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Real-Time Railhead Friction Estimation Using Machine Learning: Development of an On-Board-Train Data Capture System.

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ABSTRACT

Low adhesion between the wheel and rail interface remains a significant challenge for the railway industry, particularly during the autumn season, leading to delays and safety risks such as station overruns and signals passed at danger (SPADs). The impact of low adhesion is estimated to cost the UK railway industry approximately £355 million annually. Current methods for estimating railhead adhesion lack real-time, high-resolution spatial and temporal capability, which is critical for improving safety and operational efficiency.

This research introduces a novel real-time railhead friction estimation approach, utilizing an estimation model trained on a variety of environmental and rail-specific data, such as railhead images, friction measurements, air temperature, relative humidity and railhead temperature. To test this model in real-world conditions, a specialized data capture system (camera box) was developed and mounted on rolling stock, capturing relevant data while ensuring accuracy in location and railhead condition.

Field tests conducted at the Wensleydale Heritage Railway in the UK demonstrated the feasibility of this system, with consistent and reliable friction estimations. The results indicate that the model can effectively estimate railhead friction levels and identify potential low adhesion hotspots in real time, thus providing valuable insights for mitigating risks, reducing delays, and improving overall safety.

1. INTRODUCTION

Low adhesion at the wheel/rail interface is a major cause of delays and can cause safety issues in the railway industry, especially during autumn. During this season, leaves fall from trees and leaf layers are created on the rail head by the action of passing wheels which create very low friction conditions when damp. Also small amounts of moisture, such as those seen at dew point, and oxide on the railhead can cause a slippery paste to form known as “wet-rail”. These issues can include braking problems leading to signals passed at danger (SPADs) or station overruns, potentially resulting in collisions such as the one near Salisbury in 2021 [1]. Poor traction can also contribute to delays. In Great Britain, the effect of low adhesion costs an estimated £355 million annually. Approximately £290 million is the

performance impact cost, £0.5 million is the safety impact cost, and £64 million is spent on cleaning, management, and prevention [2].

The railway industry currently has limited methods of adhesion forecasting with the main validated method being the Met Office Adhesion index [3]. The adhesion index uses a bank of weather data and manually collected field information readily available to the Met Office. This provides information only related to weather and not the railhead state. It does not address the changing conditions during a day either, so temporal resolution is low. The index also does not have a high spatial resolution and as local environmental conditions can vary considerably in a short length of track it is important that this aspect is improved. Following the low-adhesion-related Salisbury incident in 2021, the Rail Accident Investigation Branch (RAIB) recommended researching technology to estimate adhesion and/or contamination levels (short-term) and developing new methods for low adhesion identification (long-term) [1].

There are other methods for determining railhead friction levels. These have been grouped into 3 categories, with examples shown in Table 1.

Table 1: Categories for Railhead Adhesion determination

Category	Function	Disadvantages	
Adhesion Forecasting	Prediction of possible adhesion levels in advance	Usually low resolution and little scope for real time capability.	Met Office Adhesion index [3]
Adhesion Measurement	Capturing railhead friction data with use of a tribometer	Local points assessed and little scope for real time capability	Rivelin Rail Tribometer [4]
			HO-tribometer [5]
			Push Tribometer [6]
			Pendulum Tribometer [7]
Adhesion Estimation	This method blends forecasting and measurement into one by estimating friction from data captured from on/around the railhead and from real-time train data	Extensive training data needed to capture all conditions	Acceleration based friction coefficient estimation [8] Authors Railhead Friction estimation model [9]

If low adhesion conditions occur due to wet-rail or leaf layers, mitigation is applied in the form of rail head cleaning (water jetting from rail head treatment trains or manually applied chemical cleaners or application of traction enhancers (hard particles in a gel)). In order to plan an effective mitigation strategy, there is a need for a more accurate method for determining adhesion levels over rail routes which is not available from current forecasting or tribometer based methods. Ideally this would be delivered by approaches based on train mounted instrumentation. This, however, needs further development to enable estimation

of railhead adhesion levels in real-time and give the exact location of the probable low adhesion section is required.

An optimised adhesion estimation method will reduce the amount of low adhesion mitigation needed, as currently it is applied to long stretches of track regardless of whether it all has a problem, and lower delay costs whilst improving railway safety and confidence by directly communicating the location of predicted low adhesion hotspots. Correct implementation will ultimately make the rail system safer and more efficient.

The model developed by the authors and discussed extensively in Folorunso et al. [9] has shown that adhesion estimation is possible by using relevant rail and environmental data to train a neural network model. The data used to train the model included [9]:

- Railhead images
- Forward facing images
- Railhead friction (measured using a Pendulum tribometer)
- Air, dew point and railhead temperature
- Relative humidity
- Contamination layer thickness

Field data collected for model development was split into training and validation sets. The model's accuracy and ability to handle a wide range of railhead conditions will improve with an increase in training data volume and variety, an ongoing process.

The aim of this work was to implement the friction estimation model with a real-time data collection system that could be used on a train, and use the tool to estimate friction from the collected data. The required information for the friction estimation is shown in Figure 1. In addition, a GPS device was added to determine the position for each data collection point.

GPS data acquisition was configured to operate concurrently with image and temperature capture. For each image captured, the corresponding GPS coordinates were recorded, guaranteeing that every image entry in the extracted spreadsheet was associated with a precise location marker. An example of the extracted spreadsheet is shown in Appendix A.3.

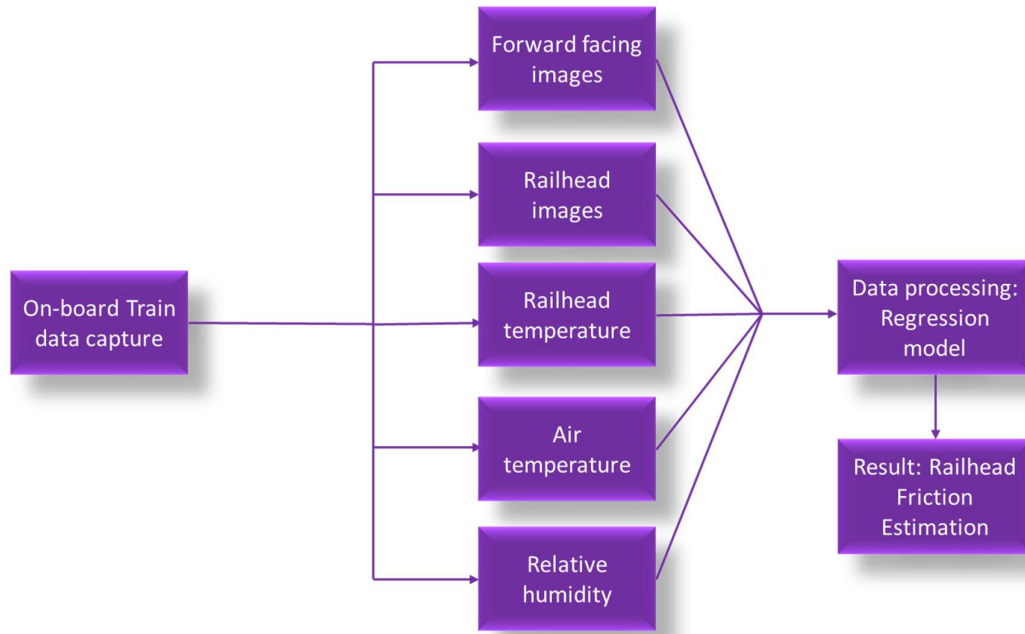


Figure 1: Adhesion estimation model flow chart (the approach for collecting this data is detailed in Section 2)

2. DATA CAPTURE EQUIPMENT

The new data collection system was designed to fit in an existing camera box design, supplied by Network Rail, which was adapted for our purpose and is shown in Figure 2 where all the main components and features are illustrated. The full component details can be found in Appendix A1. The box was already approved for fitment to several train types, on the lamp bracket at the front of the trains.

The box has a wide front Perspex window that allows one of the cameras inside to capture the required forward facing images. A new window was cut in the bottom of the camera box where germanium glass was fitted in one part and transparent Perspex glass in the rest, to close the window. The germanium glass was needed to allow the infrared thermometer (used for reading the railhead temperature) to reach the railhead without reflections. A 40mm diameter germanium glass was used as it was sufficient to transmit and focus the infrared ray. Germanium was not suitable for the camera to view through, so it could not be used for the full bottom window.

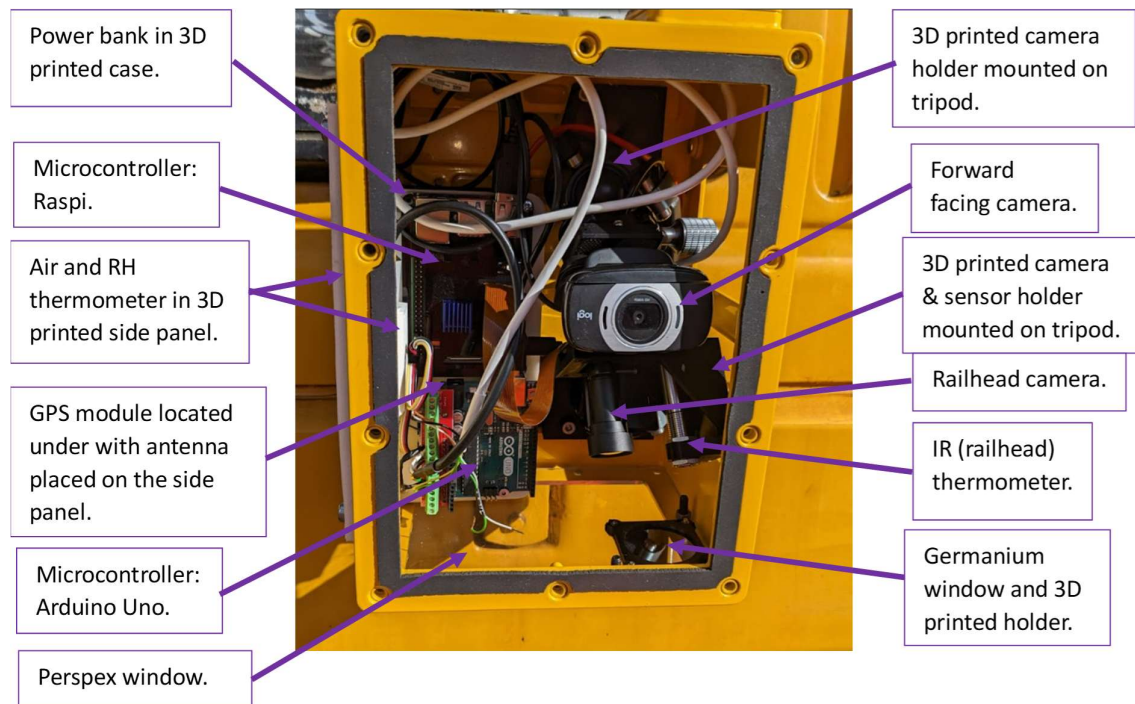


Figure 2: Labelled full components image of Camera box V2 (full details of components can be found in Appendix A1)

Both temperature sensors readings were validated by comparing the readings recorded by the sensors to a handheld infrared thermometer. The protocol is detail in Appendix A.4.

During field tests at the Wensleydale Heritage Railway (WHR), air temperature and relative humidity sensors were verified using temperature readings from the nearest weather station (Leeming Bar Airfield), found on the Met Office “Weather Observation Website” (WOW) [10]. Figure 3 shows a comparison of the data collected from the sensors with readings recorded in the weather station during several tests carried out in the field for maximum values of air temperature and relative humidity. The trends seen and temperatures recorded are similar. The differences seen are because weather station has the highest “exposure” rating and portions of the train line experience shading by other rolling stock, buildings and vegetation.

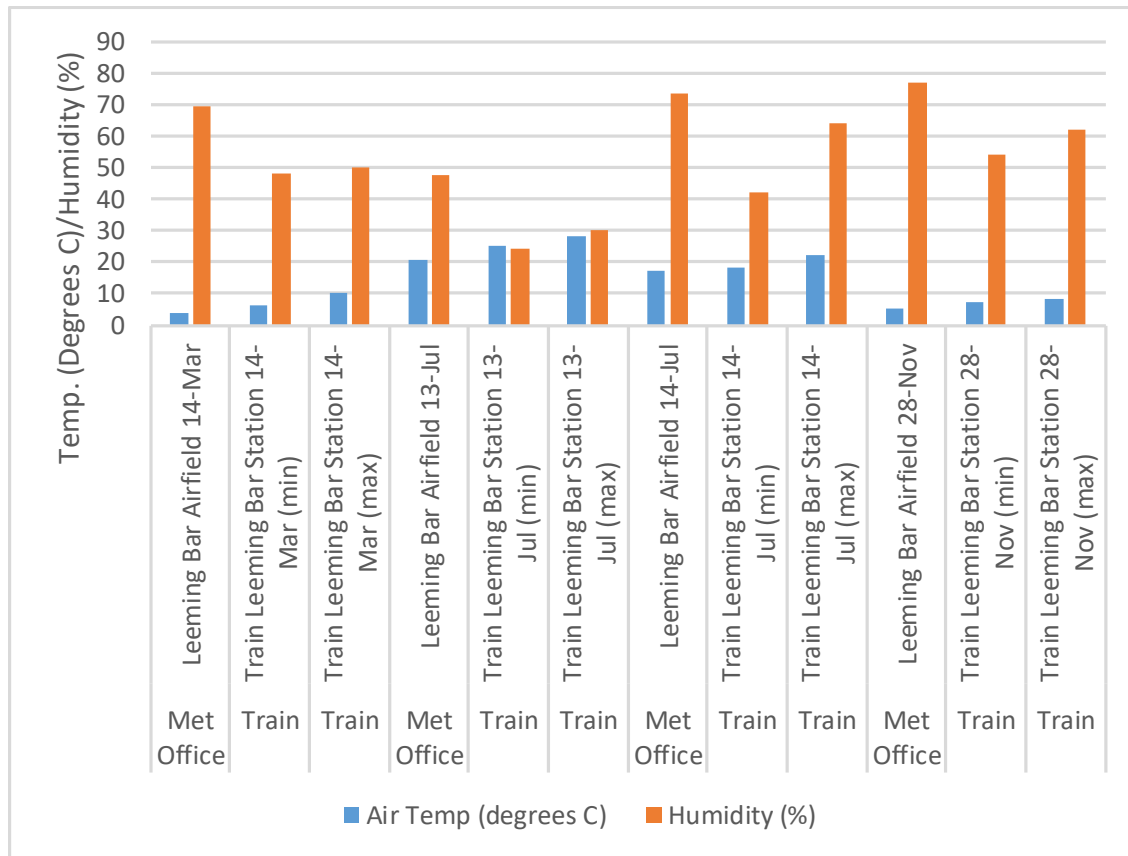


Figure 3: Met Office WOW data [10] vs temperature sensor data

3. CAMERA BOX FIELD TEST METHODOLOGY

A total of 4 tests were carried out at Wensleydale Heritage Railway (WHR), North Yorkshire, UK to trial the camera box system. The camera box was mounted on a Class 142 train lamp bracket. “Short” and “long” term tests were carried out, as detailed in Table 2.

Table 2: Details of tests carried out at WHR

Test No.	Date	Location/Route	No. of run	Distance	Railhead Condition	No. of Data points collected
1	14-03-2023	Leeming Bar station yard	10	Short (260 m)	Natural state	141
2	13-07-2023	Leeming Bar station yard	7	Short (260 m)	Natural state	357
3	14-07-2023	Leeming Bar – Leyburn (return)	2	Long (37 km)	Natural state	2677
4	28-11-2023	Leeming Bar & Leeming Bar – Bedale (return)	10 & 2	Short (260 m) & Long (5.15 km)	Natural state and leaf layer	Camera box 1-1228 Camera box 2-971

3.1 SHORT RUN TESTS

The main location for the “short” run tests was the Leeming Bar station yard, as shown in Figure 4. An overhead view is shown which indicates the approximate length of track used, marked in red. These were tests carried out in the station yard area over a short distance of approximately 260 metres, at a relatively low speed of 10 mph and data collection rate of 1 per 2 seconds. Data collection rate was not changed as speed changed on different tests. This is a parameter that could be enhanced to increase the resolution of the approach though.

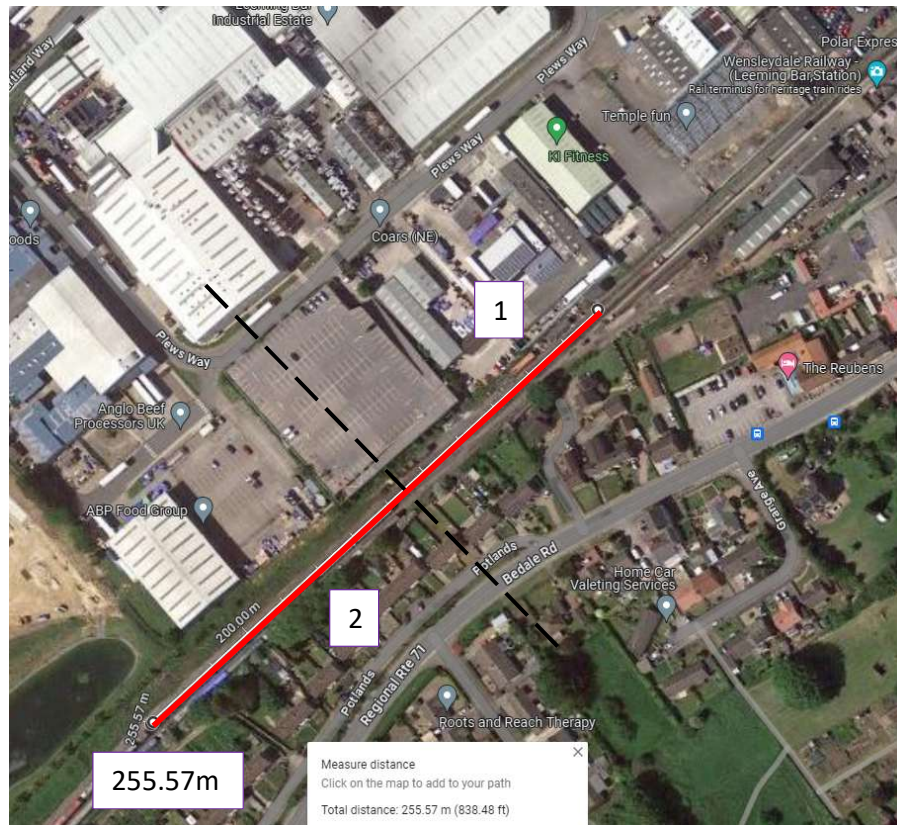


Figure 4: Google Earth image showing an aerial view of WHR (Leeming Bar station) [11]

Black leaf layers (dried Sycamore) were created for application on the railhead (see description below). Two camera boxes were used on the Class 142 train. The first camera box was attached to the front end over the right railhead while the second camera box was attached to the rear end over the left railhead.

In order to create the leaf layers, the railhead was initially cleaned with a sanding star attached to a drill to remove oxides from the surface. The Class 142 then had one pass over the track section to condition it before application of the leaf layer. Leaf paste created using the method described in [12] was applied on 2 metre sections of the rail parallel to each other (Figure 5) and left to settle on the railhead for 10 minutes to promote bonding between the leaf material and rail.

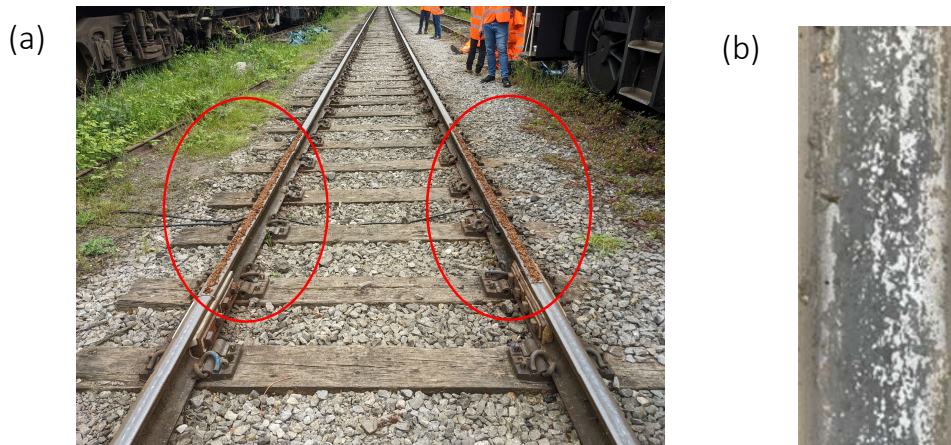


Figure 5: On track leaf layer creation: (a) leaf paste (circled in red), laid on the railhead section; (b) resultant black layer created

The Class 142 train then passed over the leaf paste twice (equivalent to 8 axle passes) at 10 mph to create a black leaf layer. The train was at a constant speed, so minimal slip was applied to the layers. In addition, railhead friction was measured using a Rivelin Rail tribometer [4] to create a benchmark for comparison to the friction estimation tool results.

3.2 LONG RUN TEST

“Long run” tests included train journeys from one station to another. Two long run tests were done on separate occasions, the first one from Leeming Bar station to Leyburn station and back (a total distance of approximately 23 miles (37 km)) on 14-7-23. The second was from Leeming Bar to Bedale station and back (a total distance of 3.2 miles (5.2 km)) on 28-11-23. The train’s maximum speed for long run tests was 30 mph with a data collection rate of 1 per 2 seconds.

4. RESULTS

4.1 TEST 1 (Short)

A total of 141 data points were collected on the first successful trial of the camera box at the WHR on 14-03-23. The camera box was placed on a Class 142 train (see Figure 6a), and it was driven over a short stretch (≈ 260 m) of track.

The image on the right in Figure 6a shows a white mug holding hot water, this was used to adjust the IR thermometer’s ‘field of vision’. The hot water was a higher temperature compared to the surroundings. It was placed on the railhead and the thermometer was adjusted until it started to read the warmer temperature from the hot water thus reading the temperature of the railhead region.

Table A2.1 shown in Appendix A2 illustrates an example data set extracted from the trial including the images and friction estimations for the points shown. Figure 6b show plots of all data collected and the friction estimations.

One of the very noticeable features in the data plotted in Figure 6b is peaks in the railhead temperature resulting from sections of railhead being exposed to the sun (discussed further in the Discussion section).

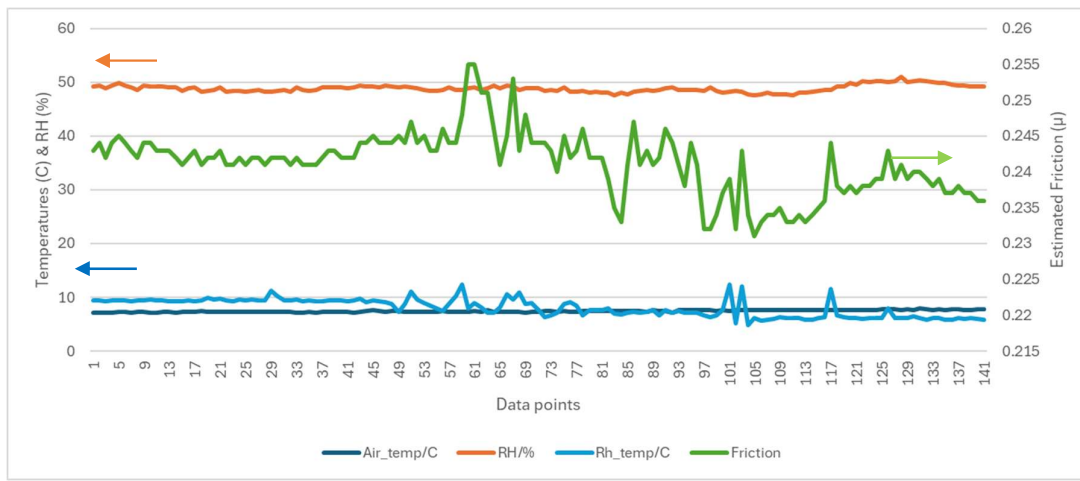


Figure 6: (a) Camera mounted on a class 142 train at WHR, and (b) Plot of all environmental data and the estimated friction against all data points for the short test on 14-03-23

4.2 TEST 2 (Short) & 3 (Long)

Test 2 carried out on 13-07-23 was in the Leeming Bar station yard using a 260m length of rail to collect data. Whereas on 14-07-23 Test 3 involved a full journey on a passenger carrying Class 142 train travelling from Leeming Bar Station to Leyburn Station and back. A total of 357 data points were collected on 13-07-23 and 2677 data points were collected 14-07-23.

Figures 7 and 8 show the plots of all the environmental data collected and friction estimations while Appendix A2 Tables A2.2 and A2.3 show examples of the camera box output with railhead images and corresponding forward-facing images for 13-07-23 and 14-07-23 respectively.

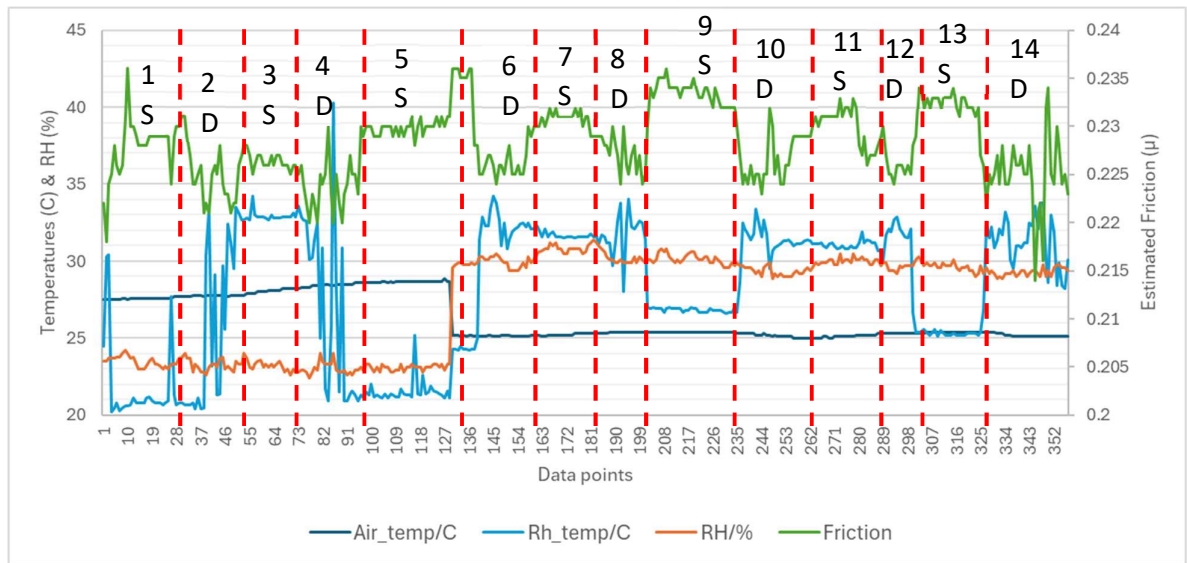


Figure 7: Plot of all environmental data and the estimated friction against all data points for the short test on 13-07-23 ('S' train static; 'D' train moving)

The results plotted in Figure 7 show a combination of stationary and moving data points. The plot has been sectioned into static and dynamic showing the repetitive runs done, using 'S' for static and 'D' for dynamic.

Testing carried out on sections 1 to 5 was done on the first half of the track (labelled 1 in Figure 4). The results can be seen in Figure 7 with similarities seen in the estimated friction in static and dynamic regions. Testing done from sections 6 to 14 was on the second half of the short-run track (labelled 2 in Figure 4). This shows slightly higher friction coefficients. Regardless of the section of the track, friction values estimated were in a reasonable range for a dry railhead [13] at 0.214 and 0.236 which is also similar to data collected in previous testing. The temperatures recorded here were warmer than what was recorded during past testing at the same location, with railhead temperature between 20.2 °C – 40.3 °C and air temperatures ranging from 25 °C to 28.7 °C, typical of summer temperatures in the UK.

Results recorded from the long run from Leeming Bar to Leyburn and return (shown in Figure 8), show the data recorded over the return trip. The results were split into 4 parts:

1. Outward trip from Leeming Bar to Leyburn.
2. Sub section showing 5 minute stop at Bedale Station.
3. Return trip from Leyburn to Leeming Bar.
4. Sub section showing 2 minute stop at Bedale Station.

A GPS conversion website [14] was used to convert the location, which yielded 54.2890100°, -001.5875400° and with a simple Google Maps search of the GPS points showed the location as Bedale Station (54°17'20.4"N 1°35'15.1"W). The friction recorded at the stations where the train was at a stop was as expected with a very small range between 0.283 to 0.287.

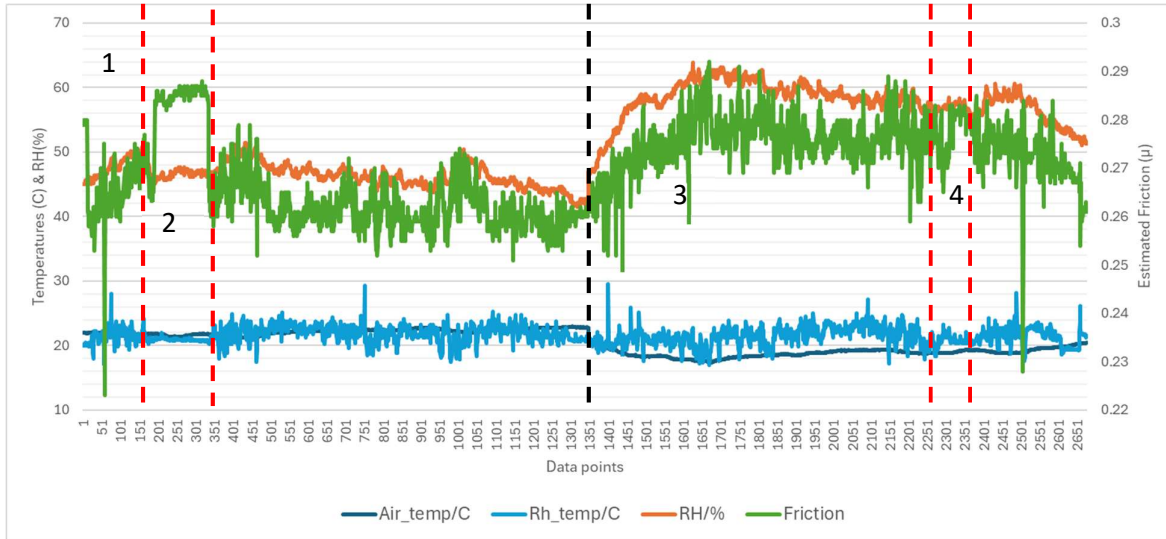
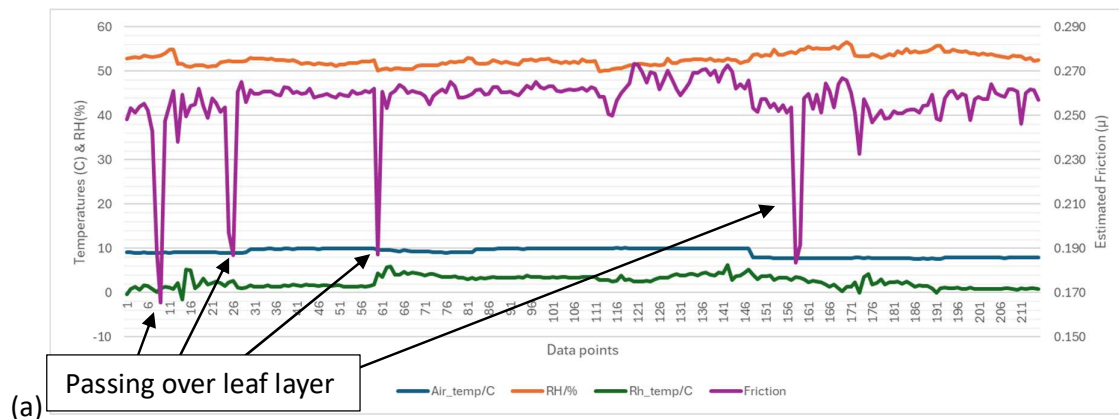


Figure 8: Plot of all environmental data and the estimated friction against for the long test on 14-07-23 (1 is outward trip (Leeming Bar to Leyburn); 2 is a 5 minute stop at Bedale during section 1; 3 is return trip (Leyburn to Leeming Bar); 4 is a 2 minute stop at Bedale during section 3)

4.3 TEST 4 (Short and Long)

For the fourth and final test, two camera boxes were deployed on the Class 142 train on 28-11-2023. The first box (camera box 1) was placed at the front end of the Class 142 and the second box (camera box 2) was placed at the rear end of the train. This was done to capture the before and after images and friction estimations of the railhead used for testing in WHR.

Camera box 1 collected a total of 1228 data points with 991 of them being good for processing while camera box 2 had a total of 971 of which all were usable. Figure 9 shows the plots of environmental data collected and friction estimations for camera boxes 1 and 2. Both of the datasets were broken into a short run and a long run return journey from Leeming Bar to Bedale. Tables A2.4 and A2.5 in Appendix A2 show four samples each of dataset collected from camera boxes 1 and 2 respectively.



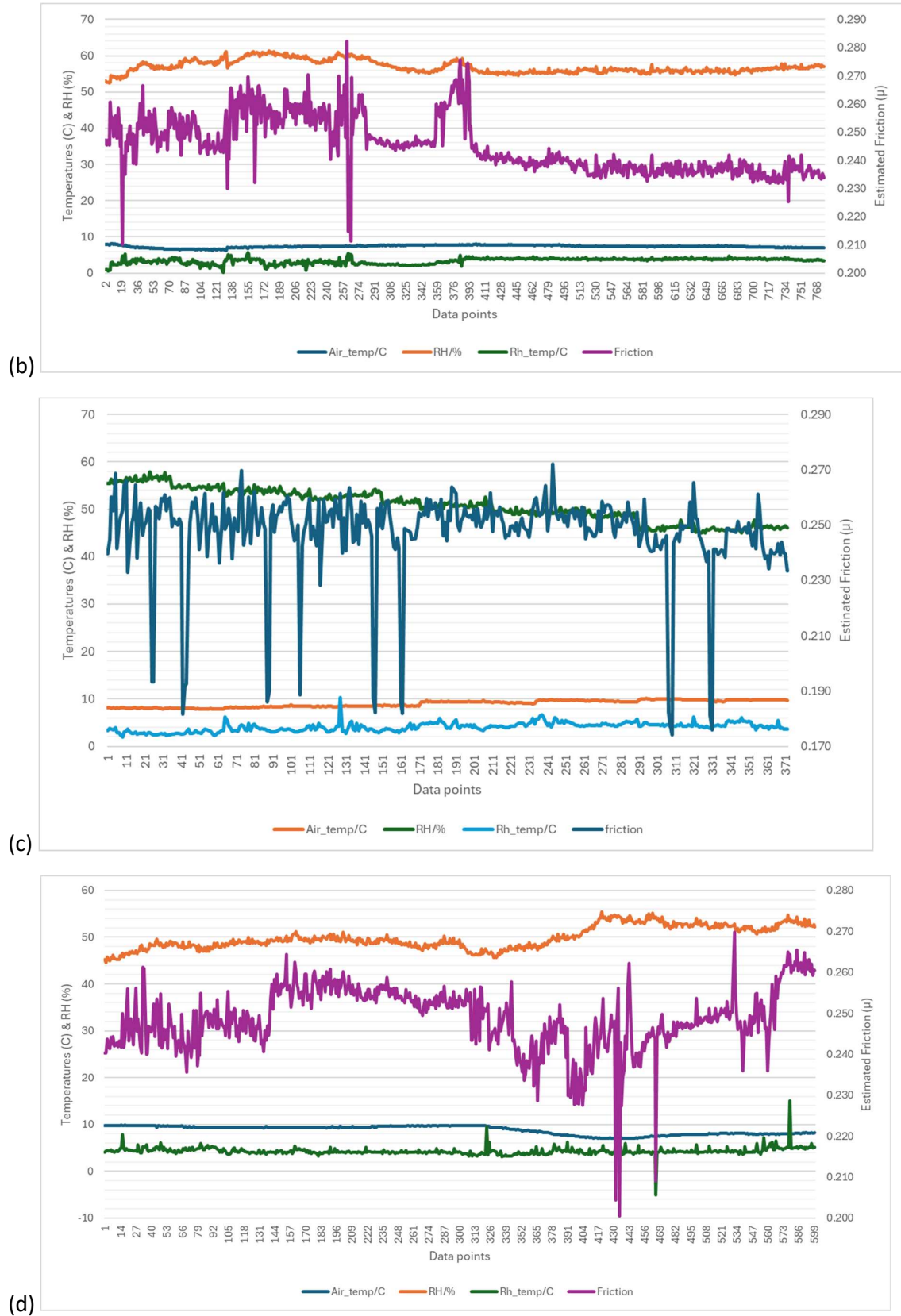


Figure 9: Plot of environmental data and the estimated friction against data points for camera box 1: (a) short run; (b) long run. Plot of environmental data and the estimated friction against data points for camera box 2: (c) short run; (d) long run

Generally, both camera boxes were not expected to predict the same friction values, as they were capturing railhead images from two different rails, and one before train passage and one after. Camera box 1 estimated a maximum friction coefficient of 0.282 and minimum friction coefficient of 0.166 while camera box 2 estimated a maximum friction coefficient of 0.272 and minimum friction coefficient of 0.174.

Figures 9a and 9c show the effects of the black leaf layers created. The clear drops seen in the friction data were at the 3m long leaf layers. The leaf layer was created on two separate occasions which has been sectioned into two on the plot using the black dotted line. Camera box 2 captured the full testing period shown in Figure 9c while there was some operational cut out on camera box 1 which reduced the data collected. Friction coefficients of between 0.166 and 0.197 were estimated for leaf layer section recorded on camera box 1 while values between 0.174 and 0.193 was estimated for camera box 2. Railhead with no leaf layer had friction coefficients of 0.25 – 0.27.

5. DISCUSSION

5.1 TEST 1 (Short)

This was a test carried out on a Class 142 train travelling a short distance within the WHR depot. The purpose of this test was to confirm the sensors in the camera box functioned properly on a moving train. The images (3 and 4) in Table A2.1 in Appendix A2 look blurry as they were captured while the train was moving. The faster the train moved the blurrier the images became. The maximum speed on this test was about 10 mph. The full detail of the image analysis is given elsewhere [9]. The level of blurriness did not affect the estimation tool's ability to process the images and make estimations, because it can still identify the colours on the image. The implementation of strobe lights on a specialised camera, positioned closer to railhead will improve the image quality and will be considered for future work.

Estimations for static and dynamic railhead images from a separate test on the same railway track with similar conditions, were isolated and compared to confirm if there were major differences in the results and it was found again (as seen in Figure 10) that the blurriness does not greatly impact the value of estimation given. In Figure 10, image 1 is a static image with a friction coefficient of 0.217 while image 2 which was captured while moving and image 3 captured during the transition period of moving to coming to a halt both had friction coefficients of 0.220 and 0.215 respectively.

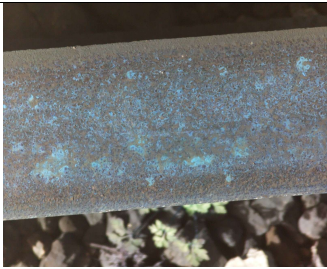
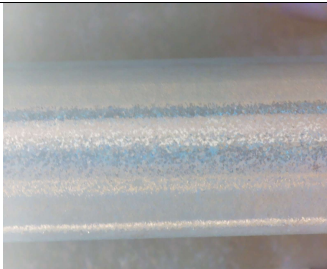
Image 1	Image 2	Image 3
		
Coefficient of Friction = 0.217	Coefficient of Friction = 0.220	Coefficient of Friction = 0.215

Figure 10: Static vs dynamic friction estimation

Figure 6b shows the environmental data obtained from the camera box and estimated friction from processing the data and images. The friction estimated ranged from 0.231 – 0.255 which is a normal range for the railhead conditions present in WHR (see Figure 14). It was also noted that the air temperature recorded had a ± 0.3 °C variation for the test duration while the railhead temperature sensor recorded temperatures ranging from 4.8 °C – 12.4 °C. This shows the railhead temperature sensor captures the real variations occurring on the railhead as the train moves. Some parts of the railhead are shaded by surrounding trains while other parts are exposed to sunshine (see Figure 11). The parts exposed to sunlight accounted for the peaks noticed on the railhead temperature plot in Figure 6b.

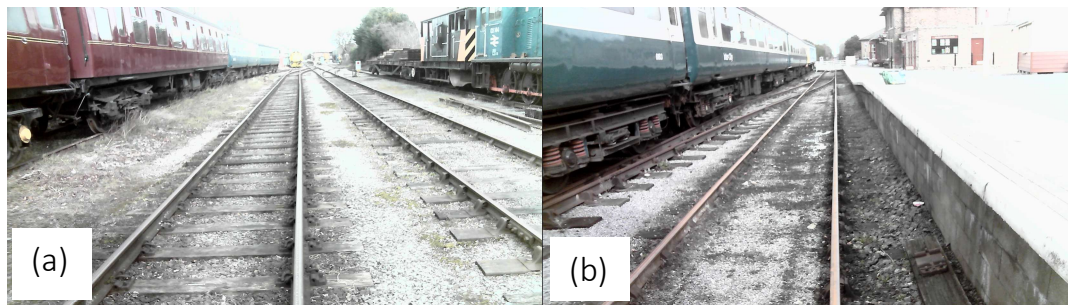


Figure 11: Forward facing images of track sections: (a) exposed to sun and (b) a shaded sections towards the platform

Figure 11a shows the section of the track that exhibited one of the peak railhead temperatures of 11.1 °C. There is no shade there. Figure 11b had a railhead temperature of 6.3 °C and, as can be seen from the image, the track was shaded from the sun by both the platform edge and the vehicles in the siding.

Research carried out previously [15, 16] has also shown that shade covering the railhead (either by clouds or anything blocking the sun) brings about a decrease in railhead temperature and exposure to the sun would increase the railhead temperature, as seen here.

5.2 TEST 2 (Short) & 3 (Long)

Tests 2 and 3 were carried out over two days. Test 2 on the first day involved repeated short runs of approximately 260 m over the track in the yard. So, repeat results were achieved and

it was also an opportunity to see once again how the estimation tool reacted to slight changes in temperature as the railhead and air got warmer. The sectioned results in Figure 7 showed similar friction ranges estimated over the same section of track for dynamic tests. For example, this can be seen in sections 6 and 8 which had an average estimated friction of 0.229 and 0.227 respectively.

For Test 3, air temperatures recorded were 19 ± 3 °C, showing the sensor was sensitive enough to record the increase/decrease due to environmental factors such as shading, cloud coverage among others, the same can be seen for the sensitivity of the railhead sensors.

Figure 12a shows evidence for why on occasions a high air temperature was seen of 28.7 °C while the railhead sensor recorded a lower value 21.1 °C (as seen in Figure 12c, sections 1 and 5). It was due to shading effects over that section of the track.

The railhead temperatures recorded for Test 2 ranged from 20.2 °C – 40.3 °C, the temperature increased and decreased with exposure to sun or shade as seen in Figure 12a. This phenomenon is very noticeable where the train is stationary at a spot with exposure to the sun, for example in sections 3 and 7 on Figure 12c, which are located on the same spot. Figure 12b shows the stationary position at section 3 recording between 30.1 °C – 34.2 °C and the right at Section 7 recording between 31.1 °C – 32.6 °C.



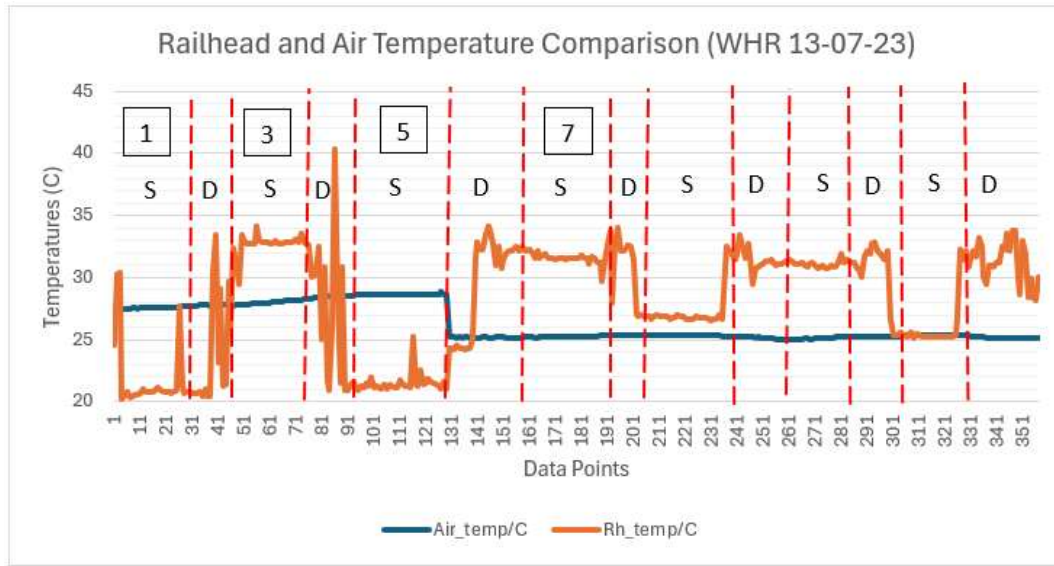
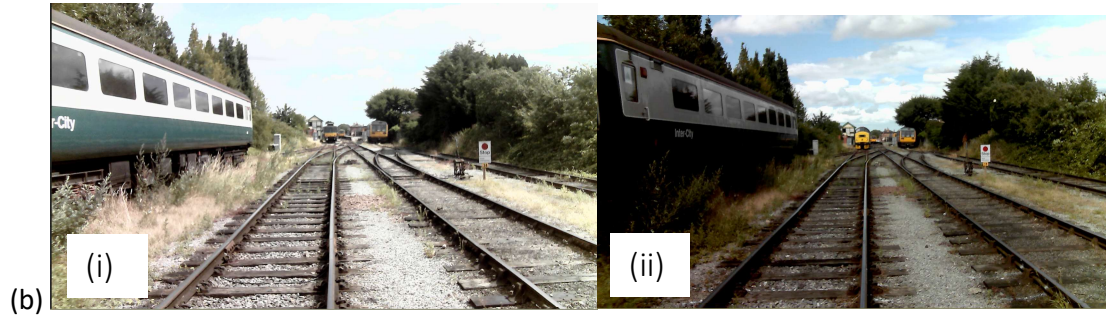


Figure 12: (a) Forward facing image of a hot spot recorded with air temperature 28.7°C with a shaded railhead section recording 21.1°C on the railhead IR sensor during test 2 on 13-07-23; (b) Spots of high railhead temperature with sun exposure for: (i) section 3 and (ii) section 7 for test 2 on 13-07-23 and (c) Railhead-Air Temperature comparison for 13-07-23 tests in WHR (Test 2).

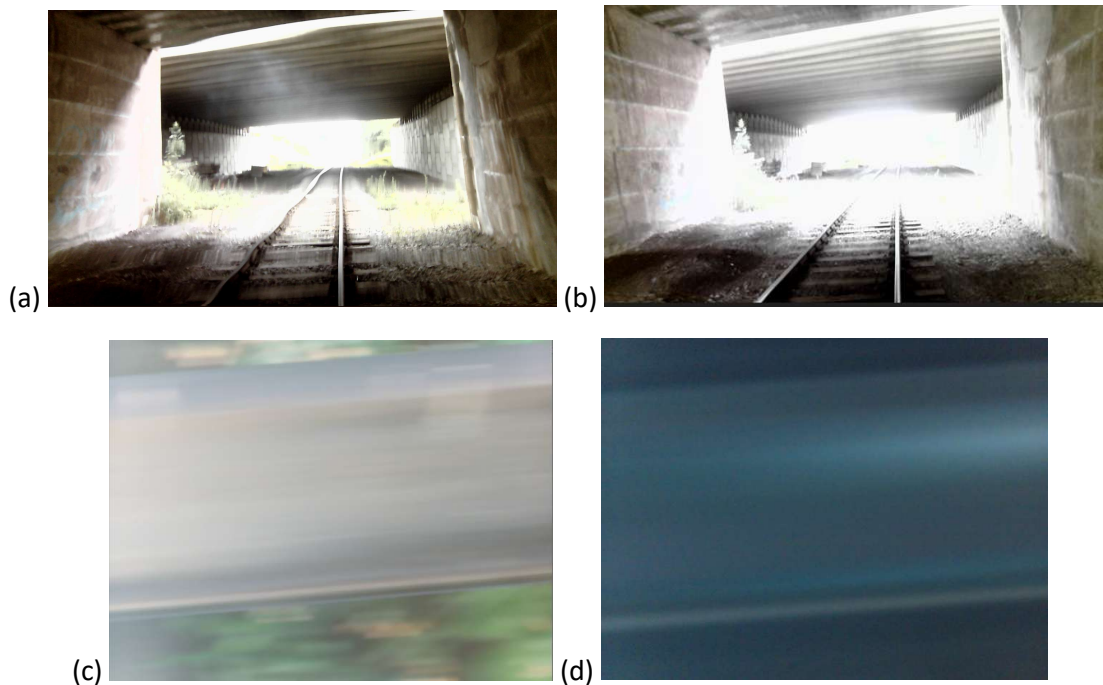
A 40.3°C railhead temperature was recorded on one occasion (the spike can be seen on Figure 10) with most temperatures ranging from 20.2°C – 34.2°C . The friction estimated on this test day ranged from 0.214 – 0.236 and steady friction estimations (with ± 0.001 variations) were recorded over the same section of railhead, that is, where the train was stationary, marked as 'S' in Figure 7. Railhead temperatures recorded at stationary spots had $\pm 0.2^{\circ}\text{C}$ variations whilst the relative humidity had variations of $\pm 0.2\%$. This furthermore shows the estimation tool takes into account changes in the environmental conditions when making estimations, which was discussed in Folorunso et al. [17] that these factors play a key role in understanding the wheel-rail adhesion. The step change noticed at the transition from section 5 to 6 was because the camera box was turned off at the end of section 5's run and then restarted at the beginning of section 6.

The trial on the second day used another Class 142 train which was travelling from Leeming Bar to Leyburn, through Bedale and Finghall Lane as a return journey. The one-way journey was an approximately 11.5 miles (18.5 km) and took 42 minutes, as shown in section 1 in Figure 8 with a 5-minute stop and a 2-minute stop on the return journey at Bedale Station, shown in section 2 and 4 and a brief stop in Finghall Lane which was not significant enough

to be noted on the plot. Section 2 and 4 at Bedale Station as determined with the GPS data, showed a uniform friction of 0.285 ± 0.002 for Section 2 and 0.276 ± 0.006 for Section 4. The data captured here was at over 20 mph. This did not change the quality of the forward facing or railhead images captured.

Air temperature recorded was 20 ± 3 °C which was similar to the previous tests and the railhead temperatures ranged from 16.9 °C – 29.5 °C with the majority of them being between 17 °C – 24 °C.

The friction estimated with all the images ranged between 0.223 – 0.292 (see Figure 8). However, sections 1 and 3 of the plot show a big drop at points “51” and “2501”. Upon further investigation it was noticed this was recorded under a bridge just outside Leeming Bar Station, as shown in Figure 14a. The decrease in the estimated friction can be accounted by the drop in temperatures experienced under the bridge from 21.1 °C to 17.1 °C and 21.1 °C to 17.3 °C in sections 1 and 3 respectively. Work done measuring friction levels using the British Rail Research Tribometer train through Saxelby and Asfordby tunnels [18] showed friction levels decreased at the entrance into the tunnels as seen in Figure 14. It showed the effects tunnels have on the moisture level, shading and temperature of the railhead.



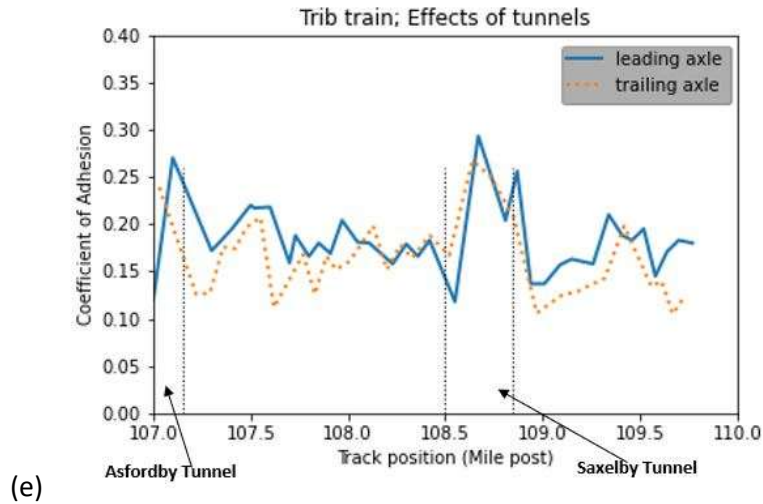


Figure 13: (a) Forward facing image in the tunnel exiting Leeming Bar; (b) Forward facing image in the tunnel approaching Leeming Bar; (c) Corresponding railhead image for 'a'; (d) Corresponding railhead image for 'b' and (e) Effects of tunnels on railhead friction measured on a Tribometer train (adapted from [16] by author)

All the images collected at WHR at this point had been under dry railhead conditions and the estimations showed consistency from the first trial to these ones, as the railhead state had not changed. This shows the estimations are clearly a function of the railhead state and environmental data.

5.3 TEST 4 (Short and Long)

For the final camera box trial in this work, two camera boxes were used. Both camera boxes recorded similar air temperatures in the range of 8 ± 2 °C, which shows the temperature sensors have a good tolerance and measure similar data at the same location. The railhead temperatures on the other hand had a temperature range from -1.6 °C to 6.2 °C for camera box 1 with -1.6 recorded on one instance and majority of low temperature was from 0.8 °C. While railhead temperature recorded on camera box 2 ranged from -5.1 °C to 15 °C with both -5.1 and 15 occurring on one occasion (commonly when the command thread was restarted) and majority of the temperature measured was between 1.9 °C – 7.9 °C. Camera box 1 measured colder temperatures than box 2 because it was installed at the front of the train which is the leading part, therefore the railhead has cooler temperatures because it has not been run over by the train wheels. While box 2 sensor measured slightly higher temperature as it was on the back of the train which was the trailing side, which had railhead that was already passed over by the wheel.

These tests offered an avenue to compare the friction estimations to friction measured using a Rivelin Rail tribometer. Figure 14 illustrates tribometer measurements taken alongside camerabox estimations for dry and leaf layer conditions. The data presented in Figures 9a and 9c were recorded during the short runs during the leaf layer creation. The leaf layer was created on a small section of the railhead as shown in Figure 5. The estimated friction is seen to reduce sharply at the sections where the leaf layer was created. The estimated friction gets progressively lower as the train continues to pass over the leaf layer creating the black layer. The leaf layer was run over six times (3 return movements) represented by the first six

sharp drops Figure 9a. The final friction estimate of the black leaf layer section was 0.187 for box 1 and 0.182 for box 2 compared to the measured friction of 0.152 on the left side corresponding to the camera box 2 position. Although the estimation tool has not received extensive black leaf layer data training, this result shows that with more data it will accurately estimate friction comparable to a friction measurement device such as the Rivelin Rail tribometer.

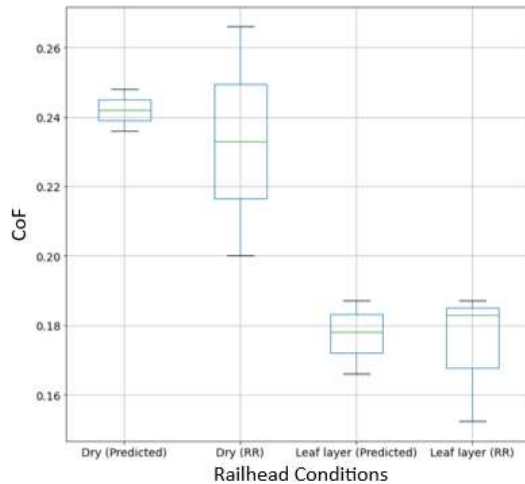


Figure 14: Comparison of Prediction tool and Rivelin Rail (RR) Tribometer Friction for WHR 28-11-23 Tests

The leaf layer was reapplied a second time on a different section of the track (seen on the second side of the black line labelled 2) and a similar trend was noticed. The model estimated a friction of 0.174 and 0.176 (return) for the leaf layer created after 2 passes while the tribometer measured friction was 0.187 on the left track. The right side of the track had an estimated friction of 0.184 compared to 0.183 measured by the tribometer.

The estimations obtained from the long run test from Leeming Bar to Bedale shown in Figure 9b and 9d have a similar trend to sections 1 and 3 of the data collected between Leeming Bar, Bedale and return seen in Figure 8d. The drop in the estimated friction was also noticed here at the same location under bridge giving an estimation of 0.210 and 0.211 from camera box 1 exiting and entering Leeming Bar respectively. Camera box 2 encountered a software error which restarted the thread when exiting Leeming Bar while under the bridge of interest, but captured it on the return journey showing the drop in Figure 9d estimating 0.201. A second drop which estimated a friction of 0.209 was noticed where a sudden drop in railhead temperature occurred from 3.9 °C to -5.1 °C where the friction reduces from 0.244 to 0.209. The ostensible drop in the temperature was likely caused by an error either from vibrations causing the IR sensor to briefly shift hence a random reading or sensor restarting. The railhead temperature returned to 4 °C after the one -5.1 °C reading which in turn returned the estimated friction to 0.244.

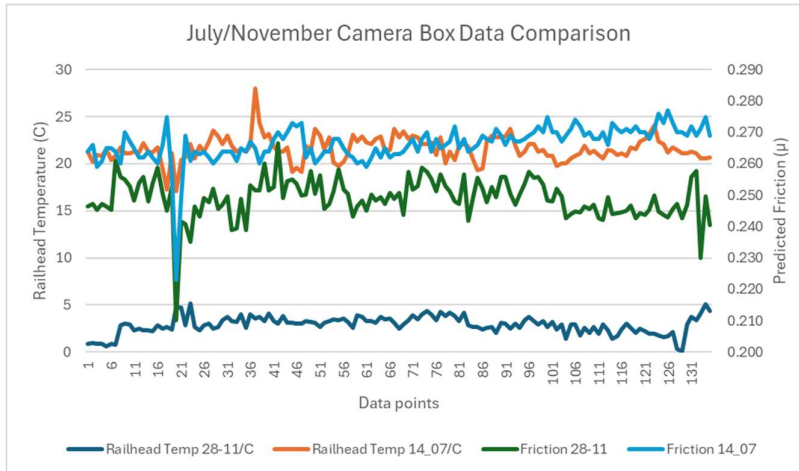


Figure 15: Comparison of data collected from the camera in the summer 14-07-23 to winter 28-11-23

The estimated friction for the long run ranged between 0.227 to 0.282 and 0.227 to 0.270 with exclusion of the tunnel effects and railhead temperature anomaly for camera box 1 and 2 respectively. These estimations are slightly lower than the estimations made by the model during the summer period on the same route. Figure 15 shows data extracted from the same route which was Leeming Bar to Bedale for 14/7/23 where the railhead temperature was warmer than 28/11/23. The estimated friction during the summer period was higher by an average of 0.016 than the estimated friction during winter. This correlates with findings of Folorunso et al. [17] that railhead temperature does affect the friction levels, although it does not have a great impact.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

- The final data collection set-up using the camera box showed that the concept of an on-train data collection and friction estimation system is feasible.
- The camera box estimations showed consistency over the same area of data collection furthermore proving the reliability in the output of the estimation tool. The estimation tool is also very sensitive to the railhead state such as wet and dry as it is expected to be. Estimating lower friction with the appearance of moisture on the railhead.
- The friction estimation model has compared well against the Rivelin Rail tribometer measurements.
- The camera box set-up created cannot be a permanent solution as the lamp bracket holder is not fitted on all rolling stock with some having them located in different positions.
- It was proven that the camera works, but an integrated data capture system on the train either close to or **attached to the train's bogie** will be beneficial for collecting clearer railhead images **and will help overcome the issue raised above regarding the**

lamp bracket approach. Here lighting provision will be required. Also approvals processes will have to be carried out and the design must fit within the dynamic gauge of the train.

6.2 RECOMMENDATIONS

- It is recommended that the camera box designed for this work be used by the railway industry for purposes other than friction estimation. It can be used for accurate railhead and air temperature with relative humidity which will inform train drivers of the driving conditions. The forward-facing images can be used for monitoring the track surrounding and vegetation management. The GPS data can also aid in narrowing down locations of events recorded.
- The next step involves integrating the developed tools and approaches with existing industry practices. This includes creating a specialised data collection (eliminating sensor noise and blurry images) and integrating within rolling stock, this will also require automation of the data processing. Collaboration with rail operators and relevant stakeholders will be crucial for adoption.
- The success of this research in the UK suggests the potential for adaptation to other railway networks globally. Assessment of applicability in different environments and climates could further extend the impact of these findings.

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Appendices

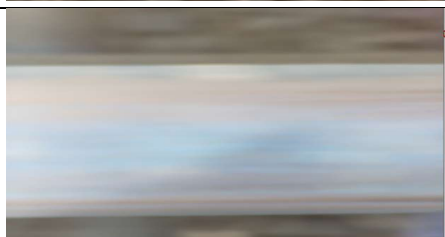
A.1 CAMERA BOX COMPONENTS

- **1 forward-facing camera:** A webcam was used to capture the forward-facing images because it has a USB connection which needs no further modification to work with the microcontroller and it can capture high-definition images (1920x1080 pixels)
- **1 railhead camera:** A 2MP, 2.8 focal length Arducam pivariety colour global shutter camera module and a narrow angle S-mount 12MP lens with a focal length of 50mm was used. Once again for ease of connectivity and to zoom in close to the railhead from the lamp bracket position.
- **1 GPS sensors:** The GPS sensor used to record the location of each data capture point was the E-1612-UB module. It is low power, high performance and ultra-high sensitivity at -160 dBm. It consumes a maximum 40 mA with a maximum power supply voltage of 3.6 V and can operate in temperature range -40 °C to 85 °C. This was ideal for the expected temperature ranges (-10 °C to 50 °C) and power source of the camera box.
- **1 Power bank:** Power source choice for the camera box was a battery pack (power bank) because it is portable, rechargeable and does not need to be continuously connected to an AC source. The power bank used here is V75 USB battery pack with two 5 V/2 A (3 A max) USB output slots. It has a capacity of 19 200 mAh, 71 Wh and output operating temperature ranges from -15 °C to 65 °C. The power bank will power the camera box's component for at least 24 hours on a single charge which sufficient for the purpose of this project.
- **1 Single board computer (SBC):** A Raspberry Pi 4 (Raspi) model B was used to collate the data from each source: (UART: GPS, USB: Web cam and environmental sensors, MIPI CSI: rail head camera). This data was saved as a csv file on the computer's SD card. The computer had an operating voltage of 5 V allowing it to be powered directly by the power bank, its operating temperature range is 0 °C to 40 °C.
- **1 Microcontroller:** An Arduino Uno Rev 3 SMD was used to interface with the analogue environmental sensors as the SBC did not have an onboard analogue to digital converter. This was connected to and powered by the raspberry pi by a USB port, using the Arduino's onboard UART to USB chip. It had an operating temperature range of -40 °C to 85 °C.
- **3D printed parts and 2 Camera Tripods:** This was used for customising and attaching the components to the camera box inner brackets and also for support. See Figure 2.

- **1 Relative humidity and Air temperature sensor:** An HTM2500LF Temperature and Relative Humidity Module was used based on it being non-contact and rugged. It had a low power consumption with a maximum of 1.2 mA, operates on a maximum supply voltage (peak) of 12 V, temperature of -45 °C to 85 °C and relative humidity of 0 % to 100 %. It can record relative humidities from 1 % to 99 % with an accuracy of ± 3 % and a temperature measuring range of -45 °C to 85 °C. This sensor was an analogue sensor meaning it can only be operated with a microcontroller that can process analogue inputs such as an Arduino uno.
- **1 railhead temperature sensor:** An Infrared (IR) thermometer was selected to measure and record the railhead temperature. The IR thermometer was pointed at the railhead to capture its temperature. An Optris CS LT IR thermometer was used because it has a 15:1 optical resolution (up to 800mm range) measuring from -40 °C to 1030 °C with an accuracy of ± 1.5 °C. This thermometer can be applied either as a digital or analogue input. It was used as an analogue input in this set-up to link it with the air temperature sensor.

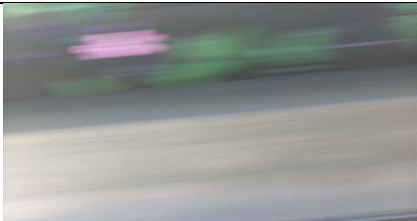
A.2 TABLES OF CAMERA BOX DATA

Table A2. 1: Table of data from WHR *Test 1* 14-03-23

S/N	Forward facing Image	Railhead Image	Air Temp/°C	Rh Temp/°C	Rh/%	Estimated Friction (μ)
1			7.2	9.3	49.0	0.242
2			7.7	6.1	50.0	0.238
3			7.6	7.7	48.4	0.241

4			7.3	10.5	49.4	0.245
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Table A2. 2: Table of data from WHR Test 2 on 13-07-23

S/N	Forward facing Image	Railhead Image	Air Temp/°C	Rh Temp/°C	Rh/%	Estimated Friction (μ)
1			28.6	22.0	23.1	0.230
2			28.4	31.4	23.1	0.222
3			27.7	20.5	22.8	0.221

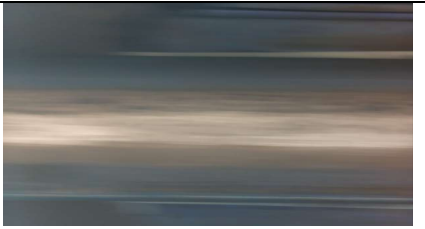
4			25.1	32.5	29.9	0.225
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Table A2. 3: Table of data from WHR Test 3 14-07-23

S/N	Forward facing Image	Railhead Image	Air Temp/°C	Rh Temp/°C	Rh/%	Estimated Friction (μ)
1			21.6	20.7	46.8	0.263
2			18.1	21.8	61.1	0.272

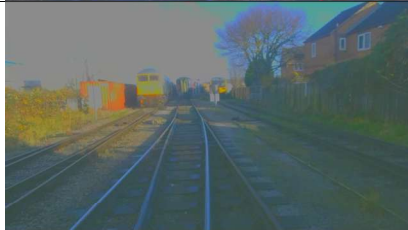
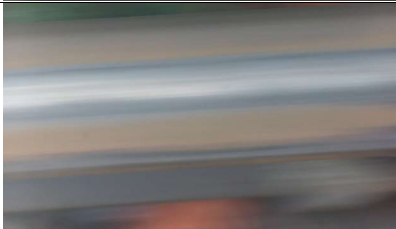
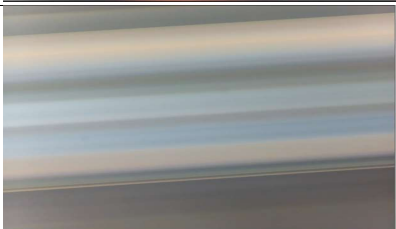
3			18.8	23.9	59.7	0.274
4			19.2	22.8	59.4	0.276

Table A2. 4: Table of data from WHR Test 4 (camera box1) 28-11-23

S/N	Forward facing Image	Railhead Image	Air Temp/°C	Rh Temp/°C	Rh/%	Estimated Friction (μ)
1			9.3	4.1	50.6	0.172

2			7.6	2.8	59.7	0.189
3			7.1	3.1	60.4	0.191
4			9.1	0.8	54.9	0.261

Table A2. 5: Table of data from WHR **Test 4** (camera box2) 28-11-23

S/N	Forward facing Image	Railhead Image	Air Temp/°C	Rh Temp/°C	Rh/%	Estimated Friction (μ)
1			8.0	2.9	57.3	0.159
2			7.9	2.5	54.7	0.178
3			8.3	3.4	53.3	0.173
4			7.3	3.6	52.6	0.241

A.3 CAMERA BOX SAMPLE DATA

	A	B	C	D	E	F	G	H	I
1	forward_filename	rail_filename	rh_temp	air_temp	humidity	gps_lat	gps_lon	speed	heading
2	forward_filename	./rail_images/1701183379.7i	41	97	452	54 deg 18.1892 min	001 deg 33.9124 min	0	217.18
3	./forward_images/1701183379.7i	./rail_images/1701183379.7i	43	98	446	54 deg 18.1892 min	001 deg 33.9124 min	0	217.18
4	./forward_images/1701183379.7i	./rail_images/1701183379.7i	44	98	458	54 deg 18.1892 min	001 deg 33.9124 min	0	217.18
5	./forward_images/1701183379.7i	./rail_images/1701183379.7i	43	98	452	54 deg 18.1892 min	001 deg 33.9124 min	0	217.18
6	./forward_images/1701183379.7i	./rail_images/1701183379.7i	44	98	450	54 deg 18.1892 min	001 deg 33.9124 min	0	217.18
7	./forward_images/1701183379.7i	./rail_images/1701183379.7i	46	98	456	54 deg 18.1892 min	001 deg 33.9124 min	0	217.18
8	./forward_images/1701183379.7i	./rail_images/1701183379.7i	42	98	454	54 deg 18.1892 min	001 deg 33.9124 min	0	217.18
9	./forward_images/1701183379.7i	./rail_images/1701183379.7i	43	98	462	54 deg 18.1892 min	001 deg 33.9124 min	0	217.18
10	./forward_images/1701183379.7i	./rail_images/1701183379.7i	41	98	454	54 deg 18.1892 min	001 deg 33.9124 min	0	217.18
11	./forward_images/1701183379.7i	./rail_images/1701183379.7i	42	98	454	54 deg 18.1892 min	001 deg 33.9124 min	0	217.18
12	./forward_images/1701183379.7i	./rail_images/1701183379.7i	44	98	452	54 deg 18.1892 min	001 deg 33.9124 min	0	217.18
13	./forward_images/1701183379.7i	./rail_images/1701183379.7i	42	98	452	54 deg 18.1892 min	001 deg 33.9124 min	0	217.18
14	./forward_images/1701183379.7i	./rail_images/1701183379.7i	46	98	452	54 deg 18.1892 min	001 deg 33.9124 min	0	217.18
15	./forward_images/1701183379.7i	./rail_images/1701183379.7i	48	98	460	54 deg 18.1892 min	001 deg 33.9124 min	0	217.18
16	./forward_images/1701183379.7i	./rail_images/1701183379.7i	49	99	458	54 deg 18.1892 min	001 deg 33.9124 min	0	217.18
17	./forward_images/1701183379.7i	./rail_images/1701183379.7i	79	98	466	54 deg 18.1892 min	001 deg 33.9124 min	0	217.18
18	./forward_images/1701183379.7i	./rail_images/1701183379.7i	49	98	458	54 deg 18.1892 min	001 deg 33.9124 min	0	217.18
19	./forward_images/1701183379.7i	./rail_images/1701183379.7i	44	99	464	54 deg 18.1892 min	001 deg 33.9124 min	0	217.18
20	./forward_images/1701183379.7i	./rail_images/1701183379.7i	48	98	466	54 deg 18.1892 min	001 deg 33.9124 min	0	217.18
21	./forward_images/1701183379.7i	./rail_images/1701183379.7i	46	98	464	54 deg 18.1892 min	001 deg 33.9124 min	0	217.18
22	./forward_images/1701183379.7i	./rail_images/1701183379.7i	44	97	462	54 deg 18.1892 min	001 deg 33.9124 min	0	217.18
23	./forward_images/1701183379.7i	./rail_images/1701183379.7i	46	98	468	54 deg 18.1892 min	001 deg 33.9124 min	0	217.18
24	./forward_images/1701183379.7i	./rail_images/1701183379.7i	44	98	466	54 deg 18.1892 min	001 deg 33.9124 min	0	217.18
25	./forward_images/1701183379.7i	./rail_images/1701183379.7i	44	98	470	54 deg 18.1892 min	001 deg 33.9124 min	0	217.18
26	./forward_images/1701183379.7i	./rail_images/1701183379.7i	43	98	466	54 deg 18.1892 min	001 deg 33.9124 min	0	217.18
27	./forward_images/1701183379.7i	./rail_images/1701183379.7i	43	98	466	54 deg 18.1892 min	001 deg 33.9124 min	0	217.18
28	./forward_images/1701183379.7i	./rail_images/1701183379.7i	45	98	472	54 deg 18.1892 min	001 deg 33.9124 min	0	217.18
29	./forward_images/1701183379.7i	./rail_images/1701183379.7i	42	98	464	54 deg 18.1892 min	001 deg 33.9124 min	0	217.18
30	./forward_images/1701183379.7i	./rail_images/1701183379.7i	57	97	468	54 deg 18.1892 min	001 deg 33.9124 min	0	217.18
31	./forward_images/1701183379.7i	./rail_images/1701183379.7i	45	98	470	54 deg 18.1892 min	001 deg 33.9124 min	0	217.18
32	./forward_images/1701183379.7i	./rail_images/1701183379.7i	39	98	481	54 deg 18.1892 min	001 deg 33.9124 min	0	217.18
33	./forward_images/1701183379.7i	./rail_images/1701183379.7i	39	97	484	54 deg 18.1892 min	001 deg 33.9124 min	0	217.18
34	./forward_images/1701183379.7i	./rail_images/1701183379.7i	53	97	472	54 deg 18.1892 min	001 deg 33.9124 min	0	217.18
35	./forward_images/1701183379.7i	./rail_images/1701183379.7i	51	97	472	54 deg 18.1840 min	001 deg 33.9110 min	1.35	234.8
36	./forward_images/1701183379.7i	./rail_images/1701183379.7i	53	97	476	54 deg 18.1836 min	001 deg 33.9122 min	1.81	238.61
37	./forward_images/1701183379.7i	./rail_images/1701183379.7i	57	97	468	54 deg 18.1830 min	001 deg 33.9133 min	2.18	237.36

Figure 16: Example spreadsheet extract post-testing with the camera box

A.4 CAMERA BOX SENSOR SET-UP AND VALIDATION PROTOCOL

Sensor and Camera Alignment

- Align the railhead camera and railhead temperature sensor with the rail surface.
- Adjust the camera focus to the nominal operating distance.

System Connection and Control

- Power the Raspberry Pi (RasPi); it automatically connects to a mobile phone via the phone's Wi-Fi hotspot.
- Access the RasPi using the RasPi Controller application on the mobile phone.
- Establish an SSH connection via the application and launch the Python data acquisition software.
- Use the live camera feed to confirm alignment and focus.

Sensor Output Verification

- Use the software's text-based interface to monitor real-time outputs from all sensors.
- Confirm correct operation of railhead temperature, ambient temperature, and relative humidity sensors.

Railhead Temperature Sensor Alignment Check

- Place a controlled hot object (e.g., a hot mug) on the rail within the sensor's field of view.
- Observe the sensor response via the text interface.
- Adjust sensor alignment if required to ensure maximum and stable response.

IR Thermometer Validation

- Prior to and following alignment, validate sensor accuracy by comparison with a calibrated handheld IR thermometer.
- Simultaneously measure the temperature of a reference surface using:
 - the railhead temperature sensor, and
 - the handheld IR thermometer.
- Compare readings to confirm agreement within acceptable tolerance of $\pm 1.5^{\circ}\text{C}$.
- Repeat the comparison to verify consistency and repeatability.

Validation Acceptance

- Confirm that all sensor measurements meet predefined accuracy criteria.
- Upon successful validation, commence normal operational data collection.