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The Reliability of Hot Axle & Hot Wheel (HAHW) Detection

Data Analysis, Possible Main Factors, and possible solutions

Internship Report

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Summary

This report focuses on investigating the reliability of hotbox detection system and their measurement data in Dutch railway network. Then, to find the possible main factors which affect temperature result and give the solution correspondingly.
The reliability of hotbox detection system is accessed by using root cause analysis (e.g. FTA & FEMA) and data analysis method (e.g. R&R study and reliability analysis). Furthermore, some possible reasons can be assumed based on the analysis result. Finally, possible solutions will be given according to the possible reasons.

The analysis shows the HBD detection system has very good internal and external consistency in most of the time. However, abnormal data are generated in some case, most of the unreliability comes from repeatability. Based on this information, some possible main factors from parts variation, condition interference and alarm criteria setting have been found. And possible solutions are given correspondingly from three aspects.

Keywords: railway network, hot box detection, reliability, data consistency, FTA, FEMA, R&R

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1 Introduction

Between Friday 19 October 2007 and Sunday 5 October 2008, there were 12 occurrences when wheel-bearings failed on wagons traveling on express freight trains at various locations in the North and South Island. Seven of the 12 wheel-bearing failures resulted in the affected wagon derailing and causing a number of following wagons to also derail. The derailments caused extensive damage to the rolling stock, freight it was conveying and the rail network. On 2 occasions, molten metal from the failed wheel-bearings resulted in fires in trackside foliage and across adjacent land. The Commission determined that wheel-bearings were critical items, the failure of which had the potential to result in a derailment.

Luckily, the HBD system can reduce accident rate by monitoring bearing and wheel temperature and it has been located in 31 different sites throughout the Dutch railway network. Not only for the axle temperature but also for the wheel. Hence, the reliability of the HBD system is an important thing for safety.

This report focuses on investigating the reliability of hotbox detection system and their measurement data in Dutch railway network. Then, to find the possible main factor which affects temperature result and gives the possible solution correspondingly.

Firstly, the report begins with defining the problem in three aspects, failure, error and data reliability. Then, the working plan can be made by considering the required time and problems defined. Secondly, root cause analysis by using FTA and FEMA can be applied to investigate the reliability of the HBD system. Thirdly, data analysis method e.g. R&R study, accessing reliability and full factorial design are used to access data reliability. Next, based on these results, some possible factors contribute to abnormal detection results would be found and the possible solutions will be applied correspondingly.

2 Define Problems

The problem will be defined in this section before giving the general working plan. The Dutch railway network is equipped with a measurement system for measuring the temperature of axles and wheels by using multi-beam infrared sensors. The hotbox detection system can be illustrated by Figure1. Three main components comprise this system viz. the sensor (HBD/HWD) in a hollow sleeper (track equipment housing), trackside electronic components in a 19” rack and rail contacts (RC1, RC2, RC4) which are directly attached to the rails. The components are connected with each other with signal and power supply cables. The task of the system is to measure the temperatures of the axle bearings and brakes of trains running past and issue an alert to supervisory staff if the temperature exceeds the alert threshold values.[1][10]

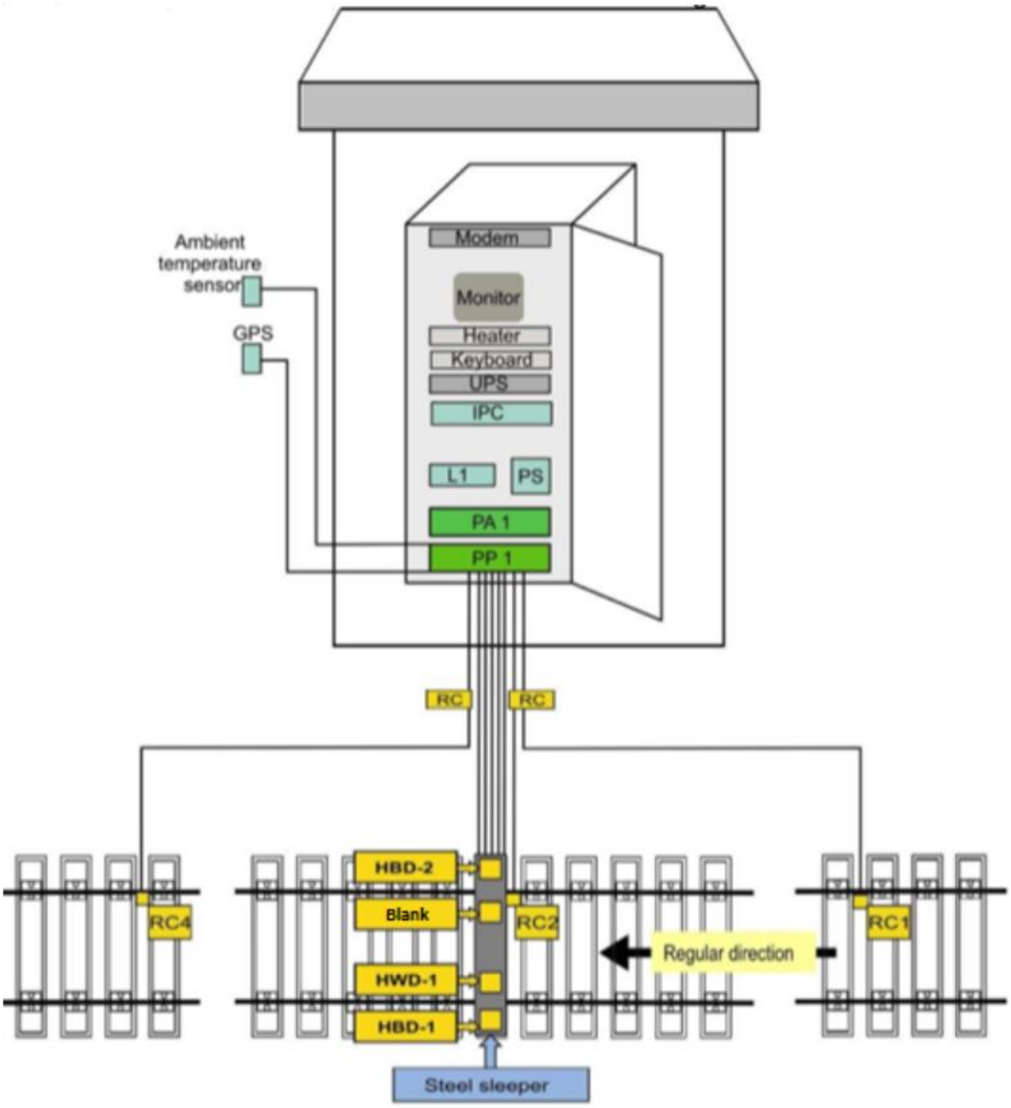


Figure1. Schematic diagram of a PHOENIX MB installation on a single-track line[10]

The temperatures of the axles on the left and right sides are measured while the temperature of the wheels is measured on one side. They are installed with a spacing of 80 kilometres along the entire length of freight corridors because an axle can develop into a 'hot axle' within 80 kilometres. There are 31 sites throughout the Dutch railway network. [1] In addition to reducing derailment risks, it also provides data to operators which can be used for prediction maintenance.

The reliability of hotbox would be high enough to achieve this goal in the way of the combination of failure, error and data reliability. However, it shows some unexpected failure and errors obey the Hot Box Dashboard 2018. The DB, Germany also advice ProRail to increase data reliability according to ir. Pieter Dings report[2]

Hence, the problem will be defined in the following 3 different sections.

2.1 Failure

The failure means losing functioning of a single component, subsystem or a whole system. It can be either hardware or software. with the help of the Hot Box Dashboard 2018, the failure is reported monthly. This can be illustrated clearer by Table1. It is the summarization of the Hot Box Dashboard 2018.

	Description		
Oct	The scanner had problems with Ref. heater.	Rail contactor 4 cable hit by the third party.	HWD1 scanner has not measured
Sep	Rail contactor 4 cable damaged	Rail contactor 4 connector melted	
Aug	RC cable has broken	TAG reader	RC 4 removed by BAM
Jul	TAG reader problem		
Jun	/	/	/
May	Rail contact 2 defective	Rail contact 2 fastening	contact 1 failure
Apr	External power failure	/	/
Mar	/	/	/
Feb	/	/	/
Jan	/	/	/

Table 1. Failure record from January to October 2018

This table shows failure description in month order and the scheduled replacement, maintenance and third party working without leading to failure have been removed. Some month have relatively high failure case while others show a quite perfect result. To category them into different component types. The proportion of specific failure out of total failure can be found as shown in Table 2.

Description	Percentage	Detail	Percentage
Reference heater	7.7%		
Rail contactor related	61.5%	Cable	37.5%
		Connector	12.5%
		Contactor	37.5%
		Fastening	12.5%
HWD scanner	7.7%		
TAG reader	15.4%		
External power failure	7.7%		

Table 2. Failure record from January to October in percentage

It can be noticed that contactor related failure is taking dominated proportion which equals 61.5% out of total failure from January to October. Furthermore, rail contactor related failure can be divided into four categories, Cable, Connector, contactor and fastening which contains all parts of rail contactor.

The second high dominate failure is TAG reader. The train information e.g. train identification number cannot be gathered properly if it is broken.

Reference heater and HWD scanner give the 7.7% of total failure respectively. These will lead to the infrared sensor lose accuracy or even cannot gain any temperature data.

One more thing deserves to see is external power failure also take 7.7%. these will lead to bot box detection system stop working after about 20min when the UPS exhausted[5].

Thanks to the remote monitoring and modular design, maintenance staff can fix the most problem by reset device or changing the module directly. But it still drops the availability and reliability apparently according to the hot box dashboard 2018.

2.2 Error

Besides failure information, the hot box dashboard 2018 also provides error information monthly. Error not means failure absolutely but imply some abnormal conditions has happened. From Table 3 the error has been summarized from January to October.

Rijlabels	Oct	Sep	Aug	Jul	Jun	May	Apr	Mar	Feb	Jan	Total	T/d
230V Supply Voltage Failure (0)	12	32	129	52	72	77	58	31	35	10	508	1.69
AEI-System offline (43)	8	16	485	670	226	219	704	356	508	50	3242	10.81
Ambient temperature too high (12)						3					3	0.01
Ambient temperature too low (6)						2			12	13	27	0.09
Axle values incomplete (02)	145	171	179	86	94	378	234	103	60	91	1541	5.14
Calibration timeout Scanner (55)						3	6		1	6	16	0.05
Calibration timeout SCT (50)			3								3	0.01
Calibration timeout SCT (50)						4	3			5	12	0.04
Channel amplification not OK (52)				1	1	4	2			3	11	0.04
Channel Factor not OK (54)	1		1	2		4	5			3	16	0.05
Channel measurement range not OK (53)					2	4	3			3	12	0.04
Cover Heating error (17)					2	8					10	0.03
Download Error (16)	3	2		5	2	4	4	2	5		27	0.09
FIFO timeout writing (33)	25	1		3	3	2	2	1	1		38	0.13
Invalid idle current on RC1 (17)	13	18	12	16	23	168	34	19	21	10	334	1.11
Invalid idle current on RC2 (18)	14	13	8	14	15	44	12	15	18	8	161	0.54
Invalid idle current on RC4 (20)	17	18	11	11	4	57	27	17	18	11	191	0.64
Link Card checksum error (36)	35	7		6	3	2	2	1	1		57	0.19
Link Card Length Error (31)	10	2	1	3	1	1					18	0.06
Link card offline (21)	9	4	1	7	9	22	13	5	20	7	97	0.32
Rack temperature too high (7)						128	6	2	23		159	0.53
Rack temperature too low (8)						107			5		112	0.37
RC Counter Error (5)	14	20	18	14	26	82	21	25	16	17	253	0.84
Reference heater temperature is too high (07)					1	4					5	0.02
Reference heater temperature is too low (06)	2					1					3	0.01
RefHeater Start Temp out of limits (28)	2			1	4	2	3		1		13	0.04
Scannertemp. too low (9)	1										1	0.00
Sensor offline (11)	35	19	3	34	32	66	47	21	40	21	318	1.06
Shutter closed during train run (04)	2	5	8	1	5	28	24	11	28	23	135	0.45
Shutter open without train run (03)	3		1	7	2				3		16	0.05
Station Offline	138	214	216	262	131	183	134	119	121	150	1668	5.56
Total amplification too high (24)					1	1	2				4	0.01
Total amplification too low (25)				1	2	3	1			6	13	0.04
UPS battery almost exhausted (1)	2	1		3	1		2	2	1		12	0.04
Warning RC1	11	73	79	17	41	216	77	79	31	4	628	2.09
Warning RC2	4	6		13	19	162	90	10	3	1	308	1.03
Warning RC4	5	32	50	3	21	252	176	27	20	18	604	2.01
Eindtotaal	511	654	1205	1232	743	2241	1692	846	992	460	10576	35.25
Times/day	17.03	21.80	40.17	41.07	24.77	74.70	56.40	28.20	33.07	15.33		

Table 3 . Error record from January to October

There are 10579 error records from January to October in 2018. This means more than 35 errors are generated every day and it could be noticed that some errors are high frequency happened e.g. AEI-System offline (43) and Station Offline; some are highly time-dependent e.g. Invalid idle current on RC1 (17) and RC Counter Error (5); some are having huge influence on the reliability e.g. Axle values incomplete (02) and Scanner temp. too low (9) or even can make the whole system broken down. e.g. 230V Supply Voltage Failure (0) and UPS battery almost exhausted (1).

Hence, error information also needs to be taken into consideration in the topic of hotbox system reliability.

2.3 Data Reliability

No matter the failure rate and error record show good result or not, the data reliability needs to be considered independently. Because the data can show inaccuracy or imprecision without failure and error. It can be noticed that some historical data show quite abnormal value or trend compare to others. This can be illustrated in Table 4 and Figure 1 to 4.

NO	Name	times of HWD	times of HAD	percentage of HWD	percentage of HAD
1	0	0	193	0	0.08%
2	lower than ambient with accuracy (HWD 3, HAD 1)	0	259	0	0.10%

Table 4. temperature equals to zero or below the ambient temperature, 5th-September 2018

Table 4 shows the abnormal temperature value in a percentage way. 5th Sep,2018 is a normal day without extreme weather and failure was reported in that day and the ambient temperature is 20 degree Celsius. Considered testing condition and sensor accuracy[5][7][8] the temperature give below 17 degree Celsius for HWD (19 degree Celsius for HAD) will be treated as abnormal. And zero temperature also need to be considered because 193 testing result shows 0 which is 0.08% of the total data gathered on that day. Another 259 data show below 19 but not zero which is 0.1%. Hence it can be found that there nearly 0.2% of data are abnormal.

All the abnormal data are found in the terms of HAD but nothing found in HWD. This is because HWD has a testing range from 80 to 650 degree Celsius which means it will show 80 for all the value below 80 degree Celsius. This leads to the low-temperature testing cannot be found in HWD data.

Figure 1 to 4 shows trend abnormal rather than the absolute value abnormal. It can be seen from Figure 1 which is a train typical axle temperature graph. X-axis from 1 to 16 means the axle number and Y-axis shows the testing temperature in left and right by using blue and orange respectively. It shows some fluctuation but has some similar trend more or less. However, there are still some curves show quite abnormal case. This can be seen from Figure 2, It's a HAD temperature graph gained from another train one same day and shows the temperature without fluctuations. This is almost impossible which means some problem happened that make the sensor give a series of the same output.

For the HWD part, Figure 3 can show a clear typical trend of wheel temperature change. This means every different wheel has different temperature and some of them might be high because of breaking. So, the peak should be seen in this case. However, as Figure 4 shows there are fewer fluctuations generated and only with several peaks. Others value shows as the same value.

Although the given case takes only a small portion of all data. But it seems still have some room to improve.

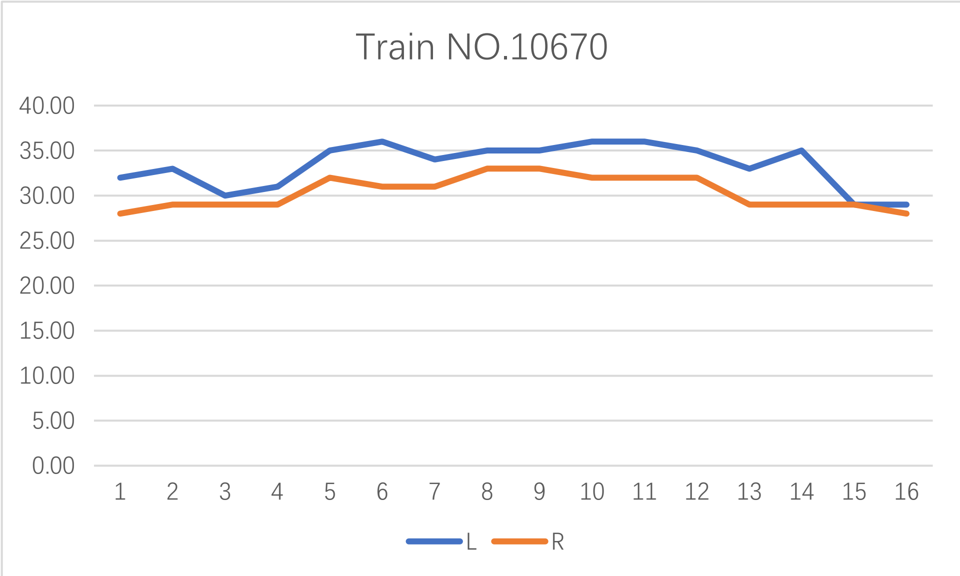


Figure 1. HAD detection result in the normal case, 5th Sep 2018

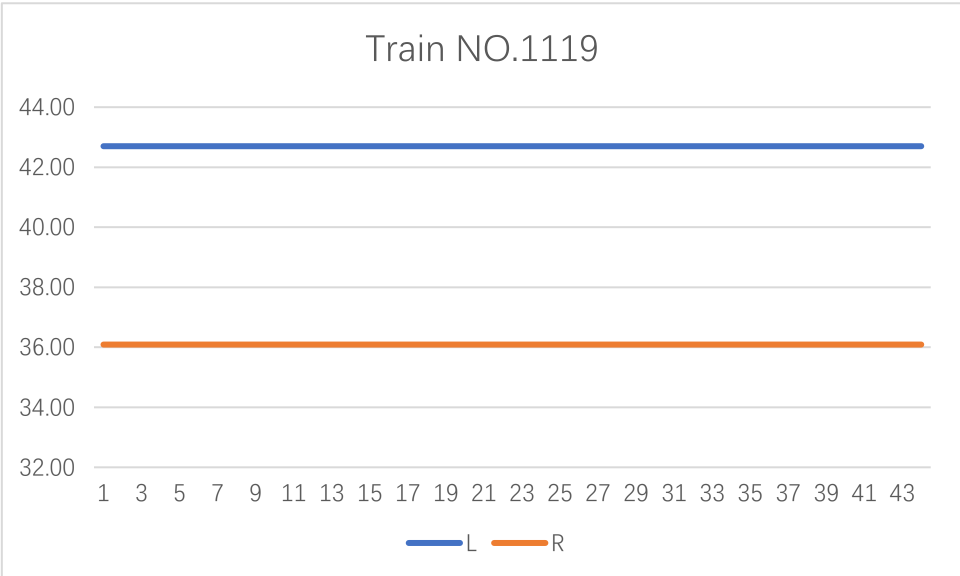


Figure 2. HAD detection result in the abnormal case, 5th Sep 2018

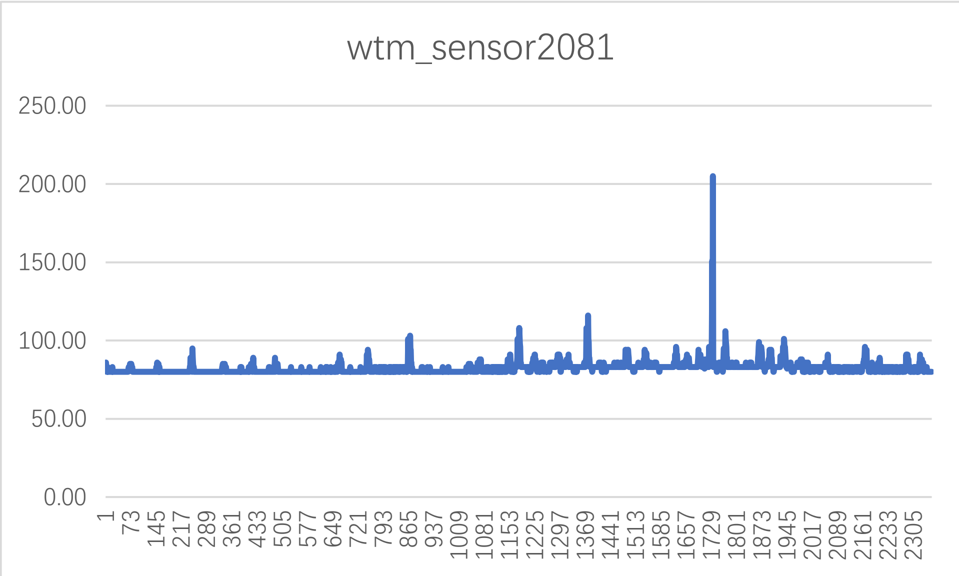


Figure 3. HWD detection result in the normal case, 5th Sep 2018

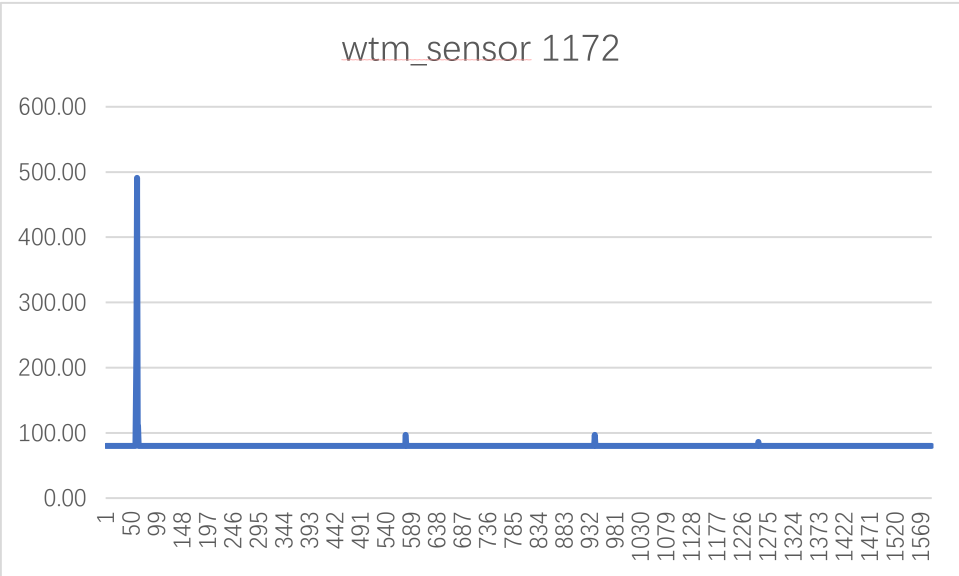


Figure 4. HWD detection result in the normal case, 5th Sep 2018

3 Working Plan

In this section, a working plan will be made to make sure the problem can be investigated and analyzed during the required period. The internship started from 1st September 2018 to 31st December 2018. There are 4 months totally and can be scheduled by week to make it more specific. Generally, 4 phases can be divided during the whole period, background knowledge, define the problem, problem analysis and report.

The background knowledge needs to be collected in the first phase which is mainly from ProRail, Voestalpine, and internet. This can build a basic view of the HBD system (PHOENIX MB) and how it is working in Dutch railway networks. Then a visiting for Voestalpine office Neverlands can make a deeper understanding of the installation and maintenance process of the HBD system. Next a field visiting of a Hotbox checkpoint can see how this system working in real condition. And the China delegation also visited Voestalpine and ProRail, so it can be an opportunity to know the information about HBD system used in China railway.

Task name	Description	Status	Weeks															
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Backgroud knowledge																		
Material from ProRail	read+note	Complete	■															
Material from Voestalpine	read+note	Complete		■														
Voestalpine office and field visit (NL)	assemble, installation etc	Complete				■												
China delegation visit	HBD condition in china	Complete				■												
Material from internet	read+note	Complete			■	■												
Define the problem																		
Voestalpine office visit (NL)	interview question	Complete						■										
FTA	RCA	Complete					■											
Reorganize data	database	Complete					■	■										
Data analysis	time domain	Complete					■	■	■	■								
Problem analysis																		
Voestalpine office visit (DE)	interview question	Complete										■						
NS visit	interview question	Complete									■							
French railway conference	web conference	Complete										■						
Data analysis	consistency,R&R	Complete								■	■	■	■					
Possible reasons	assumptions	Complete										■	■	■				
Reporting																		
Original plan	draft	Complete		■														
Midterm report	draft	Complete								■								
Second report	draft	In progress													■			
Report draft	draft	In progress												■	■	■		
Revise	adjust	Not started															■	■
final report	final	Not started																■

Table 5. Work plan by week

Then the define problem phase can be started after getting enough background knowledge. Root Cause Analysis (RCA) need to be applied to find what can lead to the system become unreliable. In this phase, some questions interview is necessary to keep the program in progress. Hence, visiting the Voestalpine office Nederland to communicate with their staff is scheduled. At the same time, historical data will be reorganized form database and analyzed initially with the help of ProRail staff.

Unavoidably, the initial analysis will lead to more questions. They are related to the HBD system itself, data usage and real apply experiences. Hence, the interview with Voestalpine single Germany and NS staff will be necessary to discuss the questions. And, the web conference with staff from the French railway can give some experience from other countries. At the same time, the furthers data analysis can be achieved based on a deeper understanding of the HBD system. Furthermore, some possible reasons can be found based on data analysis and assumptions.

Last, reporting is also important to be taken into consideration. It is not only containing the final report but also the progress meeting every Monday with company supervisor, presentation of progress for colleagues and discuss progress with the university supervisor. The final report needs to meet some requirements obey the internship website, so the revised time will be scheduled to make sure it can suitable for the requirements. And the progress meeting every Monday with company supervisor can keep the project in a good rhythm and receive feedback and advice from the supervisor. Presentation of progress for colleagues can get more advice from different people with different perspective and knowledge. Discuss progress with the university supervisor will generate more academic advice and perspectives.

And until this time most of the phases have been done already as is shown in Table 5. The plan shows only 16 weeks, but it can be adjusted when the delay happens or in case of unexpected situations.

4 Root Cause Analysis (FTA & FMEA)

The reliability problem become clearer after the problem defines process presented in section 2. Before solving the problem, the reason behind reliability problems must be identified first. Hence, Root Cause Analysis (RCA) will be applied in this section. It is a part of a problem-solving process used to examine and determine the root causes or core reasons of any failure of safety observance, accident or issues related to health, environment, quality, reliability, and production etc. In his case, only the root cause of HBD unreliability will be focused on. Because only when the definite underlying causes are identified and determined, the corrective actions to be taken for preventing any unwanted event and betterment can be achieved in the future.

There are many methods of RCA. And some comparisons have been already down by Dean L. Gano [40]

A few common ones can be summarized as Table 6.

Tools and methods	**Explanation**
Events and causal factors charting	Identifies the sequence of events with conditions
Change analysis	A six-step process that compares the event with and without problems side by side
Barrier Analysis	Traces barriers and how these caused failures or how these were compromised
Tree Diagrams	tree branch like charts those based on predefined faults
Pareto Analysis	A statistical approach based on Pareto principle that 80% of problems are caused by 20% causes
Storytelling method	A simple and direct investigation process
Fault tree analysis	A quantitative causal diagram used to find out the possible failures
Failure modes and effect analysis	Finds criticality and operability score ratio and effects of failure
Reality charting	It is similar to why/ why and a cause and effect chart is used for analysis

Table 6. A Comparison of Common Root Cause Analysis Tools and Methods

Considering the case, the expected result is finding the root cause or deep reason behind the HBD system unreliability. In other words. The purpose is to find what led to the abnormal situation happen and how these reasons affect results. So, the quantitative tools are more suitable for achieving this goal which means the Fault Tree Analysis (FTA) will be applied in this case first. Then, the hazard level will be identified to make the research focus on the most important failure. This can be achieved by using Failure Modes and Effect Analysis.[40]

4.1 Fault Tree Analysis

The Fault Tree Analysis result general graph can be seen in Appendix Figure1. Fault Tree Analysis-general view. To be more specific, the detail of FTA can be shown as Figure 5 to Figure 8.

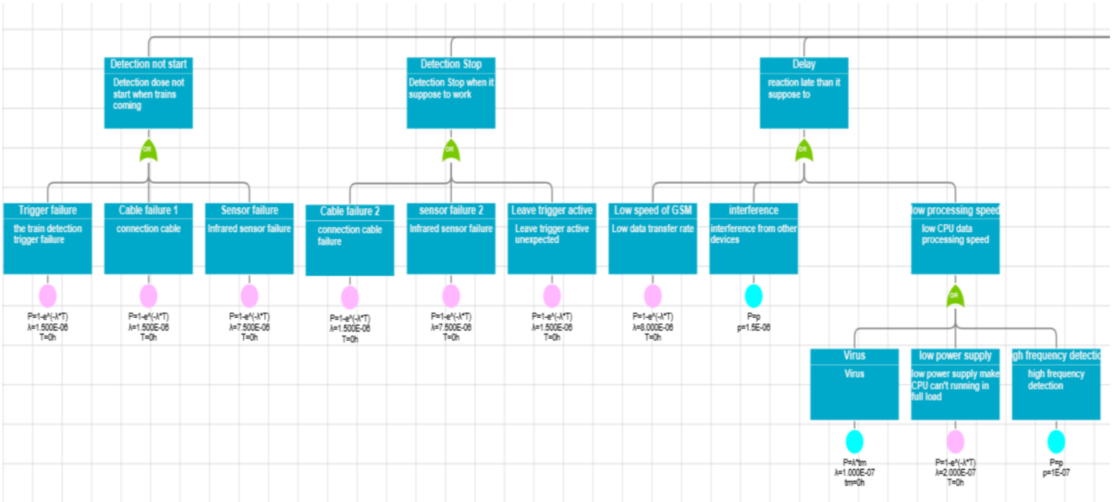


Figure 5. Fault Tree Analysis-part view 1

Figure 5 shows some possible reasons to lead to HBD system unreliable and each of them can be divided into more specific reasons. Some of them can be subdivided again to see more detail. As it can be seen, detection not start, detection stop abruptly, and detection delay can lead to the decrease of reliability of HBD system. Furthermore, there are 3 main reasons to make detection not start, contactor failure, cable failure and sensor failure. These are become electrical components level already, so, the failure rate of the components can be gained from reliability data book[35][36][37][38][39][3] then with the help of 'and' 'or 'gate algorithm. The reliability/failure rate can be calculated.

Theoretically, this method can be used to estimate HBD system reliability. But the reality is some events/components failure rate are missing.it can be seen from Figure 6 that virus could be one of possible reason to lead to system low processing speed. The question is the virus invade cannot be quantified. This problem not only happened on softer ware but hardware as well e.g. the Global System for Mobile communications (GSM) failure rate cannot be found in databook directly. The FTA for GSM needs to be done to get its failure rate. This makes the FTA quantities analysis become almost impossible.

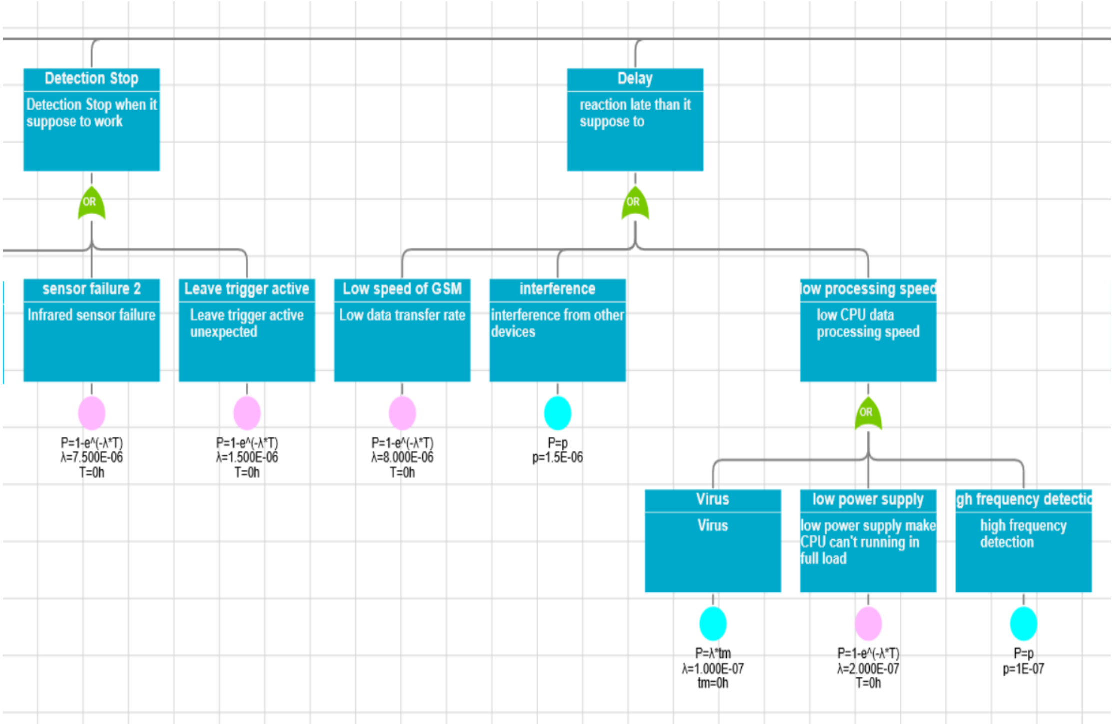


Figure 6. Fault Tree Analysis-part view 2

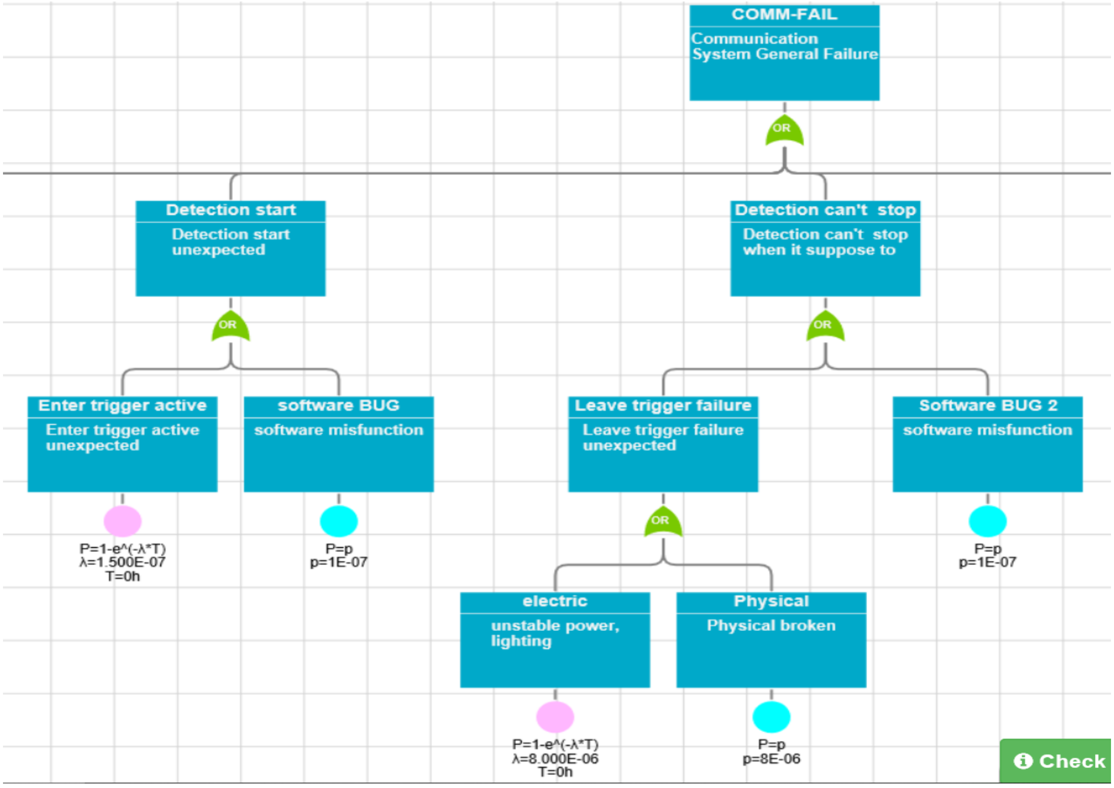


Figure 7. Fault Tree Analysis-part view 3

But something still can be found after give the available reliability data. As it is shown in the databook, the electrical components have a very low failure rate which is E-06 level approximately. This means only electrical components failure cannot make too much unreliable event. Hence, some assumption must make to explain the result. The

software bug rate and trigger wrong active rate has been assumed as E-07 level as it can be seen from Figure 7.
However, this is still a very small failure rate. There must be some other reason to contribute to the result. So, the FTA should be subdivided again until fond possible solutions.

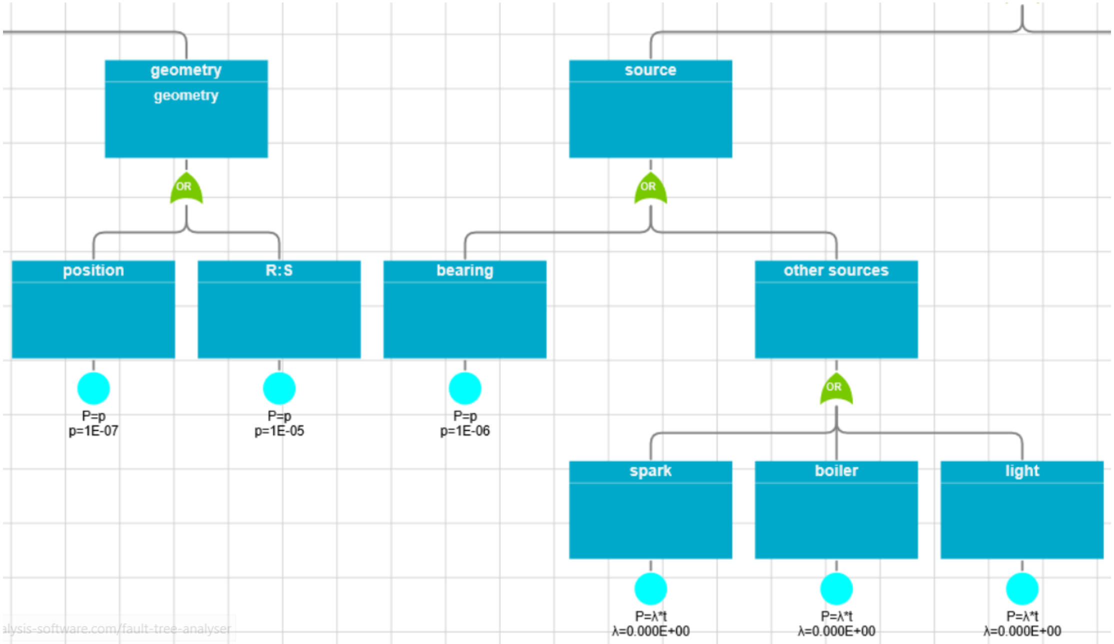


Figure 8. Fault Tree Analysis-part view 4

Figure 8 is a part of the whole FTA graph to show some possible reasons besides electrical components and software bugs. The testing objectives geometry maybe have an influence on the temperature result[34][36][37], it can be depending on testing position or infrared sensor R:S ratio[7][8][30][31]. And the bearing type even other interference heat sources e.g. spark, light and boiler might be having an influence on the result as well[14][16]. However, these events cannot be added quantitively. So, the calculation for HBD system failure rate cannot be made, but FTA illustrate some possible reason and indicate the electric components, software bugs cannot be the dominate unreliable contributor of HBD system.

4.2 Failure Mode and Effect Analysis

As it can be seen from FTA result. There are lots of possible failure event. It is impossible to cover all these failure events in reality because of a limited budget. Hence, the important event which means have possible to make huge influence will be focused on. This can be done by using Failure Mode and Effect Analysis (FMEA). As its name shows, it is a method to identify failure modes, reasons and consequences for each failure events. Then, the consequence hazard can be sorted by the severity. Thus, the important failure can be found apparently.

This kind of research has been done by EUROPEAN UNION AGENCY FOR RAILWAYS, the report’ Guide for the application of the CSM design targets

(CSM-DT)' shows the result of their research. It can be illustrated clearer by using Table 7. There are six Functional failure modes which are covered all detection process and delay in response is considered.

N°	Function	Functional failure modes	Cause	HAZARD - Consequence at level of technical system	Consequences at train level
1.	Trainborne Hot Box Detection	Detection does not start	• Hot Box Detector failed • Failure of indication system	Hot Box Event not detected by technical system when required	In case of a Hot Box Event, the driver is not informed and cannot stop the train safely.
2.		Detection starts when not required	• Hot Box Detector failed • Failure of indication system	Spurious detection of a Hot Box Event	• Driver required to stop the train whereas not necessary • Traffic operation disturbed
3.		Detection does not stop when required	• Hot Box Detector failed • Failure of indication system	Spurious detection of a Hot Box Event	• Driver required to stop the train whereas not necessary • Traffic operation disturbed
4.		Detection stops when not required	• Hot Box Detector failed • Failure of indication system	Hot Box Event not detected any more by technical system whereas still required	In case of a Hot Box Event, the driver can be misled (e.g. believes it is a false alarm) and could ignore the alarm whereas he shall stop the train safely.
5.		Detection is delayed in response	• Hot Box Detector failed • Failure of indication system	Hot Box Event may not be detected on time to permit actions to be put in place to ensure the safety	In case of a Hot Box Event, the driver is informed too late and might not stop the train safely.
6.		Detection degra-ded (e.g. wrong output level)		Not applicable. The hot box detection is a binary output	Not applicable. The hot box detection is a binary output

Table 7. Hazard Identification– Use of an FMEA[11]

Six identified functional failure modes can be classified into four categories:

(a) Failure modes 1 and 4 resulting in non-detection of a HB event and therefore to lack of information to the driver for stopping the train safely.

(b) Failure modes 2 and 3 resulting in spurious detection of a HB event and thus disturbing the traffic operation.

(c) Failure mode 5 resulting in too late detection of a HB event and therefore late information to the driver for stopping the train safely

(d) Failure mode 6 which is physically not possible for the system under assessment

In addition to that, the risks associated with failure modes 2,3 and 6 do not result in an unsafe situation. Hence, it may be considered broadly acceptable while failure modes 1,4 and 5 are not broadly acceptable because it has possible to make train not stop safely. [11] Besides, detection data unreliable also need to be taken into consideration. Because accidents might happen if the detection data cannot reflect the actual situation.

5 Data Analysis

In this section, more assessments will be done by using historical data. this is because it is the only criteria used to set alarm.it can be illustrated by Table 8 which is the threshold value set by ProRail[1]

Active signalling	Value	Action	Background
Hot axle	115^{o}C	The train is immediately halted in a controlled manner.	The bearing grease on the axle becomes so fluid that it runs off, causing the axle to seize.
Overheated axle *	90^{o}C	The train is brought to a standstill at the earliest possible opportunity, following consultation with the driver.	Axle is at risk of to developing into a 'hot axle'
Hot wheel	375^{o}C	The train is immediately halted in a controlled manner.	The tyre may come off the wheel
Overheated wheel *	200^{o}C	*See overheated axle*	The tyre may become distorted and develop into a 'hot wheel'.
*Applied on the Betuwe Route and the Port Railway Line (*Havenspoorlijn*) only, given that hot axles and wheels occur primarily in freight transport.			

Table 8. Alerting Values[1]

The absolute temperature is used to make a threshold value directly which are 115^{o}C and 375^{o}C for hot axle and hot wheel respectively. It means the reliability of the testing result (absolute temperature) is the most important factor to make a reliable alarm. Because there is not an algorithm to fix the abnormal value. Hence, to assess reliability of the testing result is necessary.

The available data need to be explained briefly before starting the data analysis process.it can be seen from Appendix figure 2 and figure 3. It is the original data with many information and some of them are redundant. Hence, the simplified data have been made as table 9 and table 10 which are original coming from Appendix figure 2 and figure 3 respectively.

N_m	N_t	S_i	S_o	L	m	A_{max}	N_a	s	T_m	T_a
213	1611	127.03	126.98	207.77	453.31	0.01	1	R	44	26
213	1611	127.03	126.98	207.77	453.31	0.01	1	L	43	26
2031	7658	118.00	117.00	123	/	/	8	R	40	27

Table 9. Axle detection data simplified

N_m	N_t	S_i	S_o	L	m	A_{max}	N_a	s	T_m	T_a
213	1719	130.96	130.94	154.77	134.40	0.04	21	R	86	21
213	1719	130.96	130.94	154.77	134.40	0.04	21	L	0	21
2081	7022	129.00	129.00	92	/	/	11	L	84	21

Table 10. Wheel detection data simplified

Where,

N_m: Number of measurement units

N_t: Number of trains

S_i: Speed in (km/h)

S_o: Speed out (km/h)

L: Length of the train (m)

M: Mass of the train (t)

A_{max}: Maximum acceleration (m/s^2)

N_a: Axle number

S: Side of detection (L for left; R for right)

T_m: Measured temperature (^{o}C)

T_a: ambient temperature (^{o}C)

Hot axle detectors are installed both left and right side of the train while hot wheel detector only scans one side of the wheel. Hence some data shows zero in wheel detection data. Another thing needs to be noticed is weight and acceleration are not measured by HBD system. So, some locations do not have any weight and acceleration information.

In this section, measurement system analysis will be applied first to give an overall view of the HBD system. Then, assessing reliability by calculating internal and external reliability will be made to check the across items-consistency and self-consistency. Last, a full factorial design can show which factor give the most contribution to the testing temperature.

5.1 Measurement System Analysis (R & R Study)

Obey Douglas Gorman and Keith M, Bower, a measurement system analysis (MSA) is a vital component for many quality improvement initiatives. It is important to assess the ability of a measurement system to detect meaningful differences in process variables[41]. In another word, measurement systems analysis is a method for determining whether a measurement system is acceptable and to prove that the measurement system is accurate and precise. So that data it is generated is reliable.

The ideal measurement system produces the true value every time. However, nothing is perfect. Obtaining data and doing measurement will demonstrate variability and produce defects. The result called observed variation which is always larger than the actual process variation. This is because the variation caused by the measurement system is taken into consideration. The observed variation is also called the total variation. The process variation is so-called part to part variation. To minimize measurement system variation, it’s important to identify and understand the factors of influence. Measurement system errors can be characterized by the following three categories:

1. Accuracy: To show how big is the systematic error
    a) Bias: The difference between the measured value and the true value
    b) Linearity: Equal accuracy over the entire range of the instrument
2. Precision: to show how big is the measurement variation
    a) Repeatability: The amount of variation that is caused by the instrument

b) Reproducibility: The amount of variation that is caused by the procedure, operator, etc.

c) Uniformity: Extent to which measurement variation is constant over the whole range of the measurement scale

3. Stability: The measurement system stable over time or not

These can be shown as Figure 9. The ideal measurement result is both precision and accuracy.

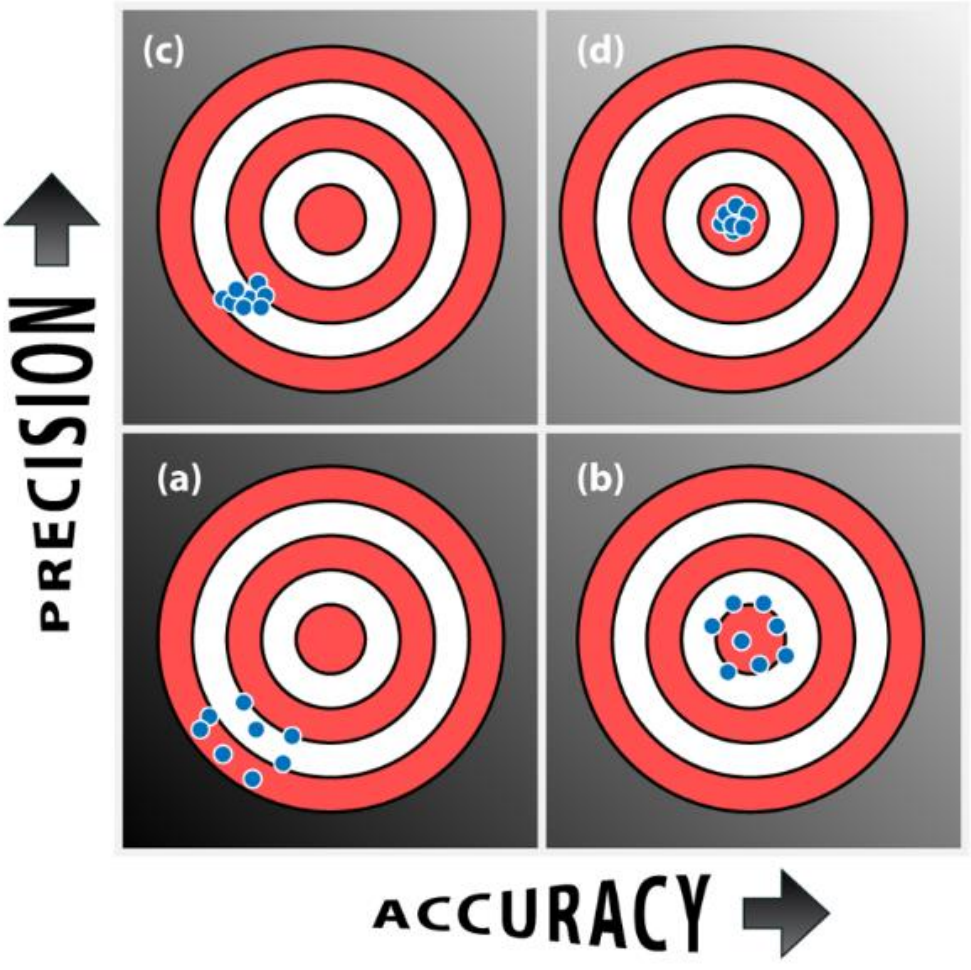


Figure 9. Precision vs Accuracy (Lies, damned lies, and benchmarks: Why mobile metrics still matter By Joel Hruska on January 3, 2012)

However, to bake to the HBD system history data, the true value is unknown. Hence, accuracy cannot be accessed because of the bias and linearity cannot be calculated. The only thing can be applied for the data is the precision assessment. For a continuous response variable, this is determined by amount of total variation which from the measurement process. This includes variation caused by the measurement instrument and the measurement process. The amount of precision variability can be determined by a reproducibility and repeatability study (R & R study). Figure 10 can illustrate these in a straighter way.

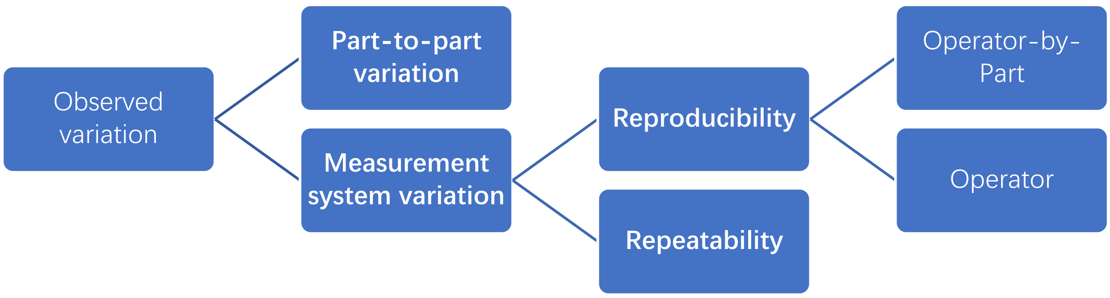


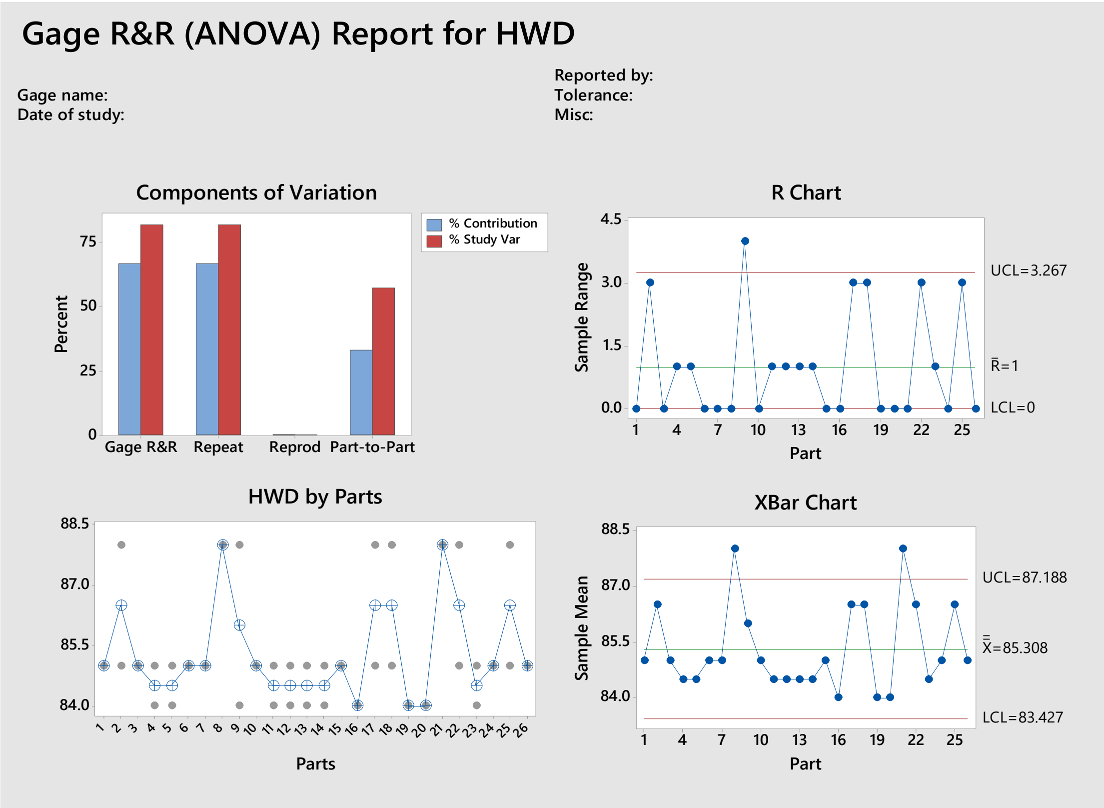
Figure 10. The relationship between observed variation and R&R study

The Measurement system variation can be subdivided into repeatability and reproducibility. Repeatability is the proportion of the inherent variation that is caused by the measuring instrument. It is the variation which occurs when repeated measurements are taken on the same object without changing circumstances; Reproducibility is the variation caused by measurement procedure. This is the variation that occurs when repeated measurements are made of the same object under different conditions. And it is the sum of the operator variation and operator by part variation.

Both HWD and HAD case show around 70% variation contribute from repeatability while part to part only take 30% approximately (reproducibility and pat to part for

HAD because it has both left and right value from the same axle). Which means the main error is caused by the instrument aspects. To be more specific, it could be the variation due to the measurement device, operators, parts, conditions. This can be illustrated better by take HWD sensor 1191 and HAD sensor 213

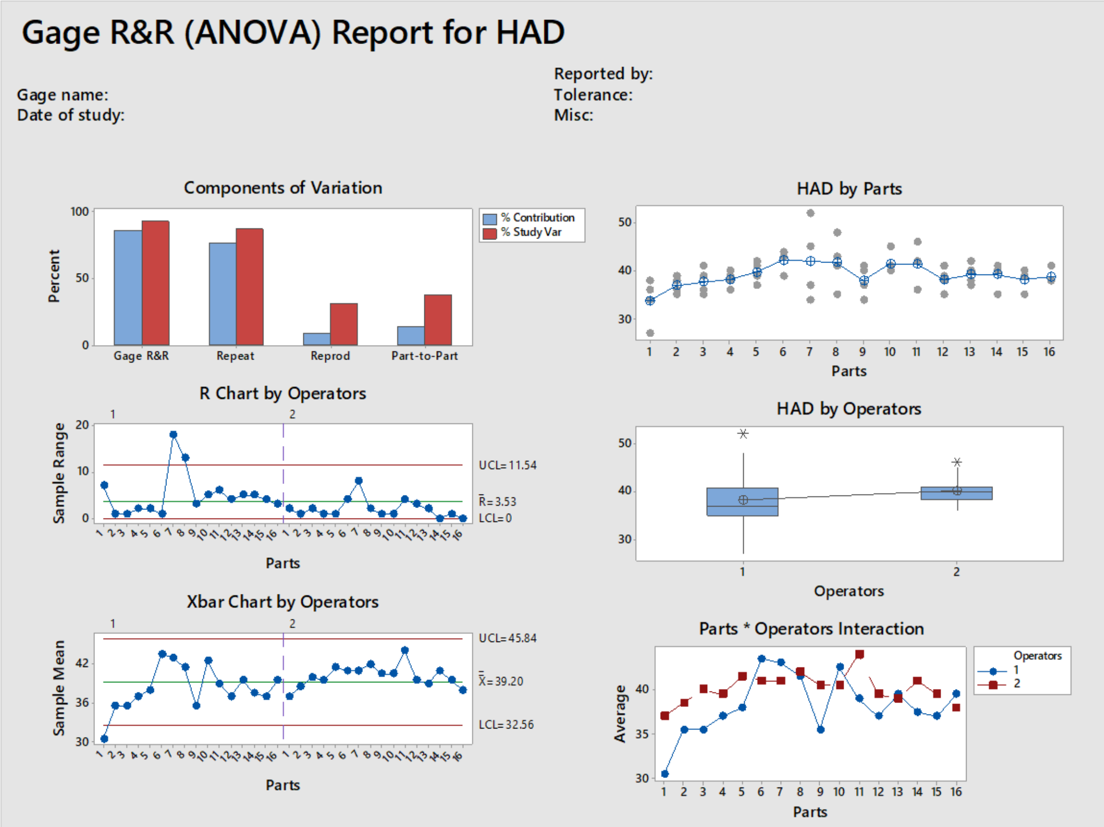
As Figure 11 shows. HWD sensor 1191 detect wheel temperature from passing train by axle number order. Two similar trains which have very resembled length, weight, speed and acceleration are selected to do this study. Theoretically, it could get very few variations which most comes from part to part source. However, the result shows part to part only contribute 33.12%. Both the R Chart and X Bar Chart show outlier value in axle 8. But it is not alarming value as it can be seen from HWD by Parts. This means the low part to part contribution rate is not because of the abnormal high temperature.



Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	1.30769	66.88
Repeatability	1.30769	66.88
Part-To-Part	0.64769	33.12
Total Variation	1.95538	100.00

Figure 11. R&R result for HWD sensor 1191

The same result can be reflected in figure 11. The repeatability gives around 70% too. And the reproducibility is little different from HWD sensor. This is because the HAD has two detectors on both left and right. Hence, there are two operators to compare to each other.



Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	13.0319	85.89
Repeatability	11.5768	76.30
Reproducibility	1.4551	9.59
Operators	1.4551	9.59
Part-To-Part	2.1410	14.11
Total Variation	15.1729	100.00

Figure 11. R&R result for HAD sensor 213

Both HWD and HAD data show the high repeatability Which means the main error could be caused by the following aspects;

1. Variation due to the measurement device.

2. Variation due to the operators.

3. Variation due to the parts.

4. Variation due to the conditions.

The variation due to the measurement device will be assessed in 5.2; Variation due to the conditions can be assessed in section 5.3 and others can be treated as possible factors which will be illustrated in section 6.

5.2 Assessing Reliability

A method can be used to assess data reliability of a measurement device. Considering what the situation is, the data is a huge amount but no reference value and multi-testing. This is rather like psychological data analysis. The researcher has no reference and multi-testing data from their research samples. Hence, the term reliability in psychological research refers to the consistency of a research study or measuring test. This can be applied in the HBD system.

To be more specific, if a train pass through 10 HBD point a day it would expect to see a similar trend between left and right. The same analogy could be applied to a checkpoint measure lots of similar train during resemble conditions. It would not be considered reliable if the data shows too much unexpecting fluctuation.

If findings from the research are replicated consistently, it means they are reliable. A correlation coefficient can be used to assess the degree of reliability. If a test is reliable it should show a high positive correlation.

Of course, it is unlikely the exact same results will be obtained each time as participants and situations vary, but a strong positive correlation between the results of the same test indicates reliability.

There are two types of reliability – internal and external reliability.

Internal reliability assesses the consistency of results across items within a test. External reliability refers to the extent to which a measure varies from one user to another. [15]

5.2.1 Internal Reliability

The split-half method can assess the internal consistency of a test, it measures the extent to which all parts of the test contribute equally to what is being measured.

This is done by comparing the results of one half of a test with the results from the other half. A test can be split in half in several ways, e.g. first half and second half, or by odd and even numbers. If the two halves of the test provide similar results this would suggest that the test has internal reliability.

In HWD case, split half by odd and even is used. This is because the odd and even way can minimize influence from the time change. The result could show a very low correlation if use first half and second half way. But this comes from daily condition change but not the sensor itself.

The result shows a very high correlation value which is above 0.9 for HWD data. This means the detection system doesn't have too much random fluctuation hence the sensor has a very high internal reliability.

Sensor 213 is taken as an example to illustrate. As can be seen from figure 12. The 1000 data getting from HWD sensor 213 and be separated into two groups by odd and even.it can be seen both odd and even group have some same trend fluctuation but some different trend as well.

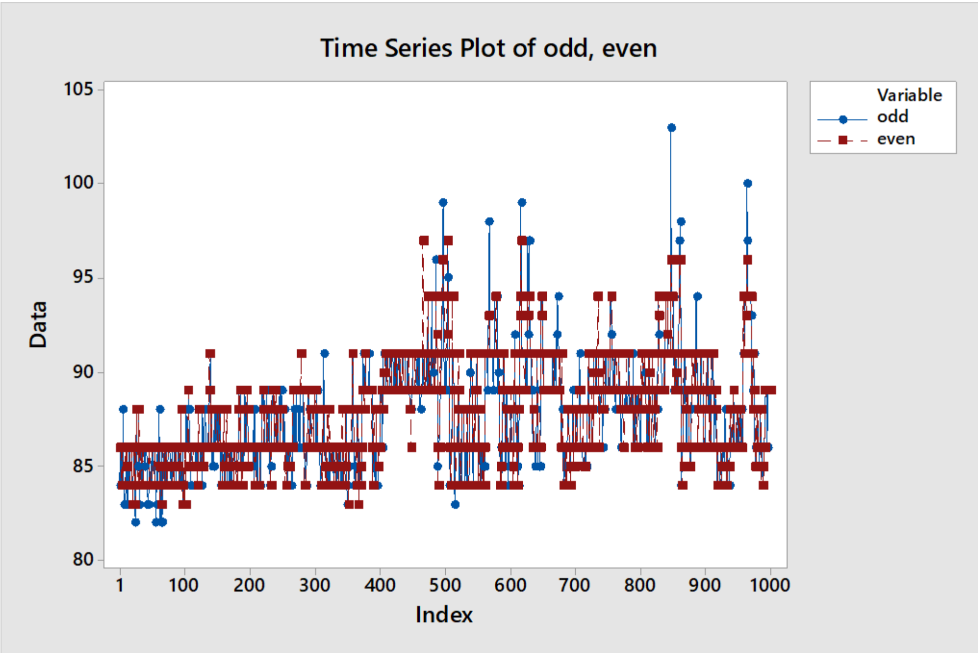


Figure 12. Time series plot odd, even, HWD sensor 213

To find the relationship of this group the cross-correlation can be calculated which is presented as figure 13. The red line is positive and almost a straight line this shows a very good correlation which is 0.9211. this means the sensor will give very similar output for resemble condition. Hence, the sensor has very high internal reliability.

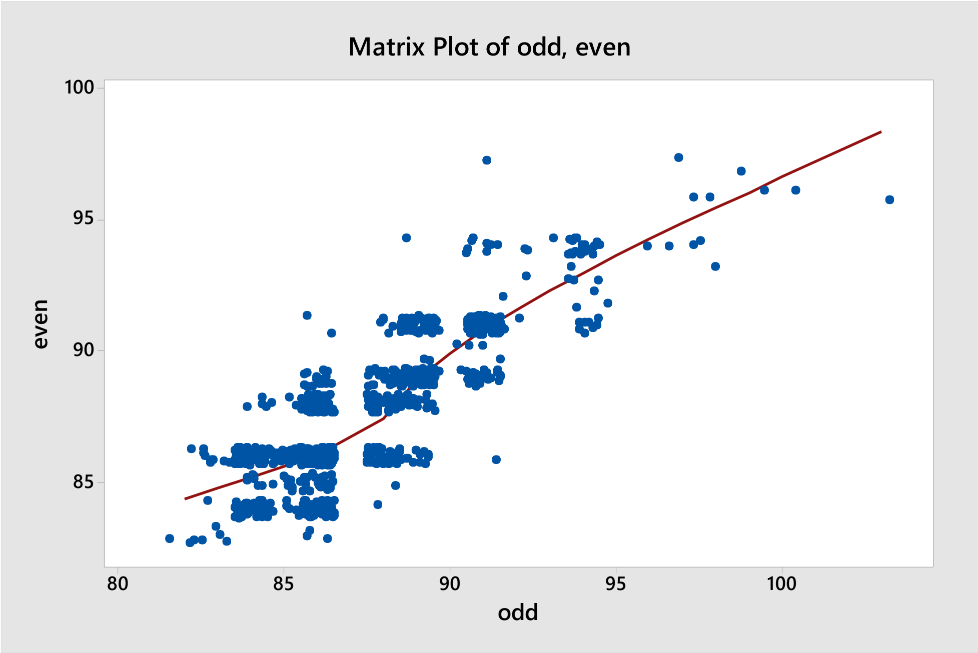


Figure 13. Matrix plot odd, even, HWD sensor 213

The same result can also be found in HAD case. And because of the two operators in HAD system. Half split method can also be treated as left and right. This can be illustrated better by figure 14. The 1000 temperature data are generated randomly to access internal consistency like what did in HWD case. But the half split is applied by left and right side.

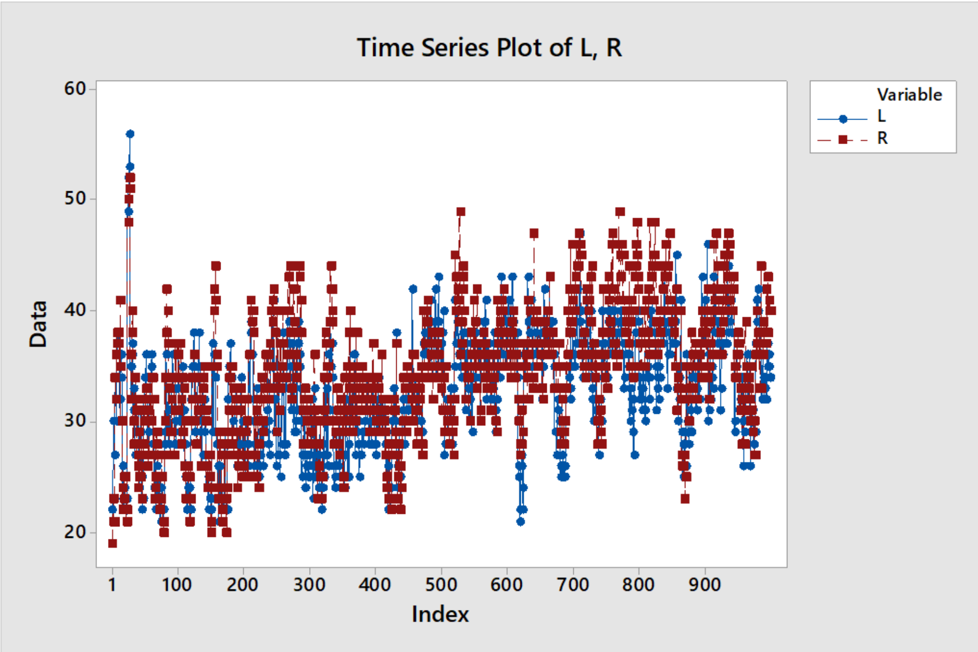


Figure 14. Time series plot of L, R, HAD sensor 213

The same cross-correlation is used to access the result.it can be illustrated by figure 15. It can be found there are still high correlation which equals to 08855 between left and right side. Hence, it can be concluded that both HWD and HAD system have high internal consistency. In another word, the consistency of results across items is very good. the system can generate corresponding value in different situations.

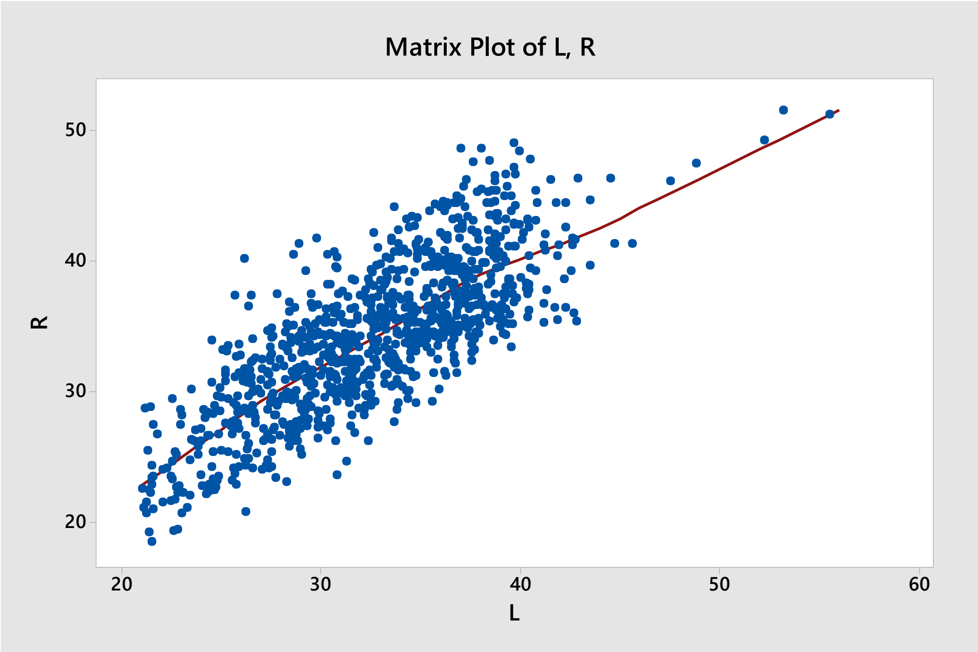


Figure 15. Matrix plot of L, R, HAD sensor 213

Next, the external reliability also needs to be accessed to know which a measure varies from one use to another.

5.2.2 External Reliability

The goal to use external reliability is to know the extent which a measure varies from one use to another. Two methods can achieve this goal. Firstly, called test-retest method, as its name shows it measures the stability of a test over time. Secondly, called inter-rater method which means to access to which different raters give consistent estimates of the same behavior.

The most difficult thing to access external reliability in the HBD system case is the actual same behavior does not exist. In another word, every testing point is checked only one time by one sensor. This makes the inter-rater method cannot be used. Hence, only the test-retest method is discussed here.

The test-retest method answered does the HBD system provide the same set of responses when nothing has changed during the time passing by. Because the ideal situation is the measurement system doesn't fluctuate when all other things are static. When correlating the two sets of measures if it shows very high correlations, it can be treated as high external reliability.

This process can be explained better by using figure 16(more information can be seen from Appendix figure 4). In HWD case, a fixed sensor is selected and find resemble train passing through this sensor in similar conditions. The axle amount, speed, length, weight, acceleration and even ambient temperature should be set as similar as possible.

Then the cross-correlation can be calculated by each other. This will be organized like a matrix. The result shows some of them show a high correlation which is great than 0.7 while most of them shows a moderate correlation which is from 0.3 to 0.7. However, some data show very low or even negative correlation. This is quite random and not related to the location, failure or error. The most data shows moderate and high correlation.

	train3625	train3627	train3633	train3635	train3639	train3641
train3627	0.095					
train3633	0.088	0.647				
train3635	0.181	0.510	0.240			
train3639	0.399	0.461	0.209	0.323		
train3641	0.353	0.400	0.315	0.386	0.638	
train3643	0.443	-0.261	-0.188	0.064	-0.059	0.085
train3647	0.116	0.290	0.223	0.196	0.152	0.359
train3649	0.554	0.077	-0.022	0.165	0.251	0.050
train3651	0.106	0.787	0.465	0.412	0.263	0.137
train3657	0.270	0.352	0.306	0.337	0.343	0.455
train3659	0.195	0.431	0.401	0.365	0.365	0.313
train3661	0.382	0.216	-0.025	0.353	0.504	0.401
train3663	0.416	0.691	0.287	0.614	0.638	0.683
train3665	0.135	0.481	0.322	0.382	0.626	0.631
train3667	-0.164	0.046	-0.211	0.182	0.313	0.308
train3673	0.258	0.320	0.132	0.377	0.419	0.163
train3675	0.123	0.292	0.226	0.083	0.516	0.485
train3683	0.315	0.474	0.667	0.361	0.188	0.574

Figure 16. External reliability by using test-retest method, HWD (part)

Similar results are generated also from HAD case, only part result shown here to make it clearer. As can be seen from figure 17, most data show cross-correlation in a moderate and high range.

Correlation Matrix

	train6613	train6615	train6627	train301130	train3645	train6647
train6615	0.945					
train6627	0.932	0.864				
train301130	0.684	0.546	0.629			
train3645	0.812	0.715	0.817	0.754		
train6647	0.903	0.821	0.979	0.665	0.837	
tain6653	0.872	0.836	0.928	0.615	0.763	0.926

Cell Contents
Pearson correlation

Figure 17. External reliability by using test-retest method, HAD (part)

Although the data did not show very high correlation, it still shows the sensor has very high external reliability. This is because the testing train should be absolutely same in order to get the ideal result. However, the testing is only similar to each other. The structure of boogie, bearing type even maintenance condition is different. These could be the reason why some results are low or even negative. Hence, moderate level of correlation can show good external consistency in HBD system.

5.3 Full Factorial Design

Except for R &R study, internal consistency and external consistency, another method can also show the data reliability in a more heuristic way. The data is more reliable if it shows result very similar to the experience.

Full factorial design can be applied here to achieve the goal. A full factorial design is a type of designed experiment that studies the effects of several factors. When conducting an experiment, varying the levels of all factors at the same time instead of one at a time study the interactions between the factors. So, the full factorial design allows the investigator to study the effect of each factor on the response variable, as well as the effects of interactions between factors on the response variable.

In the HAD case, the factor from row data can be summarized as speed in, speed out, length, weight, maximum acceleration, left and right side and ambient temperature. These can be found from table 9. And some information may be missing because of the reason mentioned in section 5. Hence, only the data which has full 7 factors can be selected to apply this analysis. The result of full factorial design is normally illustrated by two figures. A Pareto chart to show the standardized effects; a Main effects plot for testing temperature;

A Pareto chart can be seen as figure 18. It shows length give the most effects on the testing temperature. The second effect is the combination of speed in and weight. They are far more significant than the interaction of weight, maximum acceleration and length. This is somehow corresponding with experience that the speed has a huge influence on axle temperature. But the length makes the most contribution of all standardized effects is abnormal.it suppose to show the weight takes most contribution obey the experience. This is because the length and weight are not independent parameters. The length and weight have a positive correlation between each other. That is why the third and fourth term all shows the weight factor.

And more information can be found in figure 19 which shows main effects plot for testing temperature.it shows a negative correlation between testing temperature and length. When the train getting longer it makes axle temperature decrease slightly.

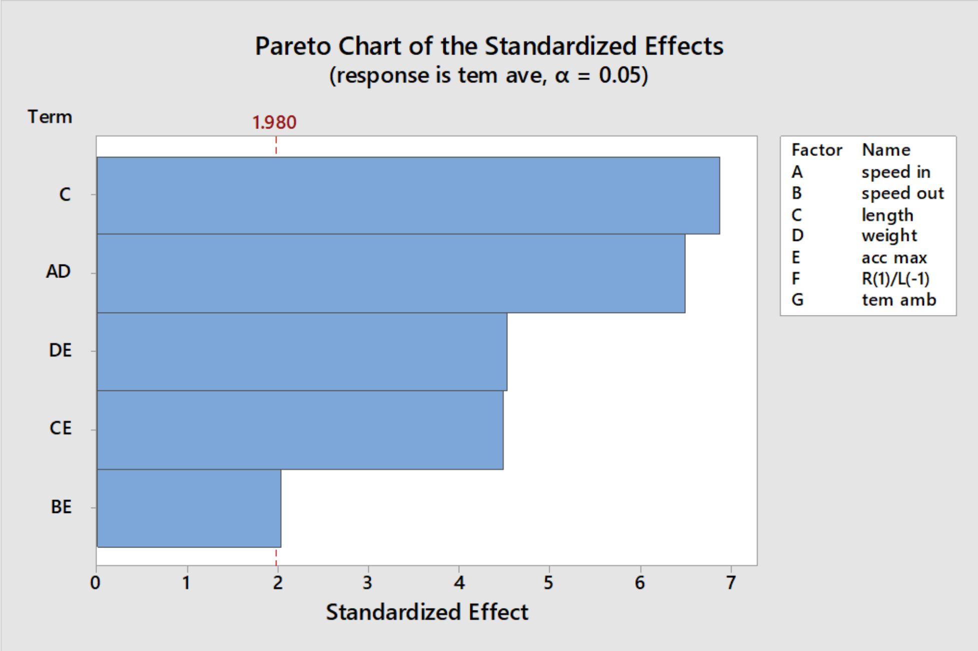


Figure 18. Pareto Chart of the Standardized Effects, HAD

This is because of the very long train has relatively low speed. It can be found that the train length above 261.61 m always less than 100km/h which is 30% lower than others. The relatively low speed makes the abnormal result.

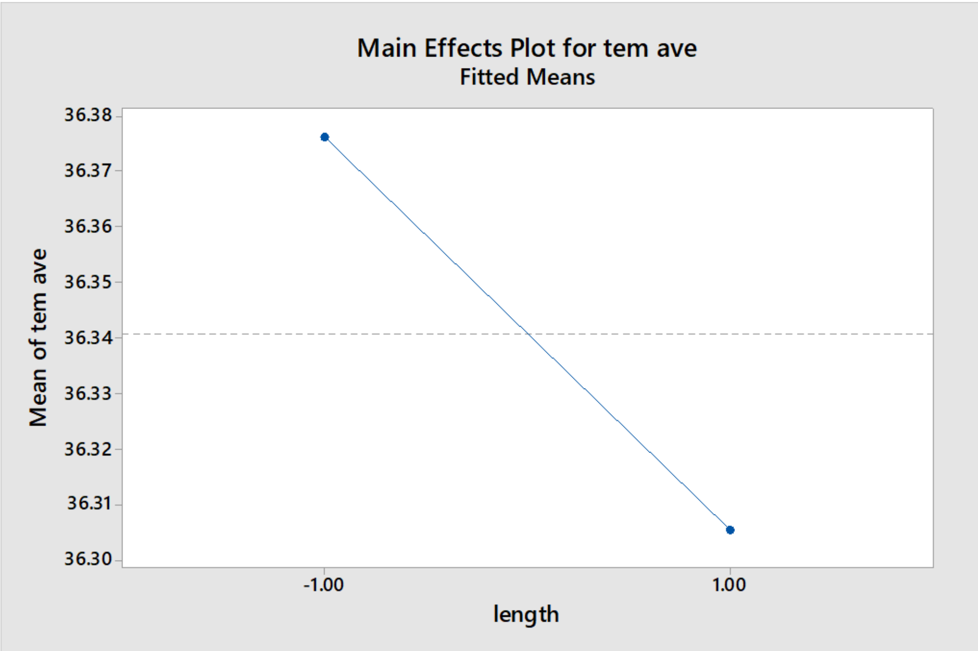


Figure 19. Main effects plot for testing temperature, HAD

If the consideration of independent factors is taken, the dominant factor would be weight and speed.

In the HWD case, the same method can be applied. And this time the independent factor will be deleted directly. Such as acceleration can be presented by using the combination of speed in and speed out. the result of Pareto chart can be seen as figure 20. The most significant effects are the combination of speed in, speed out and ambient temperature. The combination of speed in and speed out can be simplified as acceleration.

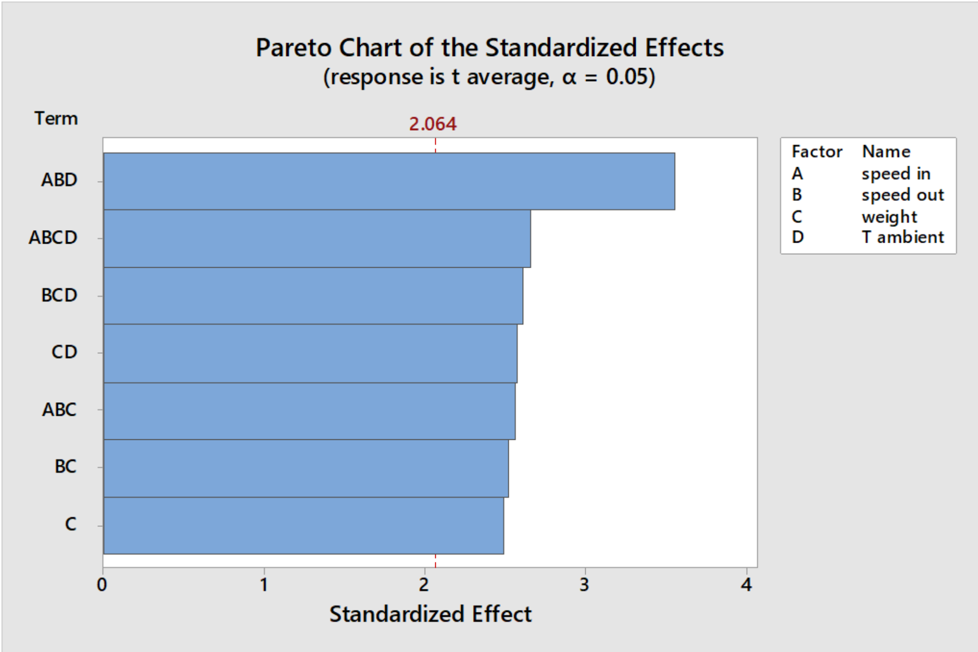


Figure 20. Pareto Chart of the Standardized Effects, HWD

And the single main effect for testing temperature is weight with positive correlation to testing temperature. It is reflected in figure 21

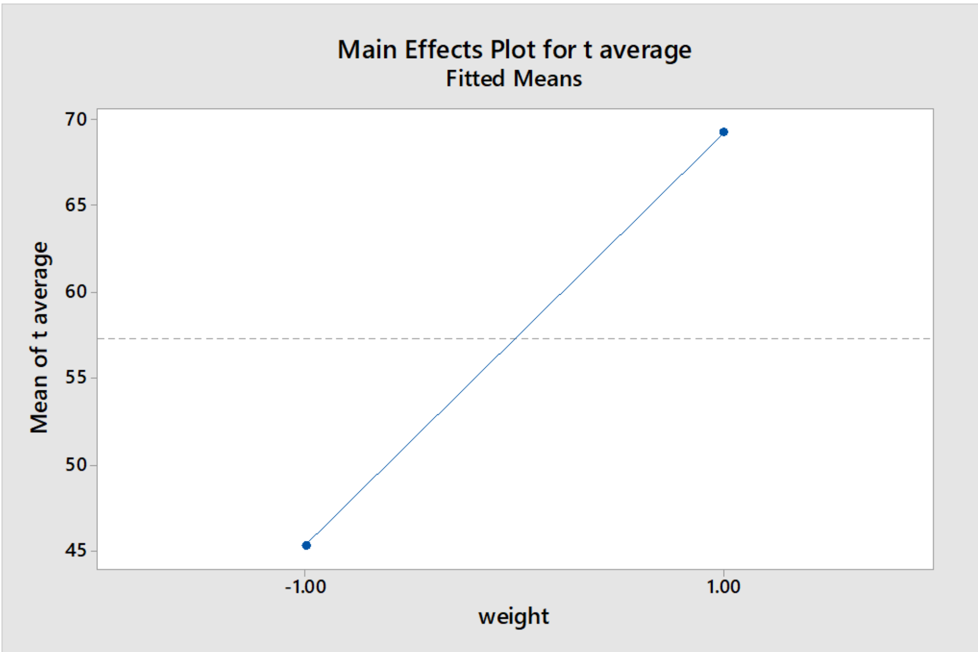


Figure 21. Main effects plot for testing temperature, HWD

Hence, it can be seen that the testing temperature result is corresponding with experience.

6 Possible Main Factors Contribute to Unreliability

As mentioned in section 5.1 the main error could be caused by the following aspects: Variation due to the measurement device; Variation due to the operators; Variation due to the parts; Variation due to the conditions.

The variation due to the measurement device has been assessed in 5.2 by using internal and external consistency analysis which shows a good consistency; Variation due to the known conditions has been assessed in section 5.3 by using full factorial design which shows corresponding with experience. Hence, other reasons become possible factors which can be considered from 3 parts:

1. Variation due to the parts.

2. Condition interference from outside of the given data.

3. Alarm criteria setting.

Hence, some possible main factors contribute to unreliability will be illustrated in this section from these three aspects. All the possible main factors are summarized in Table 11

Aspects	**Possible Main Factors**
Variation due to the parts	Boogie structure
	Bearing type and material
Condition interferences from outside of the given data	Other sources e.g. spark, sunlight
	Position change e.g. ‘snake motion’, distance changes
	Without people decision
Alarm criteria setting	Use absolute temperature directly

Table 11. possible main factors

6.1 Variation Due to the Parts

There are multiple types of trains running in Dutch railway network. Some of them have different types of boogie structure, and the locomotive may different from carriages even on the same train. While the HBD is a system with fix testing area. This led to the inferred sensor difficult to test aim in some structure.

It can be illustrated in Figure 22. Some train may be having a plate structure which is below the double row tapered bearing. The HBD system uses 8 channels rather than single channel to avoid influence from this structure. It can be seen there 5 channels out of 8 channels is blocked by the plate structure while another 3 channels can get temperature from little bit far from the heating point. This method is better than single beam but still has a problem. The highest temperature point should be just under the bearing. While the HBD system will give lower temperature because it is far from the highest temperature point. It shows clearer in Figure 23. Channel 1 to 5 shows no temperature information is gathered. Only 6 to 8 have the information and decrease one by one. The temperature from channel 6 will be recognized as the highest temperature. However, the actual temperature is unknown because of the structure and it must higher than the temperature from channel 6.

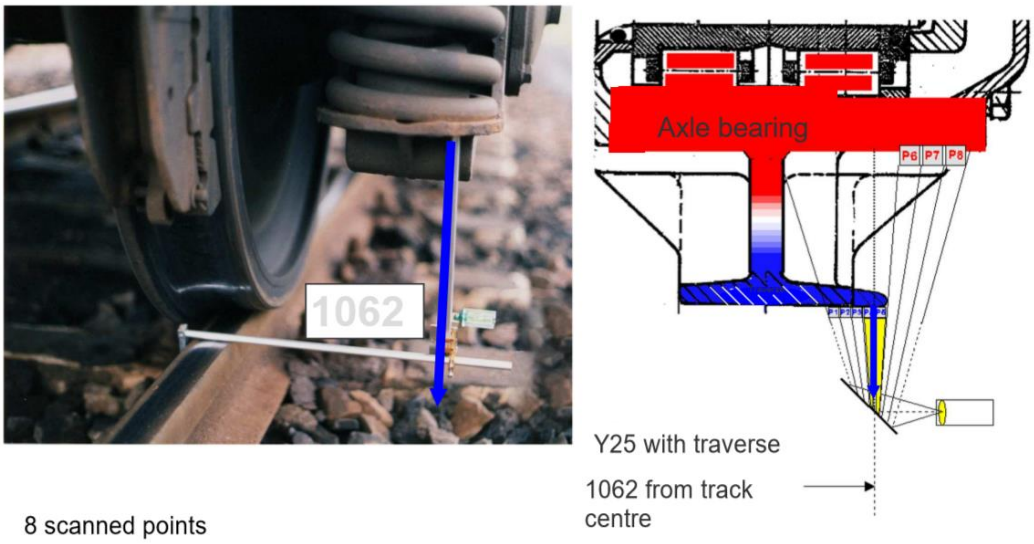


Figure 22. Multi-beam scanning for enhanced safety[36]

Another should be considered is bearing type and material. There are two types of bearing normally used in trains, slide bearing and roller bearing. And each of them can have different materials.it can be divided into metal and polymer material generally. The critical temperature and running temperature of these bearing are different from each other. While the HBD system gives alarm only based on one standard. Hence, some false alarm may happen.

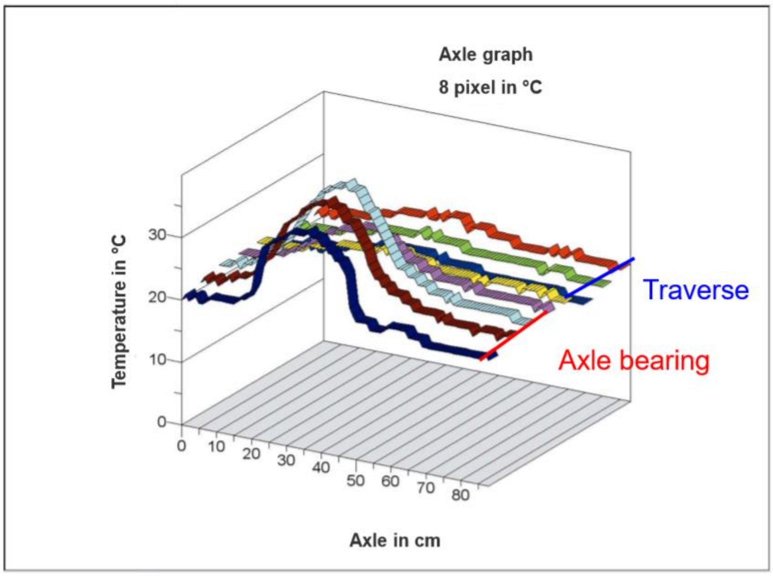


Figure 23. Temperature profile [36]

6.2 Condition Interference from Outside of the Given Data

The database can prove information e.g. ambient temperature, speed, acceleration, length and weight. However, this is far more enough because lots of interference from outside this given data can have influence on the result.

Firstly, other sources need to be taken into consideration e. g. spark and sunlight. The train wheel spark is unavoidable during the running. And the HBD system testing the temperature based on infrared emission from hot source. As Figure 24 shows the spark is becoming a new hot source which is far hotter than bearing. hence the result would be very high and could lead to false alarm.

Except for spark, sunlight is another hot source. Voestalpine already tries to avoid it by using a shutter to block the sunlight.it opens only when the train comes in. this method can prevent false alarm in most case. But if reflection happens during the train's running, the temperature will also seem high.

Figure 24. train wheel spark (from https://www.legendarylist.com/insane-train-wheel-slip-sends-sparks-flying-everywhere/)

Condition interferences can also come from position reasoning. The train running through the rail network is not straight but like 'snake' unavoidably. Which means the train is not only moving forward but also have lateral motion.

The scanning range of HBD system is shown in Figure 25. The ideal case is presented by de picture which 8 channels can cover all range of hotbox axle. But due to the lateral motion when the train running, the channel may be cannot cover the hottest point and it is even worse in the situation with outer structure like shown in Figure 22. The testing temperature could be lower than the actual temperature. this means the potential dangerous maybe cannot be detected.

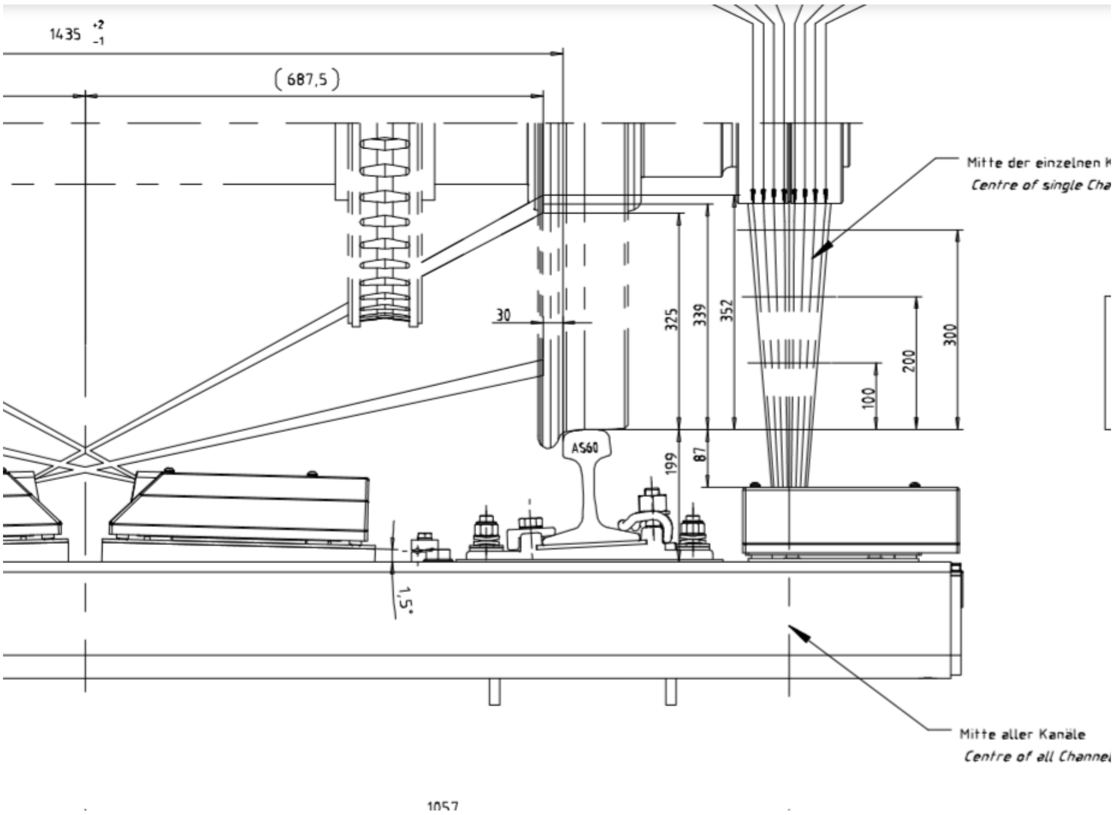


Figure 25. The scanning range of HBD system

Lastly, the detection process is fully automatic without people decision. Although some algorithm and mechanical components are used to protect HBD system from interference. It could not be interference free. It could be more reliable if the system gives possible alarm with enough information to experienced staff and the final alarm decided by people.

6.3 Alarm Criteria Setting

One more thing needs to be considered is alarm criteria setting. As it was mentioned in section 5, The absolute temperature is used to make a threshold value directly which are 115°C and 375°C for hot axle and hot wheel respectively. It means the reliability of testing result (absolute temperature) is the most important factor to make a reliable alarm. Because there is not an algorithm to fix the abnormal value.

Hence, more criteria should be set rather than to use absolute temperature value directly. This can reduce the false alarm rate.

7 Possible Solutions

Some possible solutions are given here corresponding to the possible main factors. These can be summarized in Table 12. It can be cataloged by 3 parts. Firstly, use double testing detector with a different angle. This method can be better used to tackle the boogie structure and position change problems. Secondly, use the combination of algorithm and people decision rather than give judgement fully automatically. This method can avoid lots of false alarm come from outside interference. Thirdly, a decision tree can be used rather than to use a single value threshold directly. This can reduce the false alarm rate due to the occasional high-temperature value.

7.1 Double Testing with Different Angle

As it was shown in Figure 25. The HBD system detects temperature from the bottom side of the axle. It could be blocked when there is another structure built below the axle. Hence, an easy way to improve reliability is adding an extra sensor with different angle. An extra multibeam sensor can be added outside of the original axle sensor and has a taper to the axle. Hence it can scan the axle temperature from another angle which cannot be influenced by complex boogie structure. This angle needs to be calculated based on geometry of the boogie and axle, and it can cover both bottom side and end face of the axle. The reliability will increase apparently when it has complex boogie structure.

Another big advantage is double-sensor with different angle can eliminate error comes from position change. As it was mentioned in section 6.2. there are both forward motion and lateral motion in running train. Hence not all channel can give useful temperature. The double sensor with some angle on it can make more channel have useful data when trains jump outside of the original detection area.

Possible Main Factors	**Possible Solutions**
Boogie structure	Double testing with different angle
Bearing type and material	Criteria setting by using decision tree
Other sources e.g. spark, sunlight	Algorithm and people decision
Position change e.g. ‘snake motion’, distance changes	Double testing with different angle
Without people decision	Algorithm and people decision
Use absolute temperature directly	Criteria setting by using decision tree

Table 12. possible solutions

7.2 Algorithm & People Decision

As it was mentioned in section 6.2. other heat sources have an influence on temperature result. This can be reduced by updating algorithm and filter. But some of them cannot be eliminated in some complex situation. Hence, using the combination of algorithm and people decision could be a better way to increase reliability. This can be better illustrated by comparing the same kind of HBD system used in other countries with different decision process[2]. It is summarized in Table 13.

	Nederland	Germany	Switzerland
False alarm rate	/	50-60%	200min/year delay
Axle waring（ºC）	90	70	80
Axle alarm（ºC）	115	100	100
Difference（ºC）	/	65	45
People decision	No	No	Yes
Location interval（km）	80	30-40(high speed), 40-70(normal)	30

Table 13. Comparing the HBD system used in different country (summarized from HABD en WILD Bijlagerapport met interviewresultaten per inframanager. DeltaRail bv.[2])

As the table shows, Germany and Switzerland have very resembled criteria threshold setting. The most different thing is Germany use fully automatic decision while Switzerland uses trained staff to make final decision. This reduces the false alarm rate apparently. Hence, using people to give the final alarm decision is a reliable way before the algorithm can recognize the whole false alarm.

7.3 Criteria Setting by using Decision Tree

This has been used in NS to make early warnings for failing train axle bearings by M.F.E. Peters. And the decision tree that has been developed in this work performs very well for the examined train series. The results show that the decision tree enables to predict more than half of the bearing failures.[42] And the decision tree shows in Figure 26.

As it was mentioned in section 5 and section 6.3, the absolute temperature is used to make a threshold value directly. It means the reliability of testing result (absolute temperature) is the most important factor to make a reliable alarm. But as the analysis has been done in section 6, there are lots of conditions to make the absolute temperature not that reliable. It is impossible to make the good decision directly by only using this data directly.

By comparing decision tree given in figure 26, a series threshold can be made to make the alarm more reliable. For each alarm level a handling scenario has been designed in a way that minimizes the disturbance. Not only the absolute temperature is considered in the decision trees, but also the temperature difference and time. And the alarm level can be more specific accordingly. That makes operator can stop immediately, checking after running or even just keep monitoring. It can reduce false alarm apparently.

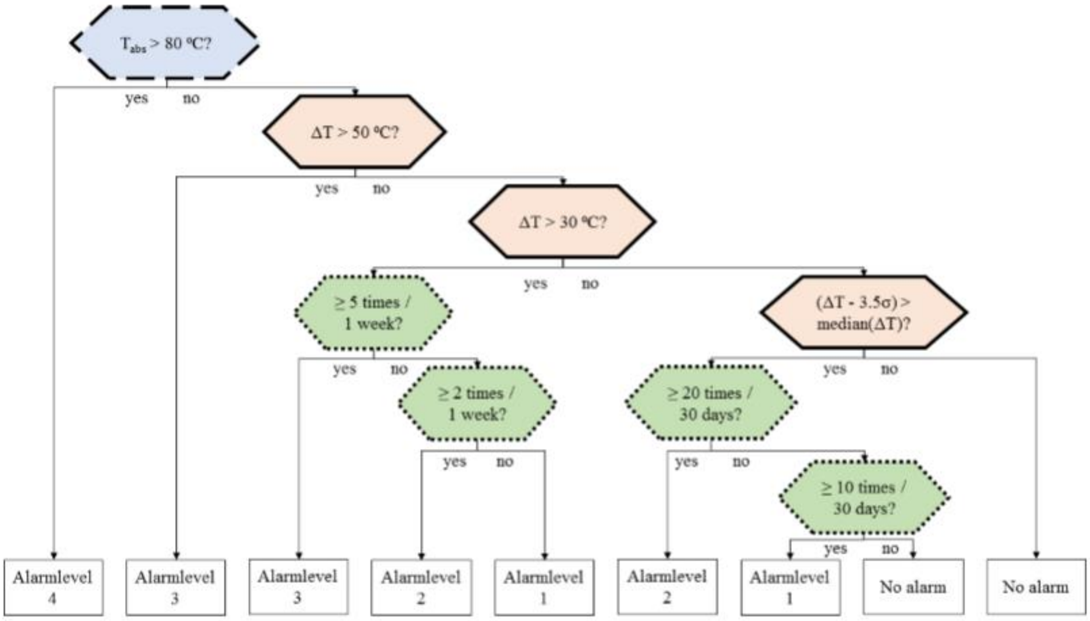


Figure 26. The decision tree of the rule-based classifier[42]

8 Conclusion and Discussion

This report analyzes the reliability of HBD system in failure, error and data reliability aspects. And it shows very good internal and external consistency most of the time. However, abnormal data are generated in some case, most of the unreliability comes from repeatability. Based on this information, some possible main factors have been found and possible solutions are given correspondingly.

There are still have a possibility to find more main factors and give better solution. such as the influence of lubrication level and heat distribution on axle box. These maybe make the highest temperature point not located on the bottom side. Hence, some possible solution might need to relocate sensor position.

And another thing needs to be taken into consideration is how to balance the reliability and other factors e.g. economics and effectiveness. For example, trained staff can make better decision than fully automatic alarm in some complex situations. But it makes decision slower and more investment need to be applied to train employees. Hence, some balance needs to be achieved between them. e.g. some high-level alarm can be given automatically but other levels which are not that serious can be assessed by people.

Furthermore, more detection point can be located across the Dutch railway network. Not only the inferred temperature detection system but also other condition monitoring systems e.g. vibration monitoring system. Multi-detection system can make decision have more supporting than using single system only. The reliability of decision will increase if multi-system can work at the same time.

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Appendix A

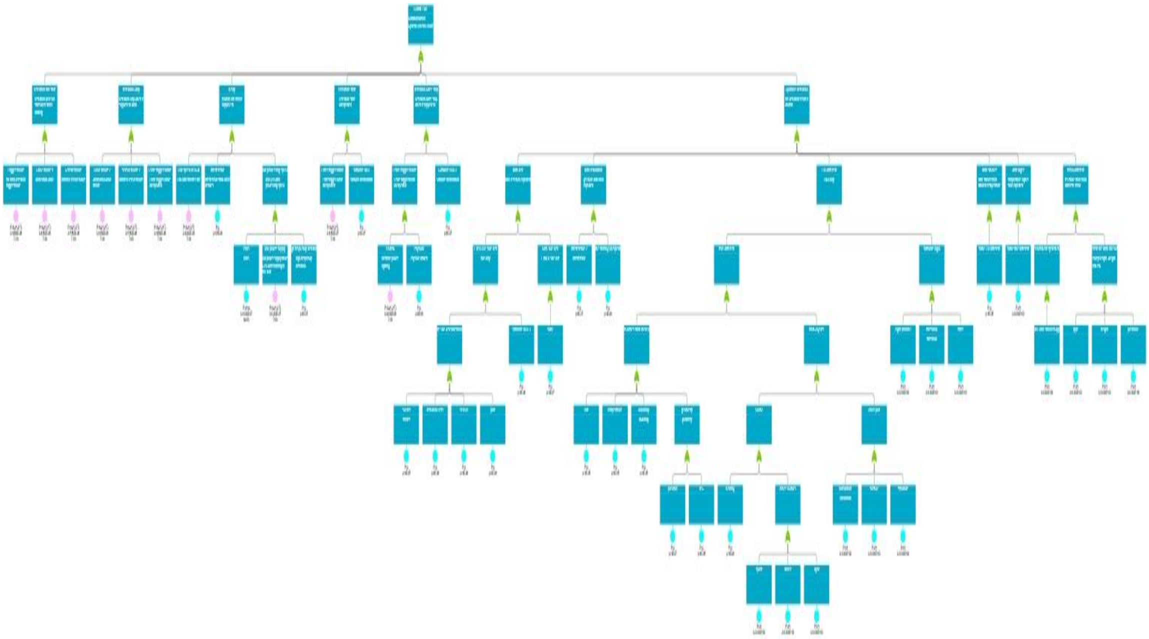

Figure1. Fault Tree Analysis-general view
(http://fault-tree-analysis-software.com/fault-tree-analysis)

qtm_me	qtm_meettijdstip_dt	qtm_ontvangst_esb_dt	qtm_tre	qtm_aa	qtm_sne	qtm_snelh	qtm_total	qtm_totaa	qtm_acce	qtm_acce	atm_a	atm	atm_gem_te	atm_tem	atm_omge
213	05Sep2018 13:10:04.743	05Sep2018 13:10:53.337	50156	76	90.51	91.54	371.32	1513.40	0.00	0.03	25	R	38.42	38.00	27.46
213	05Sep2018 13:10:04.743	05Sep2018 13:10:53.337	50156	76	90.51	91.54	371.32	1513.40	0.00	0.03	25	L	33.46	33.00	27.46
213	05Sep2018 13:10:04.743	05Sep2018 13:10:53.337	50156	76	90.51	91.54	371.32	1513.40	0.00	0.03	26	R	38.42	39.00	27.46
213	05Sep2018 13:10:04.743	05Sep2018 13:10:53.337	50156	76	90.51	91.54	371.32	1513.40	0.00	0.03	26	L	33.46	30.00	27.46
213	05Sep2018 13:10:04.743	05Sep2018 13:10:53.337	50156	76	90.51	91.54	371.32	1513.40	0.00	0.03	27	R	38.42	38.00	27.46
213	05Sep2018 13:10:04.743	05Sep2018 13:10:53.337	50156	76	90.51	91.54	371.32	1513.40	0.00	0.03	27	L	33.46	34.00	27.46
213	05Sep2018 13:10:04.743	05Sep2018 13:10:53.337	50156	76	90.51	91.54	371.32	1513.40	0.00	0.03	28	R	38.42	39.00	27.46
213	05Sep2018 13:10:04.743	05Sep2018 13:10:53.337	50156	76	90.51	91.54	371.32	1513.40	0.00	0.03	28	L	33.46	34.00	27.46
213	05Sep2018 13:10:04.743	05Sep2018 13:10:53.337	50156	76	90.51	91.54	371.32	1513.40	0.00	0.03	29	R	38.42	42.00	27.46
213	05Sep2018 13:10:04.743	05Sep2018 13:10:53.337	50156	76	90.51	91.54	371.32	1513.40	0.00	0.03	29	L	33.46	33.00	27.46
213	05Sep2018 13:10:04.743	05Sep2018 13:10:53.337	50156	76	90.51	91.54	371.32	1513.40	0.00	0.03	30	R	38.42	41.00	27.46
213	05Sep2018 13:10:04.743	05Sep2018 13:10:53.337	50156	76	90.51	91.54	371.32	1513.40	0.00	0.03	30	L	33.46	33.00	27.46
213	05Sep2018 13:10:04.743	05Sep2018 13:10:53.337	50156	76	90.51	91.54	371.32	1513.40	0.00	0.03	31	R	38.42	38.00	27.46
213	05Sep2018 13:10:04.743	05Sep2018 13:10:53.337	50156	76	90.51	91.54	371.32	1513.40	0.00	0.03	31	L	33.46	28.00	27.46
213	05Sep2018 13:10:04.743	05Sep2018 13:10:53.337	50156	76	90.51	91.54	371.32	1513.40	0.00	0.03	32	R	38.42	37.00	27.46
213	05Sep2018 13:10:04.743	05Sep2018 13:10:53.337	50156	76	90.51	91.54	371.32	1513.40	0.00	0.03	32	L	33.46	30.00	27.46
213	05Sep2018 13:10:04.743	05Sep2018 13:10:53.337	50156	76	90.51	91.54	371.32	1513.40	0.00	0.03	33	R	38.42	41.00	27.46
213	05Sep2018 13:10:04.743	05Sep2018 13:10:53.337	50156	76	90.51	91.54	371.32	1513.40	0.00	0.03	33	L	33.46	32.00	27.46
213	05Sep2018 13:10:04.743	05Sep2018 13:10:53.337	50156	76	90.51	91.54	371.32	1513.40	0.00	0.03	34	R	38.42	42.00	27.46
213	05Sep2018 13:10:04.743	05Sep2018 13:10:53.337	50156	76	90.51	91.54	371.32	1513.40	0.00	0.03	34	L	33.46	34.00	27.46
213	05Sep2018 13:10:04.743	05Sep2018 13:10:53.337	50156	76	90.51	91.54	371.32	1513.40	0.00	0.03	35	R	38.42	37.00	27.46
213	05Sep2018 13:10:04.743	05Sep2018 13:10:53.337	50156	76	90.51	91.54	371.32	1513.40	0.00	0.03	35	L	33.46	33.00	27.46
213	05Sep2018 13:10:04.743	05Sep2018 13:10:53.337	50156	76	90.51	91.54	371.32	1513.40	0.00	0.03	36	R	38.42	36.00	27.46
213	05Sep2018 13:10:04.743	05Sep2018 13:10:53.337	50156	76	90.51	91.54	371.32	1513.40	0.00	0.03	36	L	33.46	35.00	27.46
213	05Sep2018 13:10:04.743	05Sep2018 13:10:53.337	50156	76	90.51	91.54	371.32	1513.40	0.00	0.03	37	R	38.42	44.00	27.46
213	05Sep2018 13:10:04.743	05Sep2018 13:10:53.337	50156	76	90.51	91.54	371.32	1513.40	0.00	0.03	37	L	33.46	32.00	27.46
213	05Sep2018 13:10:04.743	05Sep2018 13:10:53.337	50156	76	90.51	91.54	371.32	1513.40	0.00	0.03	38	R	38.42	46.00	27.46
213	05Sep2018 13:10:04.743	05Sep2018 13:10:53.337	50156	76	90.51	91.54	371.32	1513.40	0.00	0.03	38	L	33.46	34.00	27.46
213	05Sep2018 13:10:04.743	05Sep2018 13:10:53.337	50156	76	90.51	91.54	371.32	1513.40	0.00	0.03	39	R	38.42	43.00	27.46
213	05Sep2018 13:10:04.743	05Sep2018 13:10:53.337	50156	76	90.51	91.54	371.32	1513.40	0.00	0.03	39	L	33.46	35.00	27.46
213	05Sep2018 13:10:04.743	05Sep2018 13:10:53.337	50156	76	90.51	91.54	371.32	1513.40	0.00	0.03	40	R	38.42	42.00	27.46
213	05Sep2018 13:10:04.743	05Sep2018 13:10:53.337	50156	76	90.51	91.54	371.32	1513.40	0.00	0.03	40	L	33.46	33.00	27.46
213	05Sep2018 13:10:04.743	05Sep2018 13:10:53.337	50156	76	90.51	91.54	371.32	1513.40	0.00	0.03	41	R	38.42	38.00	27.46
213	05Sep2018 13:10:04.743	05Sep2018 13:10:53.337	50156	76	90.51	91.54	371.32	1513.40	0.00	0.03	41	L	33.46	35.00	27.46
213	05Sep2018 13:10:04.743	05Sep2018 13:10:53.337	50156	76	90.51	91.54	371.32	1513.40	0.00	0.03	42	R	38.42	38.00	27.46

Figure 2. Axle detection data

qtm_meetu	qtm_meettijdstip_dt	qtm_ontvangst_esb_dt	qtm_trein	qtm_snelheid_	qtm_snelheic	qtm_totale	qtm_totaal	wtm_as_vo	wtm_w	wtm_te	wtm_gem_t	wtm_omge
214	05Sep2018 9:39:27.750	05Sep2018 9:39:57.020	31418	123.60	123.03	55.07	112.06	1	R	80.00	80.00	19.88
214	05Sep2018 9:39:27.750	05Sep2018 9:39:57.020	31418	123.60	123.03	55.07	112.06	1	L	0.00	0.00	19.88
214	05Sep2018 9:39:27.750	05Sep2018 9:39:57.020	31418	123.60	123.03	55.07	112.06	2	R	80.00	80.00	19.88
214	05Sep2018 9:39:27.750	05Sep2018 9:39:57.020	31418	123.60	123.03	55.07	112.06	2	L	0.00	0.00	19.88
214	05Sep2018 9:39:27.750	05Sep2018 9:39:57.020	31418	123.60	123.03	55.07	112.06	3	R	80.00	80.00	19.88
214	05Sep2018 9:39:27.750	05Sep2018 9:39:57.020	31418	123.60	123.03	55.07	112.06	3	L	0.00	0.00	19.88
214	05Sep2018 9:39:27.750	05Sep2018 9:39:57.020	31418	123.60	123.03	55.07	112.06	4	R	80.00	80.00	19.88
214	05Sep2018 9:39:27.750	05Sep2018 9:39:57.020	31418	123.60	123.03	55.07	112.06	4	L	0.00	0.00	19.88
214	05Sep2018 9:39:27.750	05Sep2018 9:39:57.020	31418	123.60	123.03	55.07	112.06	5	R	80.00	80.00	19.88
214	05Sep2018 9:39:27.750	05Sep2018 9:39:57.020	31418	123.60	123.03	55.07	112.06	5	L	0.00	0.00	19.88
214	05Sep2018 9:39:27.750	05Sep2018 9:39:57.020	31418	123.60	123.03	55.07	112.06	6	R	80.00	80.00	19.88
214	05Sep2018 9:39:27.750	05Sep2018 9:39:57.020	31418	123.60	123.03	55.07	112.06	6	L	0.00	0.00	19.88
214	05Sep2018 9:39:27.750	05Sep2018 9:39:57.020	31418	123.60	123.03	55.07	112.06	7	R	80.00	80.00	19.88
214	05Sep2018 9:39:27.750	05Sep2018 9:39:57.020	31418	123.60	123.03	55.07	112.06	7	L	0.00	0.00	19.88
214	05Sep2018 9:39:27.750	05Sep2018 9:39:57.020	31418	123.60	123.03	55.07	112.06	8	R	80.00	80.00	19.88
214	05Sep2018 9:39:27.750	05Sep2018 9:39:57.020	31418	123.60	123.03	55.07	112.06	8	L	0.00	0.00	19.88
213	05Sep2018 9:34:32.903	05Sep2018 9:34:56.947	31419	129.56	129.63	55.06	113.91	1	R	84.00	85.25	19.89
213	05Sep2018 9:34:32.903	05Sep2018 9:34:56.947	31419	129.56	129.63	55.06	113.91	1	L	0.00	0.00	19.89
213	05Sep2018 9:34:32.903	05Sep2018 9:34:56.947	31419	129.56	129.63	55.06	113.91	2	R	86.00	85.25	19.89
213	05Sep2018 9:34:32.903	05Sep2018 9:34:56.947	31419	129.56	129.63	55.06	113.91	2	L	0.00	0.00	19.89
213	05Sep2018 9:34:32.903	05Sep2018 9:34:56.947	31419	129.56	129.63	55.06	113.91	3	R	86.00	85.25	19.89
213	05Sep2018 9:34:32.903	05Sep2018 9:34:56.947	31419	129.56	129.63	55.06	113.91	3	L	0.00	0.00	19.89
213	05Sep2018 9:34:32.903	05Sep2018 9:34:56.947	31419	129.56	129.63	55.06	113.91	4	R	86.00	85.25	19.89
213	05Sep2018 9:34:32.903	05Sep2018 9:34:56.947	31419	129.56	129.63	55.06	113.91	4	L	0.00	0.00	19.89
213	05Sep2018 9:34:32.903	05Sep2018 9:34:56.947	31419	129.56	129.63	55.06	113.91	5	R	84.00	85.25	19.89
213	05Sep2018 9:34:32.903	05Sep2018 9:34:56.947	31419	129.56	129.63	55.06	113.91	5	L	0.00	0.00	19.89
213	05Sep2018 9:34:32.903	05Sep2018 9:34:56.947	31419	129.56	129.63	55.06	113.91	6	R	86.00	85.25	19.89
213	05Sep2018 9:34:32.903	05Sep2018 9:34:56.947	31419	129.56	129.63	55.06	113.91	6	L	0.00	0.00	19.89
213	05Sep2018 9:34:32.903	05Sep2018 9:34:56.947	31419	129.56	129.63	55.06	113.91	7	R	86.00	85.25	19.89
213	05Sep2018 9:34:32.903	05Sep2018 9:34:56.947	31419	129.56	129.63	55.06	113.91	7	L	0.00	0.00	19.89
213	05Sep2018 9:34:32.903	05Sep2018 9:34:56.947	31419	129.56	129.63	55.06	113.91	8	R	84.00	85.25	19.89
213	05Sep2018 9:34:32.903	05Sep2018 9:34:56.947	31419	129.56	129.63	55.06	113.91	8	L	0.00	0.00	19.89
214	05Sep2018 10:02:44.187	05Sep2018 10:03:24.287	1730	129.01	129.19	154.78	333.05	1	R	80.00	80.00	19.90
214	05Sep2018 10:02:44.187	05Sep2018 10:03:24.287	1730	129.01	129.19	154.78	333.05	1	L	0.00	0.00	19.90
214	05Sep2018 10:02:44.187	05Sep2018 10:03:24.287	1730	129.01	129.19	154.78	333.05	2	R	80.00	80.00	19.90

Figure 3. Wheel detection data

Correlation Matrix

	train89225	train3615	train3617	train3619	train3621	train3623
train3615	-0.215					
train3617	0.404	-0.146				
train3619	-0.427	-0.128	-0.168			
train3621	0.030	-0.043	-0.131	0.027		
train3623	0.136	-0.040	-0.059	0.170	-0.232	
train3625	0.430	-0.212	0.193	-0.235	0.179	0.104
train3627	0.267	-0.146	0.197	-0.232	-0.232	0.161
train3633	0.325	-0.155	0.014	-0.305	-0.018	-0.043
train3635	0.347	-0.013	0.145	-0.325	-0.216	-0.049
train3639	0.471	-0.054	0.354	-0.324	-0.147	0.235
train3641	0.582	-0.378	0.341	-0.373	-0.207	0.038
train3643	0.166	-0.116	0.299	-0.069	0.138	-0.184
train3647	0.068	-0.003	0.493	-0.339	-0.127	-0.019
train3649	-0.037	-0.260	-0.159	-0.164	0.033	0.283
train3651	-0.041	-0.067	0.032	-0.167	-0.024	0.267
train3657	0.541	-0.251	0.436	-0.260	-0.329	0.158
train3659	0.639	0.009	0.162	-0.440	-0.134	0.276
train3661	0.396	-0.106	0.479	-0.248	-0.140	0.559
train3663	0.419	-0.313	0.485	-0.290	-0.290	0.015
train3665	0.429	-0.045	0.393	-0.367	-0.262	0.347
train3667	0.085	-0.363	0.202	0.028	-0.309	-0.162
train3673	0.309	0.068	0.301	-0.150	-0.487	0.388
train3675	0.385	-0.244	0.323	-0.541	-0.433	0.219
train3683	0.463	-0.158	0.136	-0.412	0.015	0.020

	train3625	train3627	train3633	train3635	train3639	train3641
train3627	0.095					
train3633	0.088	0.647				
train3635	0.181	0.510	0.240			
train3639	0.399	0.461	0.209	0.323		
train3641	0.353	0.400	0.315	0.386	0.638	
train3643	0.443	-0.261	-0.188	0.064	-0.059	0.085
train3647	0.116	0.290	0.223	0.196	0.152	0.359
train3649	0.554	0.077	-0.022	0.165	0.251	0.050
train3651	0.106	0.787	0.465	0.412	0.263	0.137
train3657	0.270	0.352	0.306	0.337	0.343	0.455
train3659	0.195	0.431	0.401	0.365	0.365	0.313
train3661	0.382	0.216	-0.025	0.353	0.504	0.401
train3663	0.416	0.691	0.287	0.614	0.638	0.683
train3665	0.135	0.481	0.322	0.382	0.626	0.631
train3667	-0.164	0.046	-0.211	0.182	0.313	0.308
train3673	0.258	0.320	0.132	0.377	0.419	0.163
train3675	0.123	0.292	0.226	0.083	0.516	0.485
train3683	0.315	0.474	0.667	0.361	0.188	0.574

	train3643	train3647	train3649	train3651	train3657	train3659
train3647	-0.015					
train3649	0.210	-0.155				
train3651	-0.285	0.281	0.376			
train3657	0.153	0.496	-0.063	0.079		
train3659	-0.045	0.101	-0.209	0.079	0.398	
train3661	0.212	0.414	0.302	0.192	0.545	0.300
train3663	0.112	0.229	0.302	0.538	0.322	0.225
train3665	-0.074	0.526	0.021	0.332	0.603	0.360
train3667	-0.003	-0.163	0.103	-0.120	0.184	-0.188
train3673	0.243	0.246	0.274	0.259	0.499	0.277
train3675	0.005	0.313	0.263	0.183	0.304	0.324
train3683	0.063	0.336	0.130	0.410	0.325	0.306

	train3661	train3663	train3665	train3667	train3673	train3675
train3663	0.368					
train3665	0.770	0.444				
train3667	0.167	0.308	0.325			
train3673	0.467	0.364	0.413	0.069		
train3675	0.306	0.402	0.457	0.268	0.543	
train3683	0.192	0.410	0.396	-0.201	0.163	0.235

Cell Contents
Pearson correlation

Figure 4. HWD external consistency test-retest method

Appendix B (Description of the employer & own functioning)

ProRail is responsible for the rail network of the Netherlands which contains construction, maintenance, management and security matters. it arranges all train traffic, building and managing stations and lay new tracks as well as maintain existing tracks, turnouts, signals.

ProRail provides a secure, reliable, punctual, durable and comfortable rail network in cooperation with carriers and partners. it works efficiently and cost-conscious to a rail network which makes people can have a pleasant trip and goods can be transported unrestricted. The track is essential for the accessibility of the densely populated Netherlands and surrounding countries. With relatively little space, ProRail make sure that 1.1 million daily train trips and 51 billion tons are made annually (https://www.prorail.nl)

My job is concerning about reliability of Hotbox detection. ProRail has Hotbox detection system installed in the railway network to prevent trains to derail caused by hot axles and hot wheels. The question is how to prove the temperatures measured are reliable. And how are the temperature measurements affected by other issues.

List of Acronyms

Acronym	**Definition**
HAHW	Hot Axle & Hot Wheel Detection
HBD	Hotbox Detection
HWD	Hot wheel Detection
RC	Rail Contactor
AEI	Auto Vehicle Identification System
MB	Multi Beams
RCA	Root cause Analysis
FTA	Fault Tree Analysis
FMEA	Failure Modes and Effect Analysis
MSA	Measurement System Analysis
R & R study	Reproducibility and Repeatability study