Proceedings of the Sixth International Conference on
Railway Technology: Research, Development and Maintenance
Edited by: J. Pombo
Civil-Comp Conferences, Volume 7, Paper 7.9
Civil-Comp Press, Edinburgh, United Kingdom, 2024
ISSN: 2753-3239, doi: 10.4203/ccc.7.7.9

On the Possibilities of Using Classical Hot-Box Detectors as Condition Monitoring Systems

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Abstract

The railway industry relies heavily on the efficient operation of its infrastructure to facilitate the transportation of goods and passengers over long distances. In the last decades, wayside monitoring systems have emerged as crucial tools for ensuring the safety, reliability, and optimal performance of railway vehicles. This article investigates the evolving role of wayside monitoring, particularly focusing on the utilization of hot-box and hot-wheel detectors for proactive maintenance strategies. Traditional approaches to hot-box monitoring have been reactive, primarily focusing on detecting critical states of vehicles. However, a shift towards predictive maintenance using these classical systems may still be feasible by analysing deeply the detector data and extracting insights into the condition of bearings. The methodology involves reorganizing and redefining HB/HW data to identify anomalies indicative of changes in bearing operation or condition. Moreover, by assessing the quality of detector data and implementing adaptive thresholding and anomaly detection algorithms, false alarms and false negatives can be minimized, enhancing the efficiency of maintenance operations, and improving the reliability of railway networks. Overall, this study investigates and highlights the potential of utilising classical wayside monitoring systems to improve railway maintenance practices and contributing to safer and more efficient railway operations.

Keywords: condition monitoring, hot-box detector, anomaly, axle-box bearing, bearing diagnosis, wayside monitoring.

1 Introduction

The railway industry plays a crucial role in facilitating the transportation of goods and people across vast distances. To ensure the safety, reliability and optimal performance of the railway network, wayside monitoring has emerged as an essential tool in the last decades. Wayside monitoring uses advanced technology and sensors placed along the train tracks to collect, analyse, and interpret data to extract information related to the health status of the trains.

Historically, wayside monitoring systems have been focusing on detecting critical states of the vehicles. These systems were traditionally designed in a reactive manner to examine the asset for compliance with respect to disturbances to the traffic as well as damage to the infrastructure. As a result, the wayside systems are usually detecting wagons in an already faulty stage, having implications on both railway capacity and probability of initiating damage on the railway infrastructure.

In recent decades, the adoption of wayside monitoring within the railway industry has gained in popularity. Improvements in sensor technology and newer systems have enabled the transition from a reactive approach towards a predictive approach for wagon maintenance [1]. However, even if the railway network is being densified and upgraded continuously with new detectors, most of the infrastructure network is composed of classical wayside systems. For instance, Hot-Box and Hot-Wheel detectors represent approximately 75% of the wayside monitoring detectors in Sweden in 2023.

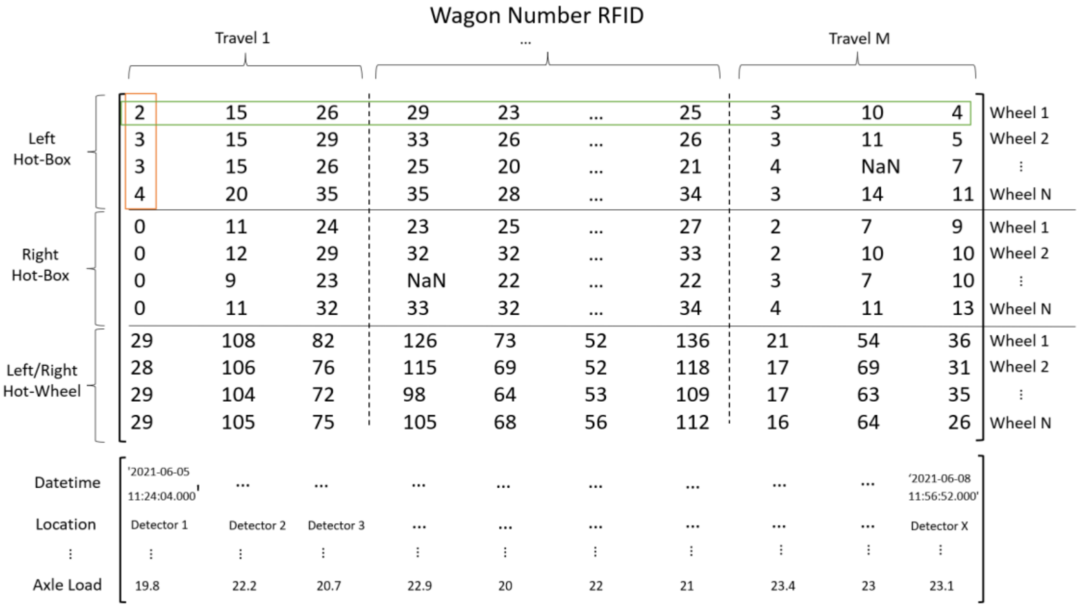
Hot-box detectors are the simplest method for identification of rolling stock axle-box breakdowns. They measure the body temperature of the axle using infrared (IR) scanners with one, two or several scanning points. A common way to estimate the health of axle-boxes is performed by examining if the bearing temperature exceeds predetermined fixed thresholds. The thresholding is divided in 2 or 3 alarm levels in terms of difference with the ambient temperature, difference with the left and ride side on the same axle and averaging of all bearing temperatures on the same train side [2]. Nevertheless, employing static thresholds across the entire network may lead to an increase in false alarms or false negatives, owing to potential variations among individual detectors. The differences observed among individual detectors may arise from a range of factors, including variations in the temperature measurement zone of the hot-box detector [3], calibration problems, and the detector's placement along the line [4]

A general concern in the field of bearing condition monitoring revolves around the utilization of Hot-Box Detectors (HBDs) primarily in a reactive manner [5]. These detectors identify faults in vehicles as they occur, aiming to prevent any subsequent damage. It is noteworthy that these vehicles can travel substantial distances with significant bearing defects, such as issues with the raceway, roller, cage, and more, without manifesting any temperature changes during this period. On one hand, a bearing can undergo rapid overheating, sometimes within just a few minutes, or in the worst-case scenario, a mere 96 seconds, all without triggering an alarm [6]. On the other hand, it might cool down as it slows down or comes to a stop, making it challenging for wayside detectors to observe the issue. Further analysis, aimed at optimizing the balance between sensor deployment costs and addressing reduced prediction accuracy revealed that there is not a significant statistical difference in placement intervals ranging from 12 to 24 km [7]. However, there is a noticeable decline in the detection rate for HBD systems with intervals exceeding 24 km.

Even though HBD possesses the above-mentioned drawbacks, the aim of this article is to investigate the possibilities of using HB/HW detectors data not only for safety reasons but also for extracting information related to the possible change of condition of the bearings. Instead of comparing the temperatures values with classical static threshold methods, a methodology to analyse the bearing temperatures is developed to improve the condition monitoring of the bearings based on the temperatures signature of wagon wheelsets over extended running periods. By re-organizing the data wagon-wise, it can be observed that anomalies in the time-series are regularly observed, which could be related to a change of operation of the bearing. To describe this concept, case studies from the freight industry in northern Sweden will be shown to illustrate the possible future applications of condition monitoring using the traditional HBD systems.

2 Methods

Classical hot-box detectors perform condition checks of the passing railway vehicles, giving information about the state of the bearings. However, when a train passes by a detector, the value of each bearing temperature is compared with predefined static thresholds. Depending on the level of this threshold, actions are specified to the driver to either stop the vehicle to a specified location or continue its route with a maximum allowable speed. Hence the HB systems are used more as inspection systems rather than condition monitoring systems.



Wagon Number RFID

	Travel 1			...				Travel M			
Left Hot-Box	2	15	26	29	23	...	25	3	10	4	Wheel 1
	3	15	29	33	26	...	26	3	11	5	Wheel 2
	3	15	26	25	20	...	21	4	NaN	7	⋮
	4	20	35	35	28	...	34	3	14	11	Wheel N
Right Hot-Box	0	11	24	23	25	...	27	2	7	9	Wheel 1
	0	12	29	32	32	...	33	2	10	10	Wheel 2
	0	9	23	NaN	22	...	22	3	7	10	⋮
	0	11	32	33	32	...	34	4	11	13	Wheel N
Left/Right Hot-Wheel	29	108	82	126	73	52	136	21	54	36	Wheel 1
	28	106	76	115	69	52	118	17	69	31	Wheel 2
	29	104	72	98	64	53	109	17	63	35	⋮
	29	105	75	105	68	56	112	16	64	26	Wheel N
Datetime	'2021-06-05 11:24:04.000'	...	...	...	...	...	...	...	...	'2021-06-08 11:56:52.000'	
Location	Detector 1	Detector 2	Detector 3	...	...	...	...	...	...	Detector X	
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	
Axle Load	19.8	22.2	20.7	22.9	20	22	21	23.4	23	23.1	

Figure 1. Reorganization of the data as a matrix that contains the temperatures in the x-direction and the wheel number of the wagon in the y-direction.

Every time a train passes a detector, information about the temperature of the axle-boxes is given as well as, the train passage timestamp, the detector location, the RFID number for train identification and the axle number, and the general information regarding the train speed and length. In Sweden, the data is gathered from the Infrastructure Manager (Trafikverket) into a specific database called DPC that gathers all the information from all detectors from different manufacturers, such as Wheel Impact Load Detectors and Acoustic Bearing Monitoring systems.

To improve the usage of these systems and transition towards condition monitoring, the wayside data must be re-organized and re-defined to extract information related to the operation or condition of the bearings. The most natural way to re-organize the data is to split the data wagon-wise based on the wagon RFID number. The data from the HB/HW can be retrieved from the specific tag number and ordered with the timestamp. Moreover, each individual wheelset should be re-ordered from the first to last wheel to ensure following the correct axle, since the direction of travel can change or be reversed depending on the train direction. Hence, for each wagon, a matrix of the bearing and wheel temperature is created as function of the detector passage in the x-axis and the wheel number of the y-axis (see Figure *1*). When passing through a hot-box detector on a specific route, there is no information about the axle-load acting on each axle. This information can be retrieved instead from the Wheel Load Impact detectors along the route and combined with the Hot-box detectors to study the influence of the axle load on the temperature reading. However, this information has not been merged in the current study, even though it is a parameter of interest.

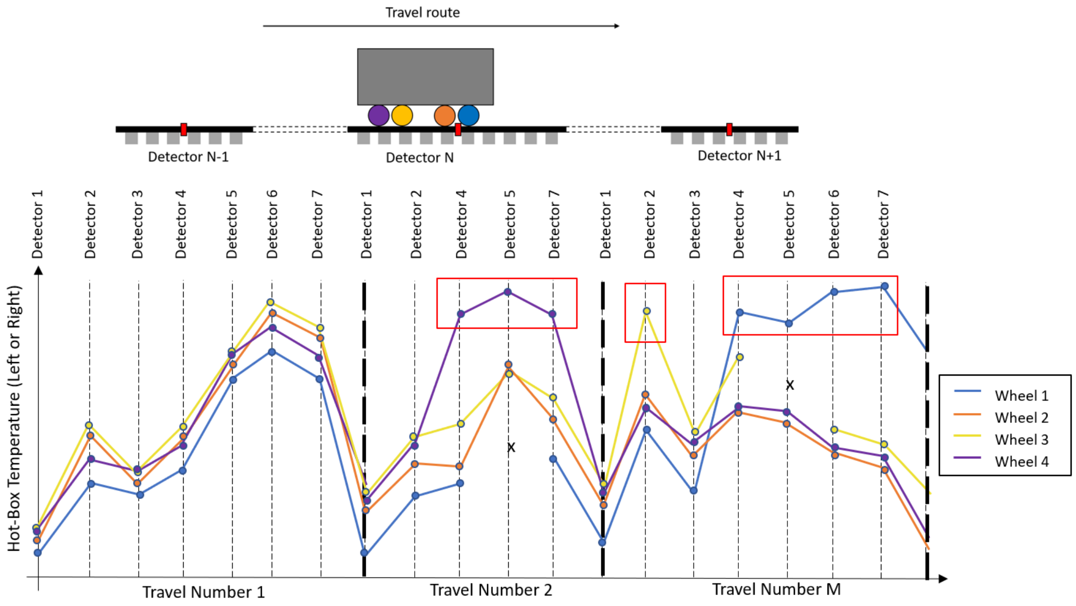


Figure 2. Visualization of the data split in time signatures as function of the travel number.

To visualize the matrices from the HB detectors, a conceptual plot from the wheel temperatures from each axle as function of time (or detector passage) and sub-divided in travel numbers is displayed in Figure *2*. To observe anomalies related to the condition of the bearings, it can be assumed that the time-signatures of each wagon wheel will follow the same behaviour under normal operating condition, which will serve as the main hypothesis.

The concept of time-signatures from the conceptual case in Figure *2* is described further below. The bearing temperatures are being recorded at different locations for a specific train route, i.e. from Detector 1 (D1) to Detector 7 (D7) in this example. For travel number 1, the wheel signatures from wheel 1 to wheel 4 will follow the same trend under normal operating conditions. During that trip, the change of temperature values between the detector can be due to different factors such as the spread of the detector under normal operating conditions or the detector position along the line. For travel number 2, it can be observed that wheel 1 and wheel 3 have a similar behaviour while wheel 4 shows an increase (or gradient) of temperature at D4, D5 and D7, in comparison to the other wheels on the same side. Hence this behaviour may be flagged as an anomaly and recorded as a suspicious event in comparison to the other wheels on the same side. The comparison can also be performed with the corresponding wheels from the other wagon side to investigate if the anomaly is related to one wheel alone or the axle itself. Moreover, in case of real data from wayside systems, it is relatively common to have some missing values from the detectors as was observed for wheel 1 during travel number 2. These missing data points will also have to be handled before performing anomaly detection on the time signals. For travel number 3, the signatures of the wheels 2, 3 and 4 have a similar behaviour, except for wheel 3 that displays a larger spread but with a similar signature. On the contrary, wheel 1 displays a strong change of behaviour starting from D4 to D7 where the temperatures increase, where the signature shape does not match with the other wheels that display a decreasing pattern. This behaviour should also be flagged as anomaly and recorded as suspicious operation.

In general, anomalies in univariate time-series can be identified as global anomalies, contextual anomalies, collective anomalies, and trending anomalies (Figure 3). Even though some of these anomaly types can be present in the HB data, the anomalies of the behaviour of the wheel signatures can be observed relatively easily by its change in mean, gradient and signature correlation in comparison to the other wheels on the same or opposite side, and not only by checking anomalies from a univariate time-series perspective.

To summarize, it is expected to visualise and extract the following information from the real case data from time-signatures:

- Anomalies related to a specific bearing can indicate a change in lubrication quality, loading or external influence (wheel defects, hot-wheels radiation...).

- Global anomalies for all wheels on the same axle that could indicate a detector malfunction.

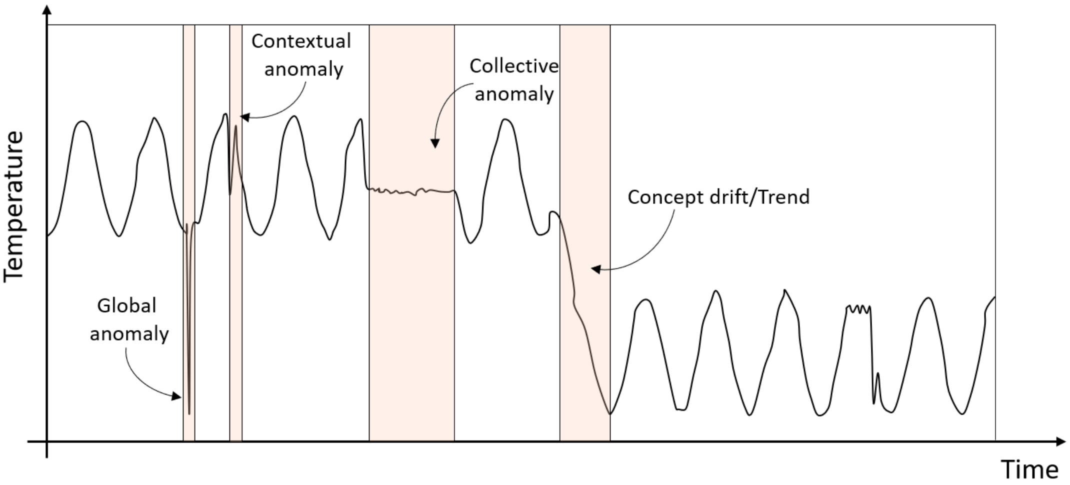


Figure 3. Anomaly types for univariate time series.

One issue that can affect the algorithms related to the anomaly detection of the bearings is the quality of the data recorded from the monitoring systems. In Sweden, 3 types of HB/HW detectors are used: the SERVO-SATT system, the FUES-EPOS and the PHOENIX MDS HB/HW. As a result, the data between the different detectors can vary in terms of mean and spread, due to certain properties of HB/HW system such as the number of beams of the IR measurements, the position of the measurement on the axle-box and calibration standards as mentioned earlier. By looking at the data as function of the wheel position, it would be clearer to assess the quality of the detector data from a passing wagon. As observed in Figure 4, when passing through the first detector D1 during the travel number 1, the sensor will read a temperature for the hot-box of each wheel and create a 4-point signature (or more if it is a 6-axle wagon, for instance locomotives). When the wagon continues its route during the first day, it will pass through detector 2 to 6 as well. It can be observed that D2, D5 and D6 have a similar signature with the same standard deviation but a different mean value. D4 has as well a comparable signature, except for the axle 3 which shows a greater increase in temperature relatively to the other axles. The signature of D1 has a low mean value and standard deviation which can be related to its first position along the line, meaning that the bearings have not reached their full operating temperature at that position. As a result, the correlation of the signature of detector D1 will be lower in comparison to the other detectors due to these low temperature readings. Even detector D3 had similar temperatures readings in terms of mean value and spread and it is observed that the signature is distinct in comparison to the other, with an increase of temperature in axle 2. This could indicate that an anomaly is present due to the change of behaviour of this wheel, or that the detector is behaving abnormally during this day, resulting as well in a lower correlation factor in comparison with the other detectors, indicating that the detector is not reliable during that travel day.

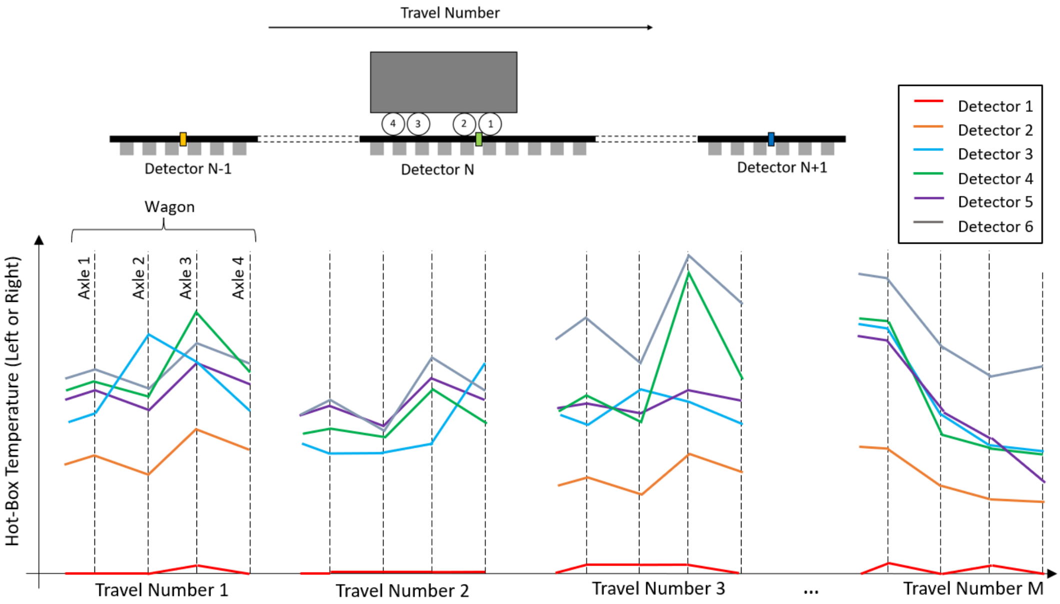


Figure 4. Visualization of the data split in wagon signatures as function of the travel number.

During the travel number 2, it can still be observed that D1 has low level values, due to its early position on the line. As for travel number 1, D2, D4 and D5 have a similar signature with close mean values and spread. In that case, D3 has again a different signature due to the low and high value of axle 1 and 4 respectively, meaning that the anomaly is not related to the condition of the wheel but to the quality of the detector itself. Finally, D2 did not provide any value as the detector could have been deactivated due to maintenance or deactivated during that specific day. During travel 3, we can observe that D1 still continue to provide low values for the readings. It can be problematic as the occurrence of an increase of temperature at this position may not produce any alarm (within the current limits), resulting in a False Negative in the worst-case scenario. As a result, it may be beneficial to introduce alarms that take in account the variation of the detectors with the current properties of their distribution, i.e. by tracking the evolution of the mean value of the detector over time and adapting the limits accordingly. During that day, D2, D3 and D6 still behave in a similar manner but with greater difference in terms of mean value and spread. D4 has as well a similar signature excepted for the large increase of temperature of axle 3 as for travel number 1. Even though this temperature is below the alarm’s limits for warnings and safety, it should be flagged as an anomaly which indicates a change of operating condition of the bearing. By tracking down the anomalies of specific wheels and accumulating the anomaly scores, a warning can be sent to the operator specifying that a closer look to the bearing should be performed in the next maintenance schedule of the operator. Finally, during travel number 4, the overall signature of the wagon is different in comparison to the previous days. This could be described as a change of operating condition such as uneven loading conditions. Excepted for D1, most signatures have the same behaviour with similar spread, but different mean values as observed the other days.

To summarize the different cases by looking at the wagon signatures, the following information can be drawn:

- Quality and reliability of the reading of a detector based on the mean, standard deviation, and correlations of the signatures between detectors. A lower value of the correlation of specific detector would indicate that the detector is not reliable, while a change of mean could lead to false alarms.
- Identify anomalies of the signature based on the signatures from the previous travels. It could be information related about the change of loading condition or any unknown event.

To illustrate the concepts of time and wagon signatures, the next section will show examples of real train data.

3 Results

The concept of train and wagon signatures will be investigated for a specific case study applied to freight wagons to the northern part of Sweden (Figure 5). The freight trains that pass this specific line are usually composed of 2 locomotives followed by several loaded or unloaded 4-axle bogies side dumpers with a maximum axle-load of 25 kN. During its route, the train passes through a maximum of 9 HB/HW detectors of type FUES-EPOS I or FUES-EPOS II at the locations of Harrtäsk, Kilvo, Polcirkeln, Lakaträsk, Sandträsk, Ljuså, Degerbäcken, Koler and Jörn. In Figure 6, the time signatures of a 4 axle wagons are displayed from the North to South route for the left and ride side temperatures of the hot-box as well as the wheel temperatures on either the left or ride side (only one side is used for the hot-wheel detector).

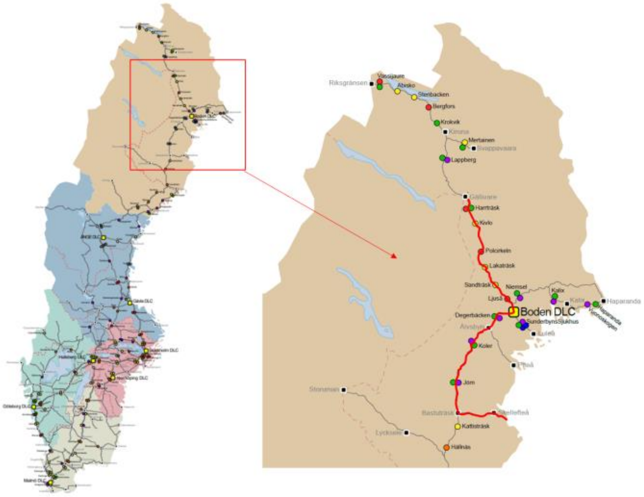


Figure 5.Overview of the detector map of wayside monitoring systems installed in the northern part of Sweden. The red dots correspond to FUES I systems, the orange dots to FUES II systems.

3.1 Variation between detectors

As mentioned in the method section, the hypothesis of time-signatures of each wheel follows the same trend over all the detectors passages can be observed. The change of temperature for one trip can vary from 0°C in the beginning of the line up to 50°C, excepted on days 10 to 21 and day 74 where the temperature is around 60°C for the right side of the wagon. By looking at the wagon signatures in Figure *7*, it becomes clear that the peaks observed in Figure *6* for the right side of the axle during day 10 and 21 occur due to a deviation of the detector in terms of mean value of the wagon side only, before going back to normal in the next days. A similar behaviour happens for detector number 7, which also shows a deviation in terms of mean value of the signatures, but on both sides of the detector.

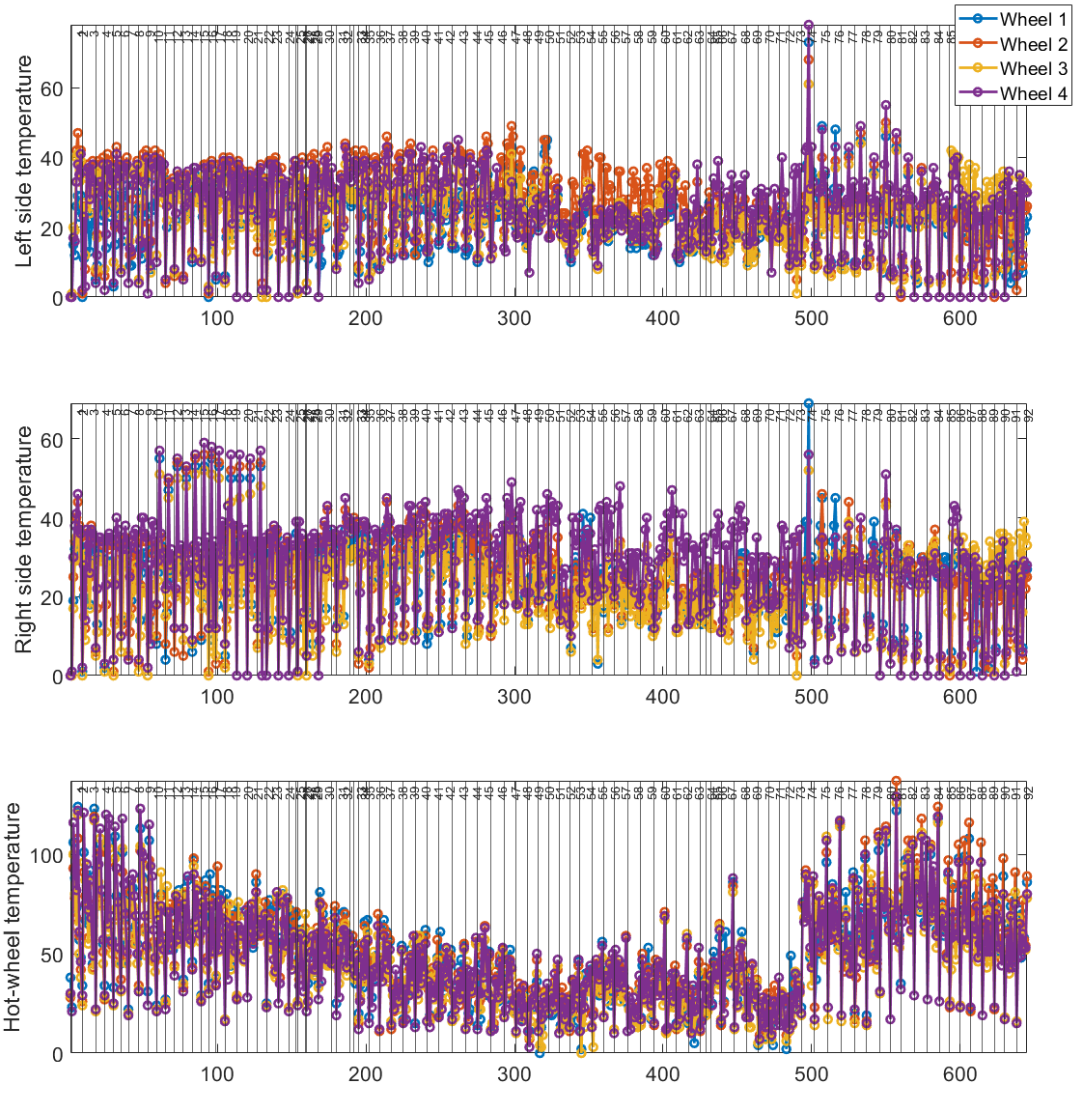


Figure 6. Overview of the data arranged in specific time-signatures for a specific wagon.

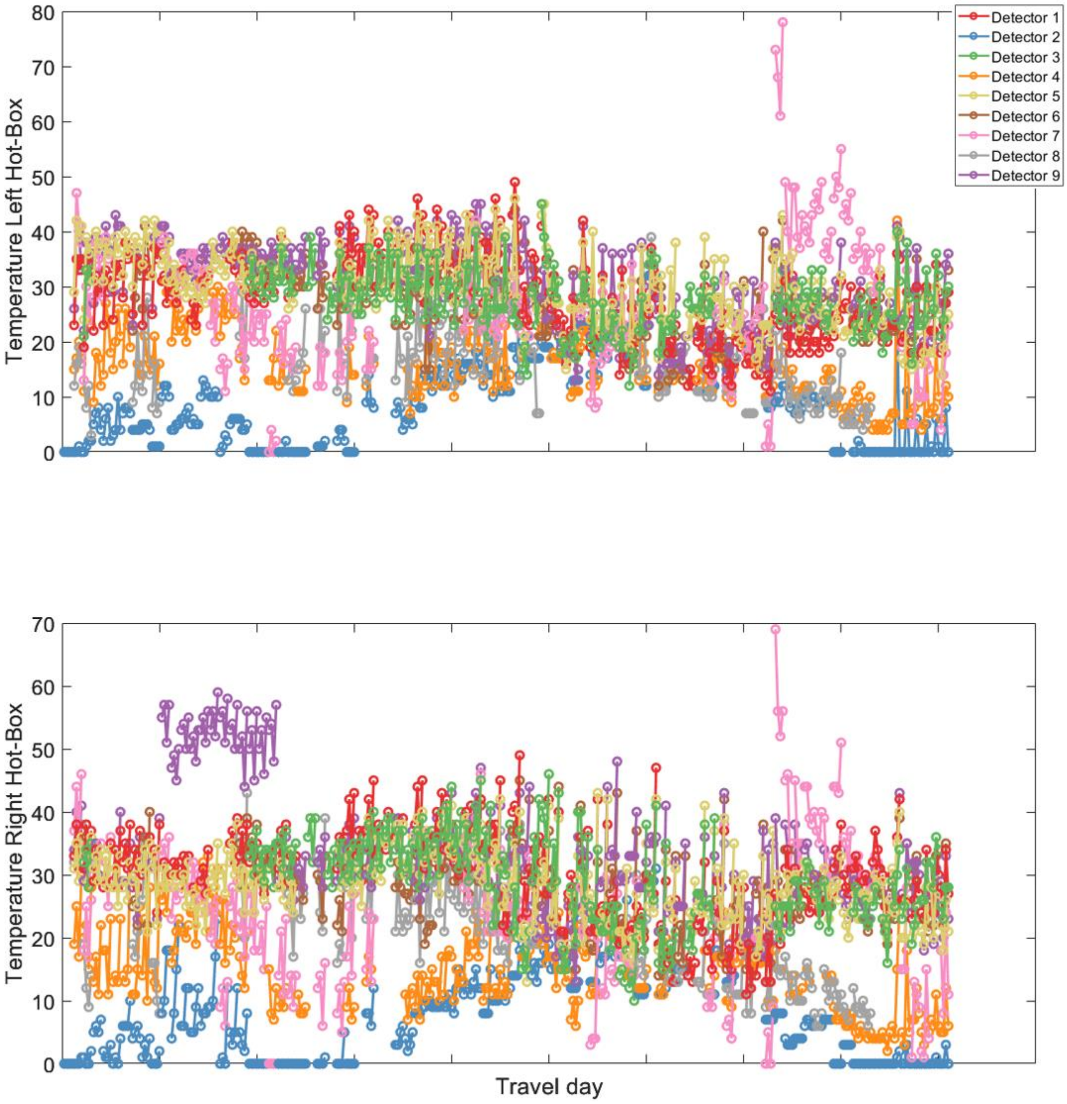


Figure 7. Visualization the hot-box wagon signatures for a specific wagon.

To evaluate the condition of the hot-box detectors, it could be more relevant to extract relevant features from the wagon-signatures. Hence, a simplified way to identify the variations of the detector quality can be performed by calculating the mean and spread of the signature for each detector over time for a specific wagon (or averaged on several wagons if possible), as well as the Pearson correlation between the signature between each wagon for each detector. The daily variation of mean, standard deviation and correlation coefficient from the wagon right side temperatures can be observed in Figure *8*. The deviations of detector 7 and 9 is clearly observed by the variation of the mean over several days. Another detector with an interesting behaviour is detector 2, that displays a lower mean value than all other detectors, but as well as a very low correlation value for most days. The low temperatures readings for detector 9 is probably due to its first position on the railway line, meaning that bearings have not reached their working temperature when passing by the first detector.

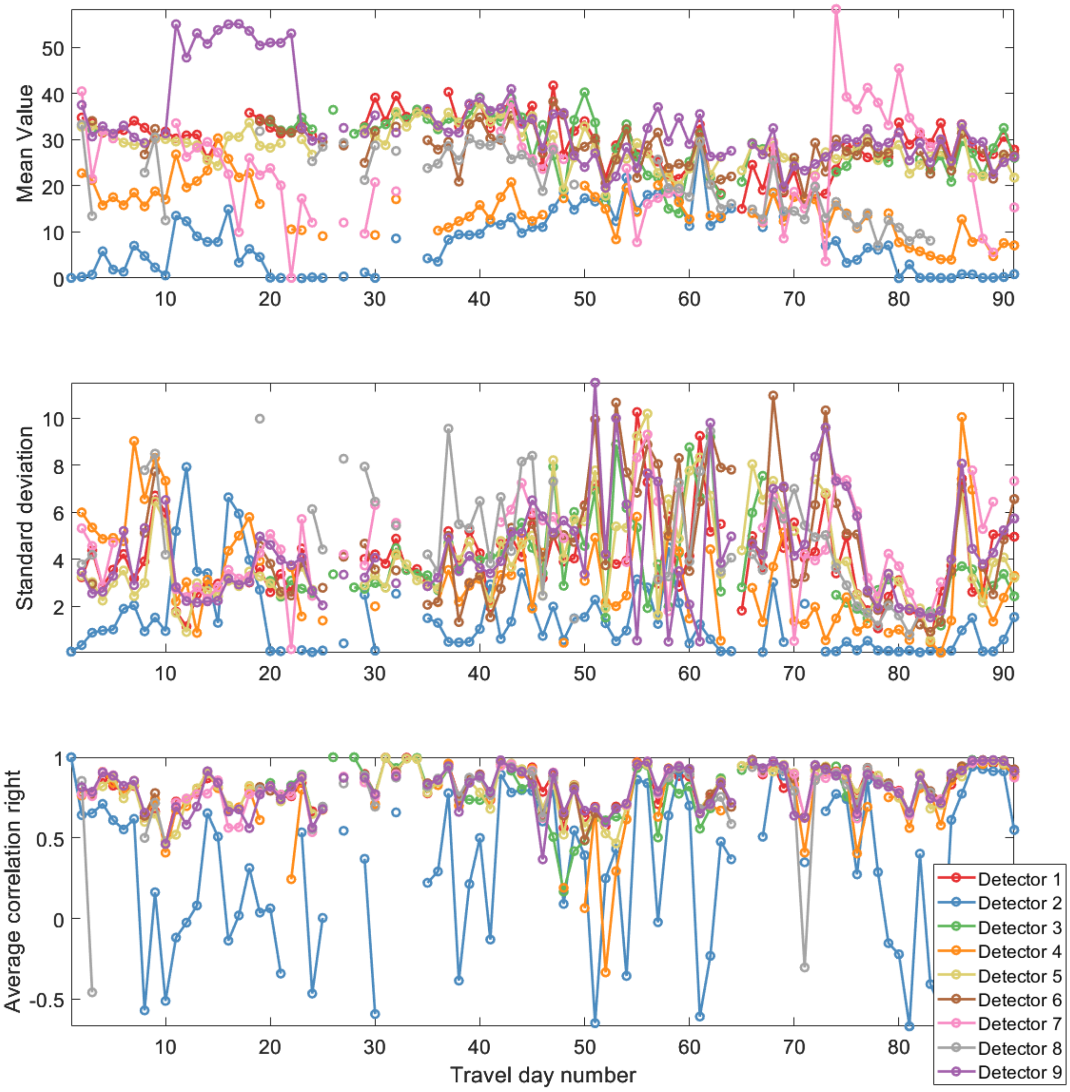


Figure 8. Visualization of the change of the mean value, standard deviation, and average correlation between the wagon right side signatures.

This variation of between the detectors is an important factor that can lead to false alarms or false negatives for detectors that tend to show a much lower trend. For instance, let us imagine that detector 2 displays a value of 55 degrees for the second wheel of the wagon, and detector 9 displays the same value for the same wheel during the same trip. If the data is compared statically with the warning limits of 80 degrees, none of the wagon will display an alarm when passing by the detector. However, the value of the detector 2 should be flagged since its value deviates from the normal values that this detector provides. By using a fixed limit for all detectors, defective axle-boxes may not be flagged by the current thresholding system due to the fixed alarm limits (which could be the case for detector 2). On the contrary, detector 9 may give rise to several false alarms since the temperatures give higher readings in the normal case scenario. Hence it may be necessary to infer adaptative thresholds for individual detectors based on their variation other time to avoid false alarms and false negatives from deviating detectors.

3.2 Axle-box anomalies investigation

For the operators, the main goal of using the time-signatures is to extract information related to the status of the bearings. Although it can be tedious to understand with what the change of behaviour is related to, finding anomalies in the time signatures could help optimize the maintenance actions by flagging suspicious bearings that start to deviate from their normal operating conditions on a long-term perspective. As seen in Figure *6*, all the signatures follow the same trend, but wheel 2 shows some deviation from the other wheels from day 46 to 61 approximately. To gain a bit more insight of all the anomaly types that can occur, some classical examples of anomalies observed in the same wagon type are displayed in Figure *9*:

- In case (a), there is a strong change of behaviour of wheel 3 and 4 in comparison to wheel 1 and 2 in terms of signature, maximum value and spread. This behaviour should be flagged as an obvious anomaly. However, after further investigation, it was observed that the Hot-wheel temperature displayed a strong increase from 50 to 250°C within 4 detector passages. Hence the wheel temperatures radiated from the wheels onto the axle-box, leading to a false anomaly (from the bearing perspective). This is a common issue with HW leaking on axle-boxes that could lead to false alarms.
- In case (b), wheel 1 shows a clear increase of temperature at the second and third passage but behaves normally afterwards. This is a type of anomaly that indicates a change of behaviour in the bearing which is not so common within the analysed data set.
- In case (c), the anomaly observed from wheel 1 is just an increase of the mean value over several days, but with the same signatures as for the other wheels. This is probably one of the most common anomalies observed in the test data.
- In case (d), the anomaly is similar to (c), but with a higher spread in the signature over the travel day. It is probably the second most occurring anomaly after type (c).

Except for case (a) where the anomaly has been related to the wheel temperature radiating on the hot-box, the reason of occurrence of the other anomalies is still unknown till this stage. Moreover, it is impossible to know what anomalies are more critical in comparison to others and if it can influence the remaining useful life of the bearing on the long term.

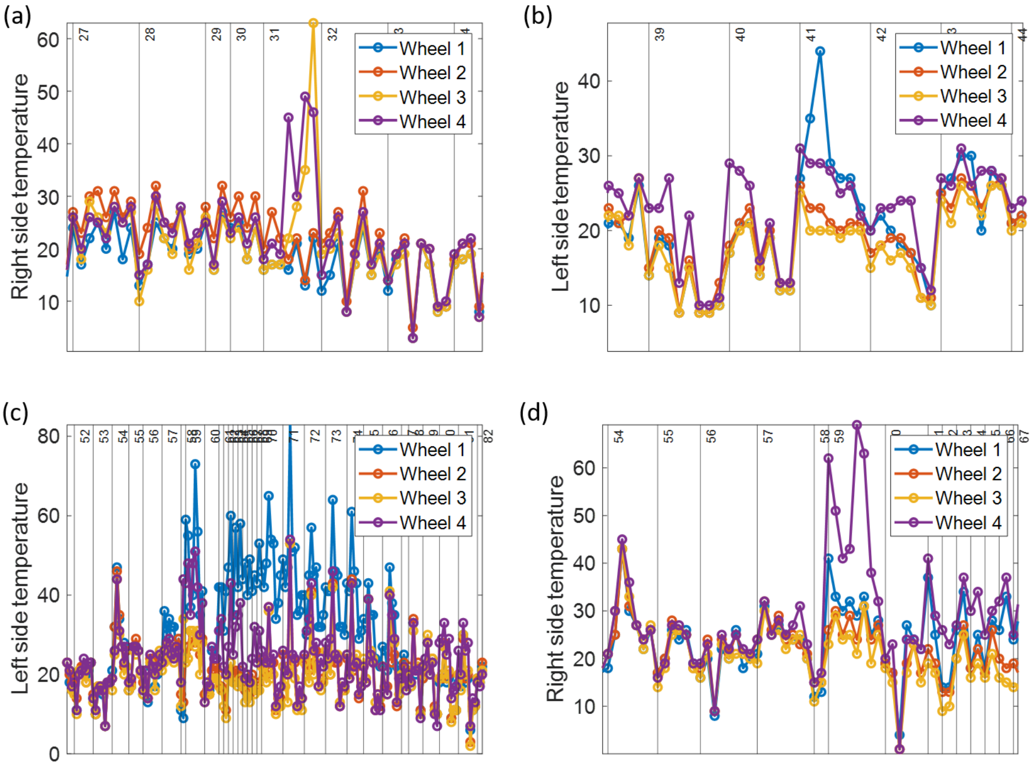


Figure 9. Example of anomalies that appear for the same wagon type.

Hence it could be relevant to explore further this concept and try to detect these anomalies in an automatic way, by using anomaly detections algorithms based on decision-rules, convolutional auto-encoders, or other suitable algorithms. To increase further the understanding of these anomalies, a better communication between the various stakeholders of the railways industry (e.g. operators and infrastructure manager, but also maintenance industries) to help labelling the data and understand the deviations in the operation of the bearings. On the long term, the hot-box detectors could help create a life status index of the bearings that will help the operators identify bearings of interests and perform appropriate maintenance actions when their behaviour starts to deviate, but still within the limits of the detectors alarm thresholds.

4 Conclusions and Contributions

The utilization of wayside monitoring systems in the railway industry has evolved significantly over the years, transitioning from reactive approaches towards more predictive maintenance strategies using new sensor technology. However, traditionally, these systems have focused on detecting critical states of vehicles, particularly through hot-box detectors (HBDs), which primarily serve as inspection systems rather than comprehensive condition monitoring tools.

This work has explored the potential of using data from hot-box and hot-wheel detectors not only for safety purposes but also for extracting valuable insights into the condition of bearings. By reorganizing and redefining the wayside data, it may become possible to analyse bearing temperatures over extended running periods, enabling the identification of anomalies indicative of changes in bearing operation or condition.

The methodology outlined in this study involves splitting the data wagon-wise, allowing for the detection of anomalies through the comparison of temperature signatures across different detectors and travel instances. By assessing the quality and reliability of detector data and identifying deviations in temperature signatures, it becomes feasible to enhance the efficiency of maintenance operations and mitigate risks associated with bearing failures. By considering variations between detectors and implementing adaptive thresholds based on historical data, false alarms and false negatives can be minimized, ensuring more effective fault detection and maintenance prioritization.

Acknowledgements

This project has received funding from the European Union’s Horizon Europe research and innovation programme under grant agreement No: 101102009.

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