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An investigation into wayside hot-box detector efficacy and optimization

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ABSTRACT
Wayside hot-box detectors (HBDs) are devices used to assess the health of railcar components including bearings, axles, and brakes by monitoring their temperatures. HBDs use infrared (IR) sensors to record the temperatures of railroad bearings. Bearings that trigger an alarm or exhibit warm trending are removed and sent for inspection. In many cases, no discernable defects were found in the flagged bearings. Motivated by this finding, an investigation was conducted which included performing a controlled field test as well as exhaustive laboratory testing utilizing an HBD simulator. Data acquired from field and laboratory testing was used to evaluate the accuracy and efficacy of wayside HBDs. The results suggest that the scanning location on the bearing cup significantly affects the temperature measurement. Different calibrations for the field- and laboratory-acquired data were also explored. An optimized calibration technique along with proper IR sensor alignment can markedly improve the accuracy of HBD measurements.

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Wayside hot-box detectors (HBDs); railcar condition monitoring; HBD optimized calibration; HBD accuracy and efficacy; Infrared (IR) sensor calibration; railroad bearing temperatures

1. Introduction and literature review

1.1. Introduction

Bearing health monitoring systems are devices used by the railroad industry to potentially identify problematic bearings so they can be safely removed from service; thus, preventing catastrophic failures that can lead to costly train derailments. The railroad industry currently utilizes two wayside detection systems to monitor the health of freight railcar bearings in service: The Trackside Acoustic Detection System (TADS™) and the wayside Hot-Box Detector (HBD). TADS™ uses wayside microphones to detect and alert the conductor of high-risk defects [1]. Many defective bearings may never be detected by TADS™ due to the fact that these devices are set to only detect high-risk defects (spalls which usually span more than 90% of a bearing's raceway), and there are less than 30 systems in operation throughout the United States and Canada [2]. Wayside Hot-Box Detectors (HBDs) are devices that sit on the side of the rail tracks and use non-contact infrared (IR) sensors to

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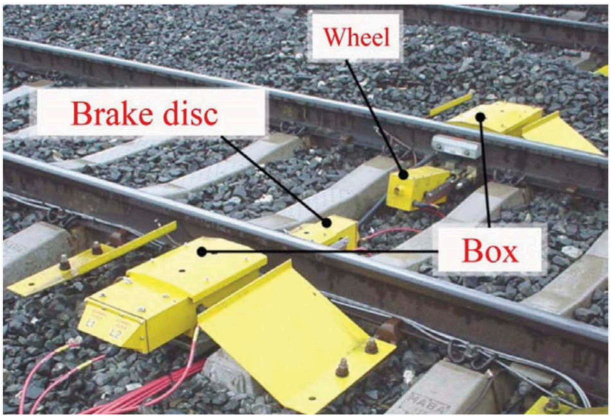

Figure 1. Photograph of a wayside hot-box detector system [6].

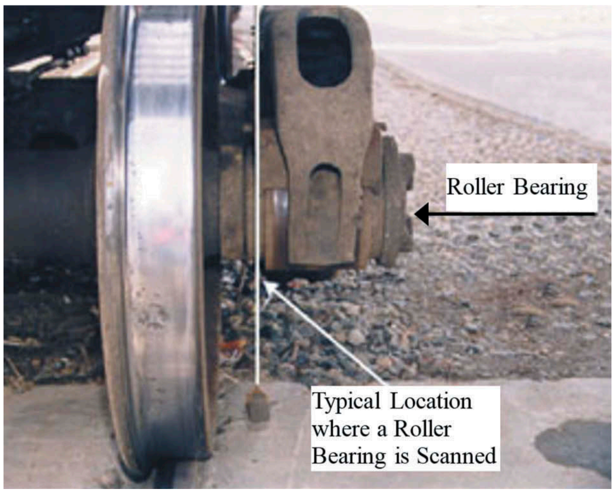

Figure 2. Typical infrared sensor scanning location for field wayside hot-box detectors (HBDs) [7].

determine the temperature of the train bearings as they roll over these detectors (see Figures 1 and 2). HBDs are the most common bearing health monitoring system utilized in the U.S. with over 6,000 of these devices spread across the nation's railways [3]. Typically, HBDs are positioned around 24 to 48 km (15 to 30 mi) apart along the track [4]. As each freight car passes, the HBDs scan the bottom surface of the bearings, recording infrared temperature measurements of the bearings as well as the ambient temperature from the surroundings. An alarm is triggered if the difference between the infrared temperature of the bearing surface and the ambient temperature exceeds a predetermined threshold. One set of common criteria that will trigger an alarm is as follows: (1) if a bearing is operating at a temperature greater than 94.4°C (170°F) above the ambient temperature or (2) if a bearing is operating at a temperature greater than 52.8°C (95°F) above the temperature of the bearing that shares the same axle [5].

1.2. Current problems and developments in wayside hot-box detector technologies

Due to the catastrophic consequences that can result from unreliable condition monitoring systems, it is critical to examine the effectiveness of wayside HBDs. Variables such as bearing class and IR scanning location may significantly affect the accuracy of HBD temperature data. These variables can cause the HBD system to underpredict or overpredict the railroad bearing operating temperature. In the event of an overpredicted temperature, a healthy (defect-free) bearing may be falsely flagged as defective and will be removed from service. Upon inspection, if no defects or other problems are found, the bearing is classified as 'non-verified'. These non-verified bearings lead to delays and unnecessary train stoppages, which cost both time and money. In a study performed from 2001 to 2007, Amsted Rail found that nearly 40% of bearings flagged by HBDs and removed from service were classified as 'non-verified'. If an HBD underpredicts the temperature of a bearing that is running hot, and an alarm is not triggered, catastrophic bearing failure may occur. Statistics show that from 2009 to 2018, wayside HBDs have failed to detect 151 defective bearings throughout the United States and Canada, all of which led to catastrophic derailments [8].

Bearing condition monitoring technologies can be divided into two categories: predictive and reactive systems. Predictive systems are capable of analyzing the condition of the equipment in order to predict any forthcoming failures. Alternatively, reactive systems detect faults on vehicles as they occur in order to prevent any further damage [9]. Wayside HBDs are generally categorized as a reactive bearing condition monitoring system. A hot-box detector is intended to detect the heat radiating from a bearing shortly before failure from overheating. The rate of heating can cause components in the bearing to rise to temperatures upward of 800°C (1472°F) in a span of nearly 25 minutes [10]. The addition of more detectors on the track has been implemented in the past, however, this has had a limited effect due to the rapid failure modes associated with overheated bearings [9]. In fact, bearing failure has occurred within 96 seconds of passing a hot-box detector without triggering an alarm [11]. Therefore, effort has been made to improve wayside HBD technology by using it as a predictive condition monitoring system. In 1997, Canadian National began to track bearing temperatures to search for any signs of temperature increase between HBDs. By tracking individual bearing temperatures, hot bearings in danger of overheating can be predicted based on prior warm bearing readings [12]. In 2003, the Union Pacific Railroad in the U.S. planned to connect upward of 1200 wayside HBDs to create an integrated monitoring system [9]. Despite attempts to improve these devices, growing concerns still exist with regards to the overall efficacy of wayside HBDs.

The most common way of assessing bearing health with wayside HBDs is to see if the bearing temperature exceeds a predetermined threshold. However, factors such as train speed, braking events, and calibration errors may affect the accuracy of HBD temperature measurements. Because of this, Union Pacific started using a relative temperature performance system in 2002 to monitor bearing temperature performance. This process involves using statistics to divide wayside temperature data from the bearings in railcars into quartiles. These statistical groups are used to calculate a 'K-Value', which is used to quantify the deviation of a single bearing temperature from the rest of the bearings installed on a train. Thus, this method is used to separate healthy bearings from defective bearings in a railcar with relatively low sensitivity to calibration and environmental factors [5].

Due to the errors present in modern HBD systems, the efficacy of HBDs were studied by the Transportation Technology Center, Inc. (TTCI) in 2013 at the Railroad Test Track (RTT) in Pueblo, Colorado. This study evaluated HBDs from four different vendors using four different classes of bearings (class K, F, E, and G). Other conditions that were varied were the scanning location of the infrared temperature measurement along the bearing and the scanning angle. The test bearings were equipped with onboard thermocouples for a continuous temperature reference. The results from the study indicated that HBD configurations that measure temperatures closer to the inboard raceway at a near vertical scan angle generally have improved results compared to bearings tested with other HBD configurations [13].

In the early 1990s, a Hot Bearing Specification Development Test was conducted by the Association of American Railroads (AAR) at TTCI in Pueblo, Colorado. The purpose of this test was to use an adjustable aperture device on heated roller bearings to vary the amount of scanning time and scanning area for wayside HBDs in order to create recommended certification procedures for new truck and HBD designs. During the test, 71.12 cm (28”) and 91.44 cm (36”) wheels were outfitted with resistance heaters, temperature control equipment, and temperature measurement transducers. The aperture that was outfitted on the wayside HBDs during testing was adjustable in both the vertical and horizontal direction so that the scanning area can be modified. Various scanning areas were tested in order to generate computer-aided drawings that define the minimum unobstructed area in truck designs that is required for compatibility with current HBDs. To assist with the process of checking for obstructions that are caused by a truck design in a field setting, a laser system that simulates the HBD scan path was utilized. If this test did not provide proof that the truck met the required specifications, an additional compatibility test was conducted to determine the actual performance of the wayside HBDs in relation to any new truck design. Additionally, recommended certification processes for wayside HBDs were developed by creating computer-generated drawings that define the area in which an HBD must be able to operate reliably [14].

Joint research between TTCI and the University of Illinois at Urbana-Champaign was conducted using mathematical models and simulations to determine the optimum spacing between wayside HBDs in service. Data obtained from HBD systems that are currently in place was used to simulate potential HBD spacing scenarios. Additionally, the tradeoff between sensor deployment cost and sensor efficacy was studied. Using a subset of 27 cases of journal burn-off incidents that was reported by the Federal Railroad Administration from 2012 to 2016, the median distance to derailment was determined to be around 14.8 km (9.2 mi). It was determined that reducing the spacing between wayside HBDs to less than 14.8 km (9.2 mi) apart could reduce the percentage of train derailments due to journal burn-off by 50%. However, after further analysis of different wayside HBD spacing distances, it was determined that there was little to no statistical advantage in a sensor spacing of 14.8 km (9.2 mi) as compared to 24.14 km (15 mi), making this latter spacing the optimum distance between HBDs positioned on the track [15].

One development that is currently being studied is the use of alternative HBD scanning technologies. Using a multiple scan HBD system, eight temperature scans of different sections of the bearing can be used to generate a diagram of the temperature distribution across the bearing in both dimensions. If the bearing is seen to be overheating, the temperature profile can be analyzed to locate defective components. For example, if the outermost scans are 6°C (10°F) hotter than the rest of the bearing, the problem inside the bearing may be located in the outboard raceway assembly. Another advantage of this system is redundancy, which is achieved by replacing one sensor with eight different sensors [16].

The study presented here builds on previous work done by the authors to assess the efficacy of wayside HBD systems [17,18]. Preliminary results showed that an IR temperature measurement taken at the inboard (IB) raceway location of the bearing is both the most precise and accurate when compared to other IR scanning locations. Additionally, it was concluded that as the bearing operating temperature increases, the temperature error between onboard thermocouples and the IR temperature measurement increases for all scanning locations [17,18]. These finding were verified using field data acquired from 21 different HBDs during a 2008 field test.

The work summarized here differs from earlier studies in that it (1) explores several calibration methods to optimize HDB measurements, (2) provides a quantifiable comparison between the different calibration methods investigated, (3) presents a laboratory-based technique for assessing HBD efficacy, and (4) proposes ways to improve the accuracy of wayside HBD measurements based on the analysis of laboratory- and field-acquired temperature data. This information will assist in the evaluation of current bearing condition monitoring systems, which will enhance safety technologies implemented in the railway industry. Improving the accuracy of current wayside HBDs can reduce operation costs associated with false bearing setouts and safeguard against train derailments which may result in loss of life. These improvements, however, are contingent on the industry standards being adjusted to reflect the more accurate HBD temperature readings recommended by this study.

2. Experimental setup and procedures

2.1. Field test setup

A field test was performed in 2008 to investigate the warm bearing trending phenomenon experienced in freight railcar service [19]. The acquired data was also used to characterize the efficacy of wayside hot-box detectors (HBDs). This test was conducted along a 483 km (300 mi) stretch of track and passed over 21 different HBDs along the way. Two freight cars, one loaded and one unloaded, were tested with a total of 16 double-tapered roller bearings. Of the 16 bearings, 14 were class F while the other two were class K. Of the class F bearings, three were previously removed from field service due to an outboard inner ring (cone) spall, an inboard outer ring (cup) defect, and a loose cone assembly. Additionally, two of the class F bearings that were tested were previously deemed ‘non-verified’ while the rest were healthy bearings and used as controls. The two class K bearings were also used as controls and were installed on an axle on the unloaded railcar. Train speeds from 40 to 85 km/h (25 to 53 mph) were tested with the train moving at 80 km/h (50 mph) for most of the trip. The ambient air temperature fluctuated throughout the day and night, reaching as high as 33°C

(91°F) during the day and as low as 6°C (43°F) during the night. Each bearing was outfitted with a custom-machined adapter that housed onboard bayonet-type (spring-loaded) thermocouples for continuous temperature measurement. The temperature data was collected using a National Instruments™ data acquisition system. After the field-test, the temperature data from the wayside HBDs was obtained from the railroad operators for further analysis. More details about this setup can be found elsewhere [19].

2.2. Single bearing tester (SBT)

To simulate field service wayside HBDs in a controlled environment, a single bearing dynamic tester was designed and built. The tester, pictured in Figure 3, suspends a test bearing at one end of an axle which is driven by a motor. The tester can simulate the various speeds that a railcar may experience in the field, from 8 km/h (5 mph) to 137 km/h (85 mph). A vertical load can be applied by a hydraulic cylinder to the bearing to simulate loads from 10% to 150% of a fully loaded railcar (full load corresponds to 153 kN or 34.4 kips per class F or K bearings). Furthermore, air is circulated around the bearing using two industrial-strength fans which provide convective cooling. The latter simulates the cooling generated by the airflow moving across the bearing as the railcar is in motion.

The bearing surface temperatures along the inboard and outboard raceways were measured using four K-type spring-loaded bayonet style thermocouples. To accommodate the bayonet thermocouple holders, each bearing adapter was drilled and tapped. The bearing surface temperature was also measured using seven standard K-type thermocouples equally spaced around the circumference of the bearing at the spacer ring location (see Figure 4). These thermocouples were held tightly in place using a hose clamp.

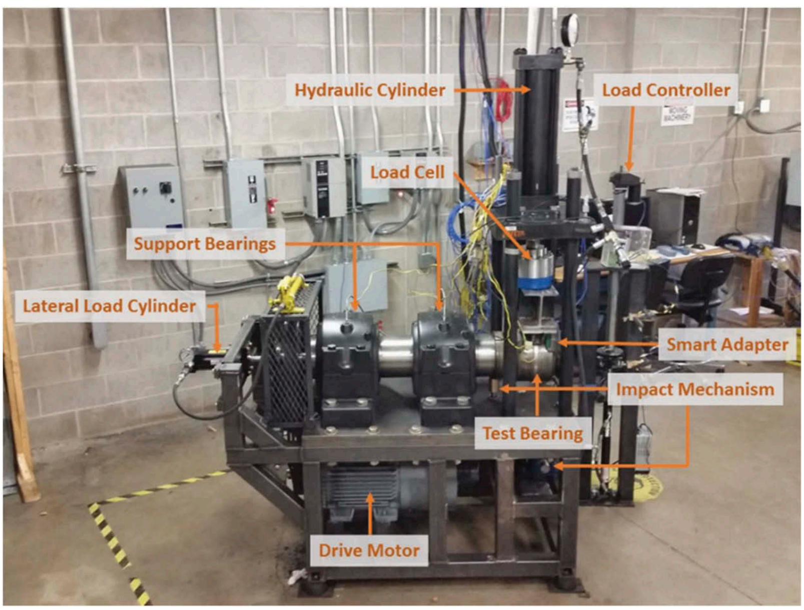

Figure 3. Single bearing tester (SBT) with annotations.

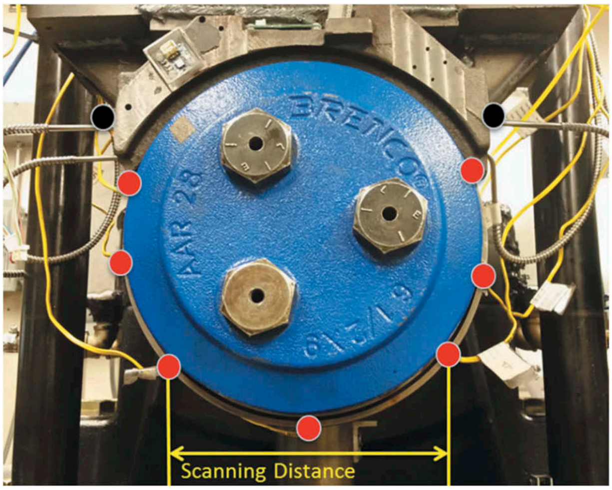

Figure 4. Bearing thermocouple locations, where each red dot represents a standard K-type thermocouple and the black dots represent spring-loaded bayonet-style K-type thermocouples.

2.3. Laboratory-based wayside hot-box detector (HBD) simulator

To mimic the functionality of the wayside HBDs in a laboratory setting, a specialized HBD simulator was designed and constructed. This system, depicted in Figure 5, propels an infrared (IR) sensor underneath the test bearing on the single bearing tester at a prescribed speed. To accomplish this, a pneumatically actuated cart system was designed and assembled which housed the IR sensor. This IR sensor was secured to an adjustable mount which allowed the sensor to be pushed underneath the bearing at different scanning locations. These locations, shown in Figure 6, correspond to the outboard (OB) raceway, spacer ring, inboard (IB) raceway, and inboard seal regions of the bearing.

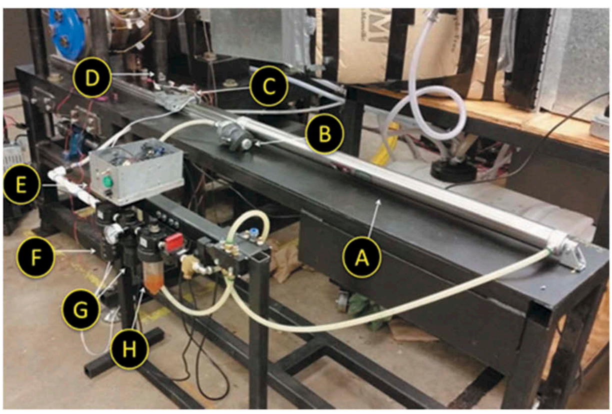

Figure 5. Hot-box detector simulation system. From A through H there is the cylinder [A], the quick exhaust valve [B], the cart [C] with the sensor [D] attached, the control box [E], the filter [F] for the pneumatic system followed by the regulator [G] and the lubricator [H].

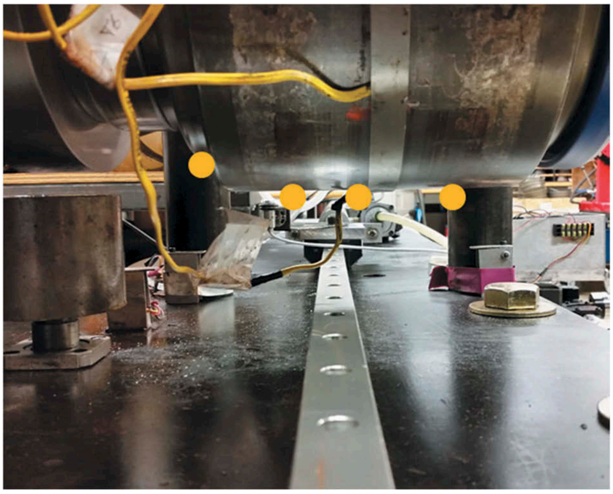

Figure 6. Infrared scanning locations from left to right: inboard seal, inboard raceway, spacer ring, and outboard raceway.

To control the cart assembly, the pneumatic cylinder is connected to a four-way valve that is controlled by an Arduino Uno R3. To calculate the traveling velocity of the cart, two pairs of IR break sensors were placed along the cart track. This setup was used to determine the time at which the cart passed two fixed locations, and this information was then used to calculate the cart velocity. Using the current setup, the sensor can travel at a maximum velocity of 11.3 km/h (7 mph). Although this speed is slower than real service conditions, the system is designed to provide a best-case scenario analysis. That is, if this lower speed results in significant error in the laboratory IR sensor, the error will be magnified in field service operation.

2.4. Infrared scanning profile

Figure 7 shows an example of the raw temperature data collected during a test run. This test was performed at full-load and a speed of 137 km/h (85 mph). From the figure, section (1) represents the temperature measurement as the sensor passes underneath the bearing; section (2) represents the temperature measurement after it has passed underneath the bearing; and section (3) represents the temperature measurement as the sensor returns to its initial position. It should be noted that section (3) is markedly longer than section (1) because the sensor return occurs at a slower speed. For each laboratory test, only the temperature data in section (1) was used in the analysis.

2.5. Test parameters

Several parameters were varied for this study including axle speed, bearing load, bearing class, and IR scanning location. Train speeds from 48 km/h (30 mph) to 137 km/h (85 mph) were simulated in this study. A list of these railcar speeds and their

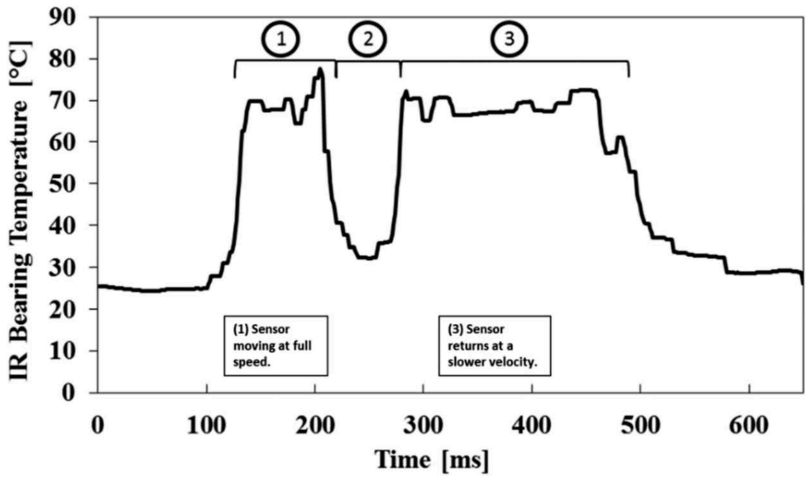

Figure 7. Typical IR sensor scanning profile.

corresponding axle rotational speeds is given in Table 1. In addition, the bearing load was varied to simulate either an empty railcar (17% load) or a full railcar (100% load). The 17% and 100% load settings correspond, respectively, to an applied load on a class F or K bearing of 26 kN (5.85 kips) and 153 kN (34.4 kips). Furthermore, the cart is equipped with a fixture that can be adjusted so that the IR sensor can scan different regions underneath the bearing. The temperature scanning regions that were explored are shown in Figure 6. Over 230 test runs were carried out on class K and F bearings at the different specified speeds and loads for each scanning location.

2.6. Data acquisition

Infrared (IR) temperature data was acquired with the CompactConnect software that came with the IR sensor. For each test, the IR sensor was propelled underneath the test bearing a total of three times at 30-second intervals. IR temperature data was collected at a sampling rate of 1000 Hz. Additionally, continuous onboard thermocouple data was acquired with an NI cDAQ-9174 data acquisition system using an NI-9213 thermocouple input module. To collect and record the onboard thermocouple data,

Table 1. Speeds used for test bearings in this study.

Axle Speed [rpm]	Railcar Speed [mph]	Railcar Speed [km/h]
280	30	48
327	35	56
373	40	64
420	45	72
467	50	80
498	53	85
514	55	89
560	60	97
618	66	106
699	75	121
799	85	137

the engineering software LabVIEW® was used. For both laboratory and field data, average temperature measurements for each onboard thermocouple were recorded at 20-second intervals by averaging 64 samples acquired at a frequency of 128 Hz.

2.7. Infrared sensor static testing and bearing emissivity

To characterize the performance of the MICRO-EPSILON infrared sensor that is employed in the HBD simulator, testing was conducted in a non-dynamic environment. In this test, a bearing outer ring (cup) was placed inside a laboratory oven where the temperature was varied from 60°C (140°F) to 120°C (248°F) at intervals of 20°C. The bearing temperature was then measured with the MICRO-EPSILON IR sensor, a non-contact IR temperature gun, and a K-type thermocouple secured tightly to the middle of the bearing cup via a hose clamp. The temperature measurement from the IR sensor closely matched the data collected from the IR temperature gun. However, the IR sensor readings differed from the K-type thermocouple data, with the IR sensor having an average error of 8°C (14.4°F) over the entire range of the oven test. In field service, wayside HBDs are calibrated using a one-point calibration procedure that utilizes a hot plate set to a temperature of 100°C (212°F). To ensure that the devised laboratory HBD simulator mimics field service wayside HBDs, the data collected using the IR sensor was corrected by adding 8°C to each temperature data point to account for the one-point calibration procedure typically performed for field service wayside HBDs. Hence, any error in the temperature read by the IR sensor is due to factors other than the inherent offset error of the sensor.

Wayside HBDs use IR technology to scan the outer surface of the bearing cup, which may degrade over time to develop rust or other discolorations caused by environmental factors or simple heat-tinting. Consequently, one concern that needed to be resolved is the effect of this discoloration on the emissivity of the surface of bearings. To this end, 25 bearings with various stages of cup surface degradation, ranging from new bearings to ones that have extensive mileage in service operation and have been exposed to severe environmental factors, were selected for emissivity testing. A forward-looking infrared (FLIR) camera was used to capture a thermal image of each bearing. By comparing the thermal image to a reference thermocouple placed on each bearing, the emissivity values of all the bearings were calculated. It was found that the emissivity values of the bearing cup surfaces fell within a small range, with a maximum value of 0.96, a minimum value of 0.86, and a median value of 0.92. The results of this study are indicative of the population of bearings that were analyzed in this paper. Hence, the emissivity for each bearing in this study has been assumed to be that of the median emissivity value of 0.92 [17].

3. Results and discussion

3.1. Bearing temperature performance

The average operating temperatures of class F and K bearings at various speed and load combinations are given in Figure 8. These operating temperatures were obtained from a statistically significant population of data acquired previously [20]. The data shows

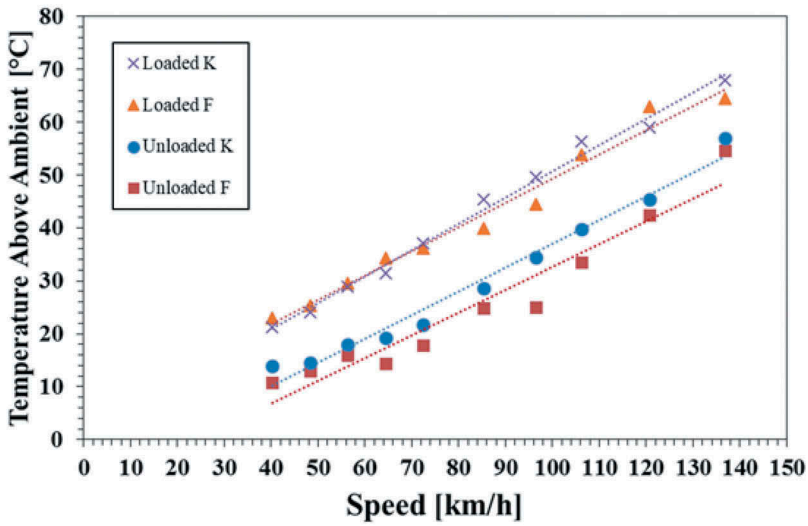

Figure 8. Class F and K bearing average operating temperatures for fully-loaded (100% load) and unloaded (17% load corresponding to empty railcar) conditions at various speeds.

that there is a linear increase in temperature as a function of speed and that increasing the load from 17% (unloaded or empty railcar) to 100% (fully loaded railcar) raises the bearing operating temperature by about 13°C (23°F). One important observation is that healthy (defect-free) class F and K bearings have similar operating temperatures at each speed and load condition.

3.2. Laboratory data analysis

3.2.1. Raw laboratory HBD simulator data

The raw laboratory-acquired data utilizing the devised HBD simulator versus the onboard thermocouple data at two of the four scanning locations are presented in Figure 9 (top two plots). The spacer ring and inboard (IB) raceway locations are shown because they were found to be the least and most precise scanning locations, respectively, as indicated in Table 2. The average of the two inboard bayonet thermocouples was used to measure the onboard temperature for the two inboard scanning locations; the average of the two outboard bayonets was used to measure the onboard temperature for the outboard raceway scanning location; and the average of all four bayonets was used to measure the onboard temperature for the spacer ring scanning location. An offset of 8°C (14.4°F) was added to all laboratory data to account for the inherent offset error of the IR sensor discussed earlier. In the figures, the solid diagonal line represents the ideal case where the HBD simulator data perfectly matches the onboard thermocouple temperatures. Data above the line are an overprediction of the actual bearing temperature, while data below the line are an underprediction. Generally, the raw laboratory HBD simulator data underpredicts the bearing temperature, in some cases by as much as 40°C (72°F). Furthermore, it is evident that the IR sensor error is predominantly dependent on the scanning location. The latter observation is

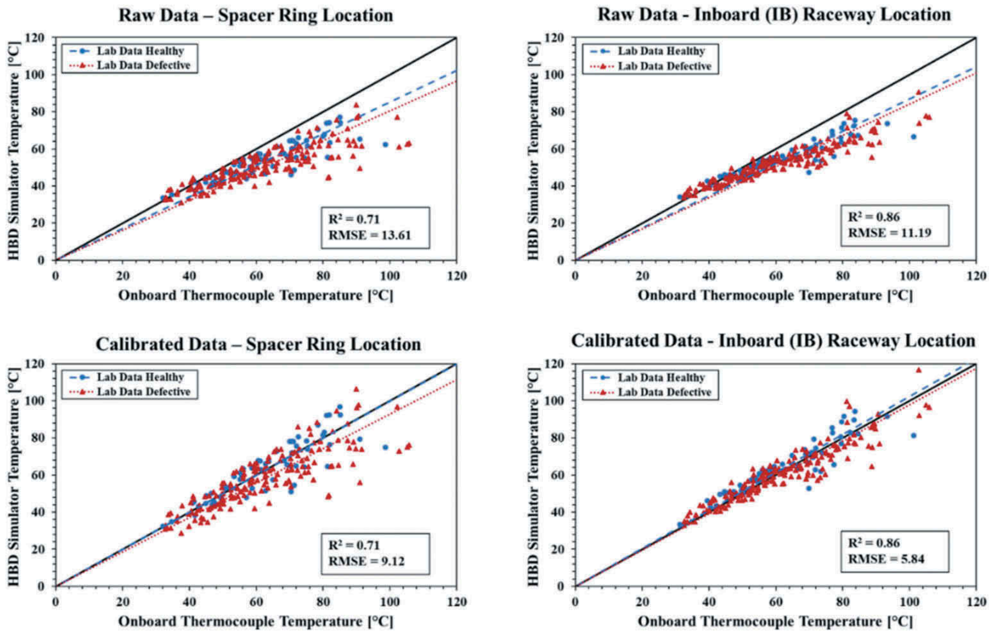

Figure 9. Raw (top two plots) and calibrated (bottom two plots) laboratory HBD simulator temperature versus onboard bayonet thermocouple temperature for the bearing spacer ring (two left plots) and inboard (IB) raceway (two right plots) locations.

Table 2. Coefficient of determination (R^2) and root-mean-squared-error (RMSE) for various calibrations.

		RMSE [°C]				
Data Description		Raw Data	2-Pt. Cal.	3-Pt. Cal.	All-Data Cal.	R^2
Unloaded	**OB Raceway**	7.27	5.94	5.85	6.37	0.81
	Spacer	8.09	6.48	6.20	5.76	0.81
	IB Raceway	5.99	3.59	3.46	4.09	0.92
	IB Seal	7.70	5.83	5.59	5.26	0.82
Loaded	**OB Raceway**	14.37	11.04	10.78	10.53	0.57
	Spacer	16.41	12.72	12.29	10.88	0.55
	IB Raceway	13.70	8.80	8.31	6.81	0.78
	IB Seal	13.25	8.81	8.41	7.53	0.76
All Laboratory Data	**OB Raceway**	11.97	9.28	9.08	9.04	0.72
	Spacer	13.61	10.61	10.24	9.12	0.71
	IB Raceway	11.19	7.13	6.75	5.84	0.86
	IB Seal	11.30	7.73	7.38	6.69	0.83

demonstrated in the data presented in Table 2. For example, the outboard raceway data has greater error compared to other scanning locations, and the error band tightens as the scanning location approaches the inboard raceway region.

3.2.2. Calibration methods

Multiple calibration equations were created to optimize the data collected by the HBD simulator. Given that more precise HBD readings are taken closer to the inboard side of the bearing, the following three calibrations use dynamic infrared (IR) temperature data taken at the inboard raceway scanning location. This data was calibrated against the

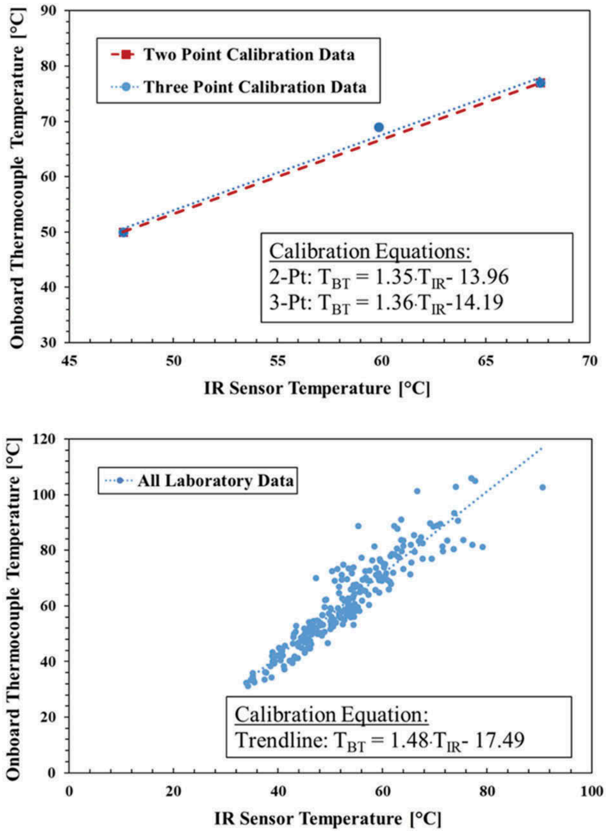

Figure 10. Two-point and three-point calibrations (top plot) and all laboratory data calibration (bottom plot) using data acquired by the laboratory HBD simulator.

average of the two inboard bayonet thermocouples. For the two-point and three-point calibrations, given in Figure 10 (top plot), the calibration points were chosen by selecting laboratory HBD simulator readings that were closest to their corresponding bayonet thermocouple measurements. In the case of the two-point calibration, the lowest temperature reading recorded by the IR sensor that matched (within ± 3°C) the average bayonet thermocouple temperature was chosen as one of the points, whereas, the second point chosen was the highest IR sensor reading that matched (within ± 3°C) the average bayonet temperature. For the three-point calibration, an intermediate third point was chosen between the lowest and highest temperatures recorded following the same criteria used to choose the other two points. The third calibration that was performed utilized, as calibration points, all the inboard raceway temperature data acquired in the laboratory, as shown in Figure 10 (bottom plot).

3.2.3. Coefficient of determination and root-mean-squared error

The root-mean-square-error (RMSE) and the coefficient of determination (R^2) values for the temperature readings obtained by the laboratory HBD simulator are provided in Table 2. The RMSE is defined as:

$$RMSE = \sqrt{\frac{\sum (T_{IR} - T_{BT})^2}{n}} \tag{1}$$

In Equation (1), T_{IR} represents the temperature measured by the infrared (IR) sensor or wayside HBD, T_{BT} is the bayonet thermocouple temperature based on the appropriate calibration equation (in the case of the raw data, it represents the actual average onboard bayonet thermocouple temperature), and n is the number of data points obtained. The RMSE is dependent on the square of the error, placing more 'weight' on outliers. Thus, the RMSE will be used as a measure of the accuracy of the IR sensor readings, with lower RMSE values corresponding to more accurate measurements. Furthermore, the coefficient of determination (R^2) is a numerically determined value that represents how well the dataset fits a regression line. Holding the accuracy of the measurement independent, the coefficient of determination will be used to quantify the precision of the dataset.

3.2.4. Calibrated laboratory HBD simulator data

In Table 2, the RMSE and R^2 improve as the scanning location moves towards the inboard raceway region for all calibrations. The results show that scanning the inboard (IB) raceway location yields the most accurate and precise results for both load conditions. These observations agree with the conclusions from the TTCI study [13]. Applying the calibrations to the raw data significantly improved the performance of the laboratory HBD simulator, as demonstrated in Figure 9. Moreover, utilizing the all-data calibration resulted in an optimized RMSE value for all HBD simulator data at both loading conditions. Note that the calibrations did not affect the R^2 value of the dataset, implying that the precision of the data cannot be improved using these calibration methods. However, this analysis demonstrates that adding more data points to a calibration can significantly improve the accuracy of wayside HBDs.

Table 3 provides the percentages of instances where the temperature difference between the HBD simulator data and the onboard bayonet thermocouples fell within six prescribed temperature ranges. For the inboard (IB) raceway scanning location, 100% of the unloaded bearing and 89% of the loaded bearing temperature difference (ΔT) fell in the range between −11°C (−20°F) and 11°C (20°F). As the infrared (IR) scanning location moves outboard, however, a larger percentage of IR temperature readings fall outside the −11°C to 11°C range. Hence, to obtain the most reliable and accurate bearing operating temperature, the IR sensor should be set to scan the inboard (IB) raceway region of the bearing cup, and the raw IR data should be calibrated using the correlation given in Figure 9 (bottom-right plot).

One interesting observation about the data plotted in Figure 9 is that there is no statistically significant distinction in the bearing operating temperature for healthy versus defective bearings. This finding concurs with the results of an earlier study where the operating temperatures for healthy bearings were compared to those of bearings containing defective inner and outer rings [20]. Thus, these results suggest that operating temperature alone is not a good indicator of bearing health.

Table 3. Laboratory bearing temperature error for unloaded (empty railcar) and loaded (full railcar) bearings.

ΔT [°C] (IR-TC)	OB Raceway	Spacer Ring	IB Raceway	IB Seal
	Unloaded (Empty Railcar)			
	Percentage [%]			
Above 11	3	1	0	4
0 to 11	68	44	73	52
0 to -6	18	35	24	35
-6 to -11	5	17	3	4
-11 to -17	4	2	0	5
Below -17	2	1	0	0
	Loaded (Full Railcar)			
Above 11	13	1	2	7
0 to 11	30	39	37	31
0 to -6	33	19	42	43
-6 to -11	10	19	10	14
-11 to -17	9	9	7	3
Below -17	5	13	2	2

3.3. Field data analysis

3.3.1. Raw field HBD data

The raw field acquired wayside HBD data is plotted in Figure 11 (top plot). Typical scanning location for wayside HBDs in field service is indicated in Figure 2. Analysis of the data reveals that wayside HBDs generally underpredict bearing temperatures, in some cases by as much as 47°C (85°F). This underestimation implies that wayside HBDs may fail to flag problematic bearings that are overheating. Conversely, the data also indicates that wayside HBDs overpredict the operating temperature of healthy bearings by as much as 25°C (45°F). The latter usually results in false temperature trending events that lead to unnecessary and costly train stoppages and delays. Note that wayside HBD field data exhibits more scatter than laboratory-acquired data using the HBD simulator, which is to be expected given the many variations in the condition and functionality of field wayside HBDs as compared to the HBD simulator which operates in a controlled environment using the same IR sensor.

Table 4 summarizes the temperature difference between the onboard bayonet thermocouples and the wayside HBD readings categorized under several temperature ranges. The results indicate that the wayside HBDs overpredict the temperature of unloaded class K bearings 35% of the time as compared to only 10% of the time for unloaded class F bearings. Hence, the raw data suggests that wayside HBDs are more likely to overpredict the operating temperature of class K bearings versus class F bearings under the same conditions, signifying that there is an inherent bias in wayside HBDs associated with bearing class.

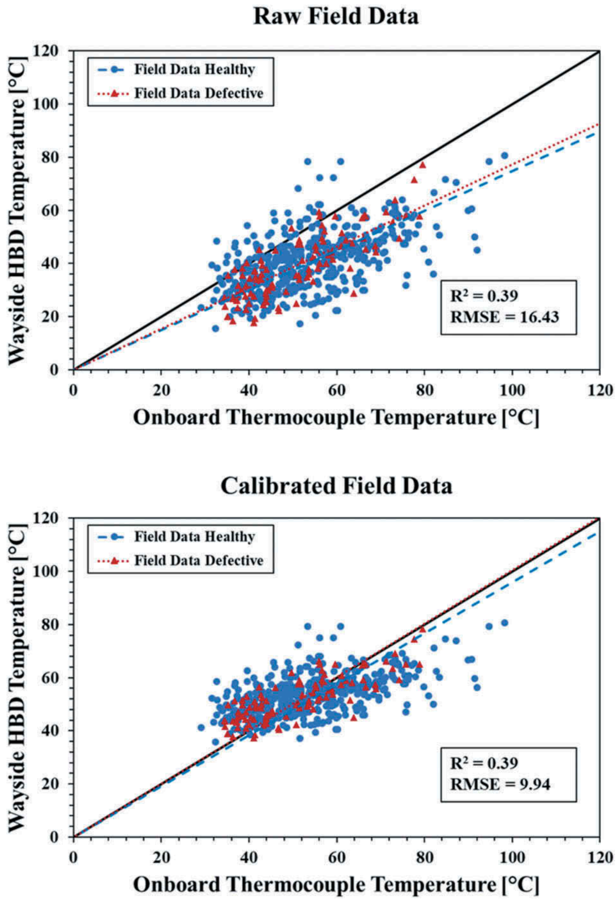

Figure 11. Raw (top plot) and calibrated (bottom plot) field-test wayside HBD temperature versus onboard thermocouple temperature.

Furthermore, wayside HBDs underpredict the loaded class F bearing temperatures 95% of the time. In fact, the HBDs underpredicted all bearing temperatures by more than 17°C (31°F) 35% of the time. Underpredicted bearing temperatures can result in the HBD system not flagging potential problematic bearings, which may lead to catastrophic derailments.

3.3.2. Calibration methods

A similar calibration procedure to that used for the laboratory-acquired data was applied to the field-test data. The two-point and three-point calibrations using the field-test data are provided in Figure 12 (top plot). The calibration points are chosen by selecting the wayside HBD temperature readings that are closest to their corresponding average bayonet thermocouple measurements. For consistency, the calibration temperatures were acquired from class K bearings only. The third calibration was devised using the trendline through all field-acquired data (including class K and F), as presented in Figure 12 (bottom plot).

Table 4. Raw versus calibrated field-test bearing temperature error.

ΔT [°C] (IR-TC)	Class K Unloaded	Class F Unloaded	Class F Loaded	Total
Raw Field-Test Data				
	Percentage [%]			
Above 11	7	0	1	1
0 to 11	28	10	4	9
0 to -6	12	18	8	12
-6 to -11	22	29	20	24
-11 to -17	12	18	21	19
Below -17	19	26	46	35
Calibrated Field-Test Data				
Above 11	34	15	5	12
0 to 11	37	57	29	40
0 to -6	16	17	26	21
-6 to -11	4	4	19	12
-11 to -17	9	6	13	10
Below -17	0	2	9	5

3.3.3. *Coefficient of determination and root-mean-squared error*

Table 5 gives the coefficient of determination (R^2) and the root-mean-squared-error (RMSE) values for the field-test data. The results show that the field-acquired data is less precise and less accurate than the laboratory data (see Table 2) as indicated by the lesser R^2 values and greater RMSE values, respectively. Moreover, in comparing the three calibration methods, there seems to be a negligible improvement in the field HBD data when applying the two-point and three-point calibrations; however, applying the linear calibration using all field-acquired data yielded the most accurate results with an RMSE value of 9.94°C (17.89°F). Note that the R^2 values do not change by applying the different calibrations, indicating that the precision of the measurements cannot be improved using linear calibrations.

3.3.4. *Calibrated field HBD data*

The raw and calibrated field HBD data are plotted in Figure 11 for comparison. The trendline through all field-acquired data was selected to perform the calibration on the field HBD data presented in Figure 11 (bottom plot). While the applied calibration significantly improves the accuracy of the wayside HBD readings, there are still instances where bearing operating temperatures are overpredicted by 26°C (47°F) and underpredicted by 35°C (63°F). The large scatter is due to the precision of the wayside HBD measurements, which cannot be corrected by linear calibrations. Moreover, just like in the data acquired by the laboratory HBD simulator, there is no distinction between healthy and defective bearing operating temperature in the field HBD data.

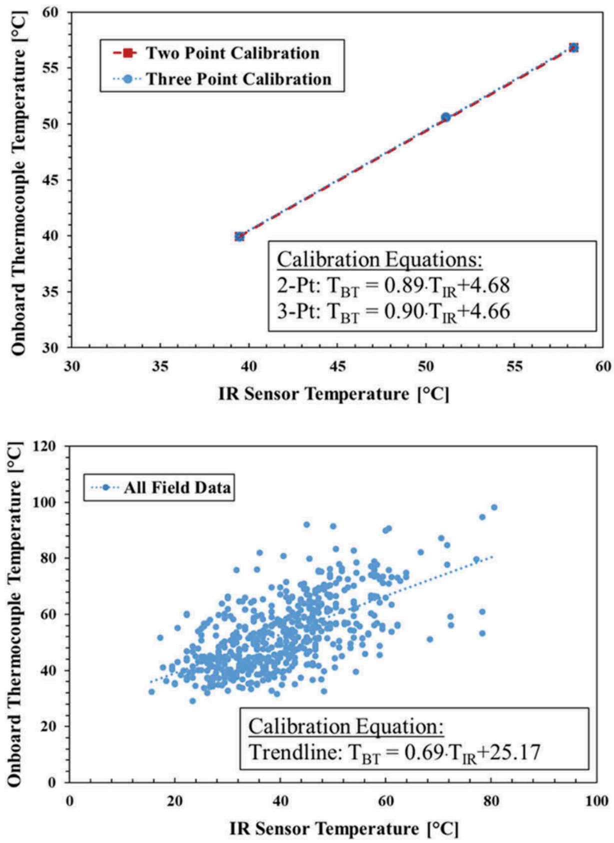

Figure 12. Two-point and three-point calibrations (top plot) and all field data calibration (bottom plot) using the acquired field-test data.

Table 5. Coefficient of determination (R^2) and root-mean-squared-error (RMSE) for various calibrations utilized for the field-test data.

	RMSE [°C]				
Data Description	Raw Data	2-Pt. Cal.	3-Pt. Cal.	All Data Cal.	R^2
Unloaded Class F	14.35	13.26	13.49	8.52	0.17
Loaded Class F	18.56	18.32	18.28	10.41	0.46
Unloaded Class K	12.73	12.20	12.32	11.67	0.13
Unloaded and Loaded Class F	16.9	16.39	15.99	9.67	0.45
Unloaded Class K and F	13.95	13.00	13.2	9.43	0.19
All Class K and F	16.43	15.92	15.57	9.94	0.39

The calibrated field HBD bearing temperature error is sorted into six different ranges in Table 4. Comparing the raw and calibrated field-test data, applying the calibration helped lessen the inherent bias in the wayside HBDs with respect to temperature measurements between class K and F bearings under the same operating conditions. Furthermore, the percentage of instances for all field HBD data where the temperature error fell between −11°C and 11°C (−20°F and 20°F) increased from 45% to 73% as a result of applying the calibration, which demonstrates a significant improvement in the wayside HBD data. Still, wayside HBDs overpredict 12% of all bearing temperatures by more than 11°C with a maximum of 26°C (47°F), which may be a potential cause for false setouts of healthy bearings.

4. Conclusions and recommendations

An investigation into the efficacy of wayside HBDs currently used in rail service was performed. A laboratory HBD simulator was designed and fabricated to mimic the functionality of wayside HBDs in field service by traversing an infrared (IR) sensor underneath a bearing to take a dynamic temperature measurement. Numerous experiments were performed in the laboratory using healthy and defective bearings at various speed and load conditions. The data was analyzed and compared with the wayside HBD data acquired during an on-track field service test.

Analysis of the data revealed that field HBD readings are influenced by bearing class because the change in bearing dimensions for each bearing class causes the IR sensor to scan different regions of the bearing outer ring (cup). To verify this observation, laboratory data was acquired at different scanning locations on the bearing cup. The results showed that the scanning location significantly affects the temperature measurement of the laboratory HBD simulator, with the most accurate and precise readings corresponding to the bearing cup inboard raceway region.

Generally, wayside HBDs tend to underestimate the temperatures of bearings in field service operation, which is not surprising given the simple one-point calibration procedure that is used to calibrate these devices. Underpredicted temperatures can have disastrous consequences, especially if a defective bearing goes undetected by a wayside HBD. The latter has occurred on numerous occasions in the past two decades in the U.S. and Canada and has resulted in catastrophic derailments.

Hence, the second part of this study focused on calibration procedures that can optimize wayside HBD measurements. Three linear calibrations were implemented on the laboratory and field-acquired data. A linear fit through all the acquired data produced the most optimized calibration technique for both the laboratory and field data. An optimized calibration along with proper IR sensor alignment can markedly improve the accuracy of HBD measurements, which in turn, can reduce: (a) costly delays and train stoppages associated with false warm bearing trending events, and (b) catastrophic bearing failures associated with HBDs underestimating the operating temperature of bearings with high-risk defects.

However, this study exposes one major shortcoming of wayside HBD systems that cannot be corrected with an optimized calibration or proper IR sensor alignment. The laboratory and field data demonstrate that HBDs cannot distinguish between healthy and defective bearings. Hence, temperature alone is not a good indicator of bearing health. Based on that, the authors have been developing a system that utilizes temperature, load, and vibration sensors mounted directly on the bearing adapter for continuous monitoring of bearing condition. Laboratory testing validated by field testing have shown that this system can reliably detect the onset of defect development within a bearing and track its deterioration with service operation. The authors believe that systems like these will shape the future of bearing condition monitoring.

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Disclosure statement

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