On-board bus air quality

Impact of changing ventilation on a double-decker bus

Technical study carried out by NIWA for Greater Wellington

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August 2023

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Executive summary

Previous monitoring undertaken by Air Matters Ltd[1] for Greater Wellington found elevated levels of CO_2 (carbon dioxide) from passenger respiration on-board a sample of in-service buses when passenger numbers were high. Although there are no guidelines for CO_2 levels on public transport, the risk of viral transmission of respiratory illnesses in indoor areas generally increases as CO_2 levels rise, should infectious people be present.

Following on from the findings of the first study, noting that the top deck of double decker buses appeared to be disproportionately affected, Greater Wellington commissioned NIWA to test the effect of introducing fresh air on levels of indoor CO_2 on a double decker bus in normal operation. The study was limited to a single bus type, where the ventilation system could be changed to either full recirculation mode or fresh air mode, where outdoor air intake was approximately 10%. The NIWA technical note is attached.

The maximum total number of passengers was a strong predictor of maximum CO_2 levels on both decks in both ventilation modes. Introducing fresh air reduced average CO_2 levels during the bus journey by approximately 60% compared to recirculation mode. Therefore, in principle introducing fresh air through the ventilation system is likely to reduce onboard CO_2 concentrations on any bus in use. However, the degree of improvement from introducing fresh air on buses on different routes under different weather conditions and ranges of passenger occupancies cannot be inferred from the testing results of a single vehicle.

In the meantime, we intend to require operators to introduce fresh air into existing buses which have adjustable air conditioning systems at a minimum rate of 10%. We will also investigate opportunities to introduce fresh air into the upper decks of buses where this is not currently possible.

We continue to share findings and liaise with the Ministry of Health and Waka Kotahi NZ Transport Agency to carry out further research and develop air quality and ventilation guidelines for public transport buses.

[1] Pilot-indoor-air-quality-monitoring-Metlink-buses-2022-23.pdf (gw.govt.nz)

ATTACHMENT 1

Technical Note: Using air quality monitors to assess impact of changing ventilation on a double-decker bus

Part one: Analysis of results

Author: Ian Longley
Version 1.3
Date: 20th July 2023

Background:

In April 2023, GWRC requested that NIWA undertake a brief study to assess whether a bus's ventilation system may be adjusted to reduce the risk of disease transmission between bus riders. A short observational study was then conducted on a single bus in operation in Wellington.

Scope:

This note (Part 1) briefly covers the findings of the study, in particular a brief evaluation of the success and limitation of our method, levels and determinants of CO_2 and $PM_{2.5}$ levels measured on the bus and how these data were used to provide a draft answer to the questions posed. Part 2 will provide a more detailed evaluation of the methods used and recommendations if a subsequent or larger scale study were to be planned.

Objectives:

The study was designed to answer two questions:

- To what degree will the introduction of fresh air through the ventilation system reduce the risk of bus users inhaling re-breathed air (and hence the risk of virus transmission if infectious person(s) board the bus)?
- To what degree will the same introduction of fresh air through the ventilation system increase the concentration of road vehicle exhaust pollution inside the bus?

This brief pilot study also needed to be executed quickly at low cost and with minimal disruption to bus operation.

Study design:

Direct measurement of contaminants that provide proxies for the risks being considered is a simple and common approach. GWRC offered to facilitate access to at least one bus on which air monitors could be installed subject to practical conditions. During the study the ventilation system could be changed from fully recirculating cabin air to introducing 10% fresh air.

Our experience working in this field led us to hypothesise that factors other than the setting of the ventilation system would also impact in-bus air quality and needed to be considered. These included at least passenger numbers, route and time (impacting outdoor concentrations, bus and wind speed and hence air pressure gradients) and bus design.

Direct comparison of data from a "before/after" study of this type can therefore be misleading if these other factors are not considered. For example, coincidental differences in passenger numbers across the two ventilation modes might obscure the effect of the ventilation changes.

These factors mean that even a comparison between two identical buses running identical routes with different ventilation settings still has the potential to yield misleading results.

Our chosen approach, therefore, was to collect pilot data from a single bus at a high temporal resolution so that it may be possible to infer the role of different processes, and where possible to capture additional data describing drivers of those processes, specifically passenger numbers (exhalation), exterior concentrations (infiltration), and bus location.

Methods:

A single double-decker (Model ADL E500, fleet number 5088) bus was selected for the study.

As a proxy for re-breathed breath and potential virus transmission we chose to measure carbon dioxide (CO_2). This method is well-established with reliable sensors with sufficient sensitivity widely available.

As a proxy for road vehicle exhaust pollution we chose to measure particulate matter (PM) using optical sensors. While PM sensors that are suitable in terms of temporal resolution, reliability, small form and low cost are available, these sensors have a relatively low and poorly quantified sensitivity to vehicle exhaust pollution meaning their suitability for this application is more questionable. However, more sensitive and suitable devices are either much more expensive or unsuitable for mounting on an in-service bus. Given the pilot nature of this study we opted to use low-cost, low-sensitivity sensors.

Six air quality monitors (Qingping) were placed on the bus, 3 upstairs and 3 downstairs. Each monitor was placed out of reach of riders (under seats, etc). These devices measured CO_2 and PM (also temperature and RH although that data is not used in this analysis).

These monitors were powered using USB sockets. "Voltaic" batteries were added mid-study to provide a more stable power supply. This arrangement means that logging would stop shortly after the bus engine was switched off. An "ODIN" monitor (measuring

PM) was also mounted on the front exterior of the bus. This was powered by a combination of solar panel and lead-acid battery. Data was logged every minute. Data from the Qingping (interior) monitors was sent to a cloud server using USB-powered mobile wifi dongles (one upstairs, one downstairs). Data from the ODIN (exterior) monitors was sent to a cloud server using its own mobile modem, and also stored onto an SD card on the device.

Data coverage and quality:

Although our initial plan was to monitor for at least one day, in practice the monitors remained on the bus from 4th – 19th April 2023. Despite this, low rates of data capture (to be discussed further in Part 2) meant – for the interior measurements - that data from only five days were considered sufficiently complete for analysis.

Data was split into "runs", ie, a complete service from origin to final destination. The ventilation of the bus was either set to full recirculation, or 10 - 20 % fresh air. Details of the data included for analysis are provided in Table 1.

Table 1: Details of days upon which analysis is based.

Date	ventilation	#runs	duration of in-service data (h:mm)	Avg. passenger numbers	Max. passenger numbers
Tue 11th April	Fresh air	9	5:55	19.8	95
Wed 12th April	Fresh air	9	5:05	16.1	48
Thu 13th April	Fresh air	9	6:50	19.9	79
Tue 18th April	Recirculation	4	3:12	35.6	108
Wed 19th April	Recirculation	3	2:09	17.5	61

Although a formal calibration study was not performed, the periods between runs allow an informal mutual calibration between monitors. We found that one monitor was systematically over-reading compared to the others. An empirical correction factor was applied before further analysis.

CO_2 results:

Table 2: Summary statistics for all analysed runs.

Date	Start	End	Run#	ventilation	Service	boardings	CO_2 / ppm		
							Min	Mean	max
11th Apr	6:40	7:10	11	fresh	36 inbound	12	405	593	1062
	7:29	8:02	12		3 outbound	56	525	1148	1910
	8:04	8:47	13		36 inbound	113	407	1482	2686
	8:56	9:29	14		3 outbound	24	498	802	1333
	9:40	10:14	15		3 inbound	18	403	599	906
	12:06	13:17	16		83 outbound	33	394	599	1129
	14:35	15:11	17		3 outbound	45	428	971	1531
	16:55	17:36	18		3 outbound	56	412	1127	1932
	18:10	18:44	19		3 inbound	16	402	569	833
12th Apr	7:00	7:36	20		36 inbound	44	403	873	1306
	8:20	8:58	21		36 inbound	55	813	1366	1786
	11:20	11:59	22		3 inbound	39	412	668	1326
	12:15	12:54	23		3 outbound	31	502	811	1275
	13:00	13:42	24		3 inbound	42	423	754	1191
	14:20	15:02	25		83 outbound	18	479	852	1527
	16:51	17:30	26		31X outbound	44	509	1380	2201
	18:00	18:33	27		3 inbound	30	402	627	976
	18:50	19:21	28		31X outbound	11	492	767	1165
13th Apr	8:55	9:39	29		3 outbound	27	419	659	1030
	9:40	10:18	30		3 inbound	36	406	744	1212
	12:07	13:34	31		83 outbound	56	403	749	1373
	14:35	15:12	32		3 outbound	61	519	883	1382
	15:40	16:27	33		3 inbound	31	403	783	1324

	16:52	17:38	34		3 outbound	98	470	1309	2419
	17:40	18:18	35		3 inbound	26	427	713	1213
	18:30	19:06	36		31X outbound	17	499	706	1070
	19:31	20:08	37		3 outbound	44	467	887	1416
18th Apr	7:41	8:26	42	recirculated	31X inbound	49	464	1361	2352
	9:57	10:36	43		3 outbound	38	746	1145	1601
	15:50	16:45	44		3 inbound	80	403	1264	2641
	17:02	17:55	45		3 outbound	144	674	2840	5039
19th Apr	6:10	6:45	46		3 inbound	24	425	745	1351
	6:55	7:44	47		3 outbound	29	684	1194	1726
	7:50	8:35	48		3 inbound	73	645	1857	3514

Figure 1 shows a sample of typical data from 13th April (mean of upstairs and downstairs CO_2 depicted, plus estimated total passenger numbers). It can clearly be seen that:

1. CO_2 on both decks rose and fell in response to changes in passenger numbers, albeit with a lag (falls in CO_2 followed 0 – 20 minutes after falls in passenger numbers).
2. There was a small and variable difference between upstairs and downstairs CO_2.
3. After most runs, CO_2 returned to a baseline level before the next run began.

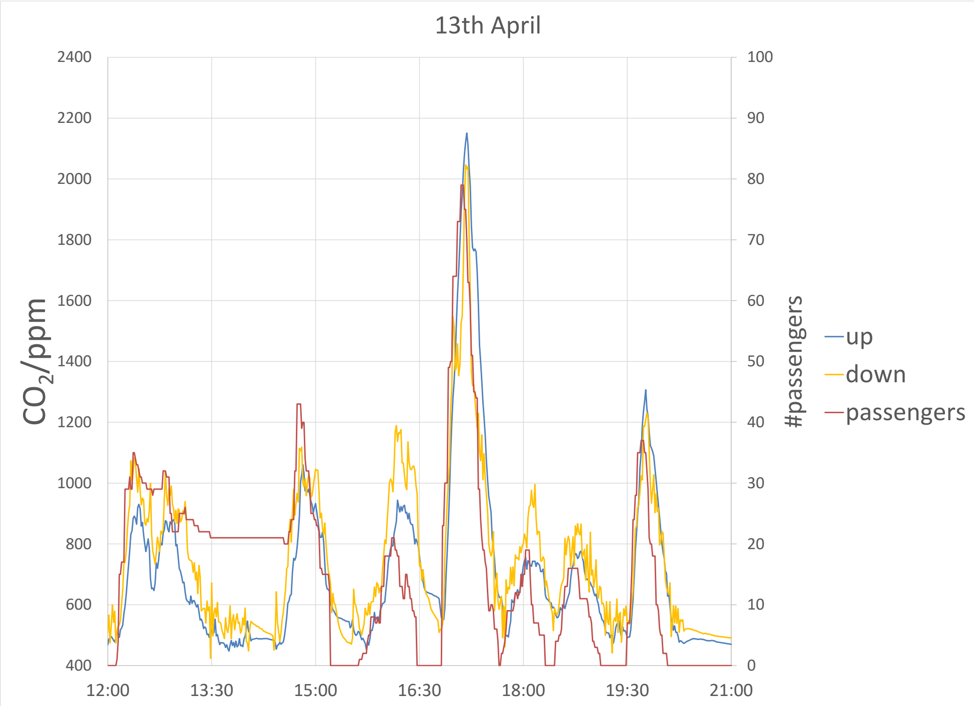


Figure 1: An example observed time series of CO_2 and passenger numbers onboard the bus.

We have calculated the mean CO_2 levels during service runs only for each monitor. A summary is presented in Figure 2.

From Figure 2 we can conclude:

1. CO_2 levels throughout the bus were substantially reduced by introducing fresh air, relative to recirculated air.
2. In the recirculated state CO_2 concentrations were marginally higher upstairs. With fresh air this difference was reversed and reduced.
3. Concentrations were slightly lower towards the front of the downstairs of the bus, especially in the recirculation mode.

Furthermore:

1. The average in-bus concentration with recirculated air was 1535 ppm.
2. The average in-bus concentration with fresh air was 869 ppm.
3. If background CO_2 is assumed to be 420 ppm, then this represents a reduction of 60% in exhaled CO_2 in the bus.

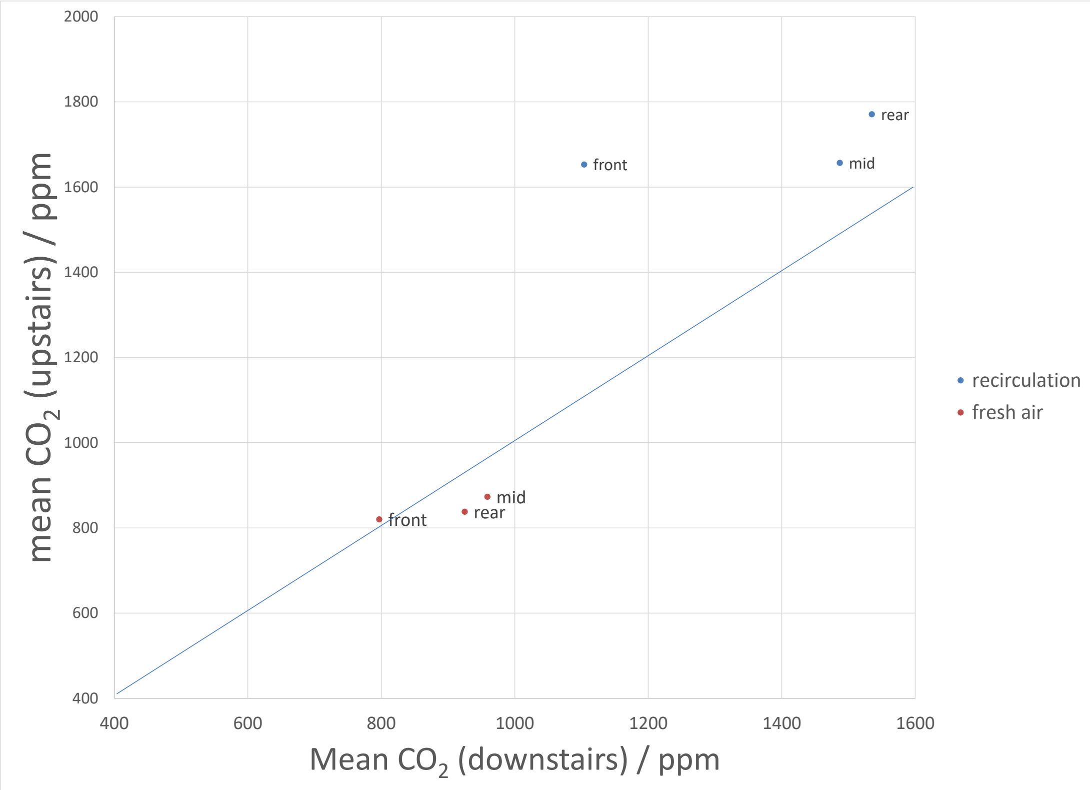


Figure 2: Comparison of all-study mean CO_2 concentrations on the upper and lower decks as a function of ventilation mode.

Figures 3 and 4 show the relationships between maximum CO_2 measured upstairs (figure 3) and downstairs (figure 4) versus the maximum number of total passengers riding the bus for each service run, split between fresh air runs and recirculated air runs.

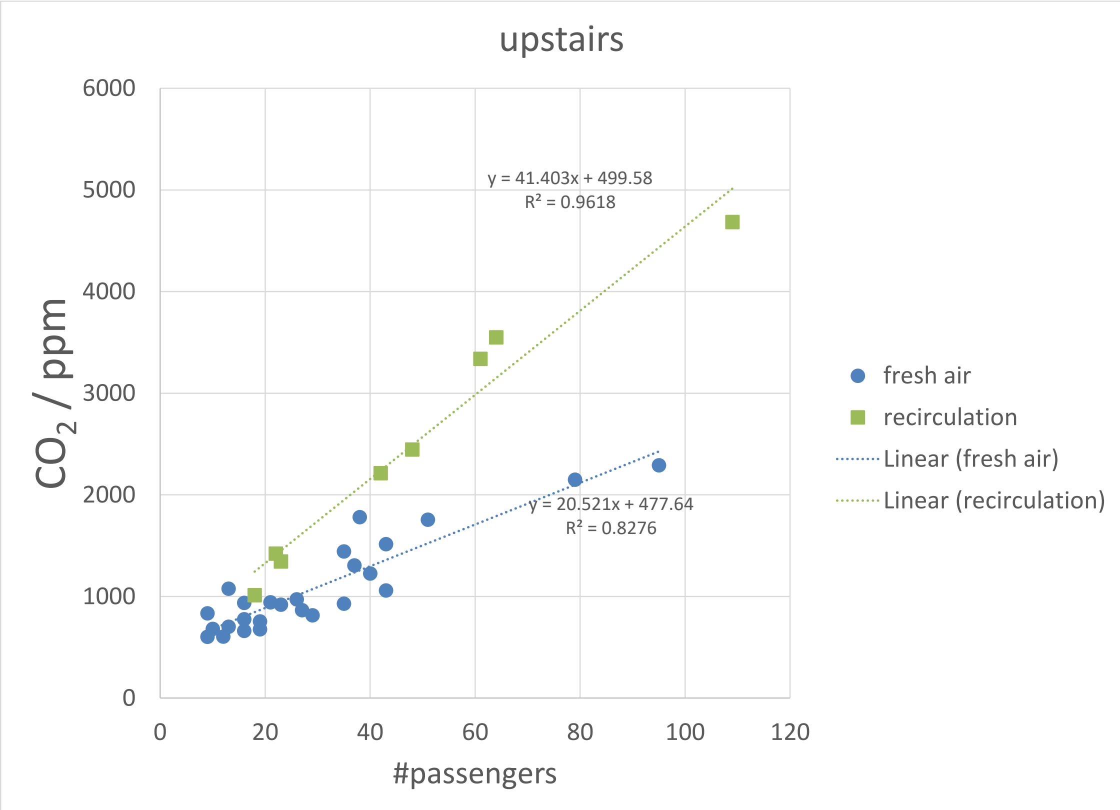


Figure 3: Relationship between maximum CO_2 concentration on the upper deck and maximum number of passengers for each service run.

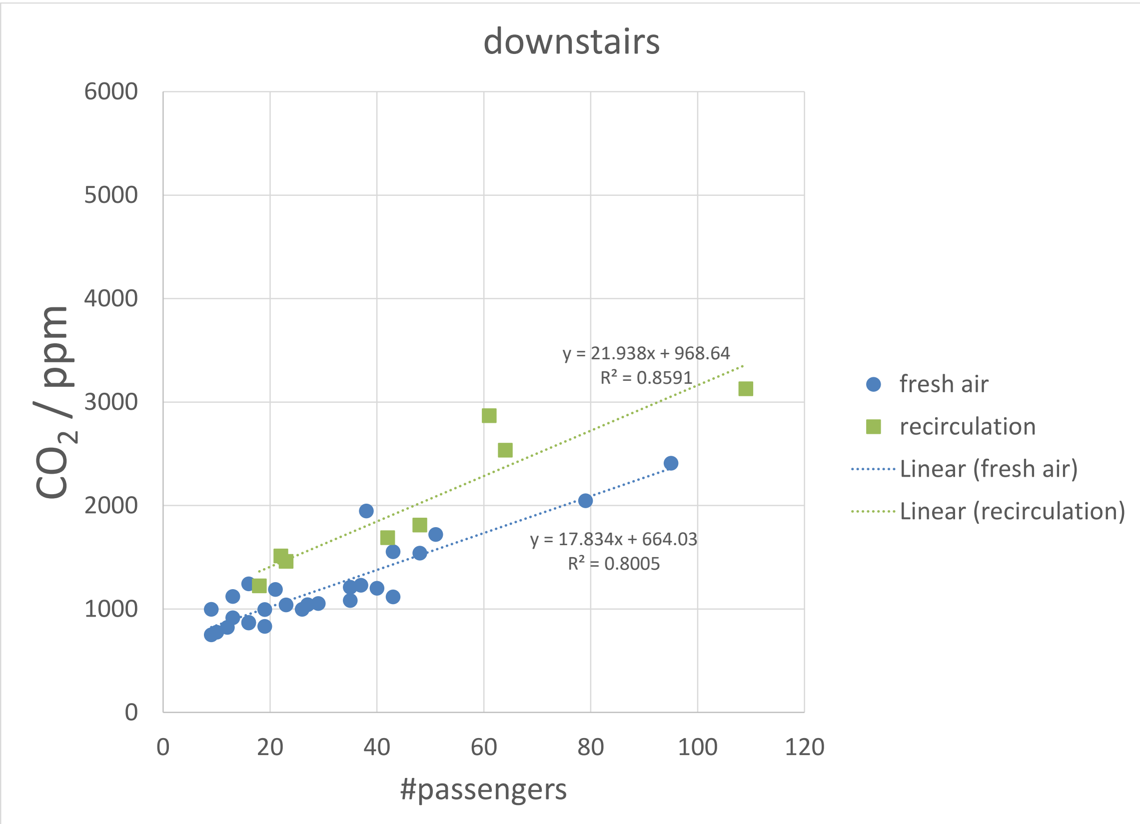


Figure 4: Relationship between maximum CO_2 concentration on the lower deck and maximum number of passengers for each service run.

From Figures 3 and 4 we can conclude:

- Maximum total number of passengers was a strong predictor of maximum CO_2 both upstairs and downstairs and in both ventilation modes. Linear fits had R^2 values above 0.8 in all cases.
- The slope of the relationship was 18 – 22 ppm increase in CO_2 per passenger, except for upstairs with recirculated air (41 ppm per passenger).
- The y-intercepts of both upstairs linear fits were in the range 470 – 500 ppm, which is approximately equal to background levels around busy roads in urban areas during daytime.
- The y-intercepts of downstairs linear fits were 664 ppm and 969 ppm for fresh air and recirculation respectively. These values are a little harder to interpret. We can speculate that this represents an additional source of CO_2 other than passengers on the service being considered. This source could be the ingress (and differential removal) of CO_2 from vehicle exhaust into the lower deck and/or accumulated CO_2 from previous service runs that has not been flushed out between runs.

Generalisability of results:

1. **Can we definitively attribute observed changes in air quality to changes in ventilation setting?**

Figure 3 appears to show a significant effect of the change from recirculation to fresh air that would be difficult to explain by other processes. Whereas Figure 4, however, is suggestive of a significant difference, there are several outliers indicating that other processes modify the simple relationship between maximum passenger numbers and maximum CO_2.

A more robust method would be to build an explanatory mechanistic model that can describe and explain the way different processes combine to result in CO_2 levels in the bus. This would allow us to definitively specify the impact that changes in ventilation caused relative to other potentially significant factors (variations in exhalation, bus speed, number and duration of stops, bus location and surrounding traffic density, wind speed).

A semi-empirical modelling approach was attempted to predict the time-series of whole-bus average CO_2 concentrations, based on a first-order box model concept with three parameters. These parameters - air exchange rate, CO_2 exhalation rate per person and average external CO_2 concentration – were assumed to be constant for each service run and (in some model runs) constant for each day. The model was successful at reproducing the whole-bus average CO_2 concentration based on passenger numbers alone for approximately half of the runs (an example is shown in Figure 5). The successful model runs predicted an exhalation rate varying over a relatively narrow range of 2.6 – 3.2 ppm/minute/person, while estimates of air exchange rate varied over an order of magnitude, seeming to corroborate that changes in air exchange rate were the second most important factor in determining in-bus CO_2, after passenger numbers.

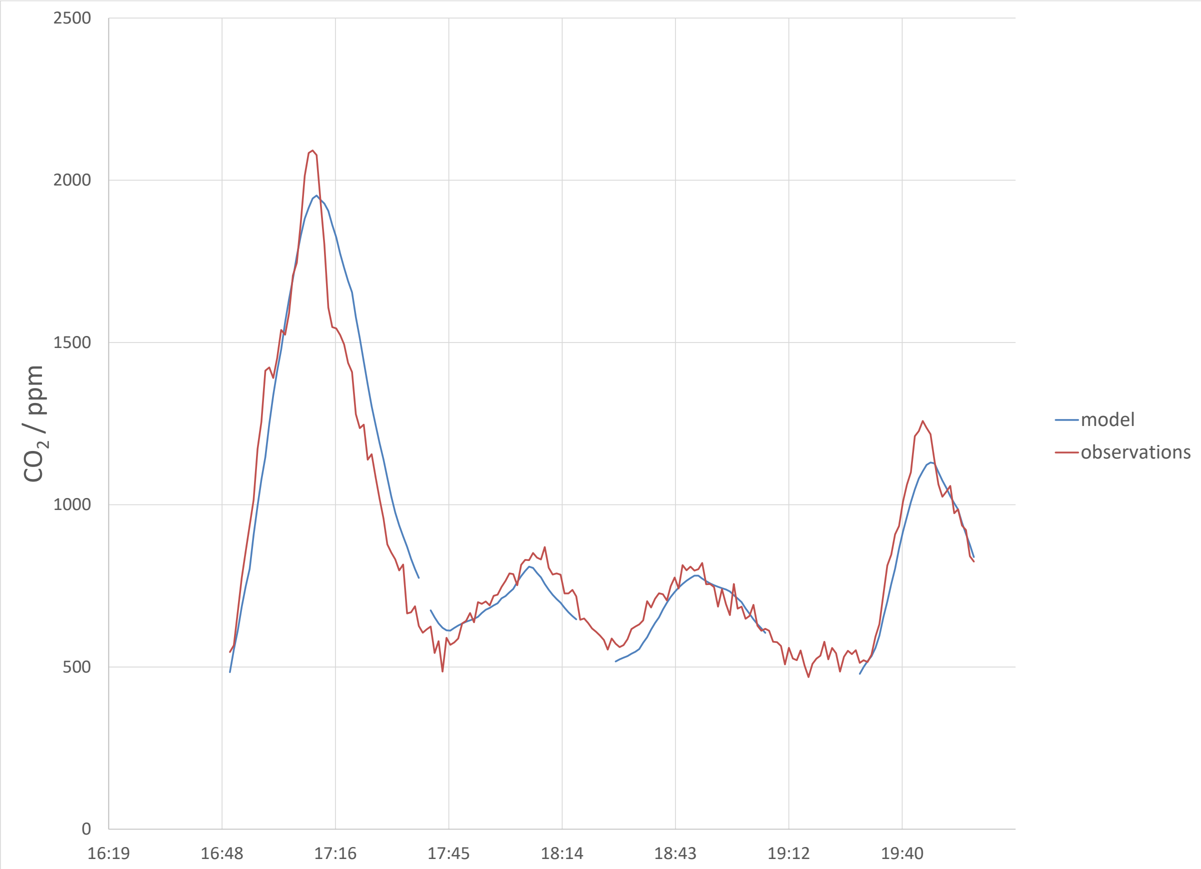


Figure 5: Example of the output of the predictive model compared to observed concentrations.

However, at the time of writing I am not yet satisfied that the results of the modelling are sufficiently robust and consistent to inform conclusions and decision-making. Specifically, the model is yet unable to explain the major changes in air exchange rate it often predicts between consecutive service runs. Two additional pieces of work may improve this. In the first instance the model should be changed to a 2-compartment model (representing the upper and lower decks and the air exchange between them). This modelling will be improved if some data on passenger split between the upper and lower decks during the study runs can be sourced or created (eg, from video surveillance). If this is insufficient, further observational work is recommended. Further details will be provided in Part 2.

2. Are the results likely to be generalisable to other buses, routes, seasons, etc

The results suggest that, as a principle, the introduction of fresh air through the ventilation system is likely to improve onboard CO_2 concentrations on any bus. However, the degree of change is difficult to predict.

The changes in slope observed in Figure 3 and y-intercept in Figure 4 suggest that there are three significant air exchange processes:

- Introduction of fresh air and removal of stale air through the ventilation system (the main subject of this study)
- Exchange of air between the upper and lower decks (which appears to be influenced by the operation of the ventilation system)
- Exchange of indoor and outdoor air through the doors, both when opened and by leakage when closed. Both of these processes may be modified by wind speed and the latter by vehicle speed.

The impact of changes in the ventilation system are likely to be dependent on the magnitude of process #1 relative to the magnitude of processes #2 and #3. The magnitudes may vary for different buses with different ventilation systems, different routes (impacting speed and frequency and duration of door opening) and according to the weather.

However, none of this can be quantified at the present time, meaning we cannot state under what conditions these variations may be significant. We propose two basic approaches to answering these questions:

- An extensive on-bus monitoring intervention study (in effect replicating this study across many buses, routes and in different weather conditions.
- Experimental data gathering studies with the purpose of developing a detailed predictive model of the relevant processes, so that any scenario can then be simulated.
- Some combination of both.

These ideas will be explored further in Part 2. Our team will be very happy to advise on what either approach may consist of and how it could be implemented.

PM (particulate matter) results:

The monitors used (ODIN and Qingping) have a resolution of 1 $\mu g\ m^{-3}$. $PM_{2.5}$ concentrations measured during the study were overwhelmingly very low. The modal and median concentrations inside the bus during service runs were both 1 $\mu g\ m^{-3}$. Outside the bus it was 0 $\mu g\ m^{-3}$. In fact, the outdoor dataset was full of holes and I currently believe it contains no usable information for this study. The potential causes and remedies will be discussed elsewhere.

A typical sample of $PM_{2.5}$ data from inside the bus is presented in figure 6. Unlike the CO_2 data the low resolution of the data is very apparent and the service runs cannot be readily distinguished.

Although disappointing, these results are not wholly unexpected given the known limitations of the instruments. It should be noted that these results do NOT show that levels of vehicle exhaust inside the bus are very low or negligible. While that it possible, these data may also just reflect the low sensitivity of the available monitors to vehicle exhaust. This is to be expected because of vehicle exhaust particulate matter is dominated by "ultrafine" particles which are significantly smaller than the wavelength of light used in optical particle sensors.

There are three potential remedies:

- Conduct careful experiments to characterise the sensitivity of the type of sensors used to road vehicle exhaust.
- Use more sensitive instruments, eg, diffusion screens or condensation particle counters. These devices are generally larger, more expensive, more fragile and require more expert attention increasing the difficulty and cost of such studies.
- Conduct "tracer" experiments in which an instrumented bus follows a vehicle releasing a safe and inert tracer at a known rate.

These options will be discussed further in Part 2.

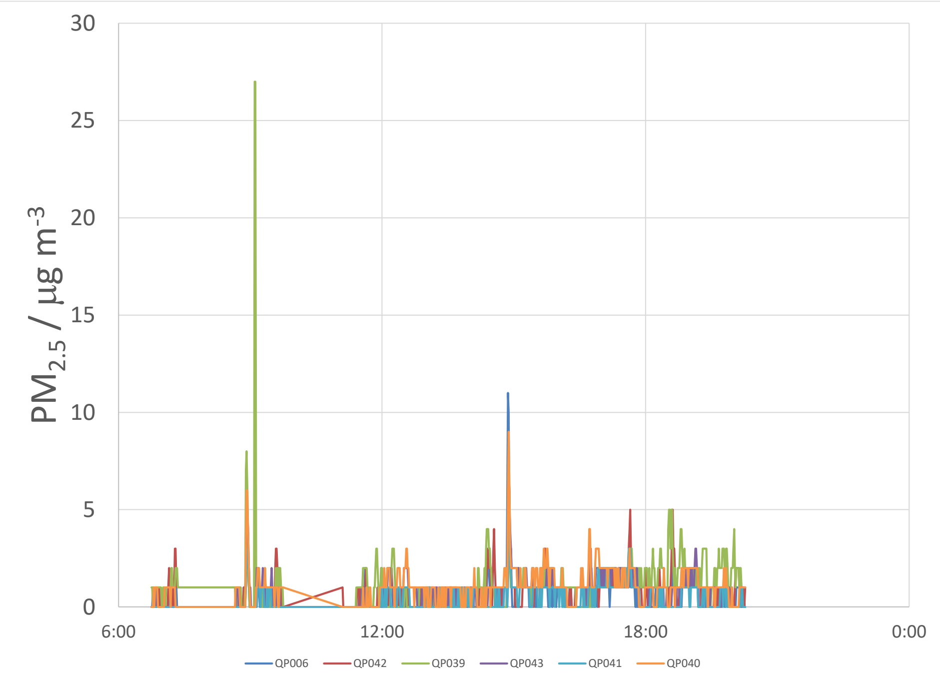


Figure 6: Sample of typical in-bus $PM_{2.5}$ data.

Despite these limitations, and in contrast to CO_2, there was a very small but detectable increase in in-bus $PM_{2.5}$ concentrations when switching from recirculated to fresh air (Figure 7) This indicates that increasing fresh air intake to reduce the risk of virus transmission in the bus does carry with it the risk of increasing exposure of bus occupants to road traffic exhaust pollution.

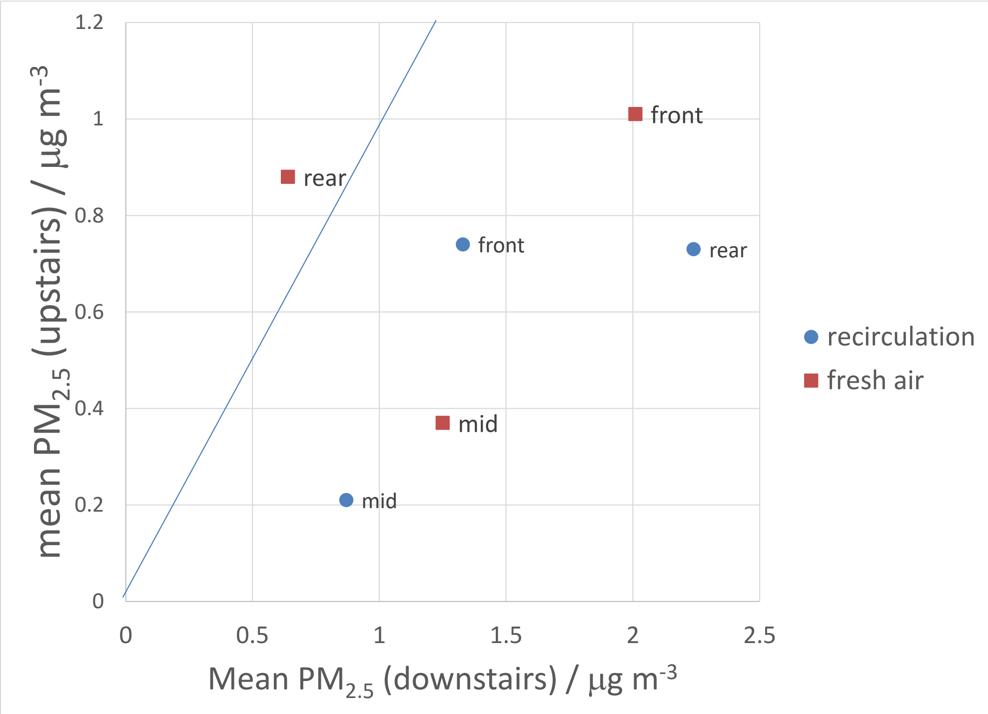


Figure 7: Comparison of all-study mean $PM_{2.5}$ concentrations on the upper and lower deck as a function of ventilation mode.

Appendix: Full results

CO_2 results:

Figure A-1: CO_2 and number of passengers on 11th April 2023 (fresh air).

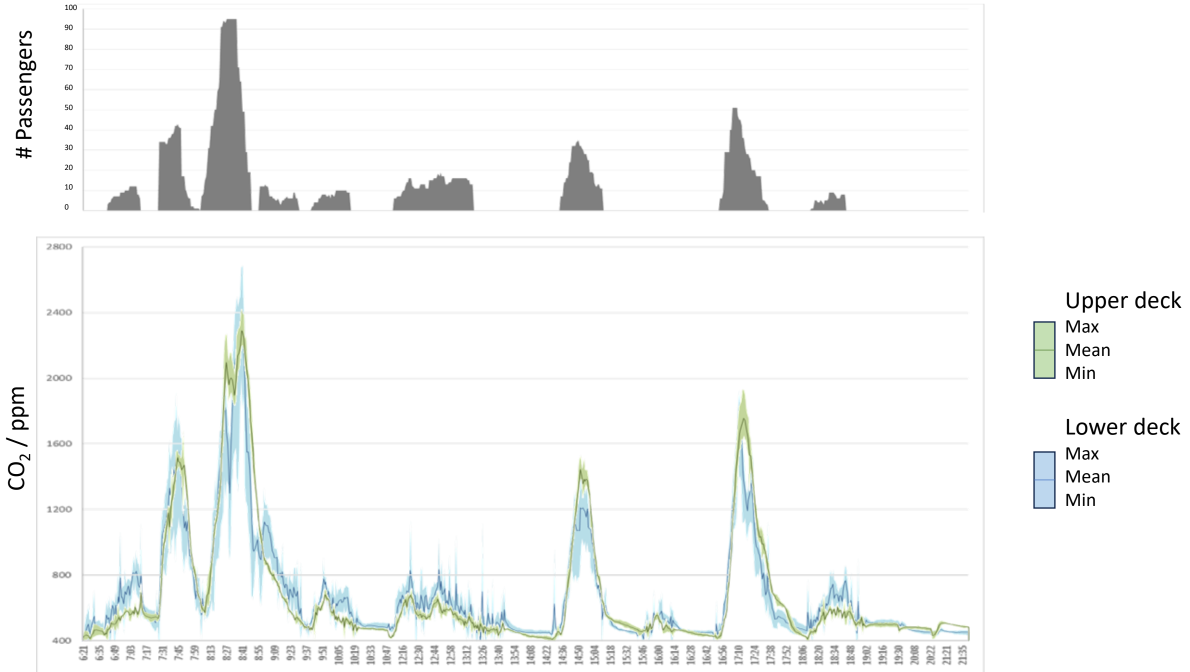


Figure A-2: CO_2 and number of passengers on 12th April 2023 (fresh air).

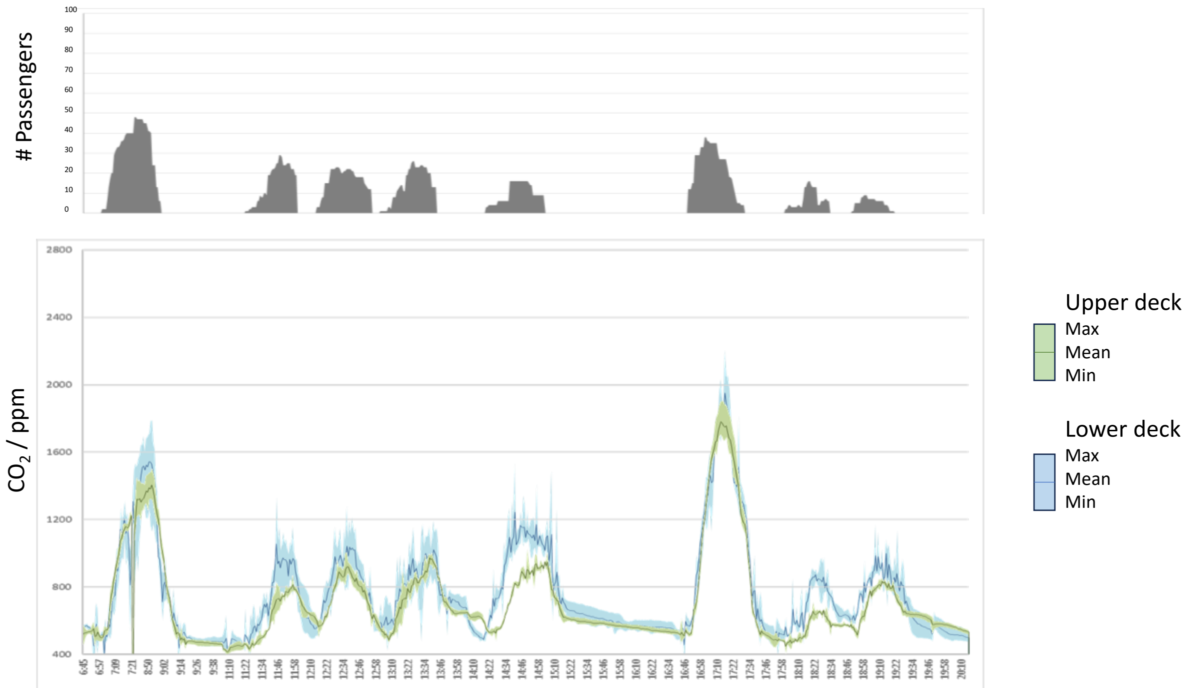


Figure A-3: CO_2 and number of passengers on 13th April 2023 (fresh air). Passenger numbers are likely in error from approx. 13:30 to 14:30.

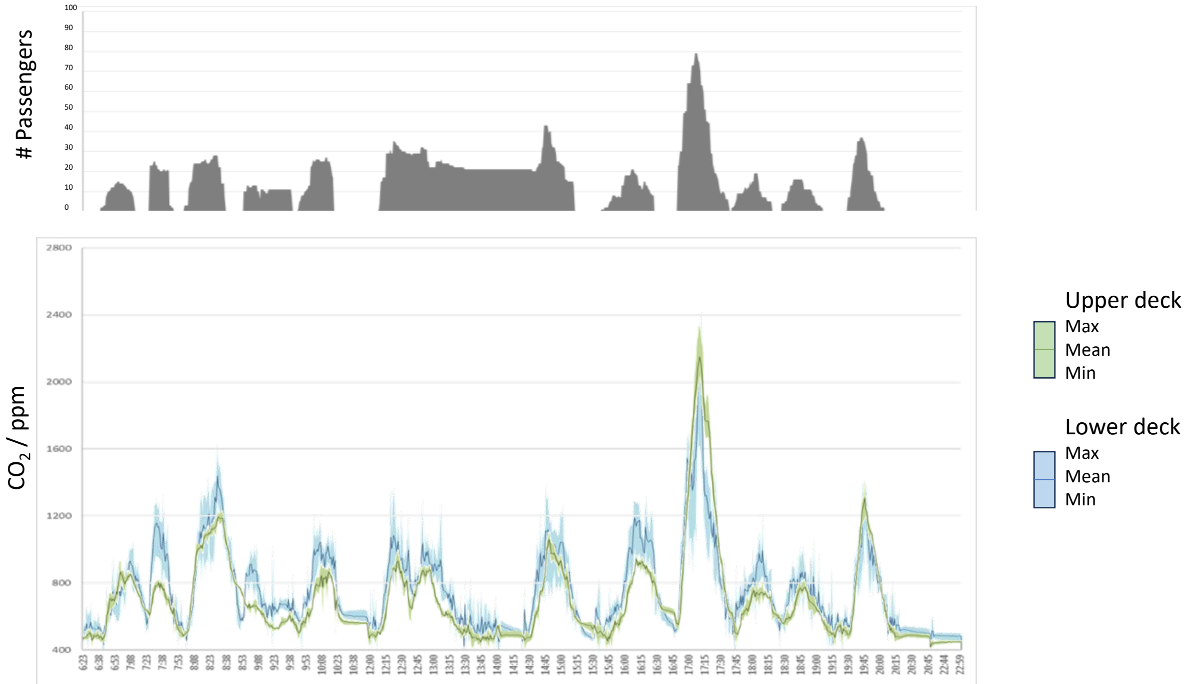


Figure A-4: CO_2 and number of passengers on 18th April 2023 (recirculated air).

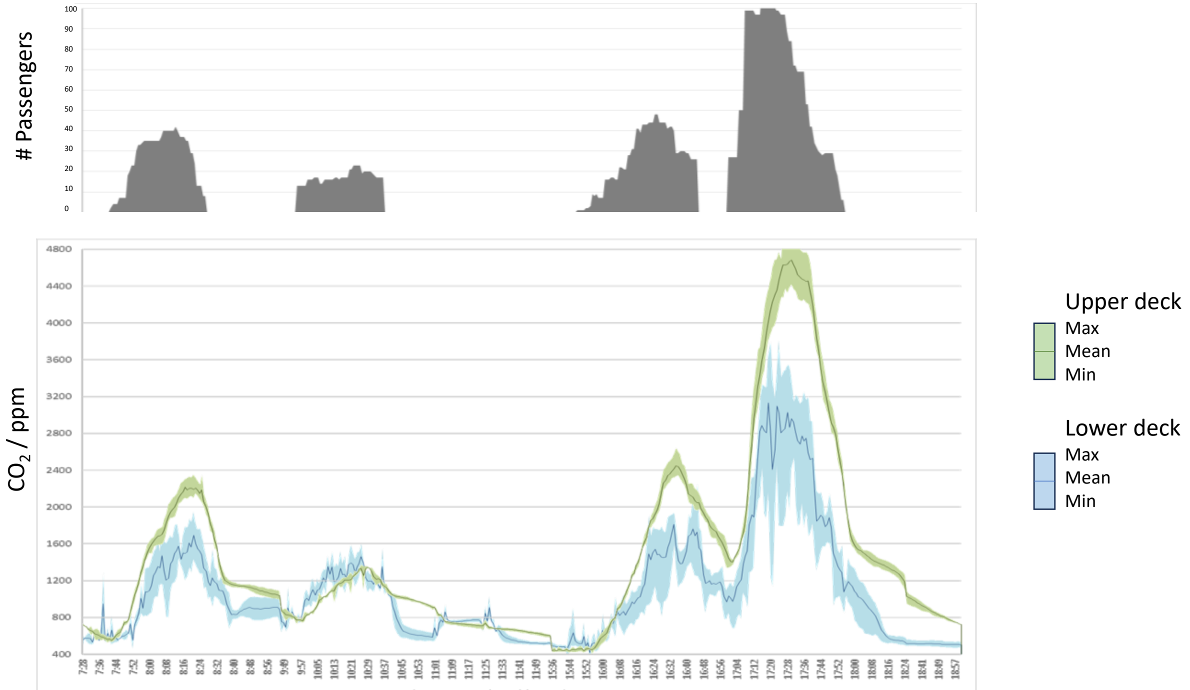
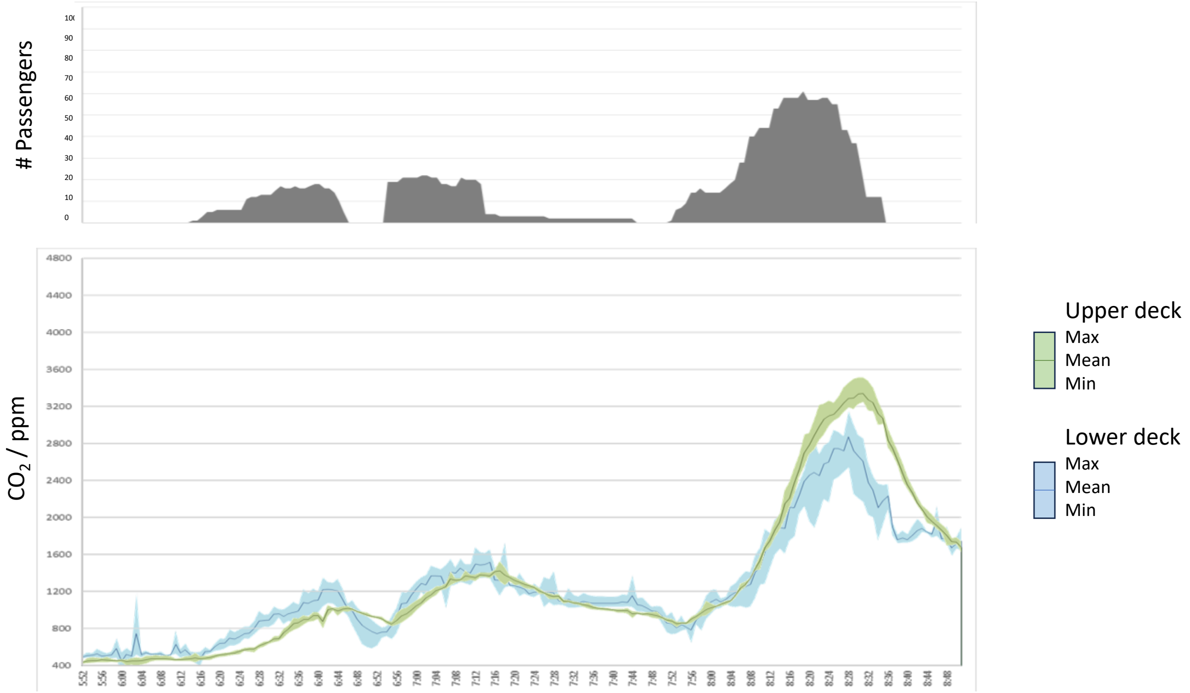


Figure A-5: CO_2 and number of passengers on 19th April 2023 (recirculated air).



PM results:

Figure A-6: $PM_{2.5}$ at six points on 11th April 2023 (fresh air).

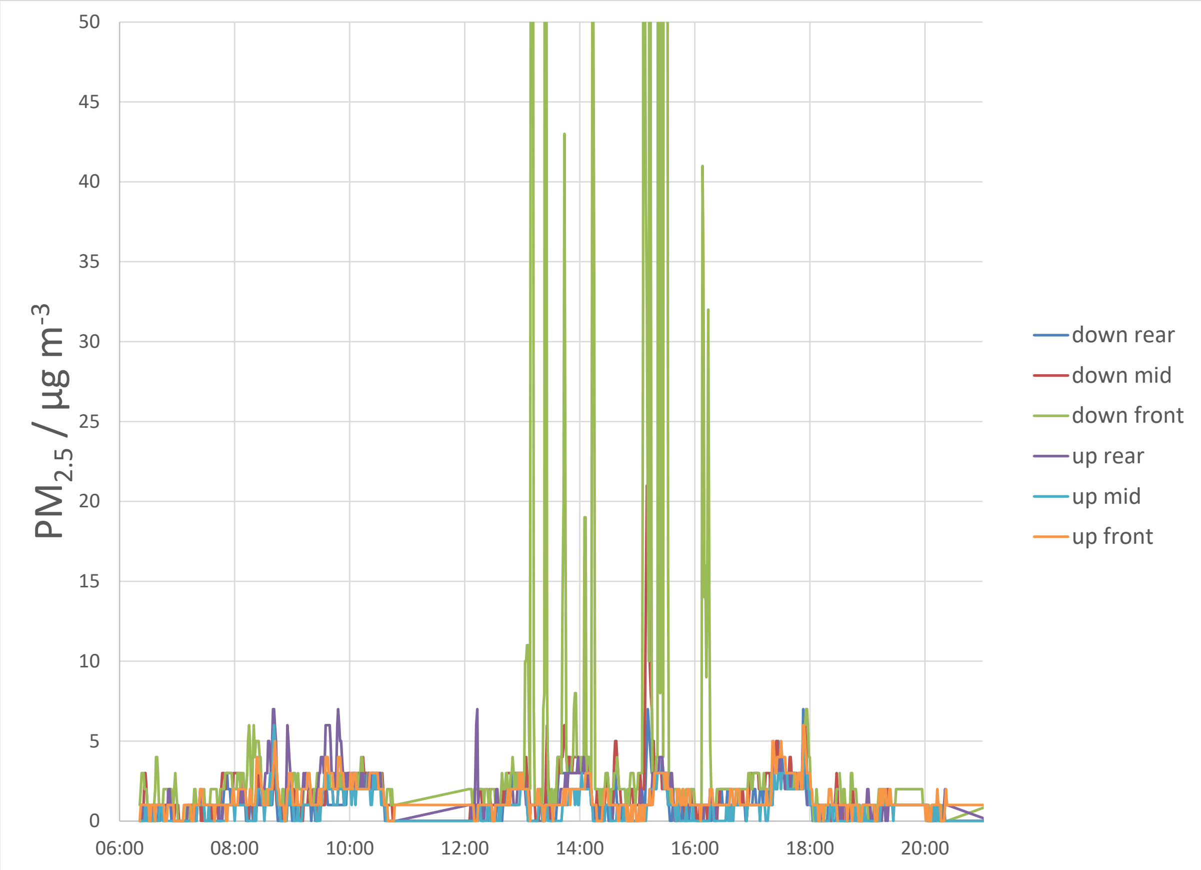


Figure A-7: $PM_{2.5}$ at six points on 12th April 2023 (fresh air).

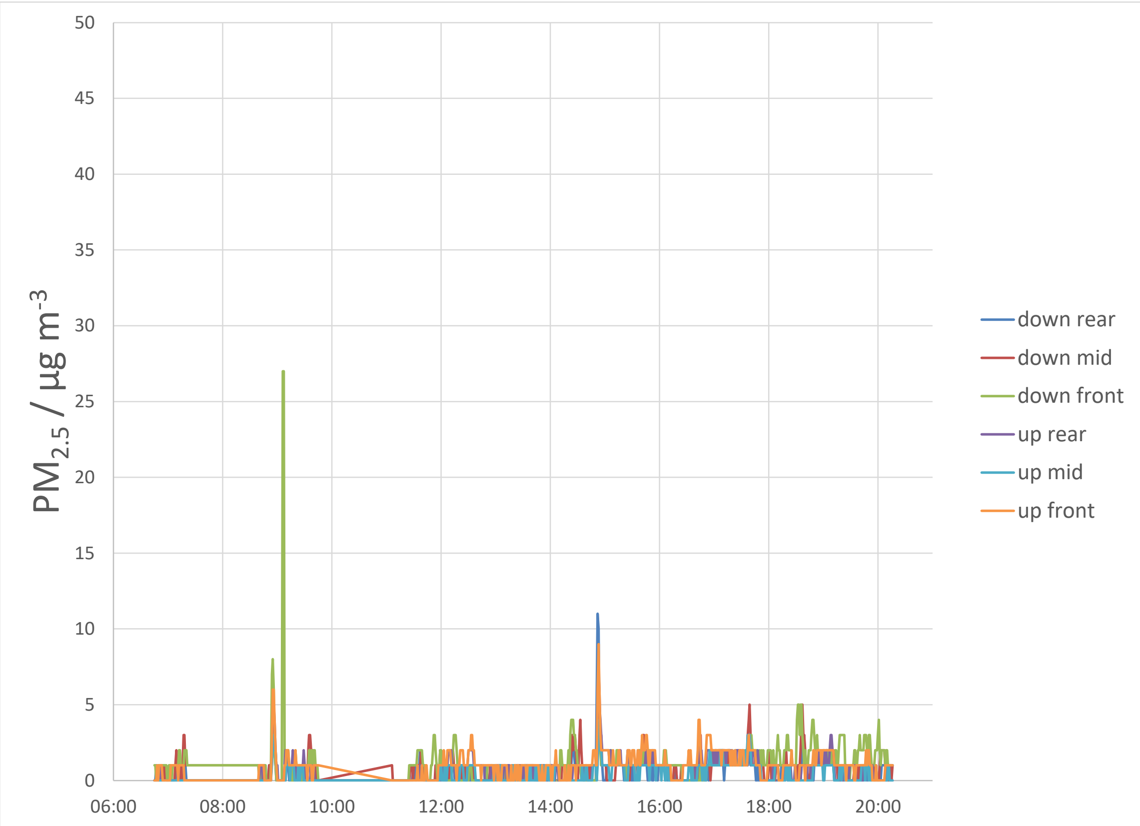


Figure A-8: $PM_{2.5}$ at six points on 13th April 2023 (fresh air).

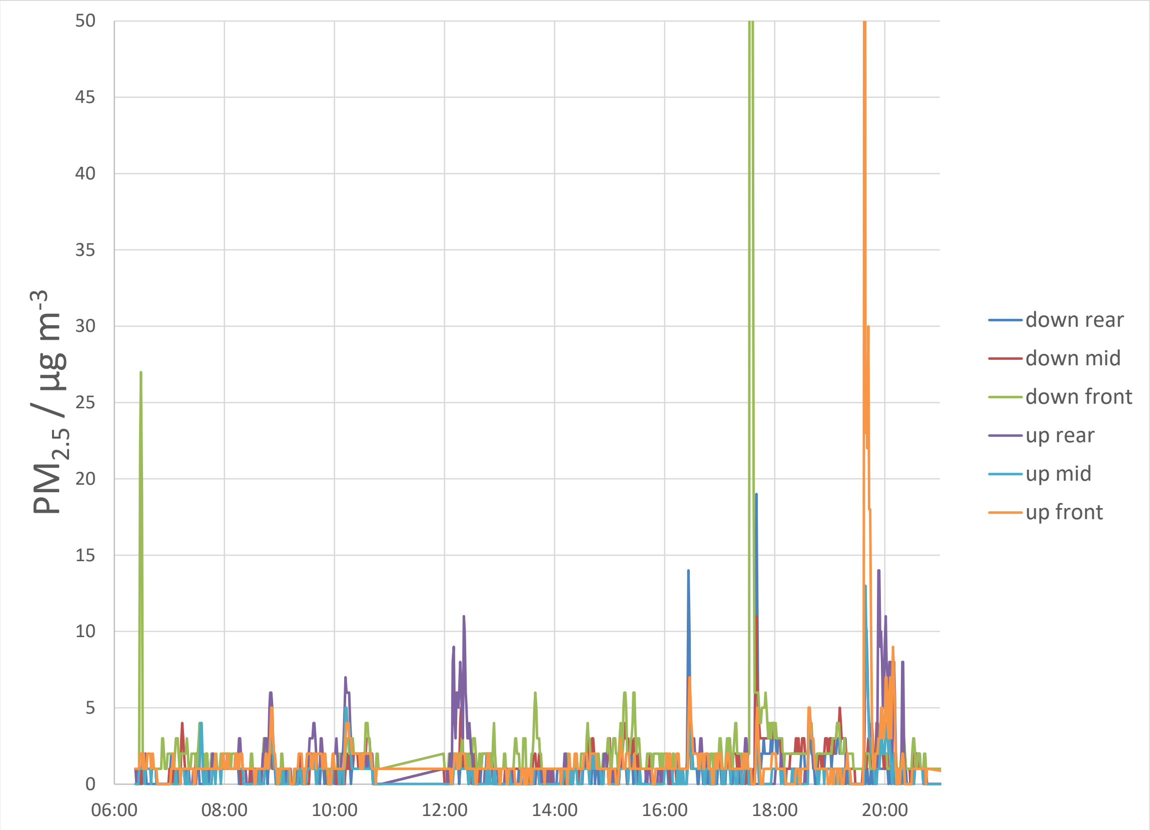


Figure A-9: $PM_{2.5}$ at six points on 18th April 2023 (recirculated air).

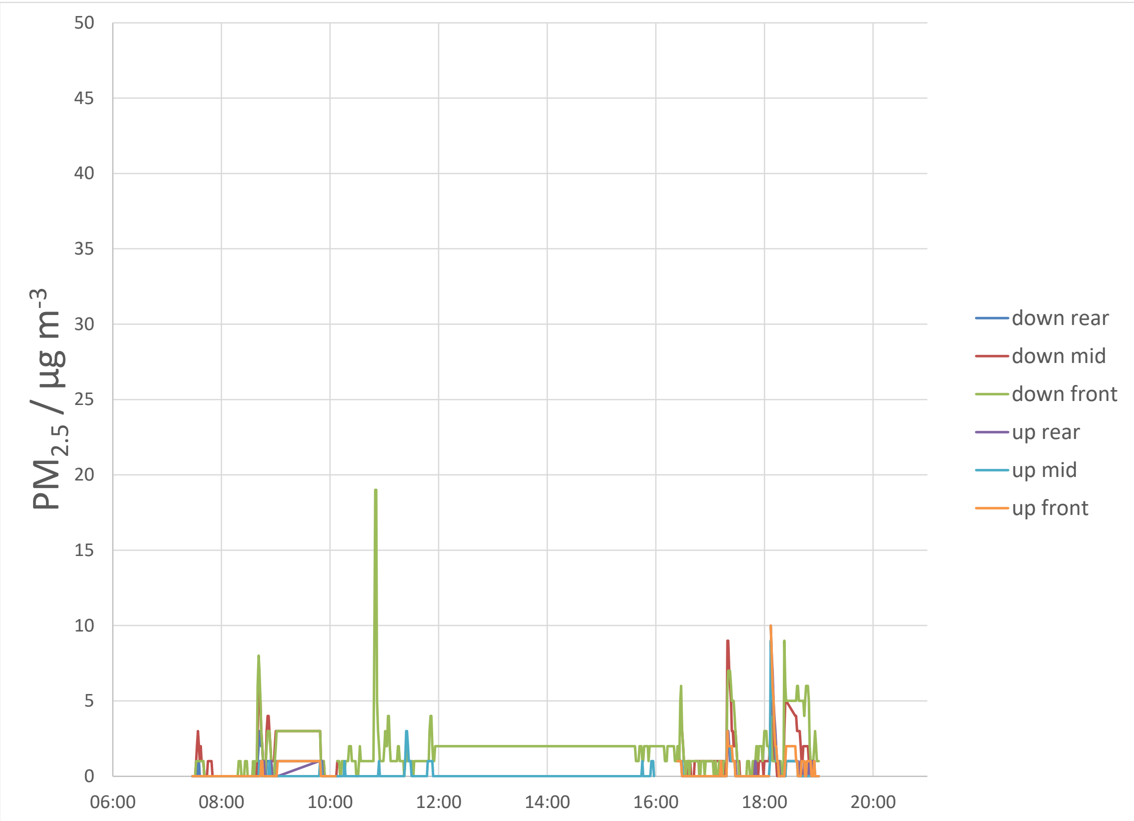
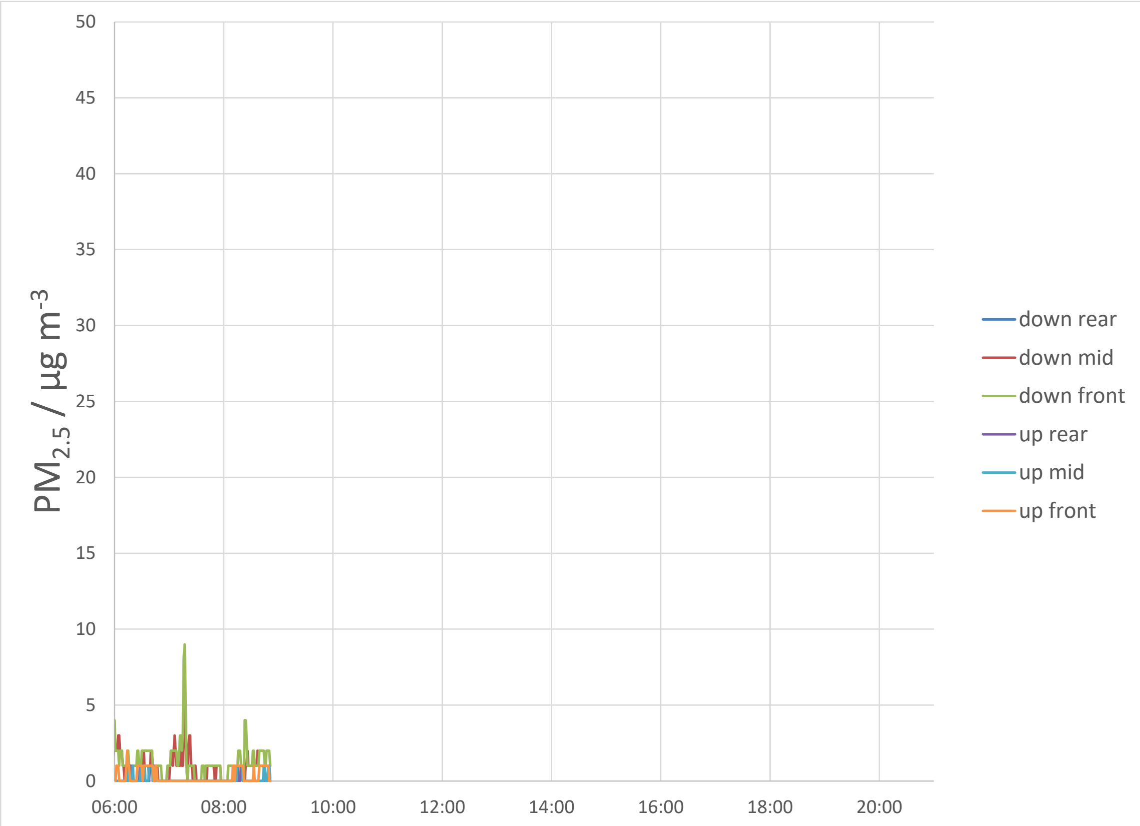
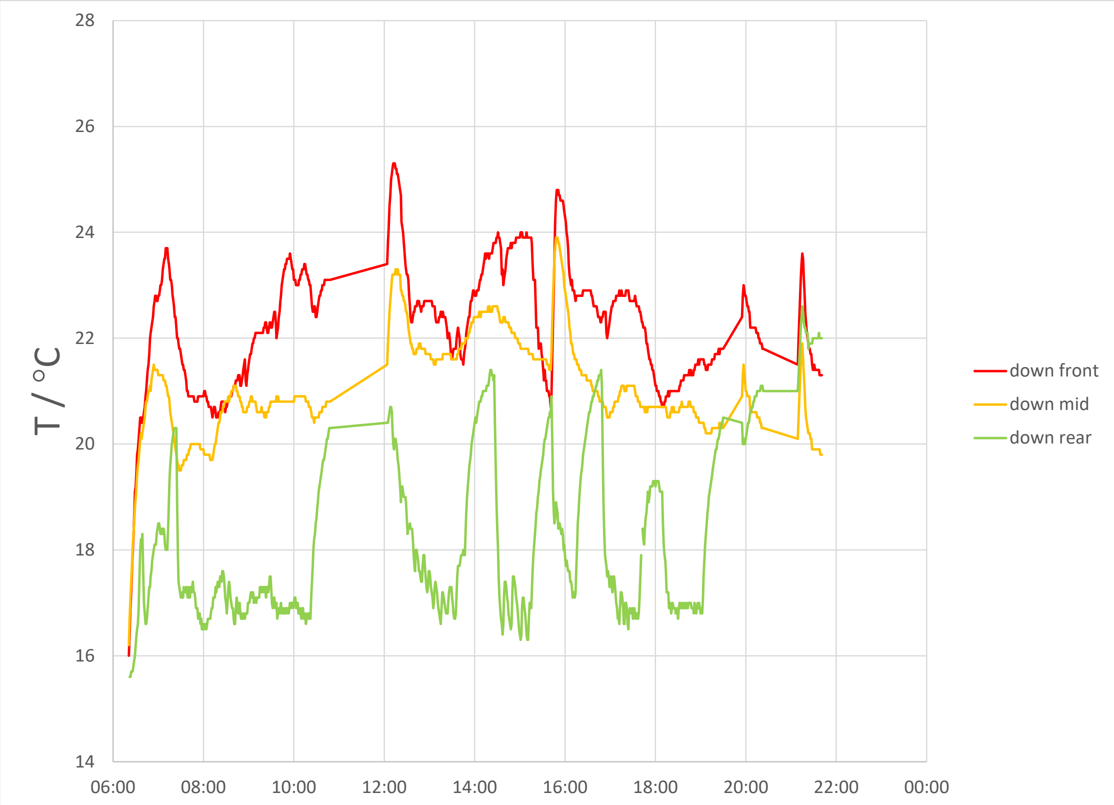


Figure A-10: $PM_{2.5}$ at six points on 19th April 2023 (recirculated air).



Temperature results:

Figure A-11: Temperature at three points each on the lower (left) and upper (right) decks on 11th April 2023 (fresh air).



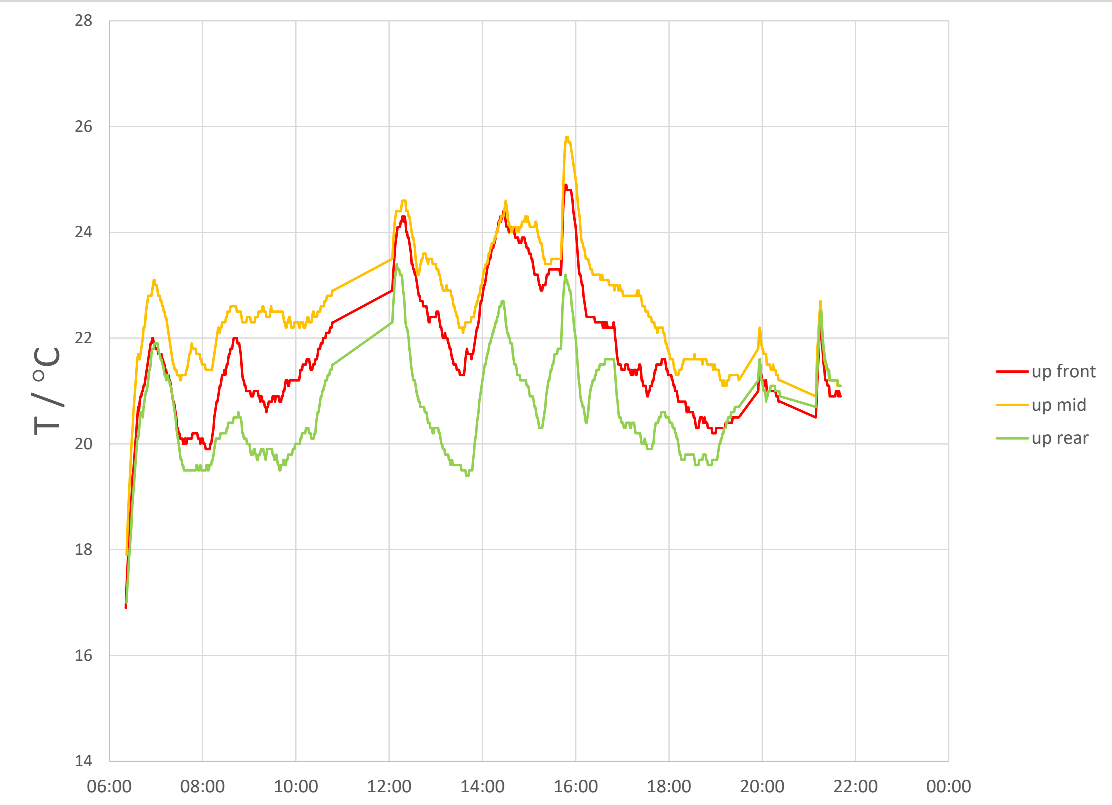
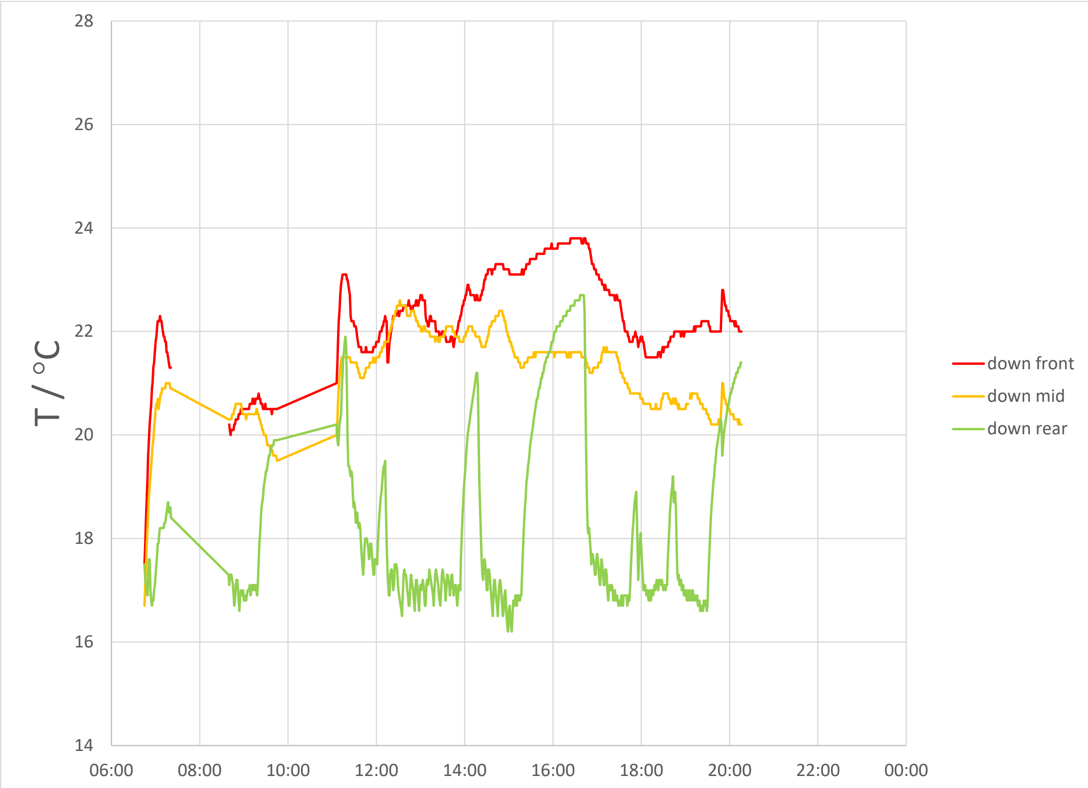


Figure A-12: Temperature at three points each on the lower (left) and upper (right) decks on 12th April 2023 (fresh air).



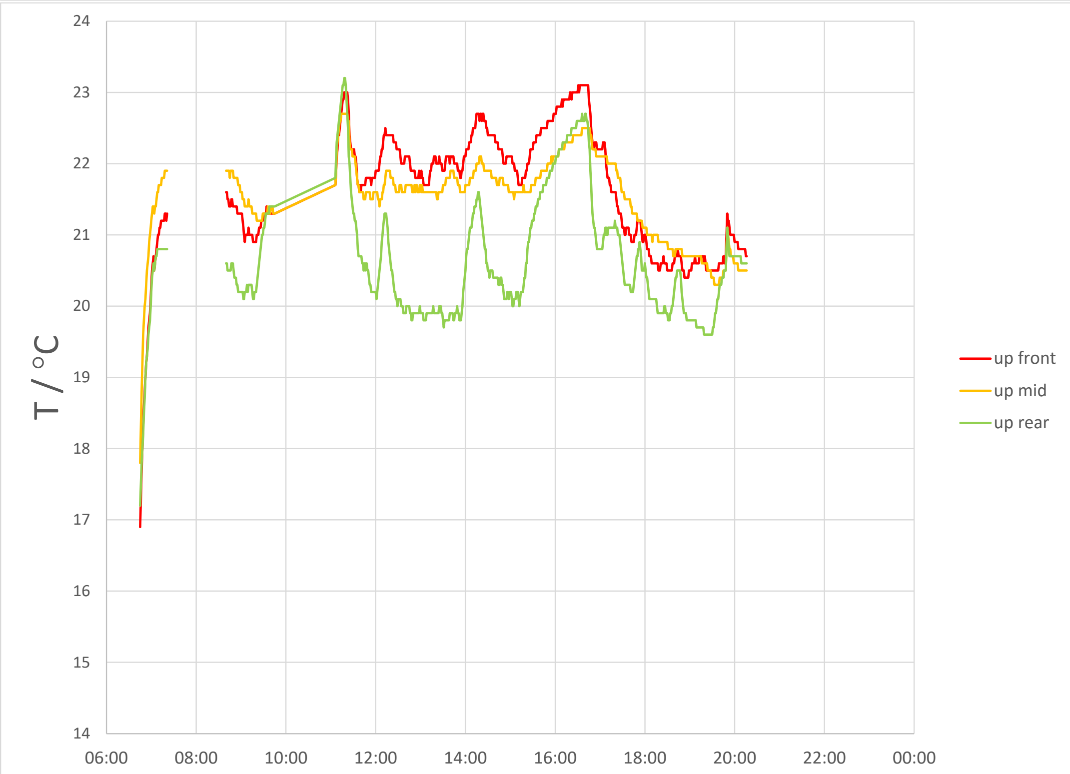
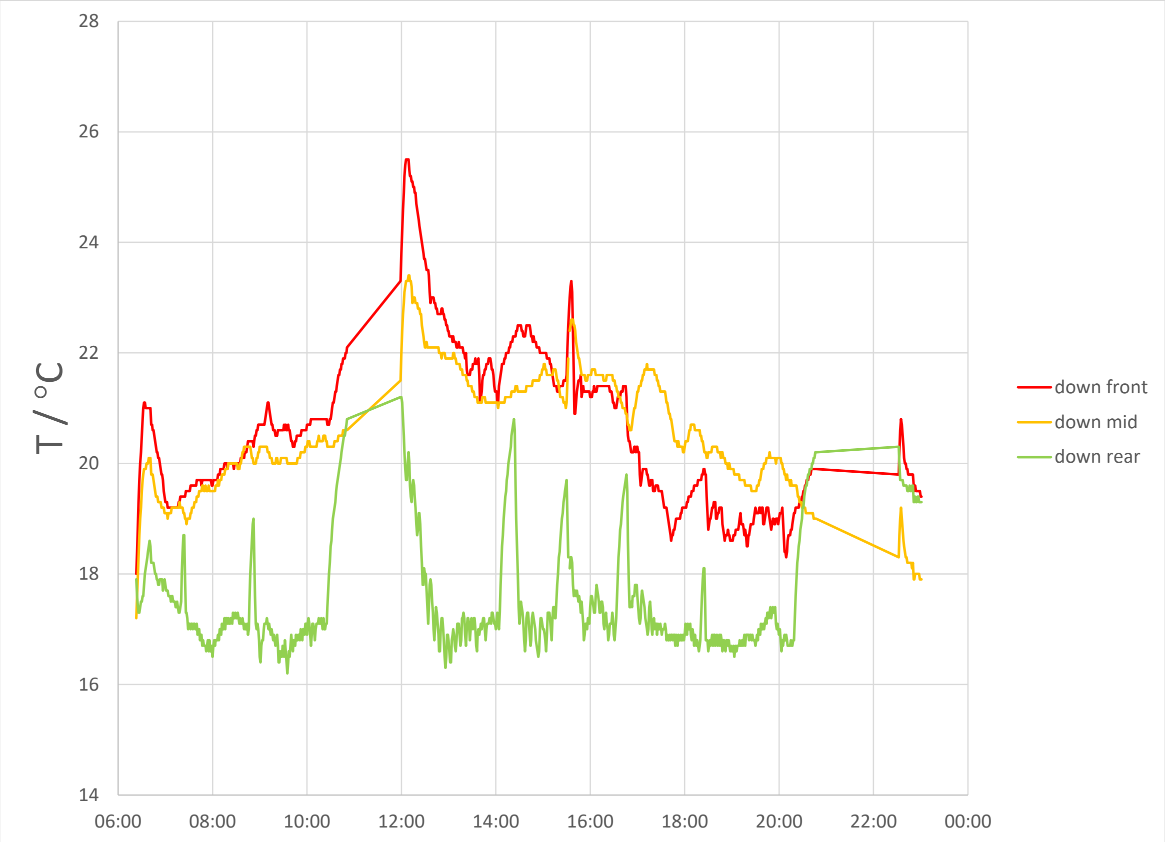


Figure A-13: Temperature at three points each on the lower (left) and upper (right) decks on 13th April 2023 (fresh air).



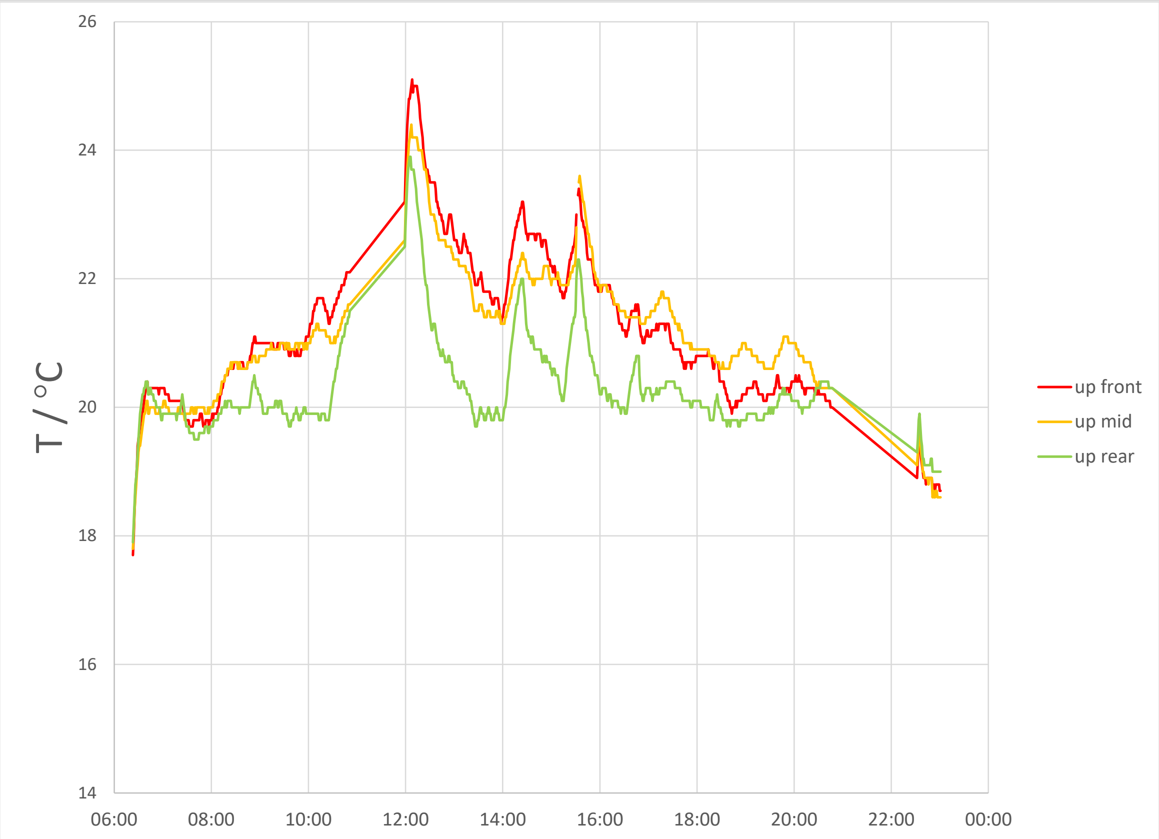
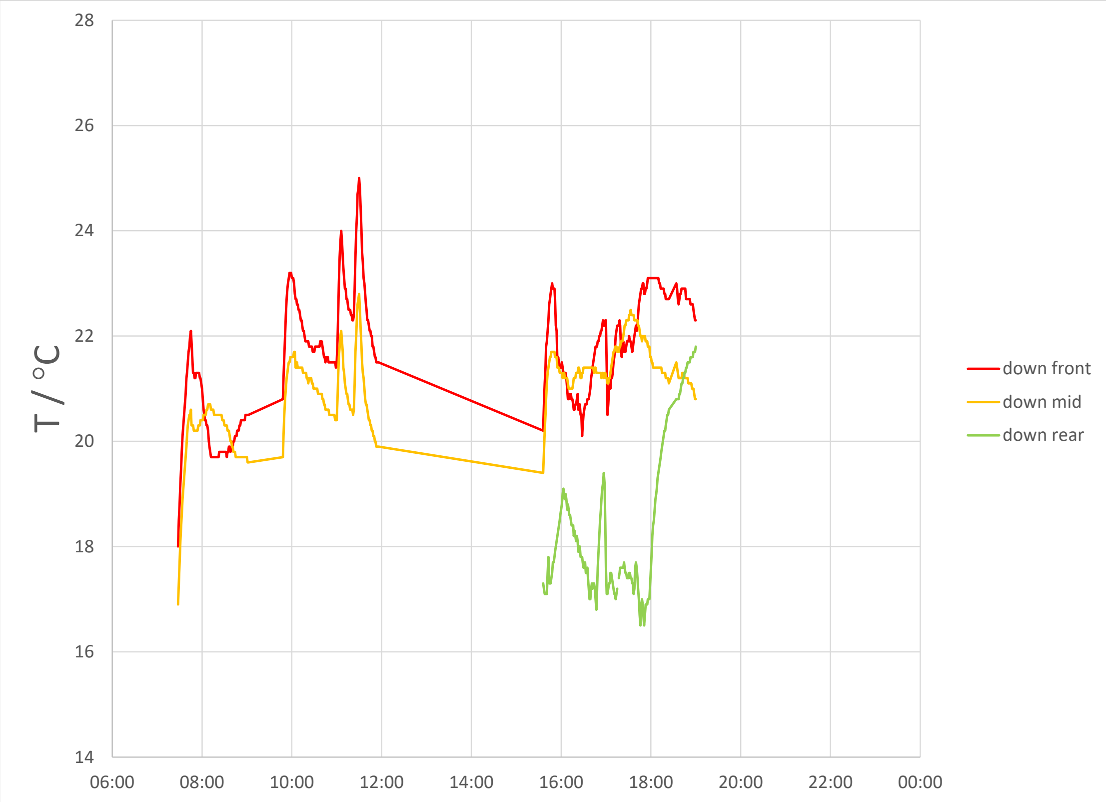


Figure A-14: Temperature at three points each on the lower (left) and upper (right) decks on 18th April 2023 (recirculated air).



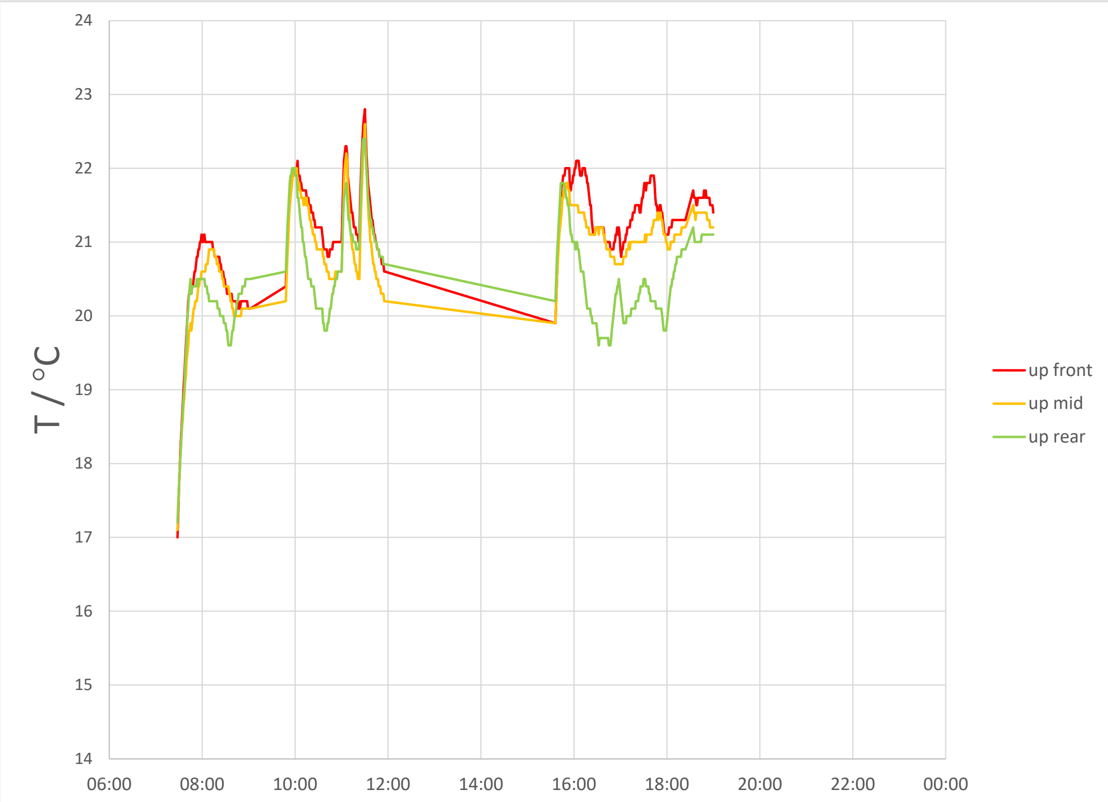


Figure A-15: Temperature at three points each on the lower (left) and upper (right) decks on 19th April 2023 (recirculated air).