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ABSTRACT

Wayside hot-box detectors (HBDs) are devices that are currently used to monitor bearing, axle, and brake temperatures as a way of assessing railcar component health and to indicate any possible overheating or abnormal operating conditions. Conventional hot-box detectors are set to alarm whenever a bearing is operating at a temperature that is 94.4°C (170°F) above ambient, or when there is a 52.8°C (95°F) temperature difference between two bearings that share an axle. These detectors are placed adjacent to the railway and utilize an infrared sensor in order to obtain temperature measurements. Bearings that trigger HBDs or display temperature trending behavior are removed from service for disassembly and inspection. Upon teardown, bearings that do not exhibit any discernible defects are labeled as "non-verified". The latter may be due to the many factors that can affect the measurement of HBDs such as location of the infrared sensor and the class of the bearing among other environmental factors.

A field test was performed along a route that is more than 483 km (300 mi) of track containing 21 wayside hot-box detectors. Two freight cars, one fully-loaded and one empty, and one instrumentation car pulled by a locomotive were used in this field test. A total of 16 bearings (14 Class F and 2 Class K) were instrumented with K-type bayonet thermocouples to provide continuous temperature measurement. The data collected from this field test were used to perform a systematic study in which the HBD IR sensor data were compared directly to the onboard thermocouple data. The analyses determined that, in general, HBDs tend to overestimate Class K bearing temperatures more frequently than Class F bearing temperatures. Additionally, the temperatures of some bearings were underestimated by as much as 47°C (85°F). Furthermore, the HBD data exhibited some false trending events that were not seen in temperature histories recorded by the bayonet thermocouples. The findings from the field test suggest that HBDs may inaccurately report bearing temperatures, which may contribute to the increased percentage of non-verified bearing removals.

To further investigate the accuracy of the wayside detection systems, a dynamic test rig was designed and fabricated by the University Transportation Center for Railway Safety (UTCRS) research team at the University of Texas Rio Grande Valley (UTRGV). A mobile infrared sensor was developed and installed on the dynamic tester in order to mimic the measurement behavior of a HBD. The infrared temperature measurements were compared to contact thermocouple and bayonet temperature measurements taken on the bearing cup surface. The laboratory-acquired data were compared to actual field test data, and the analysis reveals that the trends are in close agreement. The large majority of temperature measurements taken using the IR sensor have been underestimated with a similar distribution to that of the data collected by the HBDs in field service.

INTRODUCTION

In order to predict and prevent bearing failures, the railroad industry has implemented different bearing health monitoring systems. The most frequently used health monitoring system is the wayside hot-box detector (HBD). This system employs individual infrared temperature sensors positioned 24 to 40 km (15 to 25 mi) apart along the rail track. As each freight car passes, each HBD scans the underside of the roller bearings and records the bearing temperatures along with the ambient temperature from its surroundings. If the measured temperature of a bearing compared to ambient exceeds a predetermined threshold, the HBD generates an alarm that is used to slow down or stop the train for inspection. Many HBDs are configured to alarm when a bearing is operating at a temperature greater than 94.4°C (170°F) above ambient or when one bearing is operating at a temperature that is 52.8°C (95°F) greater than the bearing that shares the same axle. Another common practice includes averaging the bearing temperatures on one side of the railcar and comparing each bearing temperature to that average. This comparison is done by calculating a K-value that attempts to identify a statistical outlier in the bearing temperatures [1].

Although hot-box detectors are widely used and have been able to prevent components from overheating in the past, the system is not without issues. Many variables, such as bearing class and IR scanning location, can affect the temperature measurements. For this reason, a HBD may greatly under-predict or over-predict bearing temperature, leading to two possible outcomes. Bearing temperatures over-predicted by a HBD may exceed the temperature threshold, which usually results in removal of the bearing for further inspection. In many cases, the high temperature of the bearing is attributed to spalled, broken, and/or water damaged components, among other possible defects and causes. However, a significant number of bearings that exceed the temperature threshold are also found to have no discernable defects. These bearings are then classified as "non-verified". Non-verified bearing removals lead to unnecessary train stoppages and delays, which cause rail line interruptions and rail network congestion [1]. An investigation by Amsted Rail found that, from 2001 to 2007, nearly 40% of bearing removals were "non-verified" bearings, which is a serious problem for the rail industry. Although non-verified bearings are a cause of inefficiency, disastrous events may occur if a HBD under-predicts the temperature of a bearing and fails to trigger an alarm as a bearing overheats. From 2010 to 2016, wayside HBDs have failed to detect 119 severely defective bearings throughout the United States and Canada, many of which led to catastrophic derailments [2].

Work has been done in order to better characterize HBD accuracy and precision, including one study performed in 2013 by the Transportation Technology Center, Inc. (TTCI). In this study, TTCI evaluated 16 different configurations of hot-box detectors at the Railroad Test Track (RTT) in Pueblo, Colorado. The study included HBDs from four different vendors and bearings of different classes (Class K, F, E, and G). The tests were performed by scanning the bottom of the bearing at different locations and at different angles. Furthermore, an onboard thermocouple was implemented in order to assess HBD performance. The results from this study have shown that a vertical measurement taken closer to the inboard side of a bearing will optimize HBD performance [3].

In a study conducted by the University Transportation Center for Railway Safety (UTCRS) at the University of Texas Rio Grande Valley (UTRGV), field test results were recreated in the laboratory in order to better understand the sources of infrared temperature measurement error [4]. For that purpose, a single bearing dynamic test rig was designed and fabricated at UTRGV that is capable of accurately simulating a train traveling at speeds up to137 km/h (85 mph) and loads of 153 kN (34.4 kips) per bearing — the full-load equivalent for a Class F or K bearing. Additionally, an IR sensor was attached to the end of a pneumatic cylinder fixed to a track placed underneath the test bearing. In order to simulate the functionality of a HBD, a control system was designed to launch the IR sensor underneath the test bearing; thus, taking a dynamic temperature measurement. Data were compiled for unloaded and loaded bearing scenarios and for operating speeds of 48 km/h (30 mph) to 137 km/h (85 mph). It was determined that, as the bearing operating temperature increases, the error between the readings from the HBD and the onboard thermocouples increased. Furthermore, the laboratory tests at UTRGV showed that the largest source of error from the IR sensor was related to its dynamic response [4]. The study, however, did not attempt to directly compare the data obtained in the laboratory to separate data obtained from field service, which is the primary focus of the work presented in this paper.

EXPERIMENTAL SETUP & PROCEDURES

In 2008, a field test was performed to investigate the warm bearing trending phenomenon seen in freight rail service [5]. The acquired data were also used to characterize the efficacy and accuracy of HBDs. The test was conducted along more than 483 km (300 mi) of track and utilized 21 wayside hot-box detectors placed along the rail tracks. As seen in Figure 1, the hot-box detectors (HBDs) scanned each bearing at approximately the same location, regardless of the bearing class. The test train consisted of a locomotive that pulled an instrumentation railcar and two hopper-type freight cars, one fully loaded and one empty. Of the 16 tapered-roller bearings that were instrumented, 14 were Class F while the other two were Class K. Of the 14 Class F bearings, five had been removed from field service: one had an outboard inner ring (cone) spall, one had an inboard outer ring (cup) defect, one had a very loose cone/cage assembly, and two were non-verified, while the rest were healthy control bearings. The Class K bearings shared an axle and consisted of one non-verified bearing removed from service and one control bearing. The Class K axle was installed on the unloaded (empty) railcar. Each bearing adapter was outfitted with two onboard bayonet-type (spring-loaded) thermocouples for continuous measurement of the bearing operating temperature. The latter was accomplished by drilling and tapping the bearing adapters to accept the thermocouple holders. The train speeds were in the range of 40 to 80 km/h (25 to 50 mph) with the train moving at 80 km/h (50 mph) for a significant portion of the trip. The railcars traveled through conditions with ambient temperatures as high as 33°C (91°F) and as low as 6°C (43°F). A National

Instruments™ data acquisition system (DAQ), powered by the locomotive, was used to log the onboard temperature data. The railroad operators provided the temperature data collected from the 21 wayside HBDs located along the 483 km (300 mi) of track travelled by the test train. These data were then directly compared to the onboard thermocouple bearing temperature data acquired using the NI DAQ system.

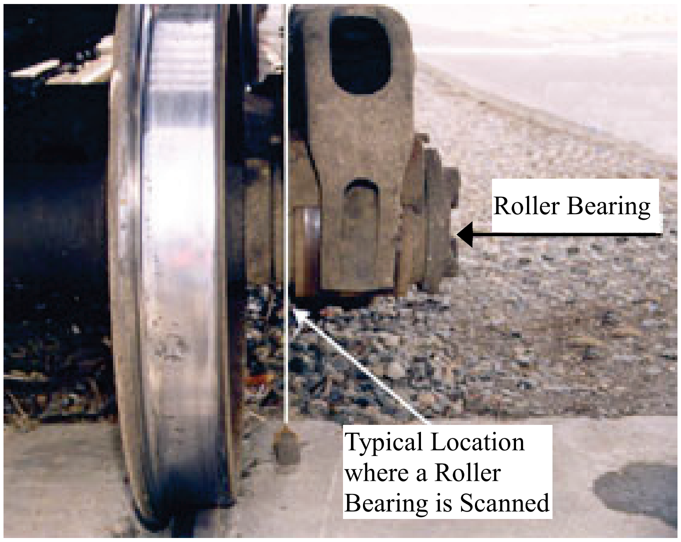

Figure 1. Typical infrared sensor scanning location for field test wayside hot-box detectors (HBDs) [6]

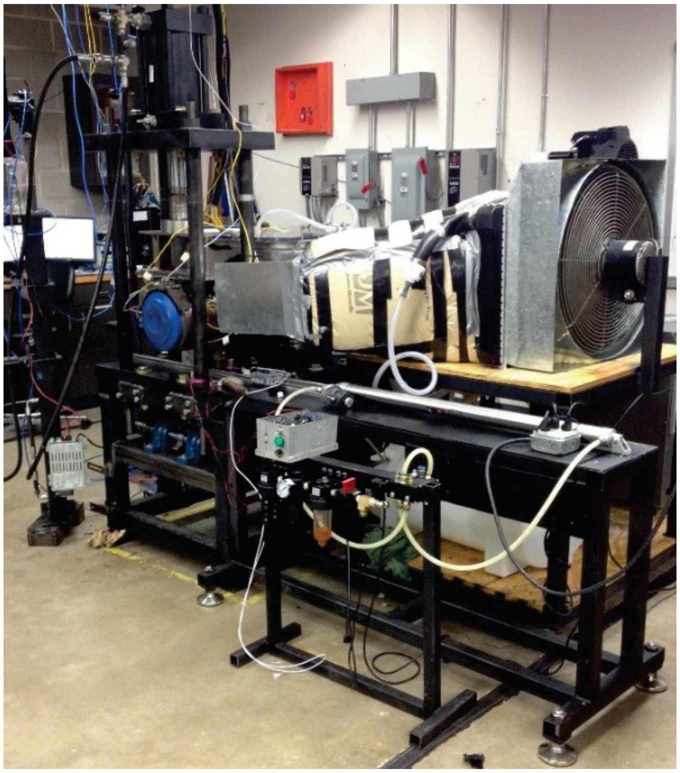

Figure 2. Single bearing dynamic test rig at UTRGV

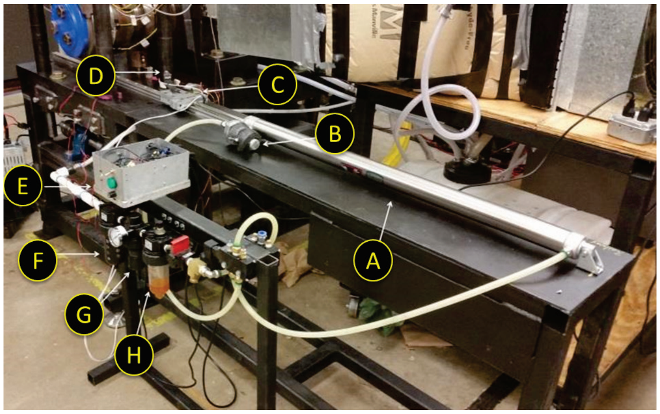

Figure 3. Dynamic infrared sensor system, where [A] is the pneumatic cylinder, [B] is the quick exhaust valve, [C] is the cart, [D] is the infrared temperature sensor affixed to the cart, [E] is the control box, [F] is the pneumatic system filter, [G] is the regulator, and [H] is the lubricator.

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

A single bearing dynamic test rig (see Figure 2) was designed and built by the UTCRS research team at UTRGV to closely mimic the conditions that a railroad bearing would encounter during field service. The test rig is composed of a test bearing that is suspended at one end of an axle. An industrial strength fan was used in the setup to provide convective cooling to the railroad bearing and to simulate the air passing across the bearing while the railcar is in motion. The bearing experiences a vertically applied load from a hydraulic cylinder above that presses down on the adapter. A specially designed pneumatic system was fabricated with the purpose of traversing an infrared temperature sensor under the bearing at a prescribed speed to simulate the functionality of a HBD in field service. To calculate the speed of the cart to which the infrared (IR) temperature sensor is fastened, two infrared break sensors, positioned below the test bearing area, were utilized as the cart passed beneath the bearing. The cart is connected to a pneumatic cylinder which is operated by an Arduino Uno controlling a four-way valve system. The component that holds the IR temperature sensor onto the cart can rotate allowing different surface areas of the bearing to be scanned. The four areas scanned by the IR sensor include the outboard (OB) raceway, spacer ring, inboard (IB) raceway, and the IB seal (refer to Figure 4). The IR sensor has a temperature range of -50°C (-58°F) to 975°C (1787°F) with an accuracy of ±2°C. The measurements were collected with the CompactConnect software that is provided with the sensor. LabVIEW^{TM} was used to collect temperature data at 20-second intervals from seven K-type thermocouples and four bayonet thermocouples. The thermocouples were attached around the circumference of the test bearing using a hose clamp in the spacer ring area, as shown in Figure 6. Two bayonet thermocouples on each side of the bearing were used to detect the temperatures along the center of the IB and OB raceways. Over 100 tests of healthy and defective bearings were conducted for this study. The travel speed and applied load were the varied parameters. The tester can provide train-traveling speeds in the ranges shown in Table 1. In the laboratory, the applied loads simulated an empty railcar (17% load) and a fully loaded railcar (100% load). The 17% load setting is approximately 26 kN (5.85 kips), and the 100% load setting is approximately 153 kN (34.4 kips). A MATLAB^{TM} script was developed to collect and analyze the thermocouple temperature data obtained by LabVIEW^{TM}, the IR temperature data of the bearing, and the IR break sensor time data from the Arduino Uno. In this post-processing step, the data that were collected underneath the bearing were averaged over the scanning distance (see Figure 6) in order to obtain one IR temperature data point. This process was repeated for each speed and load combination, and organized for easier comparison.

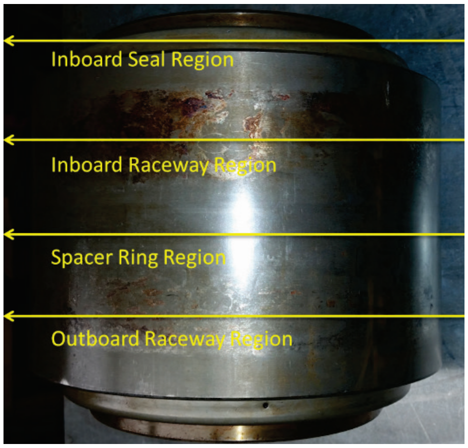

Figure 4. Infrared scanning locations on the bearing

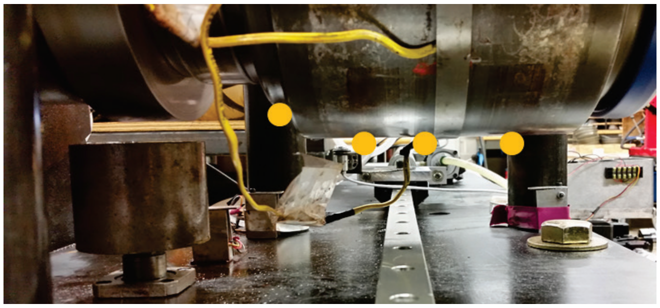

Figure 5. Infrared scanning locations from left to right: inboard seal, inboard raceway, spacer, and outboard raceway

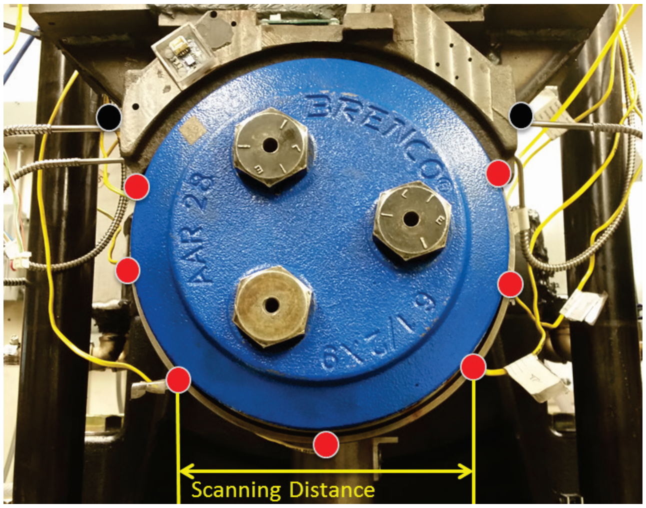

Figure 6. Bearing thermocouple locations where each red dot is a standard K-type thermocouple and the black dots represent spring-loaded bayonet-style K-type thermocouples

In general, IR sensors require calibration in order to produce accurate measurements. In an industry setting, HBDs are usually calibrated using a two-point calibration method. This process involves pointing the HBD temperature sensor at two plates, one at ambient temperature and one with a warm temperature. These two values are then used to create a linear correlation between the measured temperature and the actual temperature, which is used to devise a simple calibration for the HBD. In the laboratory setting, the IR sensor was placed underneath the bearing at an ambient temperature and the data were recorded. For the second point of the calibration, the IR sensor was placed underneath a bearing that was operating under a 100% load setting and a speed of 85 km/h (53 mph). These points were used to create a linear fit that served as the IR sensor calibration. This calibration was applied to all IR temperature data acquired in the laboratory presented hereafter.

RESULTS

Previous work has been performed by the UTCRS research team at UTRGV to characterize the relationship between the speed and load of a railroad bearing and its operating temperature [7]. Figure 7 presents data from UTCRS' bearing temperature library with the data split into a statistically significant population of both Class K and Class F bearings. The data clearly indicate that there is a linear increase in temperature with operating speed. In addition, the loading condition significantly affects the operating temperature of bearings. By increasing the load from 17% (empty railcar) to 100% (fully loaded railcar), the temperature increases by around 13°C (23°F). However, most importantly, it can be seen that the temperature data for Class F and K bearings are similar under identical speed and load conditions. Based on the latter finding, it is safe to assume that the temperature of the bearing is primarily dependent on the speed and load, but is independent of the bearing class for Class F and K bearings. This conclusion is of particular importance considering that the laboratory experiments conducted for the current study utilized Class K bearings only.

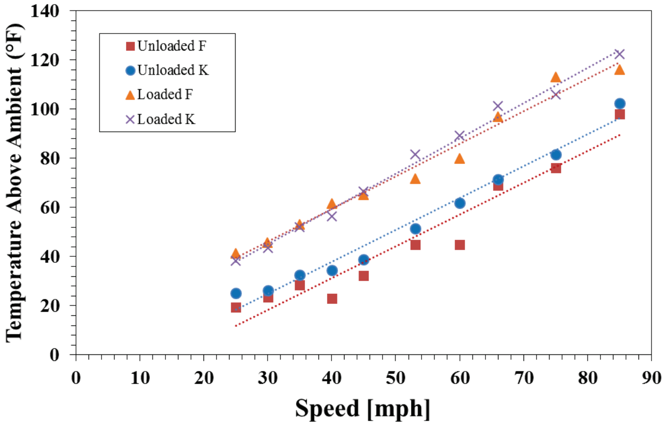

Figure 7. Class F and K bearing operating temperatures for loaded and unloaded conditions at various speeds

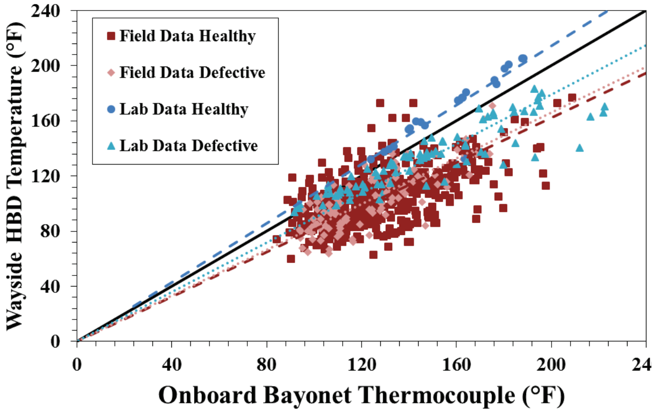

Figure 8. Wayside HBD temperature versus onboard thermocouple temperature for the laboratory bearing outboard (OB) raceway location

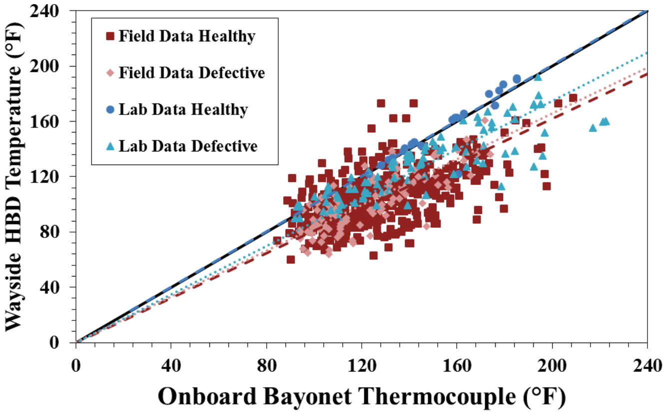

Figure 9. Wayside HBD temperature versus onboard thermocouple temperature for the laboratory bearing spacer ring location

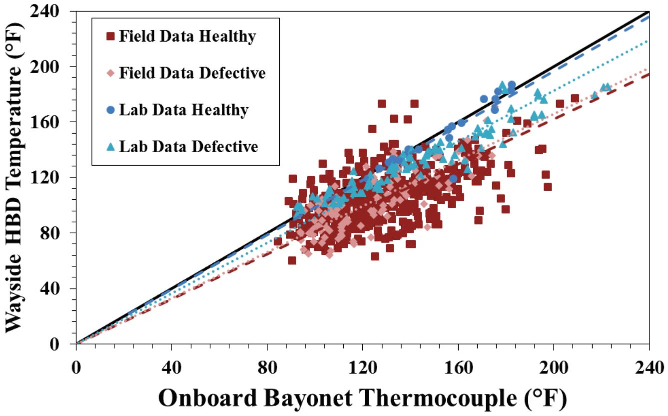

Figure 10. Wayside HBD temperature versus onboard thermocouple temperature for the laboratory bearing inboard (IB) raceway location

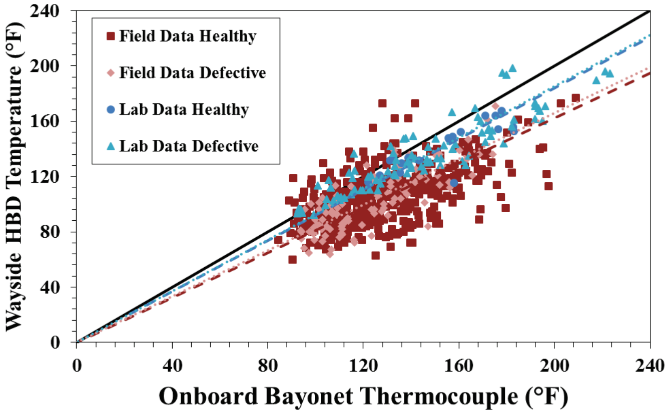

Figure 11. Wayside HBD temperature versus onboard thermocouple temperature for the laboratory bearing inboard seal location

Figure 8 through Figure 11 show the field-acquired wayside HBD temperature data versus the laboratory-acquired onboard thermocouple data at the four different scanning locations: outboard raceway, spacer ring, inboard raceway, and inboard seal. Note that the typical scanning location for the field test wayside HBD data is similar to what is shown in Figure 1. The black diagonal line in each figure represents the ideal case where the wayside HBD perfectly matches with the onboard bayonet thermocouple. Data on the left side of the line will be an over-prediction of the actual bearing cup temperature, while data on the right side of the line will be an under-estimate. Upon first observation, it can be seen that infrared (IR) data acquired in the laboratory (IR sensor) and from the field test (wayside HBDs) generally tend to under-estimate the bearing temperature. It is also evident from the laboratory data that the IR sensor error is predominantly dependent on the scanning location. The outboard raceway scanning location data (see Figure 8) has greater scatter and seems to over-predict the bearing temperature by more than 11°C (20°F) and under-estimate the bearing temperature by as much as 30.5°C (55°F). The error band tightens as the scanning location approaches the inboard raceway side of the bearing, as can be observed in Figure 10. As for the field test data, it is apparent that the error is much larger with bearing temperatures over-predicted by as much as 25°C (45°F) and under-estimated by as much as 47°C (85°F). The over-predictions by the field HBDs can result in false trending events that may result in unnecessary and costly train stoppages and delays. The under-predictions by the field HBDs may result in failure of these condition-monitoring systems to report problematic bearings that may cause catastrophic derailments [8]. One very important and alarming finding is that the IR sensors (both in the laboratory and in field HBDs) tend to predict higher temperatures for healthy bearings than for defective bearings, which is of particular concern given that these defective bearings may deteriorate very rapidly yielding disastrous consequences.

Table 2. Field test data bearing temperature error

ΔT [°F] (HBD-TC)	**Class K Unloaded**	**Class F Unloaded**	**Class F Loaded**	**Total**
	Percentage (%)			
Above 20	**8**	**0**	**1**	**2**
0 to 20	**28**	**10**	**4**	**9**
0 to -10	**12**	**18**	**8**	**12**
-10 to -20	**22**	**29**	**20**	**24**
-20 to -30	**12**	**18**	**22**	**19**
Below -30	**19**	**26**	**46**	**35**

Table 2 shows the percentage of instances where the difference between the field test HBD temperature and the onboard thermocouple temperature fell in the prescribed temperature ranges. The data were divided according to bearing class, loading condition, and six different temperature ranges. The table is configured so that each column adds up to 100% (plus any rounding off errors). For Class K bearings, the field test HBDs over-predicted the bearing temperature almost 36% of the time. Furthermore, this overestimation was greater than 11°C (20°F) almost 8% of the time. For Class F bearings, both loaded and unloaded conditions, there was a much lower rate of over-predictions but a much higher rate of under-estimations (~90%). By making a fair comparison and looking at Class K and F unloaded bearings, it can be concluded that the system is inherently biased in relation to bearing class. It is evident that the HBDs are more prone to overestimate the temperature of the Class K bearings and underestimate the temperature of the Class F bearings. When examining Class F loaded bearings, it is apparent that the HBDs frequently underestimate the bearing temperature (~95%). Furthermore, the field test HBDs underestimated the loaded Class F bearing temperatures by more than 17°C (31°F) almost half of the time. The latter is very alarming considering that fully loaded bearings are more susceptible to catastrophic failure if a defect occurs on any of the rolling raceways or surfaces.

Table 3. Laboratory bearing temperature error for unloaded bearings

Unloaded (Empty Railcar)				
ΔT [°F] (IR-TC)	**OB Raceway**	**Spacer Ring**	**IB Raceway**	**IB Seal**
	Percentage (%)			
Above 20	**0**	**0**	**0**	**0**
0 to 20	**38**	**26**	**29**	**32**
0 to -10	**47**	**55**	**44**	**50**
-10 to -20	**9**	**12**	**21**	**12**
-20 to -30	**6**	**6**	**6**	**3**
Below -30	**0**	**0**	**0**	**3**

Table 4. Laboratory bearing temperature error for loaded bearings

Loaded (Full Railcar)				
ΔT [°F] (IR-TC)	**OB Raceway**	**Spacer Ring**	**IB Raceway**	**IB Seal**
	Percentage (%)			
Above 20	**5**	**0**	**0**	**0**
0 to 20	**19**	**21**	**8**	**13**
0 to -10	**28**	**19**	**37**	**23**
-10 to -20	**26**	**28**	**27**	**33**
-20 to -30	**9**	**10**	**17**	**21**
Below -30	**13**	**22**	**12**	**10**

Table 3 and Table 4 show the percentage of instances where the difference between the laboratory IR sensor (simulating the HBD in field service) and the onboard thermocouple temperature fell in the prescribed temperature ranges. Once again, similar to the field test data, the laboratory IR sensor data tend to underestimate the bearing temperature with varying levels of inaccuracy depending on the scanning location under the bearing. It is also evident that the temperature difference (ΔT) values from the laboratory tests are closer to 0°C (0°F) than those from the field test. The unloaded bearings in the laboratory had more than two-thirds of ΔT values fall in the range of 11°C (20°F) to -6°C (-11°F). In the case of fully loaded bearings, the error band expands. For each of the four scanning locations, the temperature taken for the bearing by the IR sensor is usually underestimated, with the inboard (IB) raceway location data having the least difference from the actual bearing temperatures. Although the laboratory IR sensor data are more accurate than the field test HBD data, almost half of the laboratory IR readings have ΔT values that fall in the range of 11°C (20°F) to -6°C (-11°F) for each of the scanning locations.

Table 5 shows the root-mean-squared-error (RMSE) and the coefficient of determination (R^2) values for each loading configuration and bearing class for both the field test and the laboratory experiments. The RMSE is defined as:

$$RMSE = \sqrt{\frac{\sum(T_{HBD} - T_{expected})^2}{n}}$$

T_{HBD} is the temperature read by the hot-box detector (HBD) or the laboratory infrared (IR) sensor that simulates the HBD, $T_{expected}$ is the temperature from the onboard thermocouple, and n is the number of temperature data points. The RMSE is dependent on the square of the error between the HBD temperature and the onboard thermocouple temperature. The RMSE value is also smaller for more accurate temperature measurements while placing more "weight" on outliers. The coefficient of determination, R^2 value, is determined numerically and represents how well the data can be linearly fit to a regression line. Holding the accuracy of the measurement independent, the R^2 value can be a measure of the precision of the linear data set.

Table 5. Root-mean-squared-error (RMSE) and coefficient of determination (R^2) values for laboratory and field data

Data Description			**RMSE**	**R^2**
Lab Data	**Class K Unloaded**	**OB Raceway**	11.1	0.81
		Spacer	8.9	0.89
		IB Raceway	8.8	0.94
		IB Seal	10.0	0.83
	Class K Loaded	**OB Raceway**	22.7	0.51
		Spacer	25.8	0.53
		IB Raceway	17.1	0.79
		IB Seal	18.3	0.75
	All Class K	**OB Raceway**	19.9	0.68
		Spacer	22.1	0.67
		IB Raceway	15.1	0.87
		IB Seal	16.2	0.83
Field Data	**Unloaded Class F**		25.8	0.17
	Loaded Class F		33.4	0.46
	Unloaded Class K		22.9	0.13
	Unloaded and Loaded Class F		30.4	0.45
	Unloaded Class K and F		25.1	0.19
	All Class K and F		29.6	0.39

Examining Table 5, it is clearly evident that the laboratory IR sensor data are more accurate and more precise than the field test HBD data as indicated by the smaller RMSE and higher R^2 values. Moreover, in the field data, the loaded Class F bearing temperature measurements seem to be more precise but less accurate than the unloaded Class F and K data. On the contrary, the unloaded Class K temperature readings are more accurate but less precise than the loaded and unloaded Class F data. For the laboratory data, it is apparent from the RMSE and R^2 values that the temperature measurements taken by the IR sensor are generally more accurate and more precise for unloaded bearings as opposed to the loaded bearings. Furthermore, it can also be seen that the accuracy and precision of the measurement increases as the measurement is taken closer to the inboard (IB) raceway side of the bearing. From the laboratory-acquired data, it follows that the IR sensor (simulating the HBD) scanning location with minimal error and maximum repeatability is the inboard (IB) raceway location. This conclusion is in full agreement with the results published in the TTCI study [3].

CONCLUSIONS

Wayside hot-box detectors (HBDs) are commonly used to assess bearing health. HBDs take a temperature measurement of the underside of the bearing and will trigger an alarm if a bearing exceeds a threshold of 94.4°C (170°F) above ambient or when there is a 52.8°C (95°F) difference between the two bearings that share an axle. Additionally, one practice involves averaging the temperatures of the bearings on one side of the railcar and comparing each of the bearings to the average.

The study presented here provides a summary of the work done to evaluate the efficacy of the current wayside HBDs employed in field service. To this end, a laboratory system that utilizes an infrared (IR) sensor was designed and fabricated to mimic the functionality of wayside HBDs. This system was used to carry out numerous laboratory experiments to investigate the accuracy and precision of infrared-based temperature measurement systems. The results of the study indicate that the IR sensor data acquired in the laboratory follows a similar trend to that of the data obtained by HBDs in the field, where both systems tend to under-predict bearing temperatures, in general. However, as expected, the data obtained in the laboratory is generally more precise and more accurate than the field HBD data. The field data also show that there is an inherent bias in the readings where the wayside HBDs tend to overestimate Class K bearing operating temperatures much more frequently than Class F bearing operating temperatures under similar speed and load conditions. Additionally, the field test HBDs over-predicted the temperature of many healthy bearings and exhibited false trending events. In fact, two very important and alarming findings of this study are that: (1) the IR sensors (both in the laboratory and in field HBDs) tend to predict higher temperatures for healthy bearings than for defective bearings, and (2) the field test HBDs underestimated the loaded Class F bearing temperatures by more than 17°C (31°F) almost half of the time. The aforementioned conclusions are very distressing considering that fully loaded bearings are more susceptible to catastrophic failure if a defect initiates on any of the rolling raceways or surfaces.

Lastly, the study concluded that the inboard (IB) raceway scanning location is the most precise and accurate location to measure the temperature of the bearing using infrared-based sensors. This observation is in agreement with a study published by researchers at the Transportation Technology Center, Inc. (TTCI).

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