



DEPARTMENT OF CIVIL, ENVIRONMENTAL AND GEOMATIC ENGINEERING

## Semester Project Report

Data-driven identification and classification of rail surface defects

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# Acknowledgements

This semester project would not be possible without the help of my supervisors, Cyprien Hoelzl and professor Eleni Chatzi. I first reached out to Eleni for a semester project opportunity during ETH week – for the purpose of improving my skills in doing research. Shortly thereafter, I was introduced to her PhD student, Cyprien Hoelzl, about a project revolving around identifying and classifying defects on train tracks.

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# Chapter 1

## Introduction

Railway companies need to continuously and sufficiently maintain the train tracks and optimally detect defects in order to have a more punctual and more effective train system. However, the current track-condition assessment system is expensive, time consuming and ineffective, primarily involving manual inspection.

This condition assessment is evolving from a manual-labor based approach to a data-driven focused industrialized assessment. This paradigm shift from manual to data-driven approach is taking place at this current point in time, as more railway companies are making this transition and funding research within this area as seen in [13], [12], [1], [2].

Switzerland's *Swiss Federal Railways* (SBB), is one of those companies being a part of this paradigm shift. SBB has specifically built one special *Diagnostic Vehicle* (Diagnosefahrzeug - DFZ) designed for defect detection and identification among other purposes. For this, accelerometers have been installed at the front and back of the DFZ to collect the signal responses from the wheel and the train track (see appendix A.3).

A defect in train tracks can be seen as a discontinuity. As a train passes over this discontinuity, it will result in a perturbation that can be detected by sensors. It is our main assumption that each type of defect will have a specific signature that will allow its identification and classification. This is similar to the idea presented in [5], [10] about human activity recognition.

### 1.1 Objective

The objective of this project is to identify and classify rail surface defects. We aim to build an effective machine learning pipeline that takes information about defects as input and outputs a classification confidence for these defects. By successfully identifying and classifying the defects, we take one step further toward a predictive maintenance which will result in a more reliable network [11].

### 1.2 Defects

A defect can be seen as a deviation from a standard train track; and can be further sub-categorized based on official defect documentation [9] provided by *International Union of Railways* (UIC). Upon inspection of defective tracks, SBB inspectors reports defects

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with reference to the UIC-based, defect report document by SBB. An example of this can be seen in [A.4](#).

Generally, a defect is separated into two overarching types: range- and point-defects. I.e. a defect that is detected at a single point versus a defect that is detected at varying lengths. A point defect is perceived as a sharp signal response, whereas a range-defect is perceived over a greater time period.

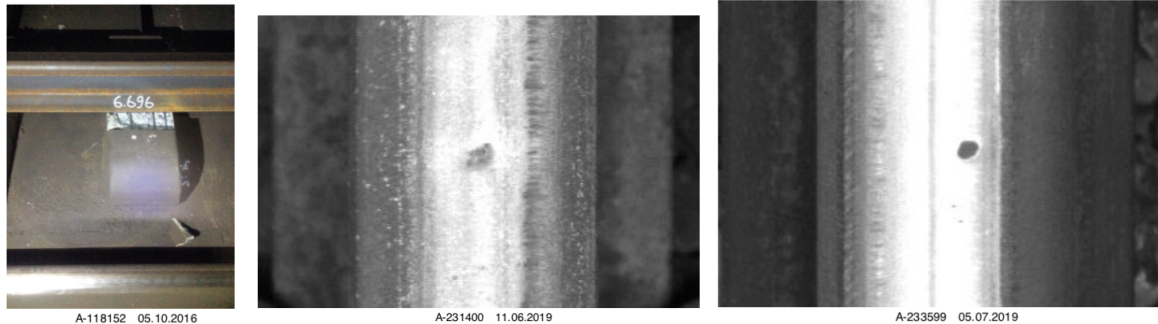


Figure 1.1: Left, middle, right:  
Schwelle: *Beschadigte Betonschwellen* (A-118152),  
Fahrbahn: *Verletzungen* (A-233599),  
Vignolschiene: *Verletzungen* (A-231400).

The format is: track component: *defect type* (defect ID). These have all been reported as defects (with subcategories) with a length equals to zero, and thus have been classified as point defects using our terminology. (Source of pictures: SBB's defect report document)





A-184063 27.05.2018



A-184063 27.05.2018



A-146358 14.10.2018



A-146358 14.10.2017



Figure 1.2: Top, middle, bottom:

Gleis-149.8m: *Head-Checking: Periodische Rissbildung / Ausbrechungen an der Fahrkante* (A-184063),

Schienenzwischenlage-5.0m: *Weiterer Abweichungstyp* (A-146358), Bankett-1169.5m: *Ungenügendes Schotterprofil* (A-103213).

The format is: track component-length: *defect type* (defect ID). These have all been reported as defects (with subcategories) with a length strictly greater than zero, and thus have been classified as range defects using our terminology. Most of these range defects have two pictures likely to give more detail. (Source of pictures: SBB's defect report document)

Furthermore, each defect is associated with a variety of attributes such as: associated component, defect component location, defect type etc. For this work, the focus has been on the defect component/category. That is, the track component with which the defect was identified on (see appendix A.1). This is, however, only a rough classification, as this attribute exists at a 'higher level', seeing that the lowest level of defect sub-division is the actual defect type (see appendix A.2 for a list of defect types).

The defect attribute for analysis is not a trivial choice, as the signal responses likely depend on the defect type its associated component, its location on the component. In the future, it will be important to account for other attributes. Albeit, this work only considers the defect components. In the following, 'defect' will thus refer to these defect components.

Finally, only the point defects are subject to analysis, as this simplifies the problem statement; range-defects and its associated factors are thus disregarded. In the future, range defects naturally also need to be taken into account.

### 1.3 Switches and insulation joints

To distinguish between defects and non-defects, this work also considers *switches* and *insulation joints*' seen in the figures 1.3 and 1.4. The defect signals can vary a lot depending on the component. In addition, these sample amounts are far less compared to that of switches and insulation joints. With the incorporation of these non-defects, we can thus have access to more samples, where these samples are suspected to have clearer signatures – easier to classify.

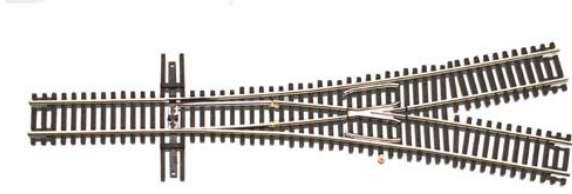


Figure 1.3: (Picture sources from right to left: [8], [6])

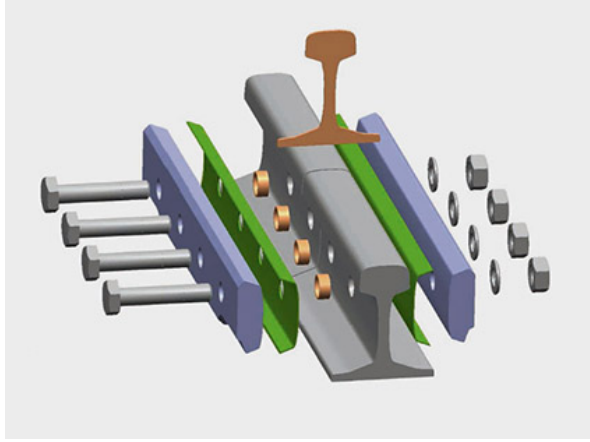


Figure 1.4: (Picture sources from right to left: [3], [4])

In this report, the word 'entity' will be used as an umbrella term for the different track entities: switch, insulation joint and defect.

## 1.4 Data

The data has been collected and provided by SBB. Using their DFZ, SBB has made trips back and forth to different cities in Switzerland in order to collect various data including but not limited to accelerometer data. After the data collection, the data is imported into a Python-VR object, which is composed of **pandas DataFrames**. Python objects with **pandas DataFrames** were chosen for their functional flexibility in terms of data storage and data accessibility.

The accelerometers capture the accelerations at the vertical (Z) and transversal (Y) axes (along with the timestamps at each recording), of which, only the Z axis was considered, as it is assumed to be the most responsive to vertical perturbations. These accelerometers are installed on both leading (axle 1) and trailing axles (axle 4) of the measurement coach. See appendix A.3 for visualisations of the accelerometer placements on the DFZ.

In this work, the following DFZ measurement rides in table 1.1 are used for classification.

---

From	To	Date	Campaign ID
Bern	Olten	2019-05-27T08_55_55	819Z DFZ01
Olten	Bern	2019-05-27T10_03_59	077Z DFZ01
Bern	Olten	2019-05-27T13_05_53	330Z DFZ01
Olten	Bern	2019-05-27T14_10_51	425Z DFZ01

Table 1.1: Measurement rides for classification. ('From' and 'To' are cities in Switzerland)

Lastly, defect attributes and locations were retrieved from SBB's database and synchronized with the measurement data.

## 1.5 Code

The code is written purely in python. To create neural network architectures, `keras` along with `tensorflow` is used. `keras` is essentially a high-level neural networks library which runs on top of `tensorflow`. It has a consistent, simple API and provides clear and actionable feedback upon user error. Models are easily made by connecting configurable building blocks together, with few restrictions [7]. The models were trained in `Google Colab`, which is a web application provided by Google that enables users to run python code in the web browser with access to GPUs<sup>1</sup>. It is very similar to `Anaconda's Jupyter Notebooks`, except that `Colab` runs in the browser, is collaborative and provides free usage of GPUs (meaning model training goes faster).

All the code can be found on github:

<https://github.com/Aiyualive/SemesterProject2.0>.

The specific model execution workflow can be found `Colab`:

[https://colab.research.google.com/drive/12VBz\\_KrJxeyR\\_pjpkC87fewv5aMSEI5\\_](https://colab.research.google.com/drive/12VBz_KrJxeyR_pjpkC87fewv5aMSEI5_)

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<sup>1</sup><https://colab.research.google.com/notebooks/intro.ipynb>

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## Chapter 2

# Design and Implementation

For the process of defect classification the pipeline in figure 2.1 was designed. In the next sections, an overview will be given of how each step was implemented.

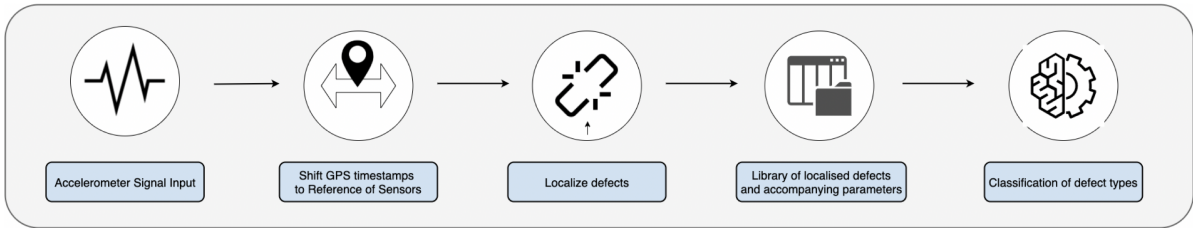


Figure 2.1: Primary pipeline

### 2.1 Localization of the DFZ

The vehicle is localized using the combination of multiple data streams: track transponders (Eurobalise) GPS signals, Odometers and Switch detection systems. The reported localization error has been determined to be quite small.

The location is reported with respect to the GPS Antenna of the vehicle which is close to the pantograph. It is reported along with a timestamp corresponding to the location of the vehicle at that time at the location of the antenna.

### 2.2 Shift of GPS timestamps

Since the exact position (covered distance) at each accelerometer at either side of the GPS antenna is unknown, the goal in this step is to compute these from the reported location of the DFZ. The GPS sensor is sampled at a lower frequency compared to the accelerometers (every 25 cm vs 24 kHz respectively). From this, the corresponding GPS positions for each accelerometer sample necessarily need to be found. This is done by linear interpolation using the timestamps of the accelerometers and GPS.

Depending on the direction of the vehicle, the offset between the accelerometers and the GPS sensor positions on the vehicle body is then added/subtracted to achieve the accelerometer positions.

---

## 2.3 Peak windows

Retrieving the signal response around the defect location forms a crucial aspect in the overarching pipeline. The goal of this step is to, around each defect, create a "window" containing accelerometer accelerations of a specified time length – wherein Within the highest acceleration recording around is found in the center. As a result, all of these windows would be uniform in the sense that they are all centered according to the highest recording of a defect. It is then assumed that each window forms the signature of each track entity.

Since we are assuming that each track entity is identified by a well-formed peak, we first need to find this peak within a reasonable offset from the defect location, after which we center around that within another reasonable offset.

In the code, this is done by defining two parameters: `find_peak_offset = 1` and `window_offset = 0.5`. I.e. given a defect timestamp, we search for the maximum, absolute acceleration recording that has occurred 1 second after and 1 second before the defect timestamp. Once the peak has been found, we then center it in a 1 second window (0.5 sec on each side).

## 2.4 Entity library

The peak windows arguably forms the central feature of the defect library. However, based on domain knowledge, other features like vehicle speed also needs to be considered for our neural network. Apart from the peak windows, we have likewise extracted other relevant features that might be useful for classification:

- **Timestamps:** timestamps for the sampled acceleration
- **Acceleration:** sampled acceleration at axle box.
- **Vehicle speed (m/s):** vehicle speed at the closest timestamp
- **Severity:** Urgency of the entity; defects have an urgency label signifying how much time is left before acting; labels 1, 2, 3, 4, where urgency decreases in ascending order. Insulation joints and switches have been self-engineered with label 5 – all entities need to have the same feature column for training.

Additional information about each entity has been retrieved as well, such as: driving direction, corresponding entity IDs etc. For each entity, we crucially set a true, class label such that we are able to do supervised learning.

Given a specific measurement ride object, we either retrieve each feature directly from the corresponding `dataframe` or with the use of designated helper functions for those requiring extra processing. Currently, we have have a 2-level nested `for loop`, looping for each axle outerly, and looping for each entity entry innerly.

The implementation of this could have made more elegant by operating directly on the dataframe, which might also increase speed of the implementation as the `pandas` library has optimised their dataframe operations. The However, speed and efficiency was not a major concern in this project.



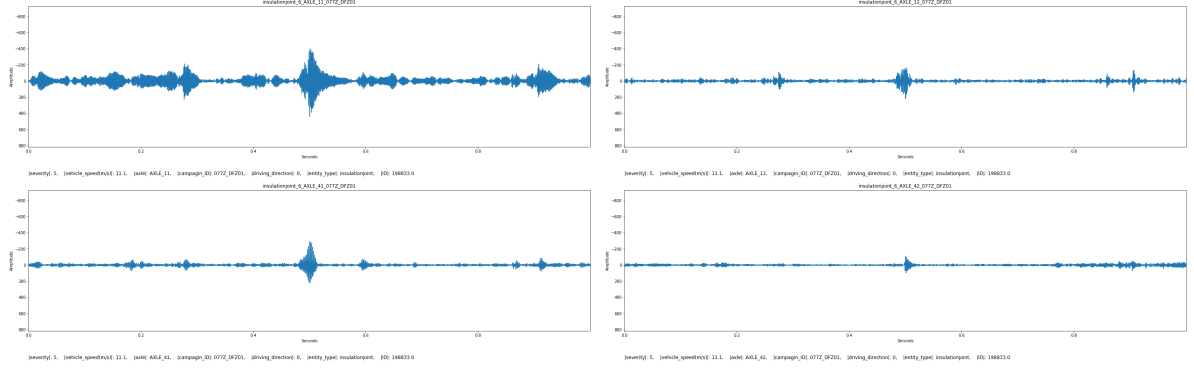


Figure 2.2: Insulation Joint

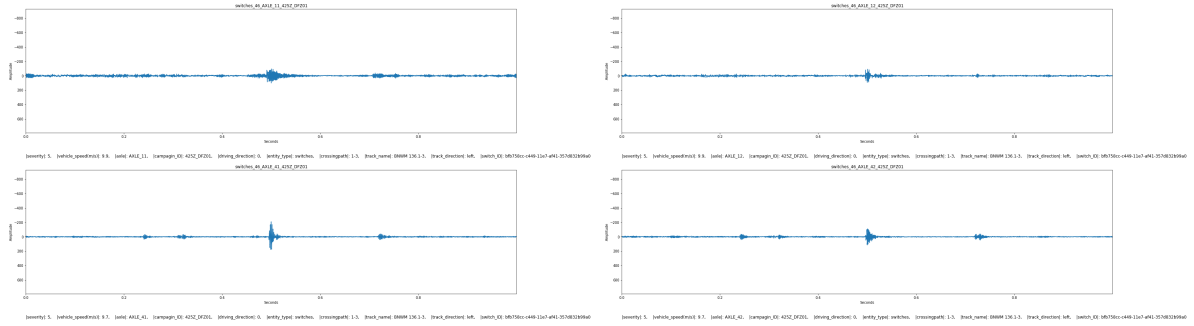


Figure 2.3: Switches

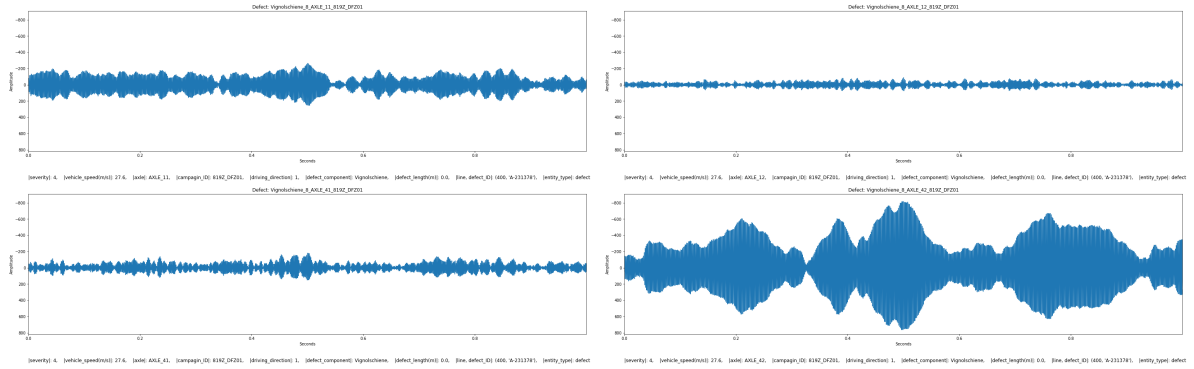


Figure 2.4: Defect: vignolschiene

## 2.5 Classification

We have created a primary NN class (short for neural network) along with a `ModelMaker` class. The former does everything from pre-processing the data to evaluating the used model. The latter, as the name suggests, is utilised for creating and using different models, which is useful as we can keep track of how the models have been modified and improved.

---

### 2.5.1 NN class

To make a classification, we first need to select the relevant features. Then we simply feed the features into an NN object, where the API of the NN class can be called for classification. The usage of the NN class is demonstrated below in 2.1.

API of NN class	
<code>__init__()</code>	initialises a NN object
<code>prepare_data()</code>	pre-process data, this includes standardisation of data
<code>make_model()</code>	uses <code>ModelMaker</code> class to select a model
<code>fit()</code>	trains the model
<code>classify()</code>	uses the trained model to classify on a test set
Other utility API functions	
<code>measure_performance()</code>	currently only on validation data
<code>plot_metrics()</code>	
<code>plot_confusion_matrix()</code>	
<code>load_weights()</code>	
<code>load_model_()</code>	
<code>save_history()</code>	
<code>save_model()</code>	
<code>save_classification_to_csv()</code>	
<code>run_experiment()</code>	evaluates the given model for a # of repetitions

Table 2.1: To train a model, the first API functions needs to be called sequentially. Other utility functions are rather self-explanatory.

### 2.5.2 ModelMaker class

As mentioned in the introduction 1.5, this is where we make use of `keras`.

epochs, batch size

conv 1 d,

kernel size

filter

flatten

dropout

sequential model

maxpooling

dense

loss

learning rate

activation functions

shape

See example of this in next chapter.

callbacks - when training



---

## 2.6 Visualisation

Finally, after evaluating the results (results can be seen in the next section) from the neural network, we have not achieved any significant results. Arguably, the visualisations of class separability should have been handled first. However, the previous steps took the majority of the time.

using PCA



---

# Chapter 3

## Evaluation

Here we will present the results and discuss the findings herein.

### 3.1 Models

Layer	Output Shape	Number of params
-	-	-

Table 3.1: Model 1

Draw models <http://alexlenail.me/NN-SVG/AlexNet.html>

do one  
model  
at a  
time

### 3.2 Model evaluations

Defect	2	%
--------	---	---

Table 3.2: Entity distribution, class distributions

In this section we evaluate our model with regard to a variety of metrics: loss (**L**), accuracy (**ACC**), true positives (**TP**), false positives (**FP**), true negatives (**TN**), false negatives (**FN**), precision (**P**), recall (**R**), area under the curve (**AUC**).

---

Model Metric	Model 1			
L	—	—	—	—
ACC	—	—	—	—
TP	—	—	—	—
FP	—	—	—	—
TN	—	—	—	—
FN	—	—	—	—
P	—	—	—	—
R	—	—	—	—
AUC	—	—	—	—
Relative diff?	—	—	—	—

Table 3.3: Average metrics times and their standard deviations in parenthesis - rel diff?

### intermediate results

Results model 1, only defects, new dataset

>>> Summarize results <<<

Overall loss: 2.969% (+/-0.009)

Overall acc: 0.074% (+/-0.014)

Overall true\_positives\_10: 0.300% (+/-0.458)

Overall fp: 0.600% (+/-0.917)

Overall tn: 3609.400% (+/-0.917)

Overall fn: 189.700% (+/-0.458)

Overall precision: 0.175% (+/-0.317)

Overall recall: 0.002% (+/-0.002)

Overall auc: 0.568% (+/-0.007)

Results model 1, only ins joints and switches, new dataset

>>> Summarize results <<<

Overall loss: 0.691% (+/-0.001)

Overall acc: 0.587% (+/-0.000)

Overall true\_positives\_11: 155.000% (+/-0.000)

Overall fp: 109.000% (+/-0.000)

Overall tn: 155.000% (+/-0.000)

Overall fn: 109.000% (+/-0.000)

Overall precision: 0.587% (+/-0.000)

Overall recall: 0.587% (+/-0.000)

Overall auc: 0.572% (+/-0.031)

average plots

## 3.3 Visualisation of class clustering

insert the pca plots

---

## 3.4 Discussion

Data amount, circumvent: could self-engineer data.

should have done visualisation first, if we have clear cluster separation, applying a neural network would be a bit exaggerated. And in that case, we could opt for a simple multi class support vector machine from the `sklearn` library. However, using `tensorflow` was the plan from the get-go as it is more industrially-applicable, so we disregarded simpler methods.

ensure that data is uniform. That is, some of the data has calibration and some hasnt.

more sophisticated use of features.

Look more into defect types, its specifics

Sometimes the defect can only be detected from one side of the track – AX11 and AX12 as one defect crossing sample with two signatures seen from different location. This would help in cases where the defect is only on one side of the track.

Many a times the validation set is used as the test set, but it is not good practice. The test set is generally well curated. It contains carefully sampled data that spans the various classes that the model would face, when used in the real world.



---

# Chapter 4

## Conclusion and future work

### 4.1 Conclusion

Results were quite mediocre, but has a lot of room for improvement. I am sure that given more time I would be able to explore and evaluate the results further.

- how good is the foundation to move onwards with further research

- library code is built in an extensible form

- overlap between switch and insulation joints

You are on tracks which are "brand new- built in 2006-2018". so the defects are all minor. The new measurement data we recently got would work much much better since they drove on pretty bad bad bad stuff :)

### 4.2 Future work

There is still a lot of work that needs to be done in this project. These are summarised in the next sub-sections – in no particular order.

#### 4.2.1 Channels

It might be interesting to consider sensor fusion of the ZY axes and the axle channels (8 total channels). The transverse axis, Y, would especially be valuable for switches as this channel can pick up sideways hits in the case of switches. These switch signals are clearly different from that of the other entities and may thus be easily separable.

In this project, only the accelerometer accelerations at the axle-boxes were considered. However, the other accelerometer sensors higher up in the vehicle: bogie(Z, Y) and body (Y) (see appendix [A.3](#)), will also be worth analyzing.

#### 4.2.2 Peak windows

we must not set the findpeakoffset too high

- track entity dependent/specific window offsets

- tune the peak finding parameters

- the window offset can be very small (as small as possible without losing the peaks).

Otherwise you will merge too many peaks using the peakfinder. 0.5 or even 0.1 should be ok.

---

### 4.2.3 Identification of infrastructure

### 4.2.4 Real-world simulated defects

I have participated in ETH Hatchery <sup>1</sup>, where our team built a prototype with a model train. We let the model train drive on the track with self-engineered defects.

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<sup>1</sup><https://sph.ethz.ch/eth-week-hatchery/>



---

## 4.3 TODO

- PCA plots and get better results
- add speed as a feature
- visualise what the network is doing using Harry's code
- concat all the axle channels and train on them
- try to use low pass filter - (would make everything faster)
- account for severity
- get rid of we



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# Appendix A

## Introduction

### A.1 List of defect components

Insulation Joint	1
Switches	2

Bankett	2
Befestigung	3
Dienstweg	4
Entwässerungsgraben	5
Fahrbahn	6
Gleis	7
Gleisbettung	8
Herzstück	9
Herzstückspitze	10
Kleber	11
Schiene	12
Schienenzwischenlage	13
Schotter	14
Schweißverbindung	15
Schwelle	16
Stockschiene	17
Vignolschiene	18
Weiche	19
Zungenschiene	20

Table A.1: Defect components along with class labels

---

## A.2 List of defect types

AT-Schweissung mit Squat
Ausbruch in der Zunge
Bankett
Beschädigte Betonschwellen
Entwässerung oder Wasserkanal verstopft
Gleisgeometrie
Grundparameter
Gleisgeometrie, Spurweite
Gleisgeometrie, Standardabweichungen
Head-Checking: Periodische Rissbildung / Ausbrechungen an der Fahrkante
Isolierstoss mit Berwalzung
Kilometer-, Hektometer- oder Metertafeln
Lose/fehlende Schienenbefestigung
Lose/fehlende Schwellenbefestigung
Mitten in der Schienenlänge: Oberflächenfehler
Mitten in der Schienenlänge: Schleuderstellen oder Schnellbrems Spuren
Mitten in der Schienenlänge: Squat / Rissbildung und örtliche Einsenkung der Lauffläche
Oberflächlicher Fehler (Flgelschiene oder Herz)
Schienenende: Sprundbruch
Schienenende: Verquetschung
Schienenende: örtliche Einsenkung der Lauffläche
Schotter auf Schwellen
Schotterfließen, weisser Schotter
Ungleiches Schotterprofil
Verletzungen
Weiterer Abweichungstyp
Zungenspitze angefahren

Table A.2: Defect types

---

## A.3 Vehicle and accelerometer placements

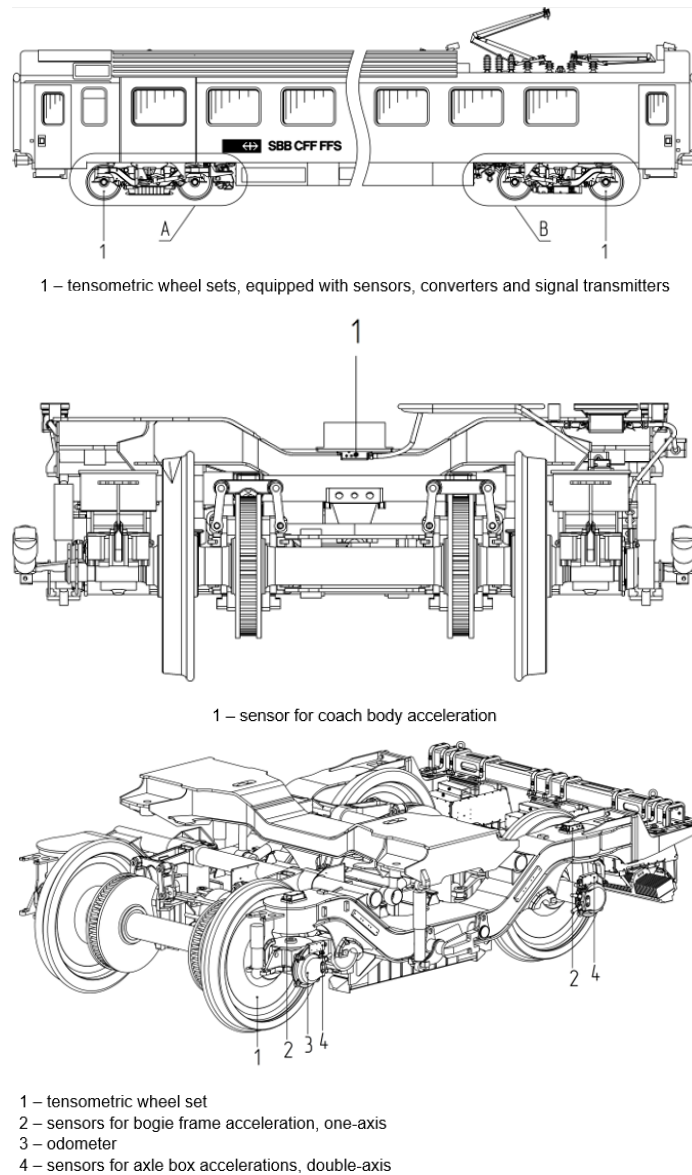


Figure A.1: Illustrations of the accelerometer placements on the DFZ. For this project we have only considered axle number 4 in the third figure. (Source of picture: SBB documents)

## A.4 SBB defect report example

<b>A-103213 (Offen ohne Massnahme)</b>		Exportdatum: 26.09.2019 10:50	
<b>Objekt-Infos</b>		Av-Region:	RME-FB-Lyss
Inspektionsobjekt:	AESP 284.2 - WANZ 112.2	Massnahmen-ID:	
Anlagenstrukturelement	Bankett		
<b>Position der Abweichung</b>		<b>FS-spezifische Positionsfelder</b>	
Linie:	400 Löchlüt - Wanzwil - Rothrist West	Gleis:	
km von:	17.2 km bis: 18.4	Weiche:	
Positionierung:	Keine Positionierung	Mast:	
Position:		FL-Sektor:	
<b>Informationen zur Abweichung</b>			
Abweichungstyp (DE):	Ungenügendes Schotterprofil	Entdeckungsart:	Av - Anlagenverantwortlicher
Schweregrad:	6	Erste Feststellung am:	30.04.16 07:09 durch: Christian Schärli
Dringlichkeit:	4	Letzte Feststellung am:	14.10.18 11:53 durch: Christian Schärli
Bemerkung:	Fast die ganze Länge am tiefen Strang	Massnahmenidee:	
<b>FB-spezifische Informationen zur Abweichung</b>		<b>Ausführung durch</b>	
SCDE Relevant:	Nein	U-Nummer:	
<b>Ultraschallfelder</b>		Datum:	
Notverlaschen:	Nein	Unterschrift:	
In Garantie:	Nein		
Qualität:			
Schienenprofil:	SBB VI bzw. EN 60 E1/E2		
Frist:			
Radius:	3197.9		
Prüfungsart:			
Hersteller:			
Jahr:			

Figure A.2



A-103213 25.03.2017

Figure A.3: A typical report for an arbitrary defect usually contains one description page followed by its picture(s)



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## A.5 Implementation



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# Appendix B

## Evaluation

<div>run #</div> <div>Metrics</div>	L	ACC	TP	TN	FP	FN	P	R	AUC
1	—	—	—	—	—	—	—	—	—

Table B.1: Experiment result of 10 runs

confusion matrix, epoch plots