TECHNOLOGY DIGEST
TD-17-034
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TIMELY TECHNOLOGY TRANSFER

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Spacing Study of Hot Bearing Detectors

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Summary

Transportation Technology Center, Inc. (TTCI) and University of Illinois at Urbana-Champaign (UIUC) conducted research using modeling and simulation to determine the optimal spacing between hot bearing detectors (HBD) based on relevant test data of HBD systems currently in place. For this simulation study, the collected HBD sensor readings from revenue service were used to simulate potential HBD spacing to alert potential bearing failures. Tradeoffs between the cost of sensor deployment and penalty of low prediction accuracy (potential hazards) were systematically studied to determine the best sensor deployment spacing. The simulation study showed there is no statistical difference between the detection rates at 7.5 miles to 15 miles, making 15 miles the ideal for sensor spacing. For greater than 15-mile spacing, there is a reduction in the detection rate for the HBD system.

The current spacing distance between revenue service HBD has at least a 99.5 percent (99.39% to 99.62%, 95% CI) successful detection rate. This detection rate is based on 14,069 bearings with Why Made Code 50 removals versus 68 Federal Railroad Administration (FRA) reported derailments.

To determine if decreasing spacing between sensors would prevent bearing failures, the researchers reviewed the failures that actually occurred and were not detected by the current sensor network. A summary of a subset of 27 of the FRA reported bearing journal burn off incidents from 2012 to 2016 showed the median distance to derailment from the previous HBD is 9.2 miles. These incidents were those that could be located on track charts and had detectors mapped on those track charts. A simplified assumption would be to state that if the distance between detectors were less than 9.2 miles, then 50 percent of these incidents would have been avoided. However, as the simulation demonstrated, there is no statistical advantage in a sensor spacing of 9.2 miles as compared to 15 miles.

This work was conducted as part of an ongoing Association of American Railroads' Strategic Research Initiative to evaluate the root causes of in-service bearing failures.

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INTRODUCTION

TTCI and UIUC conducted a study to determine the optimal spacing of hot bearing detectors (HBD) to alert potential bearing failures. The bearings of railcar wheels are among the most important components on a train to ensure safe operations. Railway companies have deployed and managed wayside HBD to monitor the state of bearings on rolling stock. A better understanding of the proper spacing or locations is needed to ensure optimum performance for reporting potential bearing failures. Due to the difficulty of testing such conditions in a live environment, this research approach used modeling and simulation based on relevant test data of HBD systems currently in place. Tradeoffs between the cost of sensor deployment and penalty of low prediction accuracy (potential hazards) were systematically studied, from which the best sensor deployment spacing was more easily determined.

CURRENT STATE OF HBD

According to Car Repair Billing (CRB) records from January 2012 to November 2016, there were 14,069 bearings replaced for Why Made Code 50 (Overheated Roller Bearings such as an absolute temperature of 200 degrees F on the surface of the cup as measured using an Association of American Railroads (AAR) approved handheld device, a temperature measured by a wayside HBD at least 170 degrees F above the ambient temperature, or a temperature measured by a wayside HBD at least 95 degrees F above the temperature of the mate bearing on the same axle.) This does not include bearings replaced for other reasons detected by wayside bearing detectors (K-value rules, composite rules, trending algorithms, or acoustic bearing detector technology), or bearing replaced that were not reported to CRB (e.g., railroads repairing their own equipment). In the same timeframe there were 68 FRA reported incidents for journal bearing burn offs. This equates to at least a 99.5 percent (99.39% - 99.62%, 95% confidence interval) successful detection rate for the HBD system at the current spacing distance between detectors.

SPACING SIMULATION DATA

Revenue service bearing readings from a single railroad were used to develop the simulation study. These 255,088 raw bearing readings were sorted and processed into 37,604 distinct bearing record series, each corresponding to a unique bearing; each bearing had a varying number of records (from 1 to about 50 detector passes). The bearings were first categorized into two groups:

- Group 1: 37,579 non-alerting bearings
- Group 2: 25 alerted bearings

The distance between existing wayside systems was incorporated between any pair of observation sites into the dataset, and the result was a set of distances versus temperatures. The AAR rules,[1,2] used to alert trains of imminent bearing failures are as follows:

> **Alarm rule #1**: Alarm is triggered if Bearing Reading >A, where Bearing Reading is the bearing temperature above ambient temperature, and threshold A = 170°F.
>
> **Alarm rule #2**: Alarm is triggered if Bearing Reading > 95°F + reading of mate bearing, where mate bearing is the bearing on the same axle.

MODELING RESULTS

The actual observations (temperature) were used as input to generate temperatures at “virtual sensors” that have certain spacing. The observed temperature trajectory was fitted by piece-wise linear interpolation/ extrapolation to determine the simulated temperature at the virtual sensor sites.

For any sensor spacing, δ, it is assumed a random off-set of the sensor locations (where the first sensor lies). This is reasonable because the bearing temperature development has nothing to do with sensor locations. Virtual sensor readings are created at every δ miles, where virtual sensors would be. For each AAR stopping rule #i, where $i = 1, 2$, applied to bearing $n = 1, 2, …., N$, the length of the “alerting” part of the bearing temperature trajectory is identified (i.e., the range of the trajectory that certain threshold is exceeded), L_{in}, such that if one or more virtual sensors is present in the range of L_{in}, then an alarm would have been triggered for this bearing. If no sensor is present in the range L_{in}, then this bearing has missed detection. For a healthy bearing that will never violate the alarm rule, the value of $L_{in} = 0$. Intuitively, some smaller δ will have a higher success rate by the higher chance of passing a sensor near peak readings. The average detection rates (DR) are then computed for each δ. Figure 1 below illustrates an example for rule #1.

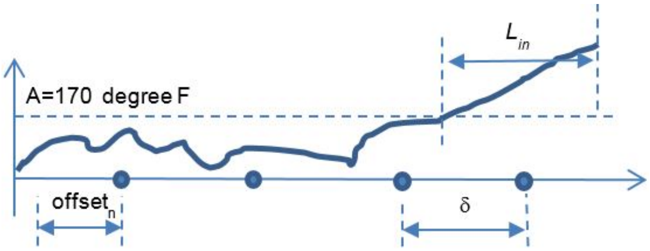

Figure 1. Illustration of Violation to Threshold-Based AAR Stopping Rule #1

For each rule #1, #2, when the offset is random, then for the given values of δ and L_{in}, the probability of having at least one virtual sensor in the range of length L_{in} is simply the following:

$$\Pr = \begin{cases} 100\%, & \text{if } L_{in} > \delta; \\ L_{in} / \delta, & \text{otherwise.} \end{cases}$$

Considering all bearings, the study formed a non-homogeneous binomial trial (with varying success probabilities) of size *N*. If L_{in} is sorted across *n* in an ascending order (including a lot of zeros for non-alerting bearings), i.e., $L_{i1} \le L_{i2} \le \ldots \le L_{iN}$, then the expected number of detections from a simulation study (i.e., summation of corresponding probabilities) based on rule #*i* would be a piece-wise smooth function as follows:

$$E[\text{detection}] = \begin{cases} 100\%, & \text{if } \delta \le L_{i1}; \\ \dfrac{1}{\delta}\sum_{n=1}^{k} L_{in} + N - k, & \text{if } L_{ik} < \delta \le L_{i(k+1)}, \forall k = 1, 2, \ldots, N-1; \\ \dfrac{1}{\delta}\sum_{n=1}^{N} L_{in}, & \text{if } \delta > L_{iN}. \end{cases}$$

Meanwhile, the variance of the number of detections, based on this Poisson binomial distribution from *N* trials and probabilities $\{\Pr_n\}$, can be computed as follows:

$$Var[\text{detection}] = \begin{cases} 0, & \text{if } \delta \le L_{i1}; \\ \dfrac{1}{\delta^2}\sum_{n=1}^{k} L_{in}(\delta - L_{in}), & \text{if } L_{ik} < \delta \le L_{i(k+1)}, \forall k = 1, 2, \ldots, N-1; \\ \dfrac{1}{\delta^2}\sum_{n=1}^{N} L_{in}(\delta - L_{in}), & \text{if } \delta > L_{iN}. \end{cases}$$

The value E (detection) decreases with δ. Dividing the above detection number by the number of defected bearings N_d, where $N_d < N$, then the expected detection rate (DR) as a function of δ is,

$$DR(\delta) = \begin{cases} 1/N_d, & \text{if } \delta \le L_{i1}; \\ \dfrac{1}{N_d\delta}\sum_{n=1}^{k} L_{in} + 1 - k/N_d, & \text{if } L_{ik} < \delta \le L_{i(k+1)}, \forall k = 1, 2, \ldots, N-1; \\ \dfrac{1}{N_d\delta}\sum_{n=1}^{N} L_{in}, & \text{if } \delta > L_{iN}. \end{cases}$$

This function is used to determine the detection rate at each sensor spacing, δ.

Assuming the total alarms are approximately normal (based on the Central Limit Theory), the 95 percent confidence interval for the detection rate (i.e., expectation plus or minus 2 standard deviations) is obtained as follows:

$$\left(DR(\delta) - \frac{2}{N_d}\sqrt{Var[\text{detection}]},\ DR(\delta) + \frac{2}{N_d}\sqrt{Var[\text{detection}]} \right).$$

The DR(δ) function provides a detection rate at each sensor spacing as shown in Figure 2.

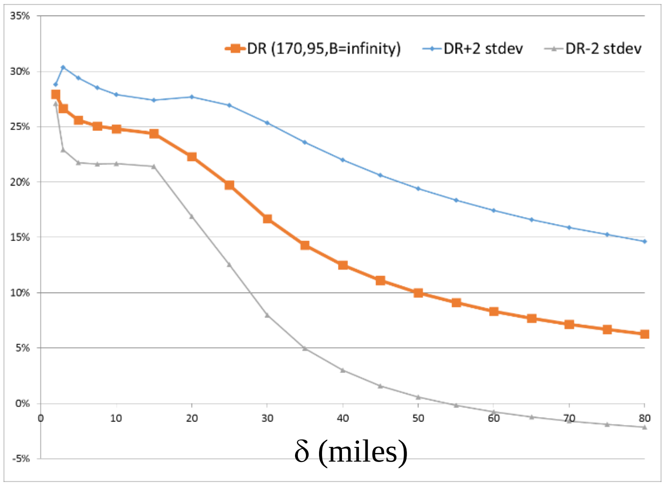

Figure 2. Detection Rate versus Sensor Spacing under AAR Rules

Figure 2 shows that the detection rates have a kneeling point around δ = 15 miles. Statistically, the null hypothesis of no difference between the detection rates at 7.5 miles to 15 miles failed to be rejected, making 15 miles the ideal for sensor spacing. There is a statistical difference between the detection rates at 15 miles and at 20 miles (24 percent and 22 percent).

The detection rate shown in this simulation is not the rate of alerting a defective bearing in revenue service. The simulation assumes that the alerting bearing readings in the dataset immediately precede a failure. In reality, a warm bearing may travel much further than the simulated distance before failure. Thus, the actual estimated detection rate of revenue service is enumerated above at 99.5 percent. The simulation attempts to discover if a different spacing optimizes detection based on current revenue sensor spacing.

To determine if decreasing spacing between sensors would prevent bearing failures, the failures that actually occurred and were not detected by the current sensor network were reviewed. Table 1 summarizes the findings of the distances from the last HBD detector to the next detector for a subset of 27 of the FRA reported bearing journal burn off incidents from 2012 to 2016. These incidents were those that could be located in track charts and had detectors mapped on those track charts.

Table 1. Miles from Last Detector and to Next Detector of Derailments

Incident	Distance to Derailment (miles)	Distance to Next Detector	Distance Between Detectors
1	55.92	11.20	67.12
2	13.20	0.10	13.30
3	2.20	69.70	71.90
4	1.80	15.21	17.01
5	11.73	1.00	12.73
6	11.33	2.10	13.43
7	21.90	6.57	28.47
8	4.61	15.48	20.09
9	10.75	20.05	30.80
10	22.10	5.30	27.40
11	3.71	10.65	14.36
12	3.00	14.48	17.48
13	2.95	11.40	14.35
14	33.50	3.20	36.70
15	8.63	20.31	28.94
16	12.26	1.70	13.96
17	9.20	4.00	13.20
18	2.17	8.00	10.17
19	1.70	16.80	18.50
20	13.60	1.75	15.35
21	12.82	0.88	13.70
22	9.12	2.10	11.20
23	3.10	7.80	10.90
24	1.05	29.57	30.62
25	6.00	9.40	15.40
26	15.23	10.52	25.75
27	14.20	0.36	14.56
Mean	11.40	11.10	22.50
Median	9.20	8.00	15.40

The median distance to derailment from the previous HBD system is 9.2 miles. A simplified assumption would be to state that if the distance between detectors were less than 9.2 miles, then 50 percent of these incidents would have been avoided. However, as the simulation demonstrates, there is no statistical advantage in a sensor spacing of 9.2 miles as compared to 15 miles. In the sample, half of the detectors have a closer spacing than 15.4 miles.

Only 5 of the 27 mapped burn offs (18.5 percent) occurred at a distance over 15 miles from the last detector. If the maximum detector spacing was 15 miles, the estimated success rate of the system would be 99.6 percent (99.51% to 99.71%, 95% confidence interval), based on the proportion for all 68 FRA reported burn offs. However, the difference is not statistically significantly different than the current HBD spacing. Therefore, the hypothesis cannot be rejected that there is no difference in the success rate if the maximum sensor spacing was 15 miles apart.

CONCLUSION

The results of this modeling and simulation study show that overly dense deployment of HBD sensors may not lead to significant increase in the prediction performance. Statistically, there is no difference between the detection rates at 7.5 miles to 15 miles, making 15 miles the ideal range for sensor spacing.

NEXT STEPS

A spacing study using multiple-beam technology is planned on the High Tonnage Loop track at the Facility for Accelerated Service Testing at the Transportation Technology Center.

ACKNOWLEDGEMENT

TTCI thanks Canadian Pacific for its support of this Strategic Research Initiative.

REFERENCES

1. Association of American Railroads. *Field Manual of the AAR Interchange Rules*, Rule 36 – Roller Bearings, 2015, Washington, DC.
2. Association of American Railroads. *Manual of Standards and Recommended Practices*, Section F, Sensors, Standard S-6001 “Bearing Temperature Performance.” 2012, Washington, DC.