Final report

Open Innovation Pipeline – Gas and Environmental Monitoring

Project code	LC.RDE.0019
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Date published	16 December 2024
Published by	LiveCorp PO Box 1174 NORTH SYDNEY NSW 2059 Meat & Livestock Australia Limited Locked Bag 991 NORTH SYDNEY NSW 2059
In partnership with	Transport Genie, Startupbootcamp

LiveCorp and Meat & Livestock Australia acknowledge the contribution from the Commonwealth of Australia to research and development undertaken in the LEP RD&E Program.

Abstract

This proof-of-concept (PoC) trial aimed to adapt autonomous gas monitoring technologies from the poultry and swine industries to demonstrate effective monitoring of potentially harmful gas emissions and micro-climate conditions on livestock export ships. This project focused on ammonia and other gas emissions from accumulated manure and urine, which can harm both livestock and workers if they reach high levels.

The trial, conducted between December 2023 and April 2024, involved installing four-in-one sensors on livestock ships to monitor gas levels (ammonia, carbon monoxide and carbon dioxide), temperature, and humidity. Data was collected over two voyages: a short- haul (eight days) and a long- haul (17 days) voyage. The methodology included sensor placement and continuous data collection via Bluetooth.

Key results demonstrated that the sensors effectively monitored gas levels, temperature, and humidity, despite some data gaps due to sensor dislodgement and mobile device battery issues. The data showed ammonia levels were consistently below the industry standard value of 25 ppm, outlined in standard 5.1.20 in the Australian Standards for the Export of Livestock 3.3 (ASEL 3.3).

The project benefits the livestock export industry by identifying technology capable of providing reliable, continuous monitoring of on-board conditions, enhancing animal welfare, and allowing for early intervention to mitigate potential risks. The successful PoC suggests that further refinement towards a pre-commercial scale implementation of the technology could improve safety and operational efficiency on livestock export ships.

Executive Summary

Background

This project, PoC trial for gas and environmental monitoring on livestock export ships, was designed to answer the question "How can autonomous gas monitoring technologies, utilised in other industries, be adapted and implemented to effectively monitor and mitigate ammonia and other gas emissions on livestock export ships, ensuring the safety and comfort of both livestock and on-board personnel?".

Accumulated manure and urine from sheep and cattle on livestock export ships form a 'pad' during voyages. However, this pad emits ammonia, and, under certain conditions, this can lead to elevated air concentrations which may cause irritation to both livestock and workers. Other gases, such as carbon dioxide and carbon monoxide from machinery, can pose similar risks.

This project was undertaken by Startupbootcamp Australia (SBC) and Canadian startup Transport Genie (TG). It evaluated sensor-based monitoring systems designed by TG for road transportation of poultry and swine, modified to be suitable for monitoring gas levels (ammonia, carbon monoxide and carbon dioxide), temperature, and humidity over two different oceanic voyages (short and long-haul). Key stakeholders for this project included livestock exporters, livestock shipping companies, ship workers and regulators.

Results from the successful PoC trial provide guidance for sensor technology scale up and pathways to commercialisation into the industry, with the anticipated outcomes being improvements in safety and operational efficiency on livestock export ships such as:

- early intervention: enabling early detection and intervention of ammonia and other gas emissions on livestock export ships
- safety improvement: enhancing the safety and well-being of both workers and livestock on board by mitigating the risks associated with harmful gas emissions.

Objectives

This project conducted a three-month PoC trial to automate the process of monitoring gas levels (ammonia, carbon monoxide and carbon dioxide) and other relevant data (temperature and humidity) through translation of TG's poultry solution into a four-in-one sensor solution adapted to a livestock export ship.

The PoC was undertaken over two livestock export voyages (eight-day short-haul voyage in December 2023 and a 17-day long-haul voyage in March/April 2024). The time taken to complete the trials and reporting was longer than anticipated due to significant challenges in transporting the sensors both within Australia, and then allowing for shipping time for the sensors to be returned to Australia from Indonesia and China for data analysis.

Key objectives were to:

1. Evaluate the performance of the TG sensors over both short and long-haul voyages, demonstrating that sensor data can be collected and transferred via Bluetooth.

2. Identify opportunities and potential solutions for early intervention of high gas levels.

3. Develop recommendations for implementation (number of sensors and locations on ship).

4. Conduct a return on investment (ROI) assessment of the overall project including compiling a comprehensive report on the viability and success of the sensor installation for gas detection (ammonia, carbon monoxide and carbon dioxide), temperature monitoring, and humidity control, including photos/videos where possible and detail any lessons learned.

5. Develop a technical document that details the requirements and technical specifications to inform ship owners interested in installing the sensors/system. Prepare a proposal for the supply and installation of sensors for gas detection (ammonia, carbon dioxide, and carbon monoxide), temperature monitoring, and humidity detection throughout livestock export ships based on the PoC trial results.

6. Identify the need for any additional research or trials to enhance sensor technology, improve data analysis, or address specific challenges related to gas detection, temperature monitoring, and humidity control in livestock export ships.

Methodology

Two trials were designed to capture data over a short-haul voyage carrying feeder cattle (from Darwin to Indonesia) and a long-haul voyage carrying breeder cattle (from Portland to China).

Nine TG four-in-one sensors were installed in a variety of locations across four decks of each ship. Mobile phones were used to collect data via Bluetooth from the sensors and were placed in locations that enabled testing the capability of data capture from sensors through different floors and from one end of the deck to another.

Sensor performance was measured by their ability to:

- transmit data via Bluetooth over the full voyage,
- collect and transmit readings of all four measurements: gas levels (carbon dioxide, carbon monoxide and ammonia), temperature and humidity.
- maintain battery life for the voyage.

Results/key findings

Sensor performance

Sensors effectively monitored gas levels, temperature, and humidity across both voyages. Some data gaps occurred due to battery drain on the mobile devices, one sensor failing and one sensor dislodging from its mounting.

Overall, the results of both voyages show that the sensors were able to transmit data for gases, temperature and humidity over Bluetooth throughout the entire voyage, if the signal between the sensors and mobile devices was able to be received.

Battery life of the sensors was able to be maintained throughout the full length of both voyages.

Trends

Because of challenges with maintaining battery life of the Bluetooth mobile devices, it was difficult to obtain multiple days in a row of data, and therefore to observe any trends. Despite this, the sensor data recorded across the two voyages showed:

- daily average ammonia gas levels were measured beneath the regulated standard of 25 ppm for both the short and long-haul voyages (ASEL 3.3).
- temperature and humidity levels rose or fell across the voyage as expected based on the temperature and humidity at the origin and destination,
- carbon dioxide and monoxide readings were highest at loading and unloading, as would be expected for large numbers of animal movements

On the balance of the results, the PoC is considered a success and provides confidence that a more robust solution for data transfer from hardwired sensors to the bridge (such as a Bluetooth mesh) would be an effective solution for measuring on-board gases and micro-climate conditions experienced by livestock and workers.

Benefits to industry

The trial demonstrated that four-in-one sensors can reliably monitor gas levels, temperature, and humidity on livestock export ships, providing real-time data accessible via a dashboard when installed on the ship. This enables the crew to quickly intervene if required, ensuring safe on-board conditions and supporting the industry's commitment to animal welfare.

Accurate monitoring offers a solid foundation for informed decision-making, helping the industry meet regulatory requirements and address public concerns. The study found no significant differences in gas and ammonia levels across varying voyage conditions.

Automated monitoring not only improves operational efficiency by reducing the need for manual data collection but also lays the groundwork for future research and innovation. This could lead to improved better welfare outcomes and enhanced compliance with regulatory requirements.

Future research and recommendations

The data from the trials has been shared and discussed with the livestock shipping company. The key area of interest is the ability for the sensors to provide real time rolling average data advising of conditions experienced by the animals, to enable trends to be identified (as opposed to individual points in time) so that timely intervention can occur, should it be required.

Because the PoC trial relied on battery powered mobile devices to collect the sensor data, ensuring these devices remained charged placed a human intervention burden onto the ship's workers. Any future PoCs or commercialised devices should ensure a solution that requires little to no human intervention, such as via use of Bluetooth low energy devices connected to the ship's power supply.

A further recommendation is to include an academic researcher as part of an advisory committee for future PoCs with startups to advise on trial design, statistical analysis of trial data and provide input on research methodology.

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1. Background

1.1. Industry challenge

The livestock export industry is of significant value to the Australian red meat sector, with 1,324,141 livestock exported by sea and air in 2023 at a total value of approximately AU$1.03 billion. Australia is an important provider of high quality protein to overseas markets such as Indonesia, which imports 54% of Australia's exported livestock (MLA 2023). Despite media scrutiny and intense animal activism, recent community sentiment surveys showing that Australian community attitudes towards livestock export, socially and economically, have improved over the last four years (Voconiq, 2023).

Accumulated manure and urine from sheep and cattle on livestock export ships form a 'pad' during voyages. On longer cattle voyages, bedding material such as kiln-dried sawdust and wood shavings is added to the pens to improve comfort to minimise the incidence of lameness and skin abrasions during the voyage. When used in conjunction with routine pen washing, bedding material also helps lower moisture in the air and maintain low levels of ammonia in the pen environment, among other benefits (Banney, 2009).

The pad and bedding emit ammonia, which under certain conditions may reach elevated air concentrations that may cause irritation to both livestock and workers. Other gases, such as carbon dioxide and carbon monoxide from machinery, can pose similar risks. Micro-climate indicators such as temperature and humidity are routinely measured and recorded during a voyage; however, gas measurements are typically conducted only with handheld devices, conducted by ship workers.

Industry stakeholders for this project are producers, exporters, shipping companies, vets, regulators and agriculture agencies, overseas breeding farmers, processors and consumers – essentially all players along the Australian livestock export roadmap[1].

Industry stakeholders across the value chain have identified ammonia as one of the top five animal welfare concerns. Implementation of the industry standard threshold of 25 ppm as outlined in ASEL 3.3 under standard 5.1.20 for ammonia exposure in the Australian livestock export sector requires the industry to reliably monitor values.

Previous research monitoring gases, temperature and humidity on oceanic voyages that relied upon hand-held measurements have identified challenges with on-board data collection due to the data being from single point in time. A study in 2017 analysing ammonia, temperature and humidity data across two voyages identified that whilst obtaining ammonia and temperature values was achievable across a modest number (8-10) of monitoring sites, relative humidity measurements were not reliable (Zhang, 2017). The findings also highlighted that "An understanding of effective sampling strategies, including those with electronic monitoring, will enable livestock exporters to improve animal welfare during live export by efficiently monitoring the micro-climatic conditions and taking appropriate actions to control excesses".

This project was designed to answer the question "How can autonomous gas monitoring technologies, utilised in other industries, be adapted and implemented to effectively monitor and mitigate ammonia and

[1] Australian livestock export roadmap, from LiveCorp website

other gas emissions on livestock export ships, ensuring the safety and comfort of both livestock and on-board personnel?".

Conducted in partnership between Startupbootcamp Australia and Transport Genie (TG), this trial was designed to evaluate adaption of TG's sensor application from a poultry/swine transport setting for road transport into an oceanic livestock transport environment.

1.2. Project team

1.2.1. Transport Genie

TG is a startup headquartered in Aurora, Canada. Founded in 2018, TG's vision is to de-risk transportation events to drive economic value, improve animal welfare, lower the impact from revenue loss and fines, enhance traceability, lower biosecurity risks, and preserve quality through real-time artificial intelligence (AI) powered automated interventions. With initial market roll-out in the poultry and swine industries, TG has a range of sensors for transportation of livestock and fresh produce in varying stages of development from commercial deployment through to minimum-viable products undergoing PoC testing. Further information on Transport Genie can be found in the Appendix.

TG was a member of the Startupbootcamp Australia FoodTech Tasmania 2022 accelerator cohort.

1.2.2. Startupbootcamp Australia

Startupbootcamp Australia (SBC) is the second largest business unit in the Startupbootcamp group of companies. Globally headquartered in Amsterdam, with Asia Pacific headquarters in Melbourne, SBC runs industry led accelerator programs all over the world. Its industry-focussed startup accelerator portfolio includes two Food & AgriTech programs, one in Amsterdam and one in Tasmania, which is running for its third year in 2024.

SBC's approach to finding startups for its programs takes a global outreach view, using a combination of proprietary AI and machine learning tools to scout for companies that meet the needs of their corporate partners. Meat & Livestock Australia (MLA) is a corporate partner of the FoodTech Tasmania program, where SBC scouts for companies that fit within the scope of the Product and Packaging Alignment program under MLA's High Value Food Frontiers Program. Other themes include circular economy, food and agritech advances (including animal welfare, traceability, mechanisation and robotics) and processing, supply chain and labour technologies.

2. Methodology

2.1. Stakeholder engagement

2.1.1. Shipping company

Meetings were held in July and August 2023 with the shipping company followed by a ship visit in Singapore. Discussion points included:

- potential trial dates and destination for Voyage 1
- travel length information (e.g. ships to Indonesia take 4.5 days, ships to China take 21 days)
- potential risks including data security, data communication plans
- suitable ships for trial
- regulatory bodies and compliance for exporters, mandatory reporting requirements, ship regulatory compliance
- benefits and challenges associated with moving to fixed and continuous on-board gas monitoring
- considerations for trial data, including data security as well as communication plans for the data
- current daily micro-climate reporting
- current situation with respect to ammonia levels and current solutions to reduce potential for high levels.

The ship visit was arranged in Singapore to observe the existing layout and conditions firsthand, as well as:

- develop a trial design and methodology based on information from stakeholders and ship inspection, including IT integration with ship systems
- identify the best location for the sensors for trial transportation
- identify any further potential impediments/issues that could arise from the trial
- obtain a baseline understanding of the sensors' ability to send Bluetooth low energy (BLE) signals in the hull of the ship
- understand what BLE or Wi-Fi infrastructure would be present
- take measurements and conduct inspections of the identified areas, considering people movement, ventilation systems and other structures that may interfere with sensor placement
- evaluate the most representative or critical areas of the ship that would benefit from the installation of sensors for monitoring gas levels, temperature, and humidity based on stakeholder feedback.

Following these initial meetings, further internal discussion at the shipping company uncovered several other risk areas such as appropriate insurance cover for a PoC, and data ownership and sharing arrangements.

Engagement with the exporter regarding the PoC was handled by the shipping company. On reflection, stakeholder engagement with the shipping company was ultimately successful but might have been more efficient by holding a more comprehensive project kick -off meeting.

2.1.2. Industry advisor

The LEP RD&E Program arranged for the assistance of an industry advisor with significant experience within the livestock export sector to provide guidance on trial design. This guidance was critical in defining the tasks of the 'Responsible Person" role (as outlined in 2.3) and understanding the time window within which the sensor installation needed to be completed.

2.2. Trial design

2.2.1. Sensors

The TG four-in-one trial sensors are manufactured in Canada by Marlex Systems and have the following parameters and design features:

- Dimensions: 230 x 230 x 145 mm
- Weight approximately 3.17 kg
- Power source: ML8-12 - 12 Volt 8 AH SLA (Seal Lead Acid) battery with a battery life designed to last for well more than the voyage without the need for recharging
- Restrictions: NOT pressure washable
- Measurement: ammonia (NH_3), carbon dioxide (CO_2), carbon monoxide (CO) ambient temperature, and relative humidity. These four micro-climatic variables were recorded every 30 seconds
- Broadcast: BLE broadcast was used to send data from the sensor to the mobile receiver.
- Mountings: sensors were mounted to the ship walls via neodymium magnets with a pull force of 41 kg and are shown below.
- Each sensor has a unique sensor identification number which was recorded with each data point collected.

Side View of TG four-in-one sensors

Magnets to affix sensors to ship walls

2.2.2. Data collection via Bluetooth low energy

A mobile phone receiver was used to collect the data from the sensors over the BLE broadcast. The mobile receiver was housed in a waterproof plastic container and affixed to the wall as shown in the image below.

The shipping company required that a power bank was not to be attached to the mobile receiver and left in the hull throughout the entire voyage due to safety reasons. Therefore, the battery levels on the mobile receiver were required to be checked by the Responsible Person once per day (see 2.3 for definition of the Responsible Person). This restriction caused challenges in that the mobile device battery did not last as predicted, and the recharging of the device took approximately two hours, necessitating more work that was expected for the Responsible Person. This is discussed in the results.

Sensor attached to wall, showing mobile device

2.2.3. Data upload

All collected data was stored on the Transport Genie Mobile App, prior to being manually exported to the cloud. The original intention was that exporting of the data could be done anytime (on-route or at the end of the voyage) when the mobile receiver has access to a Wi-Fi network. The on-board Wi-Fi connection was extremely slow and so all data had to be uploaded upon the sensors' return to Melbourne.

2.2.4. Sensor placement

The placement of the nine sensors was agreed with the shipping company during the Singapore ship visit. The sensors were placed across four decks of each ship. One sensor (in Sensor Position B1, Deck 1) was used as the control, where for both voyages the same sensor was in the same location. Table 1 shows the location of each of the sensors and the mobile devices. This is also shown visually in Fig. 1. Placement was designed to test the following parameters:

- Optimal location of the sensors on the ship to obtain representative data of the conditions experienced by the animals.
- How many sensors are required to obtain representative data of the conditions experienced by the animals.
- Distance from sensors (between decks and within a deck) from the mobile receivers, as a representation of how many BLE receivers would be required in a full commercial fit-out.

TABLE 1. Sensor locations

DECK	SENSOR POSITION	MOBILE DEVICE
1	A	Device 1
	B1 (wall)	
	B2 (centre)	
	C	
2	D	
4	D	Device 2
5	A	
	B (centre)	
	C	

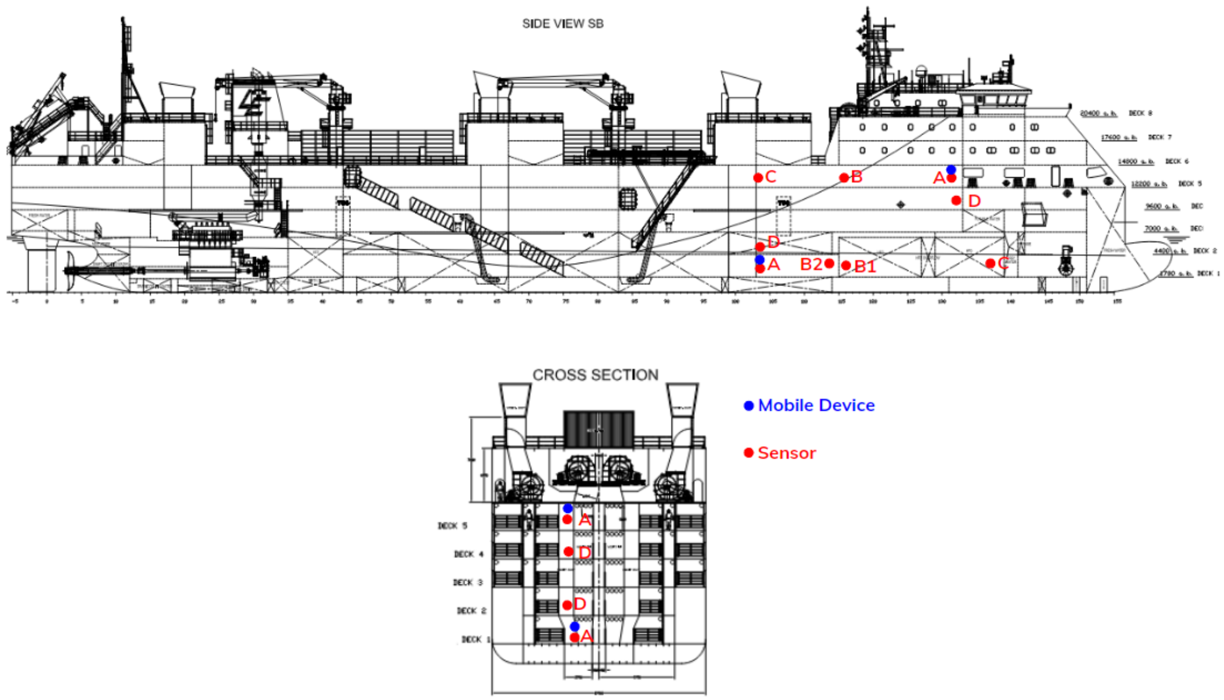


FIGURE 1: Layout of sensors and mobile devices on the ships

2.3. Responsible Person role

As the trial design was considered, it became apparent that there were several tasks that would require an employee from the shipping company to manage during the voyage. This person was named as the "Responsible Person". The responsibilities for this person included daily visual checks of the sensors, battery checks of the mobile devices, recharging the power banks and completing the end of voyage requirements such as removing the sensors and following the cleaning and sanitisation protocols. Tasks were intended to include data upload, however due to the slow speed of the on-board Wi-Fi this was not feasible.

Whilst this method did enable a significant data set from each voyage to be collected, the batteries on the mobile devices discharged much faster than expected, or were not being checked frequently enough, resulting in large sections of data not collected by the mobile devices. This is discussed further in the results and conclusion sections.

2.4. Trial voyage details

2.4.1. Voyage 1: Port of Darwin to Jakarta, Indonesia via Panjang

The ship and voyage as chosen by the shipping company for first trial was travelling from Darwin to Panjang, and then on to Jakarta, with a total voyage of approximately 6-7 days. Departure was 19 December 2023. The ship stopped in Panjang, Indonesia on 26 December 2023, discharged some cattle and proceeded to Jakarta, arriving on 28 December 2023 for the remainder of cattle to be unloaded. As it is short haul, this voyage was one without bedding for the animals. The livestock carried on this voyage were feeder cattle.


Ship for Voyage 1 shown at the Port of Darwin

Sensors were transported to Darwin via airfreight, which was not without challenges. The airline refused to load as passenger cargo due to their classification of the sensors as dangerous goods. Consultation with a dangerous goods specialist advised that the sensors and magnets were not dangerous goods; however, the magnets must be joined in pairs and be spread across the boxes to minimise any risk of any magnetic activity causing interference. The cases containing the sensors were subsequently air freighted to Darwin.

2.4.2. Voyage 2: Port of Portland to Port of Tianjin Xingang, China

The ship and voyage as chosen by the shipping company Voyage 2 was travelling from Port of Portland, Victoria, Australia to Port of Tianjin Xingang, China with a total voyage of approximately 18-20 days. Sensor installation occurred on 18 March 2024, and the vessel departed 19 March 2024. The ship arrived at the Port of Tianjin on 5 April 2024. As it is long-haul, this voyage was one with bedding for the animals. The livestock being carried on this voyage were breeder cattle.

Ship for Voyage 2 shown at the Port of Portland

2.5. Data analysis

2.5.1. Raw data processing and presentation

Data processing for both voyages was delayed until the sensors were returned on the ship's return to Australia. In both cases the sensor cases were returned to Melbourne via road freight to avoid further potential complications via air.

Approximately 1.4 million data points were collected during the two voyages. To draw conclusions from the vast amount of data, the data from each voyage was collated by day and an average for that day was calculated. This was visualised as a graph of daily averages, by sensor type, including the number of data points per day collected, as a reflection of the robustness of the data. Gaps in the data due to either sensor failure, dislodgement or mobile device being off due to battery life issues were then evident by the days where less data was collected and so was therefore less reliable.

Calculating daily averages and showing number of data points collected was a simple way to draw conclusions on success/failure of the data collection and sensor performance from the trial. Due to the volume of data collected, the project team believe it would be beneficial to conduct more sophisticated statistical analysis.

2.5.2. Diagnosis of NULL values

A significant amount of data was collected as a NULL value. This was unable to be diagnosed from data sent to the TG cloud, requiring the sensors and mobile devices to be returned to Canada to be able to replicate the errors. This will be discussed further in the results and conclusion sections.

3. Results

3.1. Trial operations

3.1.1. Sensor robustness

Of the nine sensors used for the first trial, eight were able to successfully record and transmit data over BLE data for both gases and temperature and humidity throughout the entire voyage, if the signal was able to be received by the mobile devices (which required the mobile device to be switched on). One sensor (located at position B1 (wall) on deck 1) failed to collect ammonia values early in the voyage. This sensor had passed testing before leaving Canada and again in Melbourne.

Upon the sensors' return to Melbourne, the failed sensor was retested, and data sent to the TG cloud. Results showed for all data variables including ammonia, so it was decided to use this sensor for Voyage 2.

Nine sensors were again used for Voyage 2. In this trial two sensors failed, the first being the same sensor that failed in Voyage 1, and the second failed on the second day because of being dislodged from its mounting point; believed to be due to rusting of the magnets. A third sensor appears to have been accidentally switched off during the voyage.

Table 2 shows the sensor robustness across both voyages. The battery life in the trial sensors was more than sufficient to power the sensor throughout both the short and long-haul voyages. The sensor Deck 1 position B2 acted as the control for the experiment as it was installed in the same place for both voyages, right in the middle of walkways between the pens on Deck 1.

TABLE 2. Sensor robustness

DECK	SENSOR POSITION	VOYAGE 1	VOYAGE 2
1	A	XX:22	XX:7E
	B1 (wall)	XX:AC	XX:22
	B2 (centre) • control	XX:00	XX:00
	C	XX:19	XX:44 • switched off
2	D	XX: E5	XX:47
4	D	XX:47	XX:19
5	A	XX:7E	XX:AC
	B (centre)	XX:68	XX: E5

DECK	SENSOR POSITION	VOYAGE 1	VOYAGE 2
	C	XX:44	XX:68

Key: XX: ## unique Sensor ID

Control	Sensor failure	Sensor broken

Upon return to Canada, the sensor that failed during both voyages was dismantled to diagnose the fault. The issue was diagnosed as an incomplete soldering point on the ammonia sensor inside the unit, which resulted in no connection when the sensors were mounted vertically on a wall. This was not picked up during testing as all the sensors were tested on a horizontal surface. This has highlighted the importance of testing all sensors in the same way as they will be mounted for the trial.

Each sensor was recording a data point every 30 seconds resulting in over 1.4 million data points being captured across the two voyages. In hindsight this was too frequent as the amount of data generated was challenging to display sensibly without sophisticated statistical analysis. The significant amount of data captured over the voyages has ensured there are several days' data capture on each voyage to provide confidence that the sensors can withstand and last both a short and long-haul voyage.

The failure points for the trial are related more to the mobile devices running flat, being dislodged, switched off, or having faulty soldering joint, rather than the sensors not recording and sending data. From a sensor robustness perspective, the PoC can be considered a success and provides confidence that a more robust solution for data transfer from hardwired sensors to the bridge (such as a BLE mesh) would be an effective solution for measuring on-board gases. Some data was not captured, which is discussed in section 3.1.3. Sensors could remain as battery powered, with long life batteries; however, would need to be strengthened for power washing.

Sensor Deck 5 position B (centre) before dislodgement

Sensor Position D Deck 2

3.1.2. Sensor data transmission and collection via BLE

The data captured from both voyages clearly demonstrated that transmission of data from sensors via BLE was an effective way to transfer the data to a receiver. The results also show that the sensor data is capable of being transmitted both within a floor and between at least one floor above or below the mobile receiver. Because there was no sensor on Deck 3, we are unable to confirm whether the data can be transmitted further than one deck above/below the receiver. This would be confirmed by a small modification of the trial design, and, in hindsight, this could also have been tested in Voyage 2.

3.1.3. Missing data

There are significant periods where the mobile devices were not receiving data. This occurred for both voyages but was significantly worse for Voyage 2. This is visualised in Fig. 3. for Voyage 1 and in the Appendix for Voyage 2.

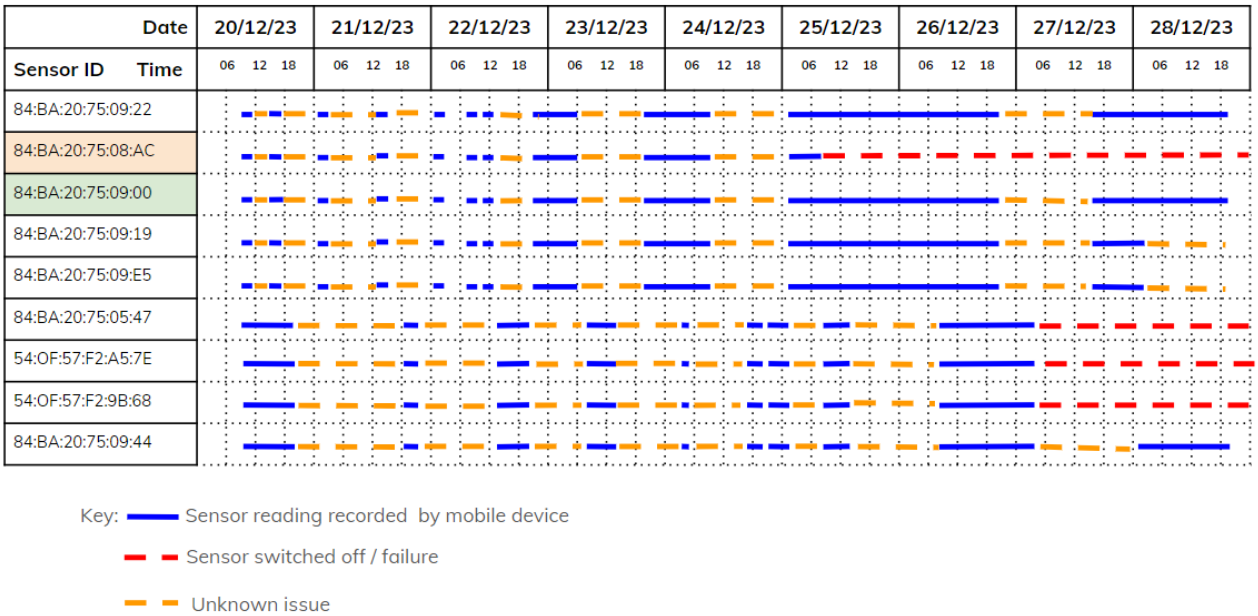


FIGURE 2: Sensor activity recorded by mobile device – Voyage 1

For Voyage 1, eight of the nine sensors collected NH_3, CO_2, humidity and temperature readings every day. However, there were periods of missing data as can be seen in **FIGURE *3***. At least one sensor (Sensor position B1 Deck 1) appears to have failed to collect ammonia data, but was still collecting CO_2, temperature and humidity data throughout Voyage 1 until 25 December 2023, when no further data was recorded.

Voyage 2 was less successful. One sensor fell off its mounting point early in the voyage, breaking its on/off switch. One sensor (Sensor position C Deck 1, Sensor ID XX:44) appeared to fail, or be switched off. Another (Deck 1 position A Sensor ID XX:AC) failed, as it had on Voyage 1.

To attempt to understand if the mobile device was switched off or if the sensor was switched off, temperature readings for all sensors were compared across the entire voyage. For example, if temperature data from other sensors were still being detected by a mobile device, then this means the sensor with no temperature data recorded was either switched off or had failed. The Sensor Position B1 on Deck 1 (Sensor ID XX:AC) recorded no further temperature data after 25 December 2023, when it must have been switched off.

If no data was recorded from *all* sensors in the vicinity of a mobile device, then this means the mobile receiver closest to the sensor was off, because it had run out of battery. This was confirmed when the mobile receivers and sensors were returned to Canada for a full diagnosis.

3.1.4. NULL values

The full data set had a significant number of NULL values recorded. To find an explanation for this, the TG development team needed to recreate the NULL values once the sensors had been returned to Canada.

This has now been diagnosed as an error in the coding for the data parsing. Data parsing is a process in which a string of data is converted from one format to another, which is what happens when the sensor data is transmitted and then received by the mobile device.

This coding error caused an exception to occur when the mobile receiver tried to save the multiple data points from several sensors at the same time. This resulted in collisions in how the device read and understood the information from the multiple sensors, before saving it to mobile receiver database. Data that was unable to be read and understood was recorded as a NULL value.

During our post-mortem analysis, we recognised that there was a mismatch between the expected and actual data structure. This exception was not recognised during the testing of the code because we only had two sensors to test against. The developers were only able to replicate this problem once they had the sensors back from the trial, did their analysis and recognised that data was not parsing correctly when there was a large array of data points. The TG team have subsequently patched the code to prevent this from occurring in the future.

3.1.5. Gas, temperature and humidity readings

Average daily sensor data is reported to demonstrate the effectiveness of the sensors. The number of readings is also shown, to give an indication of the reliability of the data set. The greater the number of readings, the more reliable the data.

Data collected and provided to the shipping company showed no concerns regarding management of gases, temperature or humidity during either voyage. There appeared to be no obvious difference in ammonia gas readings between the two voyages. However, with only eight (Voyage 1) and seven (Voyage 2) sites within the ships being monitored, and the low level of statistics performed on the data set (analysis of averages per day), further insight may come if more sophisticated statistical methods are employed to interrogate the data set further.

3.1.6. Trends

Because of the challenges of obtaining multiple days in a row of data, it was difficult to observe any trends. The best chance of seeing any trends in the data comes from analysis of the longest period that the sensor data was received by the mobile devices, and with the greatest number of data points per day.

For Voyage 1, nearly two full days of data were recorded on December 25 and 26, 2023. This period coincided with the vessel's arrival in Panjang on December 26 and the unloading of cattle, with temperature and humidity readings aligning with reported averages. Average ammonia levels remained well below 25 ppm.

For Voyage 2, the longest continuous data recordings occurred between March 26 and 30, 2024, for sensors on Decks 1 and 2, and between March 31 and April 3, 2024, for sensors on Deck 5. These time frames, representing the middle and end of the voyage, respectively, showed temperature and humidity levels consistent with the ship's location, with average ammonia values also below 25 ppm.

The locations of the sensors for the trial were chosen to ensure coverage of different parts of the ship where the animals were located. The data shows no trends (at least from simple statistical analysis) highlighting areas worse or better than others. The control sensor (Sensor ID XX:00, Sensor Position B2 (centre) Deck 1) was consider as recording the "worst case scenario" based on its position in the walkway between two rows of animal pens. This sensor did not record any average values significantly worse or better than other sensor positions.
Further work using a more sophisticated statistical analysis with an academic partner may uncover some trends.

4. Conclusions

4.1. Key findings

4.1.1. Reliable gas and environmental continuous monitoring using four-in-one sensors

The results from the PoC showed that micro-climate conditions and gases on livestock shipping ship scan be reliably and continuously monitored using fixed four-in-one sensors adapted from other industries (in this case, from the sensors adapted from TG's poultry and swine road transportation solution). Multiple sensors located around animal pens attached to the ship walls were found to reliably monitor ammonia, carbon monoxide and carbon dioxide gases and produce reliable temperature results and humidity values.

4.1.2. Device collection of data over floors

There is a limit to the distance that the BLE can be received by a mobile receiver while being in a metal environment. To make a system fault-tolerant, a data gateway device should be placed where it can best pick up the BLE data from sensors within its ideal range. The trial has shown that BLE data can be received from one level above and one level below each mobile receiver. It may be possible for data to be received over two floors; however, this was not tested during the trial and should be considered for further work.

4.1.3. Points of failure

1. Mobile device battery life: The battery life of the mobile receiver became an issue as the battery life seemed to be shorter than in testing, likely due to different temperature on the ships. In addition, the mobile receiver battery remaining in a charged state was dependent on frequent monitoring from the "Responsible Person". This dependency caused cascading issues in the data collection process since the mobile receiver and the battery bank were required to be charged to provide continuous recordings. To prevent this from being an issue in future projects, a battery fault tolerant solution should be in place. For example, having the data collection device being "hard-wired" to the ship's power supply will remedy this issue.
2. Sensor mounting finding suitable fixings to replace the magnets was also a key finding that needs to be addressed. The current solution will not work for a long period of time because the magnet surface was not protected from salt water. Solving this problem will require the magnet surface to have layers of nickel, zinc and epoxy, which inhibit the devastating effects of sea water corrosion.

3. Pre-trial sensor and protocol testing: the trial highlighted the need to test sensors in the orientation that will be used for the trial. As all sensor tests were conducted with the sensors lying on a horizontal surface, manufacturing errors such as soldering faults were not picked up. Additionally, not testing the data collection process with all nine sensors active meant that significant chunks of data were not saved by the mobile receiver. This has now been rectified with a change in the software code; however, any future trials should test data collection under the worst case scenario.

4.1.4. Knowledge gaps/extra resources

Despite significant data gaps, the trials produced a significantly large data set that could be further studied to draw out insights such as whether there are any major differences obvious across the different pens on the ship. In hindsight the project team believe they could have benefitted from a statistician with experience in handling and presenting large data sets. This could provide greater insights into any temporary spikes in readings, which could be caused by urination events, cattle loading and unloading or the very rare occurrence of a mechanical fan failure.

4.1.5. Return on Investment

The ambition was for this trial to be completed within three months. Whilst both voyages were completed in just over three months (18 December 2023 – 5 April 2024), the actual time taken for the project was almost nine months. The delays were caused by a variety of compounding issues.

The 4% overall project cost increase was a result of unbudgeted freight and travel costs as the expenses to get to the first trial assumed that the ship would be departing from the Port of Portland, or from Western Australia. The project team ensured that the cost increases were minimised by reassigning resources for the second trial to an Australian-based project team member to complete the second installation.

The value of this technology solution cannot be fully quantified in monetary terms, given this technology is about demonstrating adequate environmental conditions on board.

An additional consideration was the cost/benefit analysis of what compliance costs would be incurred if on-board monitoring, such as trialled in this PoC, were to be required – in the event compliance with ASEL Standard 5.1.20 became mandatory.

4.2. Benefits to industry

The trial has demonstrated the capability of four-in-one sensors to reliably monitor gas levels, temperature, and humidity on livestock export ships. This technology provides a significant advantage by offering real-time data that can be accessed via a dashboard installed on the ship, enabling the crew to intervene promptly if needed. This proactive capability is beneficial for ensuring safe on-board conditions, which is increasingly important as the livestock export industry faces heightened scrutiny and potential regulatory challenges.

The ability to accurately monitor and report on environmental conditions offers a robust fact-base for making informed decisions. This not only ensures the welfare of the livestock and staff on board but also strengthens the industry's position by demonstrating a commitment to high welfare standards.

The study's results further indicate that there is no significant difference in gas and ammonia levels across two voyages, regardless of varying operational conditions such as voyage length or the presence of bedding. By installing sensors across different parts of the ship, the industry can be reassured that the on-board environment is being closely managed, with the potential for rapid intervention through real-time dashboard reporting (if dashboard is installed on the ship).

The benefits extend beyond operational efficiency, as automated monitoring reduces the need for manual data collection, freeing up resources for other critical tasks. The continuous stream of reliable data also supports compliance with standards like ASEL 3.3 and addresses public concerns about animal welfare, enhancing the industry's image.

Furthermore, the data gathered can be leveraged to optimise voyage management and refine sensor placement. The trial's insights lay a strong foundation for future research and innovation, driving continuous improvement within the industry.

Long-term, these advancements may result in cost savings through better welfare outcomes, and more efficient compliance with regulatory requirements, further solidifying the value of this technology to the industry.

5. Future research and recommendations

5.1. Future research

5.1.1. More sophisticated statistical analysis of the data set

Because of the limited statistical capability of the project team, we recommend that more sophisticated statistical analysis of the data is to be completed. Although this would require permission of the data owners, there are many potential benefits that could be uncovered. If other data sets from the same voyage were available (such as livestock weight and pen storage data) this could be used to generate a baseline for further work.

5.1.2. Pre-commercial trial

A second piece of work that could be considered would be to install a pre-commercial solution on one ship and monitor multiple variables of animal welfare over a longer period and multiple voyages. This would involve aligning on which correlations between continuous on-board monitoring and animal welfare could be of value. One example that came up in our stakeholder interviews was the potential benefit of correlating microclimate conditions with pre- and post-voyage animal weights.

This trial would require a more robust solution for both the sensors and BLE data transmission, ideally would include longer battery life, stronger (able to be pressure-washed) sensors and hardwired BLE receivers transmitting data to a viewable dashboard at the bridge. The investment required for this is being worked through, and decisions need to be made regarding how many sensors, their location and how many mobile receivers. A suggestion for how this could be implemented is shown in Fig. 3.

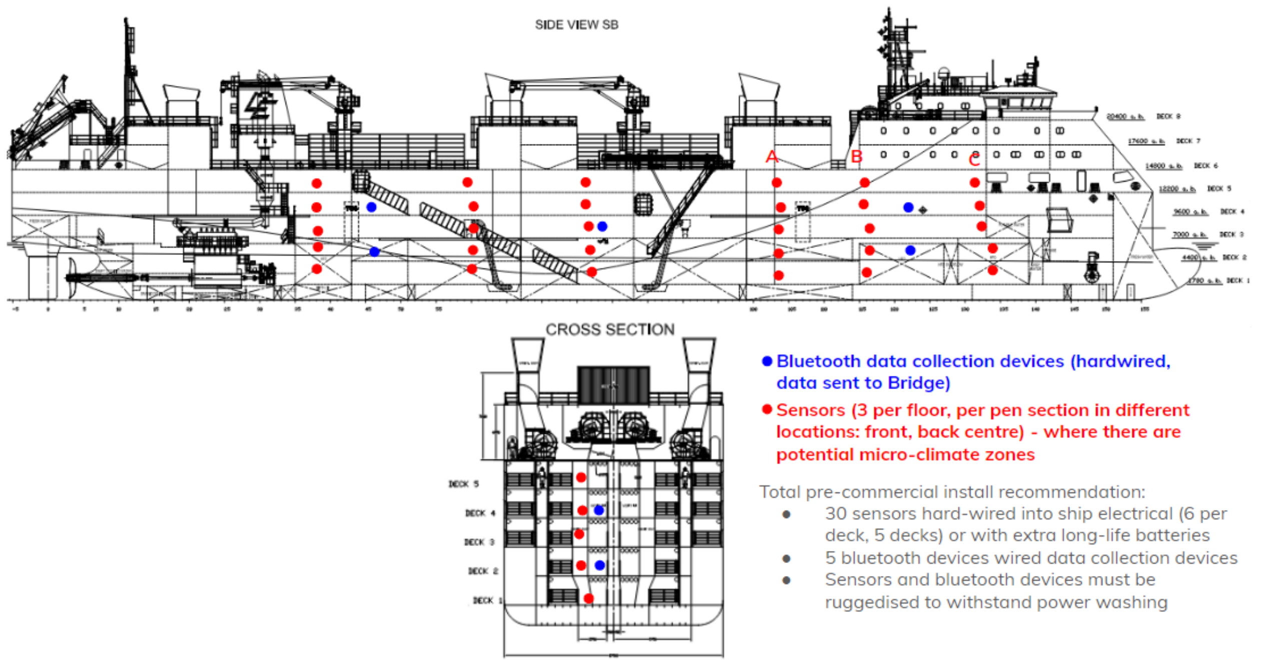


FIGURE 3: Recommendation for new layout of sensors and mobile devices on a ship

5.2. Recommendations for commercial implementation of the project findings

5.2.1. Development and adoption activities

The project team recommends a presentation of the findings by members of the project team at an upcoming industry stakeholder event. Prior to this, a reasonably accurate commercial cost estimate needs to be provided for the pre-commercial trial described in 5.1.2.

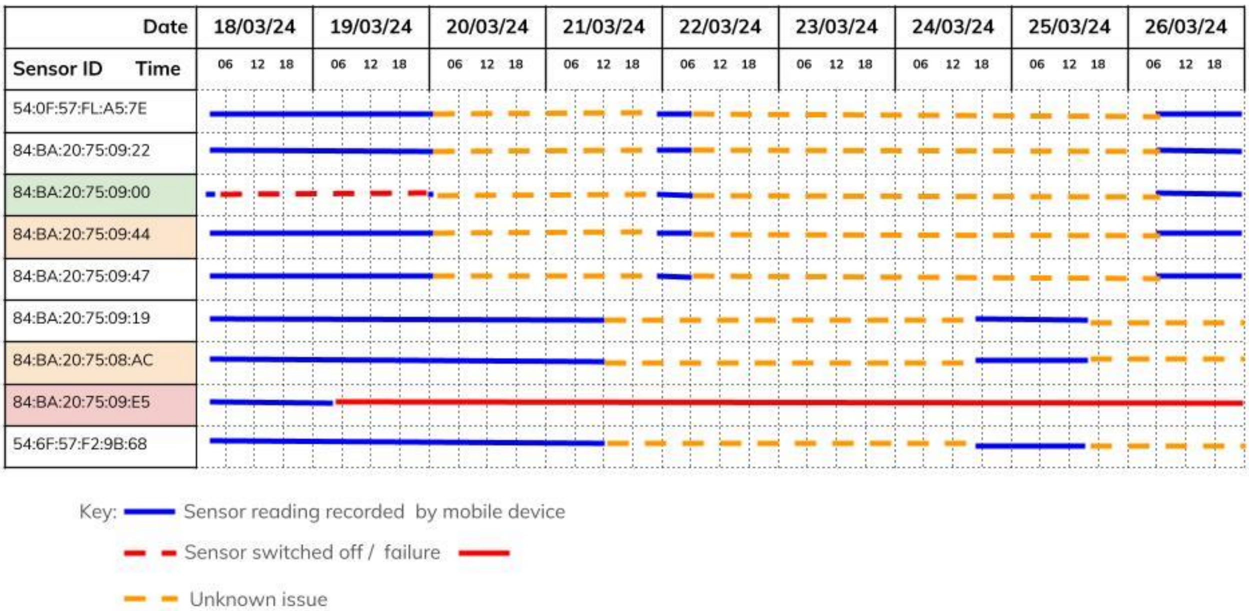
5.2.2. Practical applications of the project insights

As using an open innovation approach to adopt exist solutions is relatively new for LiveCorp, one practical application would be to combine existing research providers with startup providers to help speed up different ways of conducting research, development and extension activities.

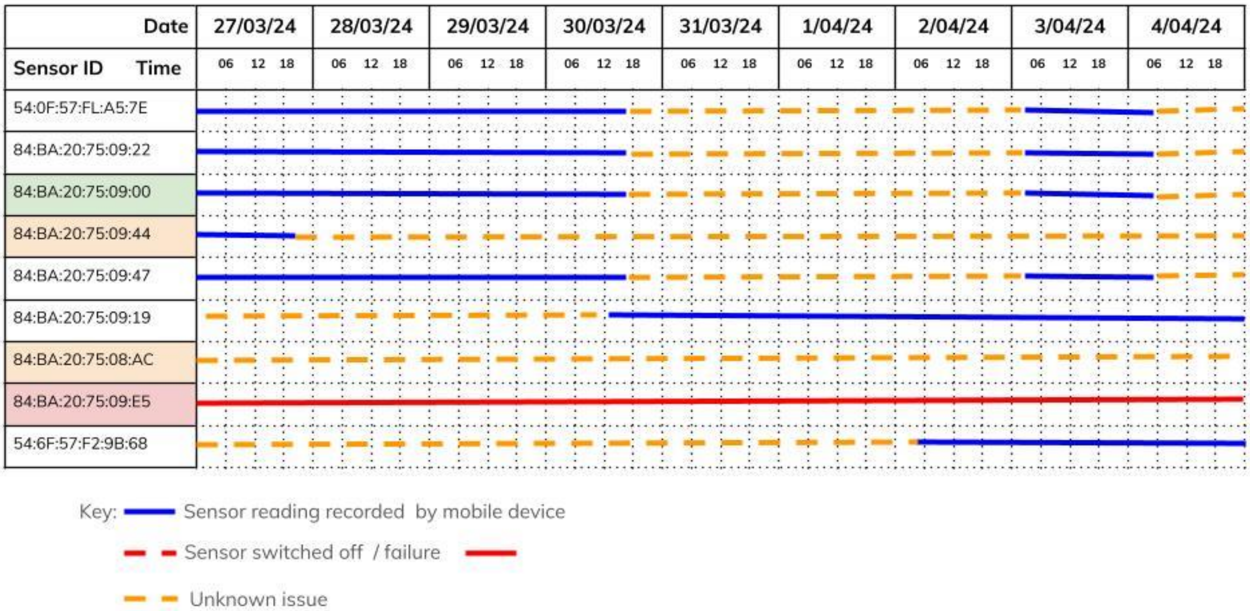
The benefit to the livestock export industry of matching research partners with startups with technical solutions to these industry-wide problems is that validation and implementation become better integrated.

6. Sensor data collected by mobile device – Voyage 2

Sensor activity recorded by Mobile device - Voyage 2 18/03/24 - 26/03/24



Sensor activity recorded by Mobile device - Voyage 2 27/03/24 - 4/04/24



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