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Proceedings of the ASME 2022
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JRC2022-78173

PILOT FIELD TEST OF AN ONBOARD WIRELESS CONDITION MONITORING SYSTEM FOR RAILROAD ROLLING STOCK

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ABSTRACT

The "internet of things" has revolutionized the methods in which many industries have optimized performance and component defect detection by providing real-time feedback through the implementation of data processing and wireless communication. Despite these advancements, the railway industry has lingered stagnant in its approach of adopting these advanced prognostic detection systems, and instead relies on discretely (25-40 miles) placed trackside condition monitoring systems, aka wayside. These wayside systems are primarily used to detect abnormal operating conditions in railcar rolling stock components. However, while they have been used for decades to address imminent threats to derailments and/or safety, they have unfortunately been shown to erroneously flag and misdiagnose components. These "false positive" cases usually result in unnecessary and costly delays and train stoppages. In worst case scenarios, these wayside systems have been known to mis-identify problematic components which can potentially lead to catastrophic derailments, risking property and safety. Overall, these limitations to established methods, and current technological innovations, allow for the introduction of a pioneering technology that addresses these deficiencies to enable constant, reliable, and precise onboard component health monitoring through vibration and temperature tracking. With these advancements, railroad car owners and operators can preemptively assess any rolling stock maintenance issue well in advance of an anticipated catastrophic failure.

To validate the efficacy of these onboard sensors, a field study was conducted using 40 such monitoring devices that were affixed to the bearing adapters of randomly selected railcars in a dedicated coal service route. After the span of two months of ongoing testing, three wheelsets were selected for removal based on data collected that indicated non-normative operating conditions. The wheelsets were inspected, analyzed, and the corresponding bearings were shipped to the University Transportation Center for Railway Safety (UTCRS) for laboratory evaluation and testing. This paper summarizes some of the preliminary results acquired from this field test and provides a comparison between the field and laboratory data, demonstrating their agreement and the prospective integration of these sensor technologies into the rail industry.

Keywords: onboard monitoring module, continuous condition monitoring, bearing health index, wheel health index.

NOMENCLATURE

BHI	Bearing Health Index
WHI	Wheel Health Index

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1. INTRODUCTION

Although tailored to have the robustness for continued cargo hauls, rolling stock has demonstrated an intrinsic susceptibility to degradation in its wheelset elements (i.e., bearings and wheels). In turn, if left unmonitored, these components can catastrophically fail and trigger railcar derailments, causing adverse economic, social, and environmental impacts. The recurrence and gravity of these events has propelled the railway industry to adopt prognostic detection systems that target abnormal bearing and wheel behaviors. Hence, rail transit unit owners can receive status reports of their assets and any irregularly operating components can prompt rational maintenance scheduling. The most common of these devices include Hot Box Detectors (HBDs), Trackside Acoustic Detector Systems (TADS^{TM}), and Wheel Impact Load Detectors (WILDs).

HBDs utilize infrared thermal technology to identify overheating bearings in rail service [1]. When a bearing is operating at a temperature that is 94.4°C (170°F) above ambient conditions or 58.3°C (105°F) hotter than its mate bearing that shares the same axle, the bearing is flagged for removal. Nonetheless, even though HBDs have proven to detect overheating bearings, they lack the capability of continuously monitoring bearing thermal signatures. With only 6000 HBDs in North America, spaced out anywhere from 40 to 64 rail kilometers (25-40 rail miles) apart, hundreds of bearings run undetected with temperature issues caused by possible defective inner bearing components.

Uncertainties in the HBD's defect detection capabilities have also resulted in misdiagnosed and/or falsely flagged bearings, leading to superfluous expenditures from unnecessary maintenance, or in extreme cases, unforeseen accidents. For this reason, acoustic bearing defect detection systems or ABDs have been employed in support of HBDs, to reduce the amount of these misidentifications. A prevalent example of an ABD is known as a Trackside Acoustic Detector System (TADS^{TM}). This system utilizes wayside microphones to detect high-risk bearings by listening for characteristic acoustic frequencies of inner bearing components such as cones, cups, or rollers [2]. TADS^{TM} can detect bearings reaching their end-of-life cycle where about 90% of the bearing raceway surface areas have deteriorated. These defects are classified as "growlers". Minor defects and inner ring (cone) defects, however, cannot be detected with the same accuracy and reliability as outer ring (cup) defects. Consequently, a defective bearing may only be flagged when it reaches an end-of-life state. Furthermore, with only about 30 TADS^{TM} in North America, most freight railcars can operate their entire service life without passing by one of these systems.

WILDs monitor railcar wheel conditions by measuring the wheel-rail contact force using strategically track-mounted strain gauge sensors. Generally, anomalies in the wheel profile will cause high impact forces at the wheel-rail interaction. If an impact force reaches condemning limits, then a series of recommended practices are advised for the operator depending on the amount of kN or kips that are registered. Nonetheless, like HBDs and TADS, this wheel health monitoring solution is also limited by the strategic placement of these sensors along the track. According to a wayside system implementation guide by the Federal Railroad Administration (FRA), only about 185 WILDs were operational nationwide as of 2017 [2]. Thus, progression of a pre-existing defect or the propagation of a new anomaly within the wheel will not be monitored nor detected until the next WILD location. Concerns about the reliability and accuracy of the system also arise. If the system is not operated within the specifications of the manufacturer, the accuracy and reliability of the WILD can be affected. Some specifications include the speed and load of the passing railcar through the system, the ambient temperature, track stability, and the number of integrated WILD systems that can verify the readings of other WILDs.

Over the past decade, the absence of continuous and effective onboard condition monitoring systems has motivated researchers at the University Transportation Center for Railway Safety (UTCRS) to work on developing an onboard temperature and vibration-based failure detection technology for railroad rolling stock. Years of study have materialized into promising wired modules that can provide accurate and timely bearing health diagnostics that can characterize the condition of tapered-roller bearings and identify defects smaller than 6.45 cm^2 (1 in^2) [3]. Furthermore, with the current innovations in technology, wirelessly transmitted bearing analytics via wireless modules and energy-harvesting devices that can support these systems using rail operation conditions have been the subject of recent studies [4]-[5]. The significance of this work has led to a partnership with Hum Industrial Technology, Inc. (Hum), a private company that has licensed the technology and developed an onboard monitoring device that is capable of monitoring real-time condition metrics to provide immediate prognostic feedback to the owners and operators of rail fleets. This wireless onboard technology utilizes temperature and vibration sensors that assess real-time bearing health indices (BHI) and wheel health indices (WHI) based on established algorithms developed with over a decade of supporting research. This device, when paired with GPS technology, not only provides the location of the asset in the case of a critical event but can also provide key insights into deviations from expected behavior, such as the aberrant running condition of the track, or yard impacts.

2. PILOT TEST SETUP AND UNIT INSTALLATION

To evaluate the performance of this onboard device, and to establish field and laboratory data agreement, forty sensor modules were assembled and readied at the UTCRS and installed on privately owned railcars of a dedicated coal service route. Field test installation was conducted by Hum on-site. The wireless condition monitoring system that was installed consisted of two main components: (1) the Hum Boomerang: a wheel/bearing health monitoring module that mounts to the bearing adapter, and (2) the Hum Gateway: a communication unit used to process and transmit the acquired data to a cloud service.

2.1 Field Test Installation and Axle Removal

As shown in FIGURE 1, a single Gateway was installed per railcar while ensuring adequate positioning. Proper placement of the unit is critical to enable optimal solar exposure and communication as the Gateway is a solar-powered device that acts as a data relay bridge between the onboard condition monitoring modules and the railcar owner. Specifically, the Gateway receives the data collected by the Boomerang via cellular data transmission services. Then, the bearing and wheel analytics are transferred and saved in Hum's internet-based server. There, the data is analyzed by the server's software interface, generating automated email notifications when a threshold is surpassed either by vibration or temperature. Stored data can also be downloaded, allowing for thorough inspections of operating bearing and/or wheel states. Any progression into levels of concern by a component can be mapped and identified since its inception.

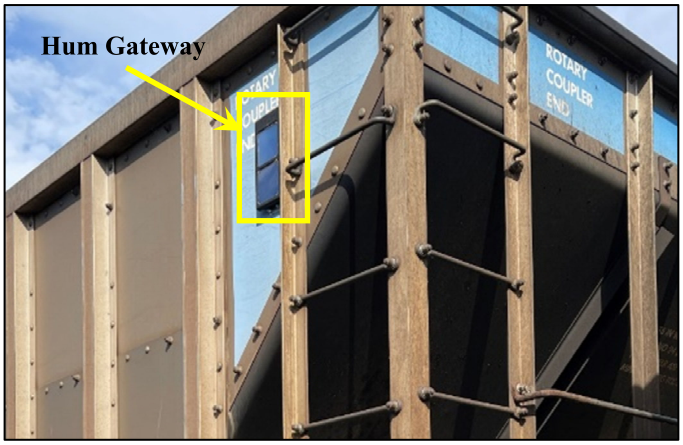

FIGURE 1: HUM GATEWAY INSTALLATION

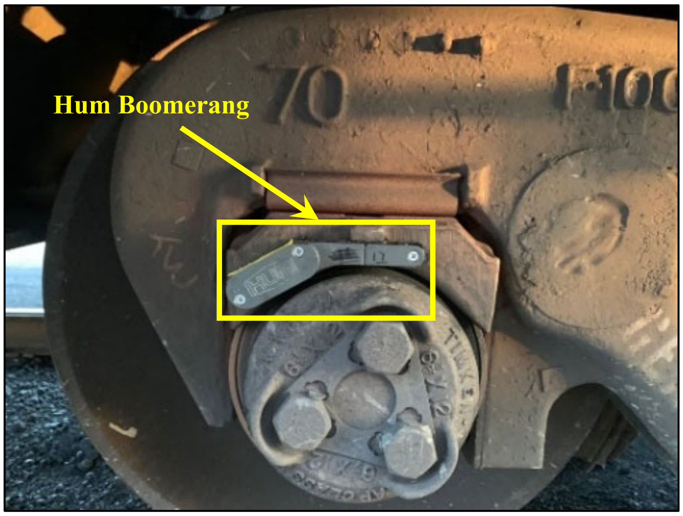

FIGURE 2: HUM BOOMERANG INSTALLATION

Prior to installing the Boomerangs, the bearing adapters on the selected railcars were modified using basic drill and tap techniques to secure the Boomerang at three specific mounting locations with screws as seen in FIGURE 2. The placement of the Boomerang was methodical to ensure accelerometer alignment with the bearing center.

Additionally, following the Association of American Railroads (AAR) wheel identification diagram shown in FIGURE 3, the Boomerangs were then registered onto Hum's server using their respective installation positions to facilitate identification of the bearings, wheels, and axles when analyzing the acquired health metrics.

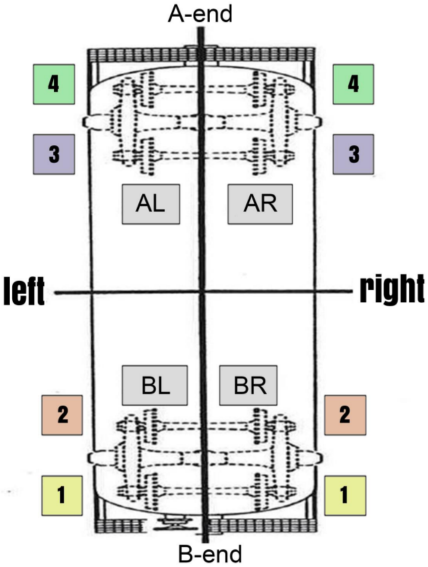

FIGURE 3: RAILCAR SIDE AND END IDENTIFICATION DIAGRAM

Over the course of two months, the real-time data output of the 40 modules was closely monitored to evaluate the sensors' capabilities in diagnosing the health of bearings and wheels. This entailed scrutinizing the incoming data for any BHI and WHI values exceeding preliminary thresholds established by Hum and UTCRS for both indices. After continuous analysis of the transmitted data, two modules that were fixed to the same railcar axle displayed WHI values corresponding to a plausible wheel abnormality. Following the presentation of this finding by Hum to the railcar owner, it was decided that three axles were to be removed from service and inspected. This axle removal process would target two apparently normal wheelsets along with the atypically performing wheelset to allow for suitable comparison.

Careful inspection of the three removed wheelsets revealed the identification of defects on the wheel treads and flanges of the axle of interest, confirming the abnormal wheel diagnosis. The other two wheelsets, used for comparison, demonstrated conformity to AAR wheel profile standards. Furthermore, even though BHI signatures from all three axles indicated no bearing abnormalities, the six bearings pertaining to these wheelsets were shipped to the UTCRS laboratory facilities for systematic testing to validate the BHI readings from the field.

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For brevity, only two out of the three wheelsets removed were selected for presentation in this paper. These include a healthy and a defective wheelset as pictured in FIGURE 4 and FIGURE 5, respectively. Since the defective (high-concern wheelset) was in the Axle 2 position (refer to FIGURE 3), a healthy (low-concern wheelset) in the Axle 2 position on a different railcar was removed for direct comparison. Following the AAR wheel identification diagram of FIGURE 3, the paper refers to the wheels as “L2” and “R2” to indicate the left and right locations of the railcar, respectively, while the number “2” indicates the wheelset position on the railcar (i.e., Axle 2).

FIGURE 4: AXLE 2 LOW-CONCERN WHEELSET (HEALTHY)

FIGURE 5: AXLE 2 HIGH-CONCERN WHEELSET (DEFECTIVE)

2.2 Laboratory Setup

The UTCRS Single Bearing Tester (SBT) shown in FIGURE 6 was used to evaluate the bearings removed from field service. The SBT can accurately mimic rail service speeds and railcar load conditions. The tester’s specialized axle can accommodate one class K or F bearing that is loaded using a hydraulic cylinder. Class K and F bearings are rated for a load of 153 kN (34.4 kips), which represents a fully loaded railcar (100% load), whereas a load of 26 kN (5.85 kips) per bearing corresponds to an empty railcar load or equivalently 17% of the full railcar load. The SBT is also instrumented with several K-type thermocouples to monitor and record the bearing operating temperature. Specifically, four spring loaded bayonet K-type thermocouples that are in direct contact with the outside surface of the bearing cup (outer ring) measure the bearing temperature at both raceways, and the average temperature reading of all four thermocouples denotes the bearing operating temperature.

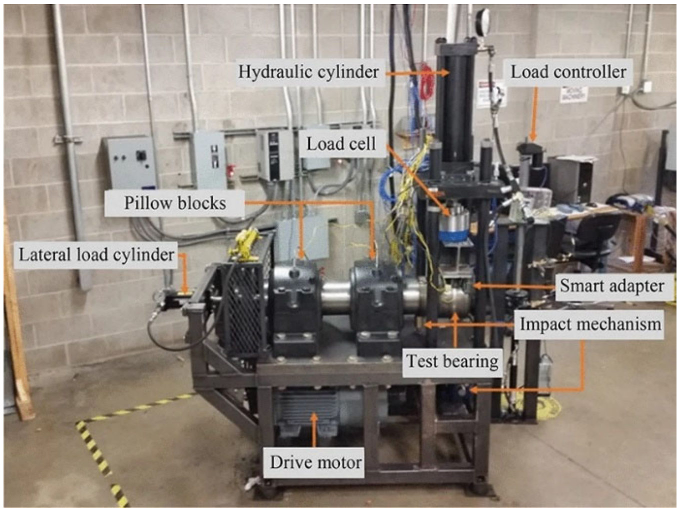

FIGURE 6: UTCRS SINGLE BEARING TESTER (SBT)

As depicted in FIGURE 7, the SBT is also equipped with a spring-driven impact mechanism that is used to simulate high wheel impacts or bad segments of rail track. By using springs of different spring constant, a wide range of wheel impact forces can be simulated ranging from low impacts of 67 kN (15 kips) to high impacts of 267 kN (60 kip) and 320 kN (72 kip) at a 3 Hz frequency (i.e., 3 hits per second). According to an article published by the Federal Register in 2015, a 267 kN wheel impact force indicates the issuance of a maintenance advisory for the affected rail vehicle, while a wheel with a 320 kN impact force is subject to a wheel/axle assembly removal and replacement at the railcar’s next stop at a repair shop [6]. Note that the 3 Hz frequency is equivalent to a 36"-wheel diameter with a single wheel tread defect travelling at roughly 31 km/h (19 mph).

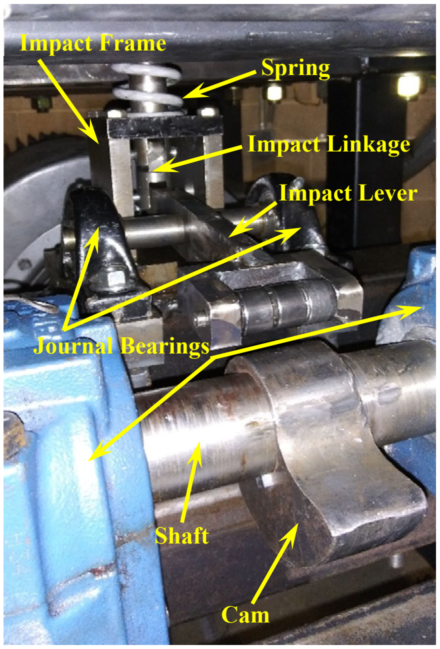

FIGURE 7: UTCRS SBT IMPACT MECHANISM

As shown in FIGURE 8, an identical onboard health monitoring Boomerang to those used in the pilot field test was utilized for the laboratory testing. The same mounting procedures implemented in the field were also used to affix the Boomerang to the bearing adapter of the UTCRS SBT.

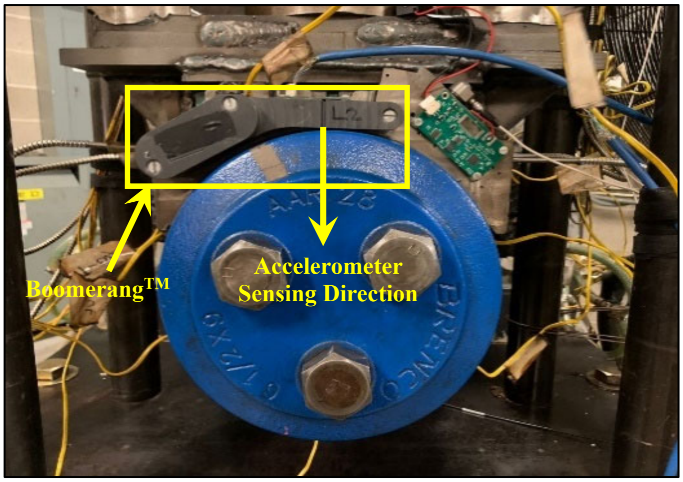

FIGURE 8: LABORATORY BOOMERANG MOUNTED ON BEARING ADAPTER AND ACCELEROMETER SENSING DIRECTION

3. RESULTS AND DISCUSSION

The upcoming discussion highlights the similarities in BHI and WHI between laboratory and field operations. Note that the BHI is a devised bearing health indicator developed from a decade's worth of vibration data acquired from laboratory testing conducted on railroad bearings. The BHI is coupled with adaptive railcar operation thresholds that signal bearing distress at distinct railcar speeds. When a BHI value exceeds a particular threshold value, this indicates the bearing is operating normally. For instance, a BHI of 25 corresponds to a railcar at rest. When a bearing manifests a BHI below the threshold, the bearing earns a high concern designation. In some cases, the BHI may manifest near the appointed threshold without falling beneath it (e.g., 1 unit over). Under these circumstances, the bearing is still considered functional, yet it warrants increased monitoring in anticipation of its transition into a high concern state.

Comparably, the WHI or wheel health index was developed by Hum to gauge the condition of a railcar's wheel utilizing a 1.6-100 scale. Like WILDs, the basis of this scale employs the emitted impact forces from wheel-rail interactions. From experimentation practices at UTCRS, a WHI of 1.6 implies the railcar is at rest while a WHI of 100 indicates a 267 kN (60 kips) wheel impact reading.

Thus, using these parameters, the following results will focus on the bearings of the healthy Axle 2 and wheels of both the healthy and defective Axle 2. An average BHI was computed from the field results and compared to the average laboratory BHI results acquired from unloaded (empty) and fully loaded railcar tests at different speeds. To provide examples of what the BHI of defective bearings resembles, the BHI of a defective cup and a defective cone propagated at the UTCRS will also be provided. The difference between low concern and high concern wheelsets will subsequently be explored. Both field and laboratory evaluations for bearings and wheels will encompass speeds of 40, 65, and 85 km/h.

3.1 Laboratory and Field BHI comparison

FIGURE 9 and FIGURE 10 present healthy Axle 2 BHI field data in comparison to BHI laboratory data. As the speed increased, the BHI began to decrease, but no bearing fell below the BHI threshold. The BHI responses of the laboratory and field data were mostly analogous with each other. At the higher speeds of 65 and 85 km/h, the BHI values for field and laboratory operations were within 1 BHI unit difference. The slightly larger BHI difference at 40 km/h was due to railcar vehicle dynamics. The systematic laboratory testing verified that the bearings on Axle 2 were healthy and of low concern.

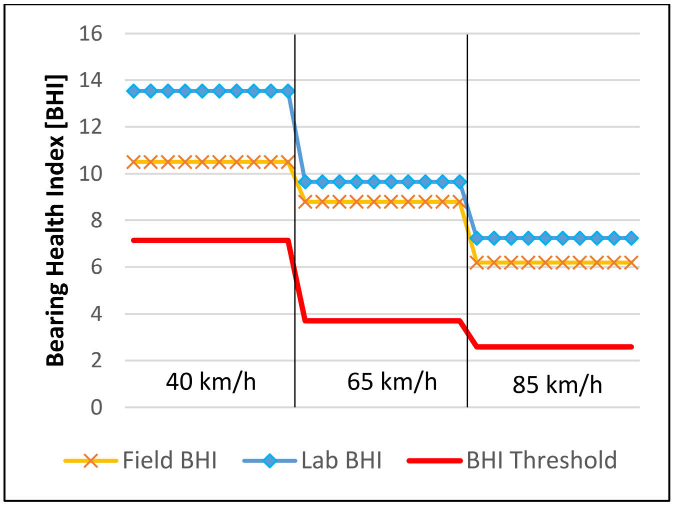

FIGURE 9: HEALTHY AXLE 2 L2 BEARING BHI COMPARISON BETWEEN LABORATORY AND FIELD DATA

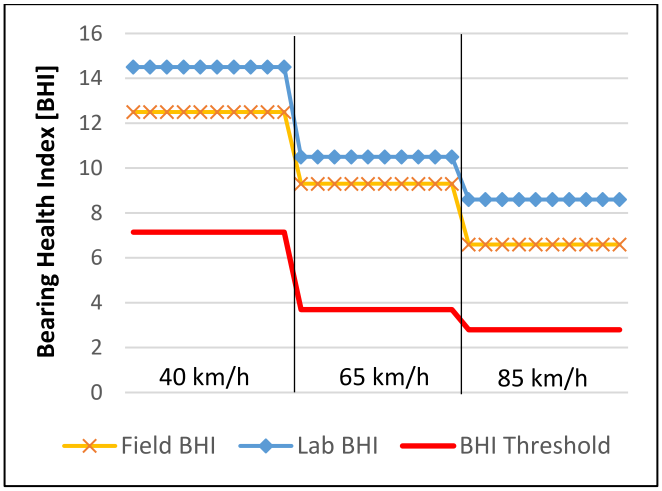

FIGURE 10: HEALTHY AXLE 2 R2 BEARING BHI COMPARISON BETWEEN LABORATORY AND FIELD DATA

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Without the success of discovering high concern bearings in the pilot field test, FIGURE 11 and FIGURE 13 present laboratory results for high concern bearings at or below the BHI threshold.

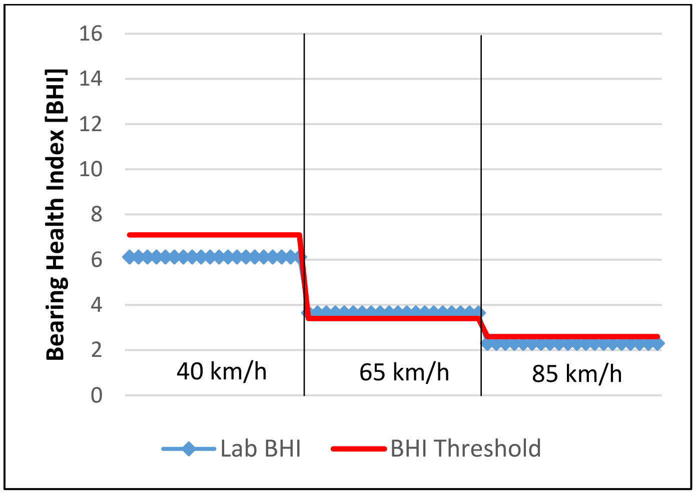

FIGURE 11: LABORATORY CUP SPALL BHI RESULTS

FIGURE 11 demonstrates the laboratory BHI results acquired from testing performed on a bearing containing a cup spall with a defect area of 10.13 cm^2 (1.57 in^2). The BHI values were at or below the threshold at the selected speeds of 40, 65, and 85 km/h, which implied the presence of a bearing defect. A picture of this bearing defect is provided in FIGURE 12.

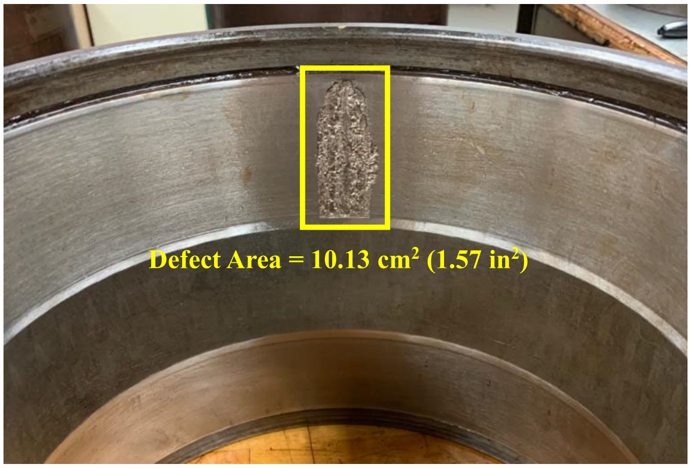

FIGURE 12: CUP SPALL TESTED AT THE UTCRS FACILITIES

The BHI values for a bearing with a cone defect having an area of 11.16 cm^2 (1.73 in^2) are shown in FIGURE 13. At each tested speed, the laboratory BHI remained over the prescribed BHI threshold. However, as speed increased, the gap between the BHI threshold and the laboratory operation BHI subsided. Nonetheless, the relative adjacency to the BHI threshold at higher speeds indicates that the bearing is on the verge of converting into a high concern bearing in need of being closely monitored and tracked.

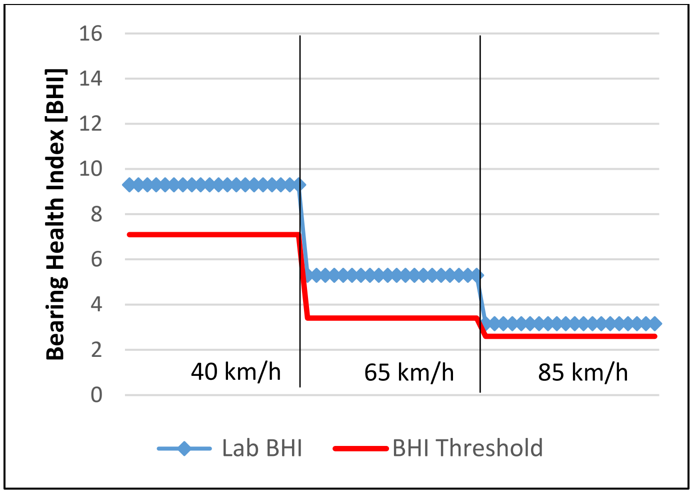

FIGURE 13: LABORATORY CONE SPALL BHI RESULTS

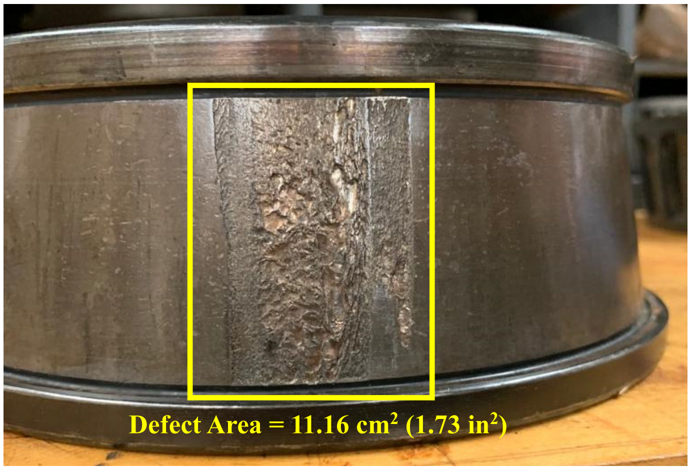

FIGURE 14: CONE SPALL TESTED AT THE UTCRS FACILITIES

3.2 Wheelset WHI Comparison

The following presents the WHI data collected over the two-month testing period along with post-changeout wheel health indices for both the healthy and defective Axle 2, allowing for a direct comparison between typical and atypical wheel health indices.

To characterize certain WHI ranges and support the results, a preliminary nominal operational WHI threshold and experimentally established thresholds were also introduced. The first limit, at a WHI of 20, was introduced in relation to the dominant WHI behavior seen in the field. That is, within both healthy Axle 2 data sets, the wheel health indices remained generally under 20 for all operating speeds. This suggests a WHI of 20 can be a preliminary threshold for nominal wheel operation. Lying at a WHI of 55, the second threshold is the equivalent of a 133 kN (30 kips) wheel impact determined from experiments conducted at the UTCRS. As this limit is half the 267 kN (60 kips) threshold at which the FRA advises maintenance for wheels, it prompts those wheels operating at WHI levels within 20 and 55 should be observed closer but are

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of low concern. Lastly, a 267 kN limit was set at a WHI of 100. The WHI to kip threshold was also developed from laboratory studies conducted at UTCRS. As previously discussed, a wheel presenting this impact is deemed worthy of a maintenance advisory. Hence, any wheels displaying a WHI within the 133 and 267 kN levels enter a state of high concern where railcar owners should attentively monitor their vehicles for any WHI manifestations at 100. Once at 100 WHI, railcar owners should follow the appropriate countermeasures indicated by the FRA.

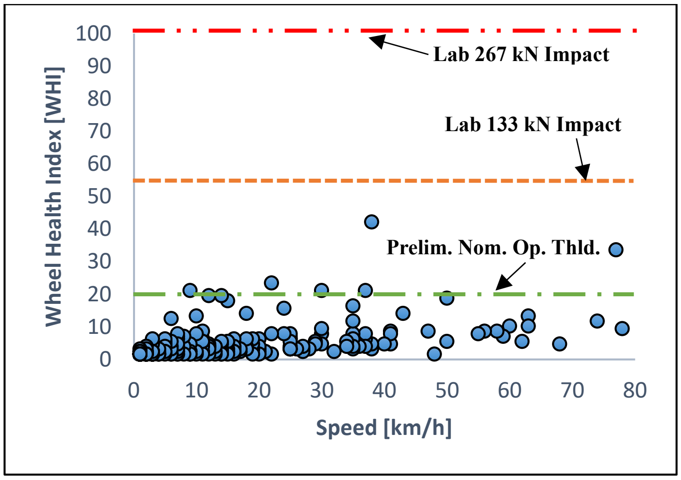

FIGURE 15: HEALTHY AXLE 2 WHI VALUES PRE-CHANGEOUT

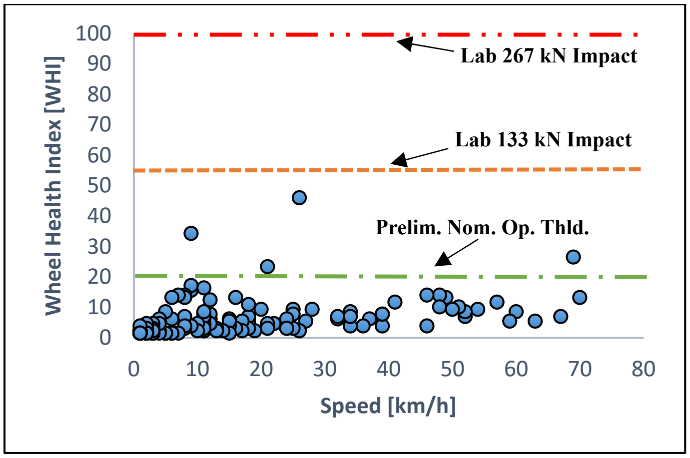

FIGURE 16: HEALTHY AXLE 2 WHI VALUES POST-CHANGEOUT

FIGURE 15 and FIGURE 16 delineate the WHI behavior for the healthy Axle 2 before and after its wheelset interchange, respectively. Despite the occasional outlier, which could be the result of bad track segments, there was no significant deviation in WHI caused by the changeout operation establishing that the original wheelset was indeed performing under nominal conditions. The pre- and post-changeout predominant WHI values that fall within a WHI of 20 also exemplify the introduction of the nominal wheel operation threshold.

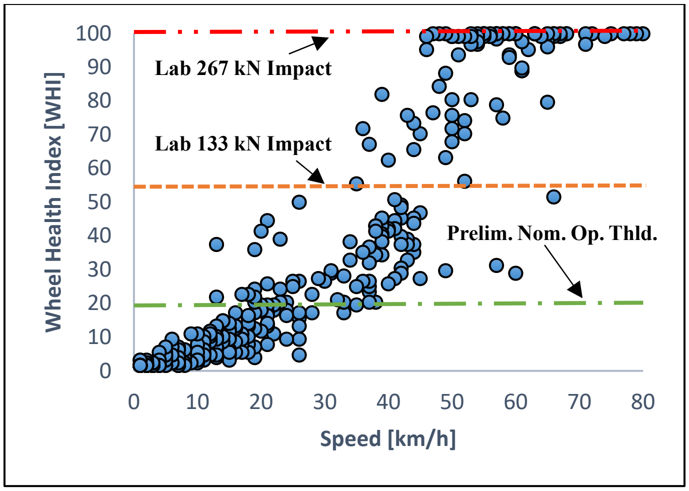

FIGURE 17: DEFECTIVE AXLE 2 WHI VALUES PRE-CHANGEOUT

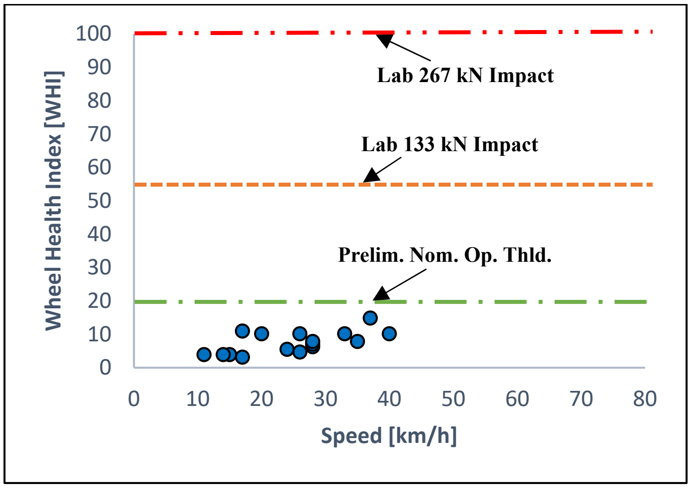

FIGURE 18: DEFECTIVE AXLE 2 WHI VALUES POST-CHANGEOUT

Unlike the healthy Axle 2, a smaller set of data was acquired for the defective Axle 2 wheelset post-changeout, as seen in FIGURE 18. This impeded a robust analysis to be performed between the exchanged axles of the Axle 2 position. Yet, comparing FIGURE 17 and FIGURE 18, it can still be observed that, at the 30 to 40 km/h speed range, the WHI values reduced below the proposed nominal wheel health index of 20 WHI.

Nonetheless, by juxtaposing FIGURE 15 and FIGURE 16 onto FIGURE 17, the non-normative wheelset behavior for Axle 2 becomes apparent. Furthermore, superposition of the previously discussed WHI thresholds onto FIGURE 17 clearly map the transition of the wheelset into all the denoted WHI limits until reaching the FRA advised maintenance stage around 50 km/h. The behavior of the data in FIGURE 17 also shows that the effects of wheel irregularities are amplified with increases in speed.

FIGURE 19 and FIGURE 20 provide visual evidence of the wheel flats and spalls found on the defective Axle 2. These

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defects further justify the WHI values seen in FIGURE 17. It was also determined that the wheel-rim thickness of one of the wheels of Axle 2 was already at the 1-inch condemning limit [7]. Therefore, reprofiling of the wheel was unfeasible and the wheelset was discontinued from service.

FIGURE 19: WHEEL DEFECTS ON L2 OF AXLE 2

FIGURE 20: WHEEL DEFECTS ON R2 OF AXLE 2

4. CONCLUSIONS

The data and results presented in this paper proved the efficacy of Hum's novel rolling stock onboard condition monitoring system. This was accomplished by conducting methodical laboratory and field testing that successfully validated the Boomerang's ability to detect high concern bearings and wheels. Bearing Health Index (BHI) and Wheel Health Index (WHI) metrics were introduced and thresholds for normal and abnormal operation were specified. Furthermore, field implementation of the technology through the pilot test was successful in identifying a defective wheelset. Inspection revealed end-of-life cycle characteristics as the wheel profile lacked adherence to AAR standards for continued operation. This highlights the capability of the Boomerang in relaying accurate and critical wheelset health metrics. Although additional field tests are needed to continue the optimization of this system for an official integration into the railway industry, the presented findings suggest that railcar owners will soon have access to an onboard tool that can facilitate proactive maintenance scheduling and mitigate costly derailments.

ACKNOWLEDGEMENTS

This study was made possible through funding provided by Hum Industrial Technology, Inc. and the US National Science Foundation (NSF 2112650). The opinions expressed are solely those of the authors, and do not necessarily represent those of the NSF.

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