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Field Implementation Statistical Analysis of an Emerging Bearing Condition Monitoring System

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Abstract

Current wayside detection methods utilized for freight wagon bearing health monitoring do not constitute a true continuous bearing condition monitoring system, and have resulted in costly false bearing setouts and removals. Consequently, efforts in this area have shifted towards more efficient forms of on-board detection. One such system uses battery-operated wireless sensor nodes (WSNs) attached to the bearing adapters and managed by a central monitoring unit (CMU). This system is capable of continuous monitoring and recording (at set sampling rates and frequencies) of the temperature of each bearing within the freight wagon along with the ambient temperature. Laboratory conducted experiments and subsequent field-test trials have verified that this system provides accurate bearing condition monitoring, and with the use of carefully developed criteria, can also be used to predict the onset of bearing failure. The main drawback of this system, however, is battery life. Hence, the WSN-based system has undergone several optimization processes which include prototype redesign and reductions in the data sampling rate, frequency, storage, and upload in order to prolong the battery life of the WSNs and CMU. This paper presents a detailed statistical analysis of data acquired from several field-implemented trials with varying data sampling rates, frequencies, storage, and upload. The main objective of the study presented here is to examine the effects of the latter factors on the developed WSN criteria in an attempt to determine the optimal parameters and thresholds that will provide uncompromised system accuracy while maximizing battery life.

Keywords: wireless sensor nodes, bearing condition monitoring, bearing temperature analysis, derailment prevention systems.

1 Introduction and background

The railroad industry has predominantly relied on wayside hot box detection systems as the main method of bearing condition monitoring. A hot-box detector is designed to identify those bearings which are operating at temperatures greater than 94.4°C (170°F) above ambient. In service, bearings that are identified as running hot are set out for later removal, disassembly, and subsequent inspection. Some railroads have adopted a new practice of tracking the temperature data and comparing individual bearings against the averages of the remainder along a train [1]. Identifying those bearings which are *trending* above normal allows the railroads to determine which bearings appear to be distressed without waiting for a hot-box detector to be tripped. Even though the latter practice has helped reduce the number of train derailments in the past decade, it has resulted in a dramatic increase in the number of *non-verified* bearing removals. A non-verified bearing is one that, upon disassembly and inspection, is found not to exhibit any of the commonly documented causes of bearing failure such as: spalling, loose bearings, water contamination, damaged seals, broken components, lubrication, raceway defects, etc. According to data collected by Amsted Rail from 2001 to 2007, an average of nearly 40% of bearing removals are non-verified. This figure approached 60% in 2003 and 2004, and never dropped below 24% during the period from 2001 to 2007. In other words, a considerable percentage of bearings pulled from service based on hot-box detector readings have no discernible defects. The latter is cause for concern considering the delays, waste of resources, and costs associated with the unnecessary train stoppages.

Based on the aforementioned discussion, The University of Texas-Pan American (UTPA) Railroad Research Group in collaboration with Amsted Rail have concentrated their research efforts on innovations in bearing health monitoring systems. Over the past few years, several theoretical, experimental, and field studies have been conducted focusing on determining the main cause of bearing temperature trending and ways to accurately identify it in field service using continuous onboard health monitoring systems [2-8]. The performed work was methodically planned and consisted of mapping out and quantifying the different heat transfer paths within the railroad tapered-roller bearing [2-5], followed by experimental and field studies conducted to determine the cause of temperature trending in field service [6-7], and concluding with experimental and field testing of wireless temperature sensor nodes mounted on bearing adapters that provide continuous condition monitoring of bearings in service [8]. These studies were successful in identifying vibration-induced roller-misalignment as the cause of temperature trending in field service. The studies also determined that current wayside detection systems utilized in field service are not able to distinguish between healthy bearings undergoing temperature trending events and defective bearings nearing failure. On this premise, it was decided that wireless sensor nodes (WSNs) mounted on bearing adapters, shown in Figure 1, that can monitor the bearing condition more frequently, and with better accuracy, are better suited than wayside detection systems which are sometimes positioned up to 64.4 km (40 mi) apart.

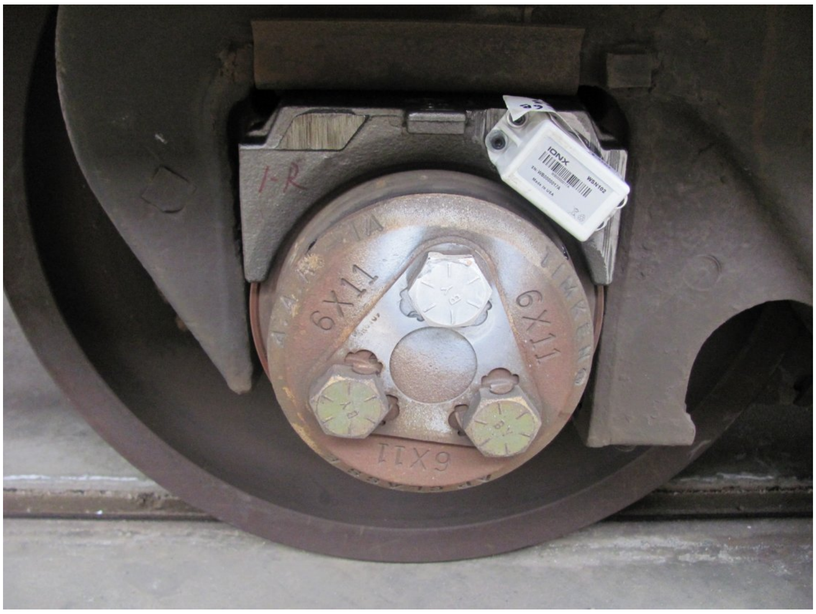

Figure 1: WSN typical installation in the field

Since the developed WSNs are designed to be mounted on the bearing adapter, initial experimental studies focused on calibrating these devices to accurately estimate the bearing outer surface (cup) temperature (which is the surface of the bearing typically scanned by the infrared wayside detection systems). An excess of one million data points were acquired for four different bearing classes (Class F, K, E, and G) during the calibration process, which yielded five different calibration curves, one for each one of the four classes tested, and an overall calibration curve that combined all the collected data. The calibration process along with the different calibration curves can be found elsewhere [8]. To evaluate the efficacy of the developed WSNs as a continuous bearing condition monitoring system, a year-long field test was conducted in Australia as a collaborative effort between Amsted Rail and SCT Logistics. The UTPA Railroad Research Group carried out the analysis of the acquired data. Amsted Rail engineers and UTPA researchers were able to use the results to develop and implement a validated bearing health monitoring algorithm consisting of three different levels and several criteria within each level. This latter algorithm was successful in identifying two defective bearings that were removed from service by SCT Logistics and tested and inspected at UTPA. In what proved to be a staggering validation of the developed algorithm, one of removed bearings failed on the test rig at just 86,000 km (53,438 mi), which represents only five and a half weeks of normal service for this bearing [8].

Currently, the WSN bearing condition monitoring system is being implemented in two different field tests in two continents, each with at least one year worth of data. Apart from serving as further proof of concept validation, these field trials have the added objective of optimizing the system in terms of battery consumption while still reliably reporting sufficient amounts of data to make a meaningful assessment of bearing health. The first trial consists of ten wagons which have been outfitted with WSNs which record temperature once every four minutes, whereas, the second trial consists of only two tank-cars with the WSNs recording temperature once every fifteen minutes. It should also be mentioned that the cell-phone coverage area (which is the method that the WSNs utilize to upload their acquired data) for the first field trial is limited to specific locations within the route traveled by the wagons, whereas, the second field trial has good cell-phone coverage throughout the entire route. Furthermore, the second field trial required the use of some additional sensors to monitor the braking system and the hatch locks for the tank-cars which limited the number of available channels and resulted in the absence of an ambient node. Hence, the main objective of the study presented here is to provide a detailed analysis of the acquired data from the ongoing field tests in an effort to refine the thresholds used in the previously developed criteria in order to provide baseline information for the minimum amount of data needed to make an accurate and reliable assessment of bearing health while optimizing battery usage.

2 Criteria and metrics

As discussed in the previous section, an algorithm comprised of three distinct levels was devised to categorize problematic bearings, as detailed in Table 1 [8]. The three levels range in urgency from potential imminent failure requiring immediate attention (Level 1) to near- or mid-term (~3-6 months) maintenance or replacement required (Level 2) to potential long-term (beyond 9 months) defect in early stages (Level 3) [8]. Furthermore, these levels consist of different sets of criteria that were devised based on metrics acquired from the railroad industry and from a number of experimental and field tests conducted over the past several years. Level 1 sets absolute thresholds that are in line with Association of American Railroads (AAR) standards. If any of the Level 1 criteria are violated, then the train must be immediately stopped in order to remove the bearing from service to avoid a potential derailment. Levels 2 and 3 allow the railroads, train operators, and/or wagon owners sufficient time to schedule routine maintenance cycles in which they can address any problematic bearing issues without causing unnecessary and costly train stoppages and delays. The two levels have identical criteria but differ in the fact that Level 2 criteria are associated with specific thresholds that are meant to quantify the severity of the defective bearing, whereas, Level 3 criteria are intended to provide a watch-list of potentially problematic bearings at an early stage (i.e.; bearings that need to be monitored more closely). The temperature data collected by the WSNs is systematically processed, analyzed, and compared against the established criteria on a regular basis so that operational decisions can be made in a timely manner. Based on Level 2 and 3 criteria and depending on the severity of the issue, bearings may have to be scheduled for an early inspection and/or removal from service. In Table 1, multiple symbols are used to represent lengthy and repetitive terms. The standard deviation of a bearing's temperature is represented by σ, the change in temperature is represented by Δ, and $\frac{dT_i}{dt}$ denotes the rate of temperature increase which is a direct measure of the heat rate within the bearing.

Level	Criteria	Metric
1	1	$T_i \geq 160^oC$ (320^oF)
	2	$\Delta T_i \geq 94.4^oC$ (170^oF)
	3	$T_i - T_{i,mate} \geq 58.3^oC$ (105^oF)
2	1	$\geq 25\%$ of T_i readings $\geq 93.3^oC$ (200^oF)
	2	$\geq 25\%$ of ΔT_i readings $\geq 66.7^oC$ (120^oF)
	3	$(T_{i,avg} - T_{wagon,avg})/\sigma_{wagon} \geq 1$
	4	$(T_{i,avg} - T_{fleet,avg})/\sigma_{fleet} \geq 1$
	5	$dT_i/dt \geq 0.694^oC/min$ ($1.25^oF/min$)
3	1	Count T_i readings $\geq 93.3^oC$ (200.0^oF)
	2	Count ΔT_i readings $\geq 66.7^oC$ (120.0^oF)
	3	Calculate $(T_{i,avg} - T_{wagon,avg})/\sigma_{wagon}$
	4	Calculate $(T_{i,avg} - T_{fleet,avg})/\sigma_{fleet}$
	5	Calculate dT_i/dt

Table 1: Criteria and metrics used in the three levels of the bearing condition monitoring algorithm

3 Statistical analysis of existing thresholds on new field trials

The thresholds used in the Level 2 criteria were obtained by preforming detailed statistical analyses on one full year worth of data acquired from the SCT Logistics field test in Australia and observing any statistical outliers. However, the two new ongoing field tests differ from the Australia trial in terms of the environment, bearing class, wagon type, operating conditions of the freight wagons which includes loading capacity and traveling speeds, and the programming of the WSNs and CMUs which is set to conserve battery life by reducing the data acquisition frequency. Hence, the statistical study presented in this paper investigates the effects of the latter differences on the previously determined thresholds with the objective of optimizing and generalizing these thresholds for use in railroads across the globe. The temperature data collected by WSNs over the course of an entire year is studied and sorted so that each of the criteria may be individually evaluated and assessed. Once calculated, the distribution of the data is plotted and specific points of interest are identified in order to determine which values fall outside of the normal range, which aids in the development of refined thresholds that represent a broad range of freight wagon operating conditions.

The number of temperature reports from the individual bearing WSNs for each of the ten outfitted wagons in one of the ongoing field trials are shown in Table 2. Data from the entire study is collected and parsed to identify where the distribution for the different criteria lies in comparison to the initial field study for which these thresholds were devised [8]. Looking at Table 2, it can be noticed that the number of temperature data collected for each wagon by each of the WSNs is different. It should be noted that not all ten wagons are connected to the same train, which means that these wagons can be in different locations at different times and some may be parked at areas without any cell-phone coverage for prolonged periods of time. Furthermore, in an effort to conserve battery life, the WSNs and CMUs are programmed to stop logging data once the temperatures of all the WSNs for an individual wagon are within 11.1^{0}C (20^{0}F) from ambient temperature.

Number of Temperature Reports per Wagon for each WSN (1 Year)									
	L1	**R1**	**L2**	**R2**	**L3**	**R3**	**L4**	**R4**	**Ambient**
WAGON 1	**1070**	**1080**	**795**	**1035**	**1036**	**1080**	**1036**	**947**	**1036**
WAGON 2	**6002**	**6096**	**6162**	**32066**	**7676**	**16762**	**7678**	**6823**	**31972**
WAGON 3	**14832**	**15367**	**15008**	**15514**	**13777**	**14931**	**14931**	**14947**	**14789**
WAGON 4	**6602**	**13047**	**8462**	**11812**	**10945**	**13237**	**13237**	**13012**	**13129**
WAGON 5	**2948**	**2948**	**2948**	**3011**	**3092**	**3012**	**2883**	**2884**	**2883**
WAGON 6	**15290**	**15499**	**15239**	**93**	**16142**	**15740**	**14633**	**15976**	**15936**
WAGON 7	**6072**	**6017**	**6021**	**5980**	**5997**	**25895**	**6144**	**6116**	**25634**
WAGON 8	**12492**	**20935**	**25468**	**25685**	**6387**	**12092**	**6434**	**17489**	**25781**
WAGON 9	**15299**	**15328**	**15402**	**15722**	**15840**	**15805**	**15457**	**15330**	**15433**
WAGON 10	**11452**	**24106**	**11293**	**11483**	**11536**	**11594**	**11429**	**11419**	**24189**

Table 2: Number of temperature reports per wagon for each WSN over the course of one year

The overall temperature distribution for the ongoing ten-wagon field test is compared to that from the SCT Logistics field test, as shown in Figure 2 and Figure 3, respectively. Table 3 lists the 5%, 2%, and 1% cut-off temperature values for both field tests. To clarify, the cut-off values indicate the percentage of temperature readings that fall above the listed operating temperatures. Comparing the histograms of Figure 2 and Figure 3, it can be observed that the ongoing ten-wagon field test has slightly higher temperature values corresponding to the 5%, 2%, and 1% cut-offs as compared to the SCT Logistics field test. The latter is not surprising considering that the operating conditions of the ongoing ten-wagon field test are characterized as heavy haul with unfavorable track conditions when compared to the SCT Logistics field test operating conditions. Nevertheless, the devised criterion associated with the absolute bearing temperature (Level 2 and Level 3 Criterion 1) seems to be appropriate for both field test applications. The implication here is that any bearings with temperatures falling above the 93.3^{0}C (200^{0}F) threshold are a cause for concern and should be monitored closely. Note that this threshold constitutes less than 1% of the entire temperature data sets acquired from two distinctly different field tests, which will aid in minimizing the number of non-verified bearing removals. Moreover, the dissimilarity in the shape of the temperature distributions of the two field tests is the direct consequence of the measures taken in the ongoing ten-wagon field test to conserve battery-life of the WSNs and CMUs by reducing the frequency of temperature data acquisition and upload, and putting the system to sleep whenever the bearing temperatures of a wagon are within 11.1^{0}C (20^{0}F) from ambient temperature.

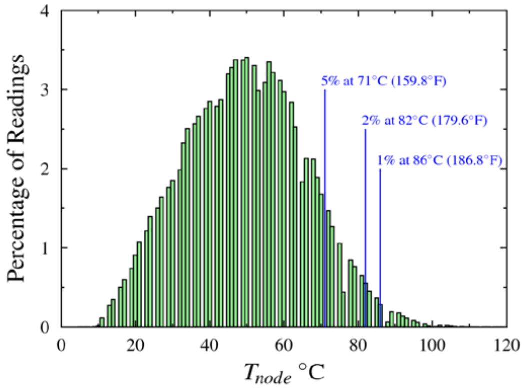

Figure 2: Overall temperature distribution for SCT Logistics field test (1 year) [8]

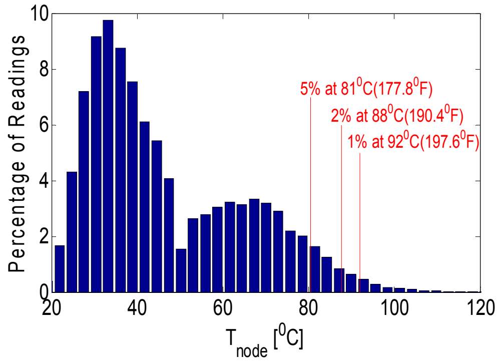

Figure 3: Overall temperature distribution for ongoing ten-wagon field test (1 year)

Cut-off	SCT Logistics Field Test	Ongoing Ten-Wagon Field Test
5%	71^{0}C (159.8^{0}F)	81^{0}C (177.8^{0}F)
2%	82^{0}C (179.6^{0}F)	88^{0}C (190.4^{0}F)
1%	86^{0}C (186.6^{0}F)	92^{0}C (197.6^{0}F)

Table 3: Overall temperature data comparison for two different field tests (1 year)

Figure 4 and Figure 5 show the temperature above ambient distribution plots for the two different field tests, and Table 4 lists the 5%, 2%, and 1% cut-off values. Again, the 66.7^{0}C (120^{0}F) threshold used in the Level 2 and Level 3 Criterion 2 seems to be appropriate for general use as less than 1% of the entire temperature data sets acquired from two distinctly different field tests fall above that threshold. The lower above ambient temperature values associated with the 5%, 2%, and 1% cut-offs for the ongoing ten-wagon field test can be explained by the differences in the environment of the two field tests and the operating speeds. Wagons in the SCT Logistics field test traveled at speeds up to 112.7 km/h (70 mph); whereas, the wagons in the ongoing field test generally do not exceed 80.5 km/h (50 mph).

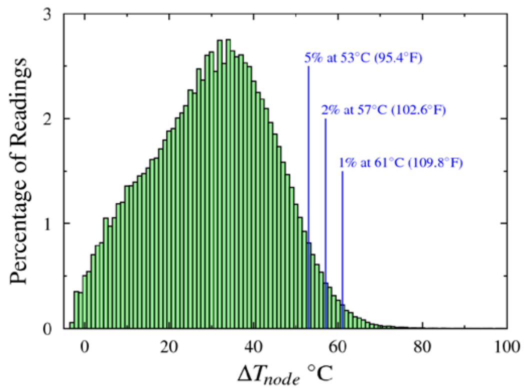

Figure 4: Temperature above ambient distribution for SCT Logistics field test (1 year) [8]

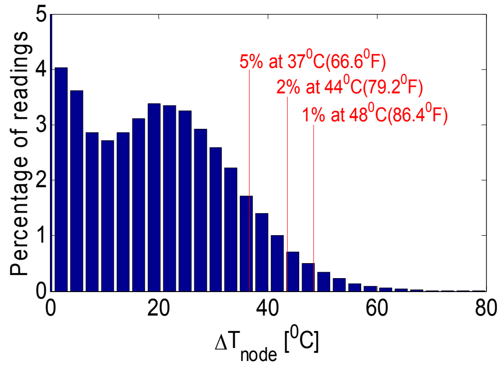

Figure 5: Temperature above ambient distribution for ongoing ten-wagon field test (1 year)

Cut-off	SCT Logistics Field Test	Ongoing Ten-Wagon Field Test
5%	53⁰C (95.4⁰F)	37⁰C (66.6⁰F)
2%	57⁰C (102.6⁰F)	44⁰C (79.2⁰F)
1%	61⁰C (109.8⁰F)	48⁰C (86.4⁰F)

Table 4: Temperature above ambient comparison for two different field tests (1 year)

The standard deviation (σ) for each bearing from the SCT Logistics and the ongoing ten-wagon field tests is plotted in Figure 6 and Figure 7, respectively, and the cut-off values comparison is summarized in Table 5. At first glance, it appears that the standard deviation threshold of 1σ set for Level 2 and Level 3 Criteria 3 and 4 is appropriate and justified for general use. An argument can be made to increase this threshold to 1.25σ to lower the percentage of any false bearing setouts and ensure that bearings that trigger this alarm are problematic requiring attention.

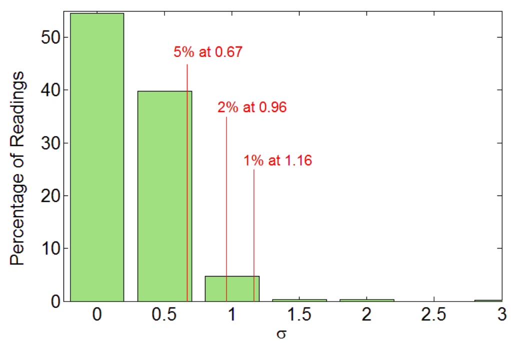

Figure 6: Standard deviation (σ) for each bearing from the SCT Logistics field test (1 year)

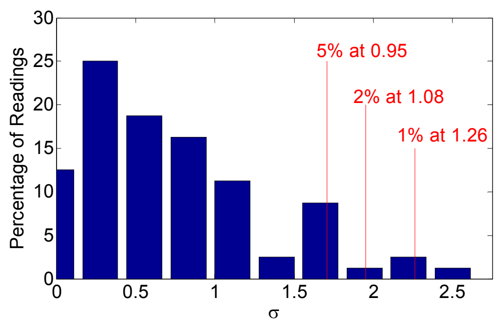

Figure 7: Standard deviation (σ) for each bearing from the ongoing ten-wagon field test (1 year)

Cut-off	SCT Logistics Field Test	Ongoing Ten-Wagon Field Test
5%	0.67 σ	0.95 σ
2%	0.96 σ	1.08 σ
1%	1.16 σ	1.26 σ

Table 5: Standard deviation comparison for two different field tests (1 year)

The rate of temperature increase, which is a direct measure of the rate of heat generation within the bearing, can only be evaluated when the sampling frequency is no less than one sample every four minutes. Sampling periods beyond four minutes make it very difficult to obtain reliable rate of temperature increase estimates, as this metric assumes that the train is accelerating long enough to acquire at least four data points during that period. A comparison of this metric for the SCT Logistics and the ongoing ten-wagon field tests can be seen by looking at Figure 8, Figure 9, and Table 6. The histograms indicate that the rate of temperature increase values for the ongoing ten-wagon field test are slightly higher than those from the SCT Logistics field test. The latter result in not surprising considering the harsh operating conditions of the ongoing field test, described earlier. A strong argument can be made to increase the threshold set for this specific criterion from 0.694^{0}C/min (1.25^{0}F/min) to 0.944^{0}C/min (1.7^{0}F/min) to make it more applicable for general use. The latter threshold will aid in reducing the percentage of bearings flagged by this criterion while signifying a potential problem with any bearing exceeding this new threshold.

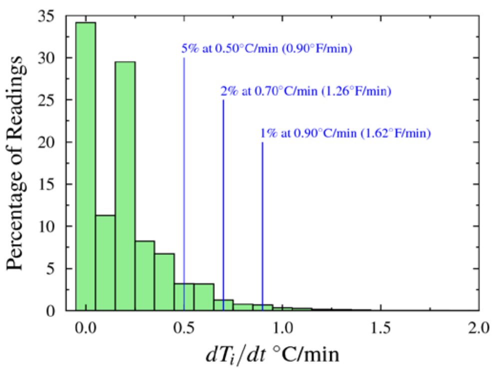

Figure 8: Rate of temperature increase for all the bearings in the SCT Logistics field test (1 year) [8]

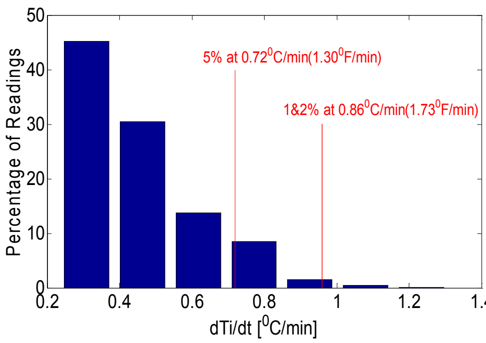

Figure 9: Rate of temperature increase for all the bearings in the ongoing ten-wagon field test (1 year)

Cut-off	SCT Logistics Field Test	Ongoing Ten-Wagon Field Test
5%	0.50^0C/min (0.90^0F/min)	0.72^0C/min (1.30^0F/min)
2%	0.70^0C/min (1.26^0F/min)	0.96^0C/min (1.73^0F/min)
1%	0.90^0C/min (1.62^0F/min)	0.96^0C/min (1.73^0F/min)

Table 6: Rate of temperature increase comparison for two different field tests (1 year)

4 Statistical analysis of devised thresholds over a shorter time period

A minimum number of data points must be evaluated to yield a valid analysis of individual nodes. Different time periods were tested and analyzed to determine the minimum number of points needed to perform a meaningful analysis. It was concluded that a period of one month is adequate as it yields roughly six thousand points for a moderately consistent node. To be considered for this analysis over a shorter period of time, a bearing node must have at least 4000 data points and a minimum of seven nodes must be reporting on that wagon. For this study, one of the more consistent wagons in terms of WSN reporting (Wagon 8 in Table 2) was chosen to validate the five Level 2 and Level 3 criteria, and to determine the optimal time frame necessary for a meaningful assessment of bearing condition. For comparison, the data for Wagon 8 is plotted against the data of the entire fleet for the same time period. Figures 10 through 17 and Tables 7 through 10 summarize the results of this study.

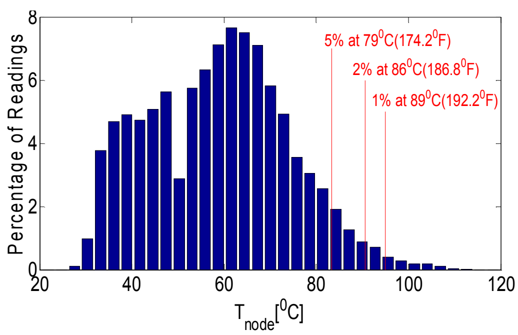

Figure 10: Overall temperature of the ongoing ten-wagon field test (1 month)

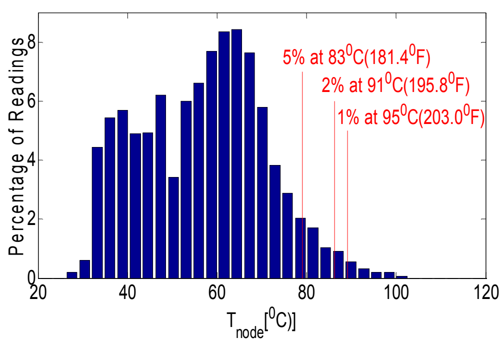

Figure 11: Overall temperature for Wagon 8 (1 month)

Cut-off	Ten-Wagon Fleet	Wagon 8
5%	79^0C (174.2^0F)	83^0C (181.4^0F)
2%	86^0C (186.8^0F)	91^0C (195.8^0F)
1%	89^0C (192.2^0F)	95^0C (203.0^0F)

Table 7: Overall temperature comparison between the entire ten-wagon fleet and Wagon 8 data (1 month)

Looking at the histograms presented in Figure 10 and Figure 11 and the cut-off values listed in Table 7, the threshold set for Level 2 and Level 3 Criterion 1 appears to be well justified.

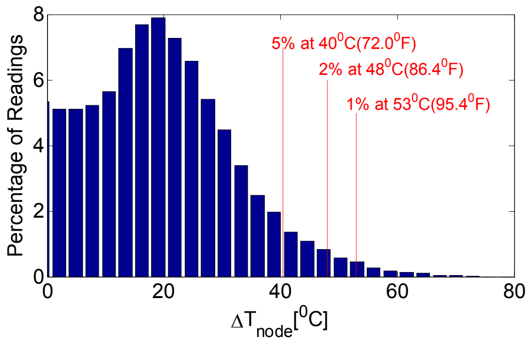

Figure 12: Temperature above ambient for the ongoing ten-wagon field test (1 month)

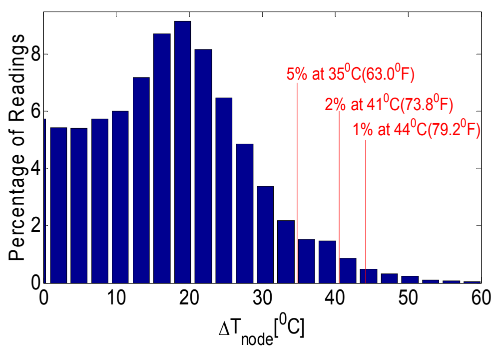

Figure 13: Temperature above ambient for Wagon 8 (1 month)

Cut-off	Ten-Wagon Fleet	Wagon 8
5%	40^0C (72.0^0F)	35^0C (63.0^0F)
2%	48^0C (86.4^0F)	41^0C (73.8^0F)
1%	53^0C (95.4^0F)	44^0C (79.2^0F)

Table 8: Temperature above ambient comparison between the entire ten-wagon fleet and Wagon 8 data (1 month)

The temperature above ambient data comparison results for the one month period for the ten-wagon fleet vs. Wagon 8 are shown in Figure 12, Figure 13, and Table 8. The displayed histograms are representative of the above ambient temperature data for the entire study. Even though an argument can be made to lower the threshold set for Level 2 and Level 3 Criterion 2, it should be kept in mind that the main objective of these criteria is to be applicable to a broad range of field service operating conditions. With the SCT Logistics field test data in mind, it is highly suggested that the threshold set for this criterion be kept as is (see Table 1) to avoid preventable false setouts.

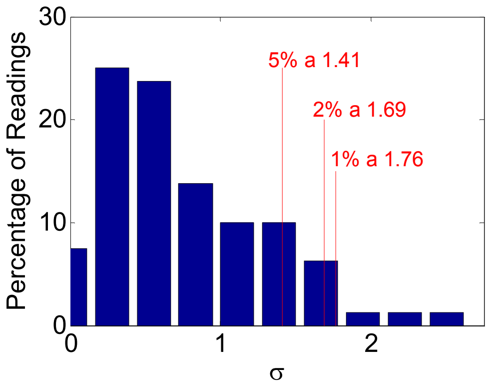

Figure 14: Standard deviation (σ) for the ongoing ten-wagon field test (1 month)

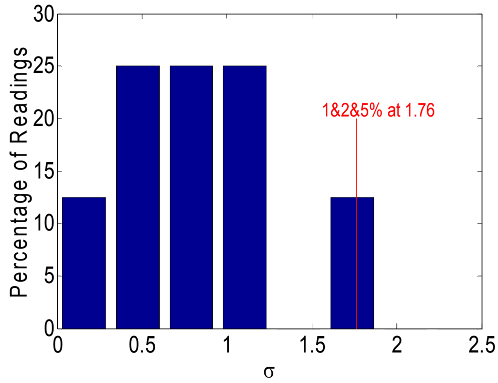

Figure 15: Standard deviation (σ) for Wagon 8 as compared to the entire ten-wagon fleet (1 month)

Cut-off	Ten-Wagon Fleet	Wagon 8
5%	1.41 σ	1.76 σ
2%	1.69 σ	1.76 σ
1%	1.76 σ	1.76 σ

Table 9: Standard deviation (σ) comparison between the entire ten-wagon fleet and Wagon 8 data (1 month)

The standard deviation (σ) analysis shown in Figure 14, Figure 15, and Table 9 suggests that threshold value of 1σ is not representative of heavy haul applications with challenging track conditions. A strong argument can be made to increase this threshold to 1.25σ or 1.5σ to account for harsh operating conditions and avoid triggering unnecessary Level 2 and Level 3 Criteria 3 and 4 alarms. Note that these two criteria are not the only ones used to evaluate and assess the overall health of a bearing as the other three criteria provide additional supporting evidence that can be used to make an informative decision regarding the condition of a bearing.

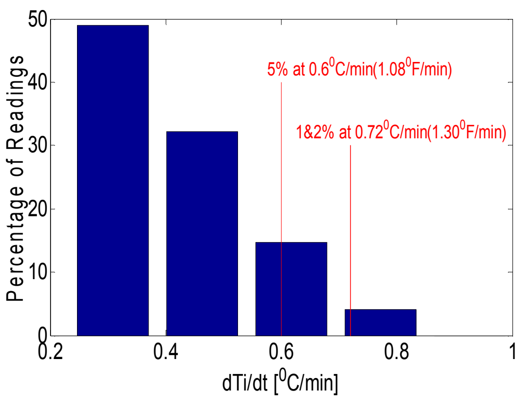

Figure 16: Rate of temperature increase for ongoing ten-wagon field test (1 month)

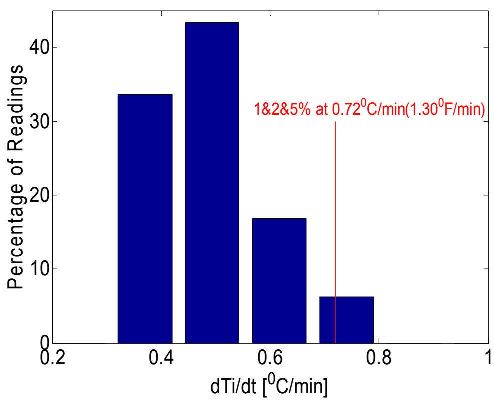

Figure 17: Rate of temperature increase for Wagon 8 (1 month)

Cut-off	Ten-Wagon Fleet	Wagon 8
5%	0.60^0C/min (1.08^0F/min)	0.72^0C/min (1.30^0F/min)
2%	0.72^0C/min (1.30^0F/min)	0.72^0C/min (1.30^0F/min)
1%	0.72^0C/min (1.30^0F/min)	0.72^0C/min (1.30^0F/min)

Table 10: Rate of temperature increase comparison between the entire ten-wagon fleet and Wagon 8 data (1 month)

The ten-wagon fleet vs. Wagon 8 comparison results for the rate of temperature increase, over a period of one month, are given in Figure 16, Figure 17, and Table 10. The presented data supports increasing the Criterion 5 threshold value of 0.694^0C/min (1.25^0F/min) to 0.944^0C/min (1.7^0F/min) to make it applicable for a broad range of field service operating conditions while reducing the number of triggered alarms.

Finally, the overall temperature distribution acquired from the two ongoing field tests over the one year period is presented in Figure 18. The two tank-car field test is characterized as low speed operation (< 60 km/h), whereas, the ten-wagon fleet field test is considered normal speed operation (speeds up to 90 km/h). The histograms clearly indicate that train traveling speed is one of the major factors that control the bearing operating temperature. The data also suggests that the devised bearing condition monitoring algorithm composed of the various levels, criteria, and thresholds described in Table 1 will hold true for low speed service operation.

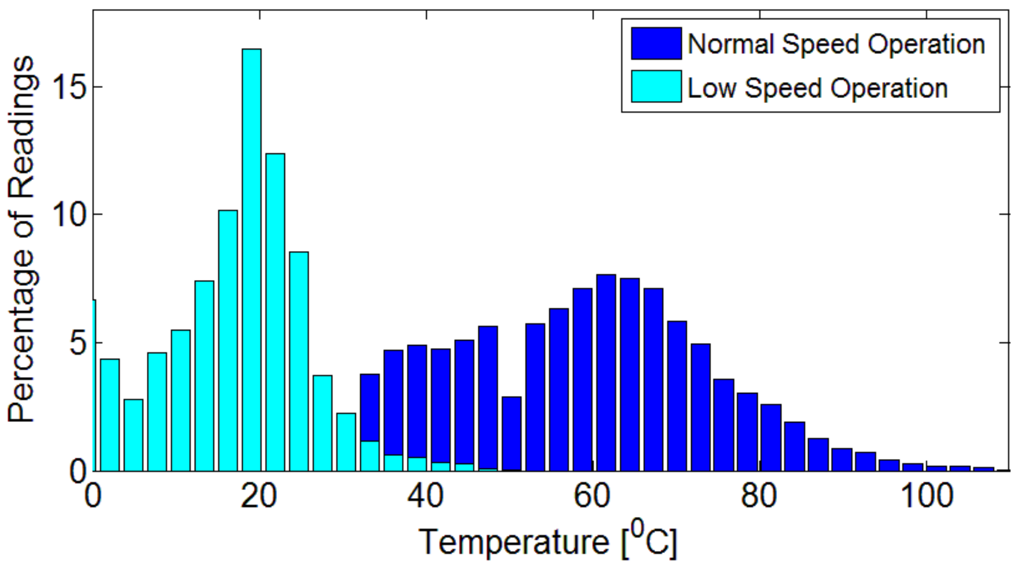

Figure 18: Overall temperature comparison for the two ongoing field tests (two tank-car low speed operation, and ten-wagon fleet normal speed operation)

6 Conclusions and recommendations

This paper presents a statistical analysis of data acquired from three distinctly different field tests in which wireless sensor nodes (WSNs) were employed to monitor bearing temperatures as part of an onboard bearing condition monitoring system. One year worth of data was collected for each of the three field tests beginning with the SCT Logistics field test carried out in Australia [8]. Data from this initial field test was used to develop a bearing health monitoring algorithm consisting of three levels and several criteria within each level, as outlined in Table 1. Specific threshold values were carefully selected to go with the devised criteria based on the data analysis performed on the SCT Logistics field test. Using the SCT Logistics as a benchmark, two more field tests (still ongoing) were carried out with two main goals in mind: (1) to investigate the effects of several implemented WSN policies, aimed at prolonging the battery life, on the devised bearing condition monitoring algorithm, and (2) validate and optimize the developed algorithm for use in a wide range of field service operating conditions. The statistical analysis provided here suggests that both objectives were met as the criteria and thresholds previously established seem to hold true, in general, regardless of the measures implemented to conserve WSN and CMU battery life.

While the first two criteria, overall temperature and temperature above ambient, seem to be applicable for all field-tested operating conditions, a strong argument can be made to slightly modify the thresholds used in the remaining three criteria. The standard deviation (σ) Criteria 3 and 4 can benefit from increasing the threshold from 1σ to 1.25σ or 1.5σ to account for harsh service operating conditions. For the same reason, the rate of temperature increase Criteria 5 can be increased from 0.694^{o}C/min (1.25^{o}F/min) to 0.944^{o}C/min (1.7^{o}F/min). The suggested new thresholds make the developed algorithm applicable to a wider range of service operating conditions while reducing the number of preventable triggered alarms and signifying, with greater certainty, that bearings which are flagged for violating these new thresholds are problematic requiring attention.

Another important finding of this study is the determination of the minimum WSN reporting requirements for a meaningful evaluation and assessment of bearing health. The minimum requirements are: (1) number of acquired data points should not be less than 4000 per wagon, (2) number of WSNs reporting should not be less than 5 nodes per wagon, (3) ambient temperature should be available at all times, and (4) sampling frequency should not be less than one sample every four minutes. Not meeting one or more of the four aforementioned requirements will undermine the reliability of the performed analysis and might limit or eliminate some of the criteria. For example, reducing the data acquisition frequency to once every 15 minutes will make it very difficult to acquire enough consecutive temperature points in which the wagon is accelerating; thus, rendering the rate of temperature increase (Criteria 5) impossible to determine. Similarly, if the ambient temperature is not available, the temperature above ambient (Criteria 2) cannot be calculated. On the contrary, higher reporting frequencies will result in a more reliable and meaningful assessment of bearing health in a much shorter time period at the expense of WSN and CMU battery life.

Finally, it should be clear from this statistical analysis that the developed algorithm (Table 1) used in conjunction with the WSNs and CMUs provides a validated on-board bearing condition monitoring system. The suggested thresholds for the five criteria are based on data collected from three distinctly different field tests, and appear to be applicable for general use. However, it is ultimately left to the end-user to establish appropriate thresholds that are in line with their specific service operating conditions. It is estimated that the measures taken to prolong WSN and CMU battery life will result in an increase in the battery life from 2-3 years to 4-5 years depending on the reporting frequency, cell-phone coverage reliability, and environmental factors. Caution must be exercised when making decisions involving railway safety as it is ill-advised to reduce the reporting frequency for wagon fleets operating in harsh service conditions for the sake of saving on battery consumption.

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