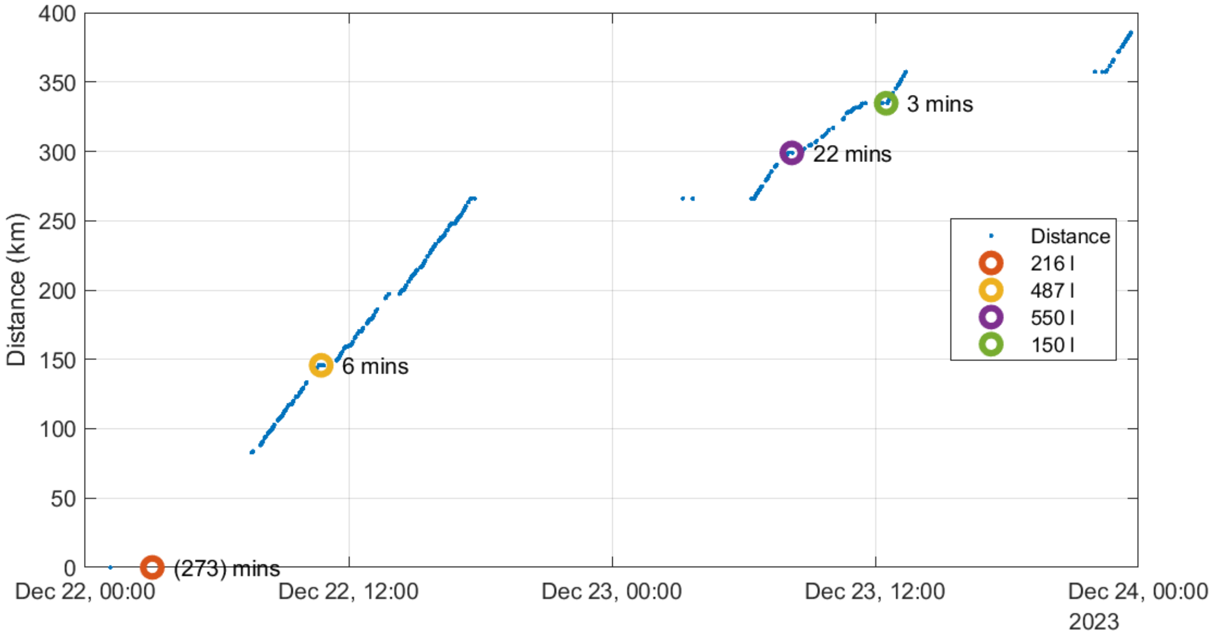

Figure 13. Re-fuelling of H38.