
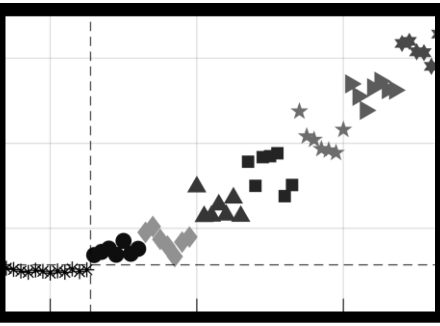


AI-Enhanced Condition Monitoring of Railway Infrastructure Using Onboard and Wayside Systems

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ISEP

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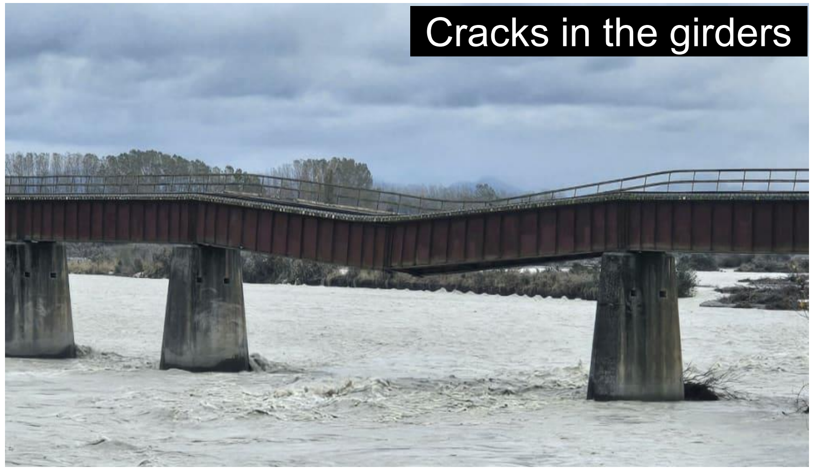
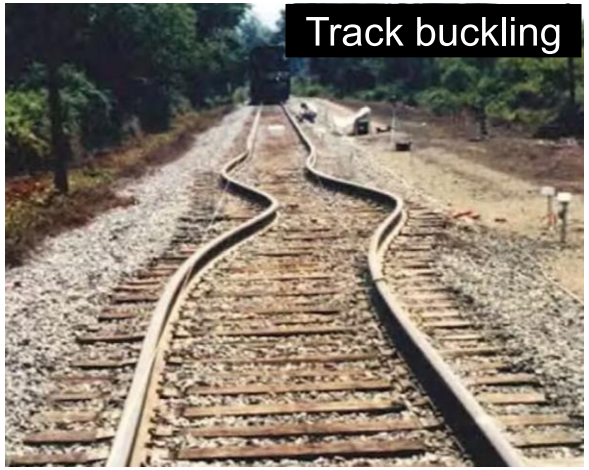
Contents

1. Introduction

Bridge & track damages





Increase in bridge & track inspections and repair interventions by railway infrastructure managers worldwide

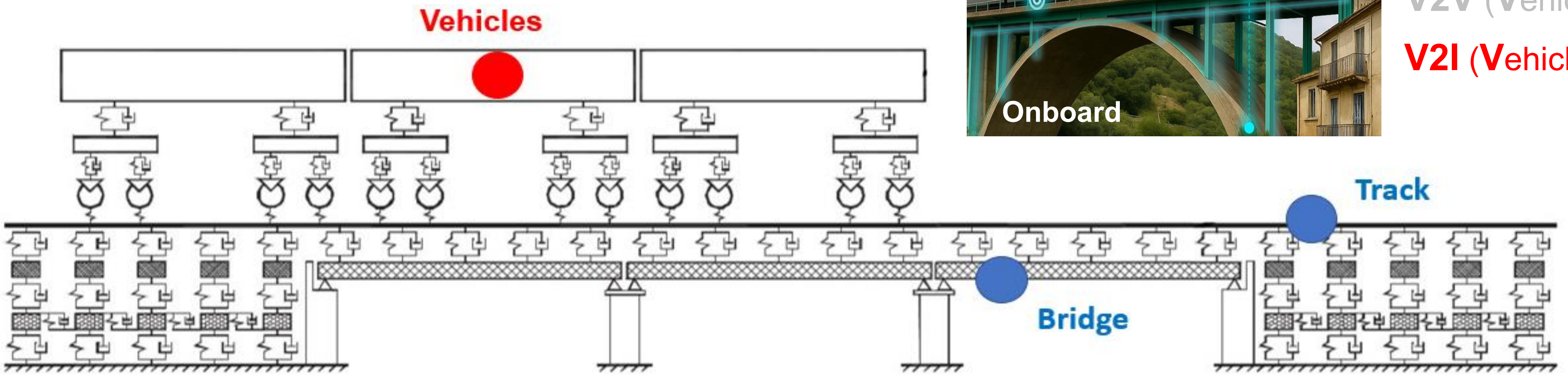
1. Introduction

Onboard vs direct monitoring

Condition monitoring strategies

V2V (Vehicle-to-Vehicle)

V2I (Vehicle-to-Infrastructure)

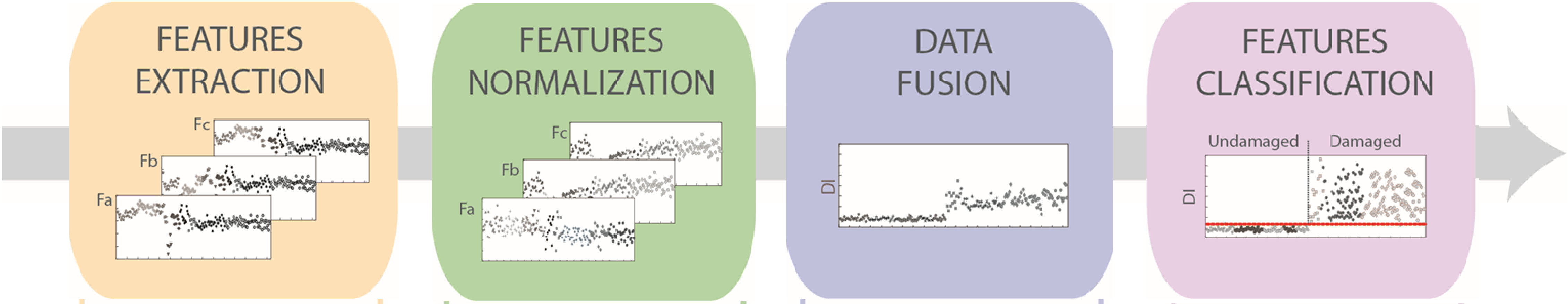


I2V (Infrastructure-to-Vehicle)

I2I (Infrastructure-to-Infrastructure)

2. AI-based damage identification methodology

Overview



CLASSIC METHODS
Basic Modal Properties
Statistical features

ADVANCED METHODS
Time Series Models (AR, ARX)
Continuous Wavelet Transform (CWT)
Principal Component Analysis (PCA)
Mel-frequency cepstral coefficients (MFCC)

INPUT-OUTPUT
Multivariate Linear Regression (MLR)

OUTPUT-ONLY
Principal Component Analysis (PCA)

Mahalanobis Distance (MD)
1st level – features fusion
2nd level – sensors fusion
3rd level – different type of data fusion (acceleration, strains, etc.)

Outlier Analysis
(statistical threshold)

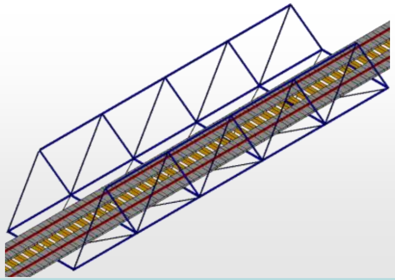
Cluster Analysis

3. Onboard monitoring systems

Use cases

Degradation in a Warren truss bridge

Numerical



Track degradation in Ferrovia Tereza Cristina (Brazil)

Experimental

3. Onboard monitoring systems

Degradation in a Warren truss bridge

Main challenges

- Ability to detect damage on bridges using the dynamic responses of **freight service vehicles** with operating speeds typically less than 100 km/h.
- Use of **experimentally calibrated numerical models** for the bridge and vehicle.
- Introduction of damage in **primary and secondary components** for more precise identification and efficient maintenance.
- Consideration of a **broader range of EOVs**.

3. Onboard monitoring systems

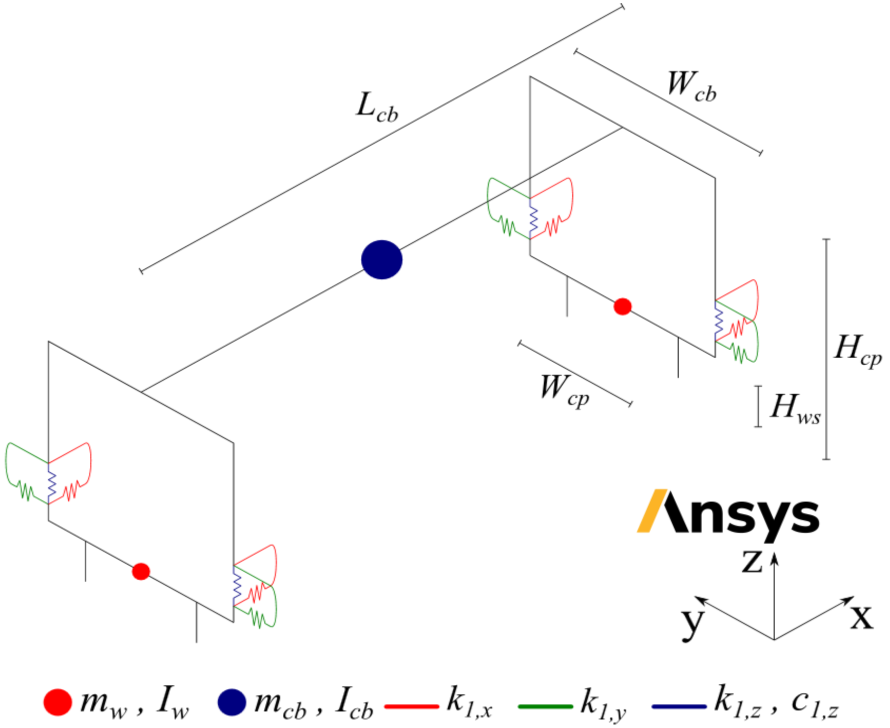
Degradation in a Warren truss bridge

Freight vehicle

- Laargss freight wagon for container transportation
- Total length: 14.8 m
- 2-axles spacing 10 m
- 4-sets of progressive stiffness parabolic springs
- Max. load capacity: 52 t

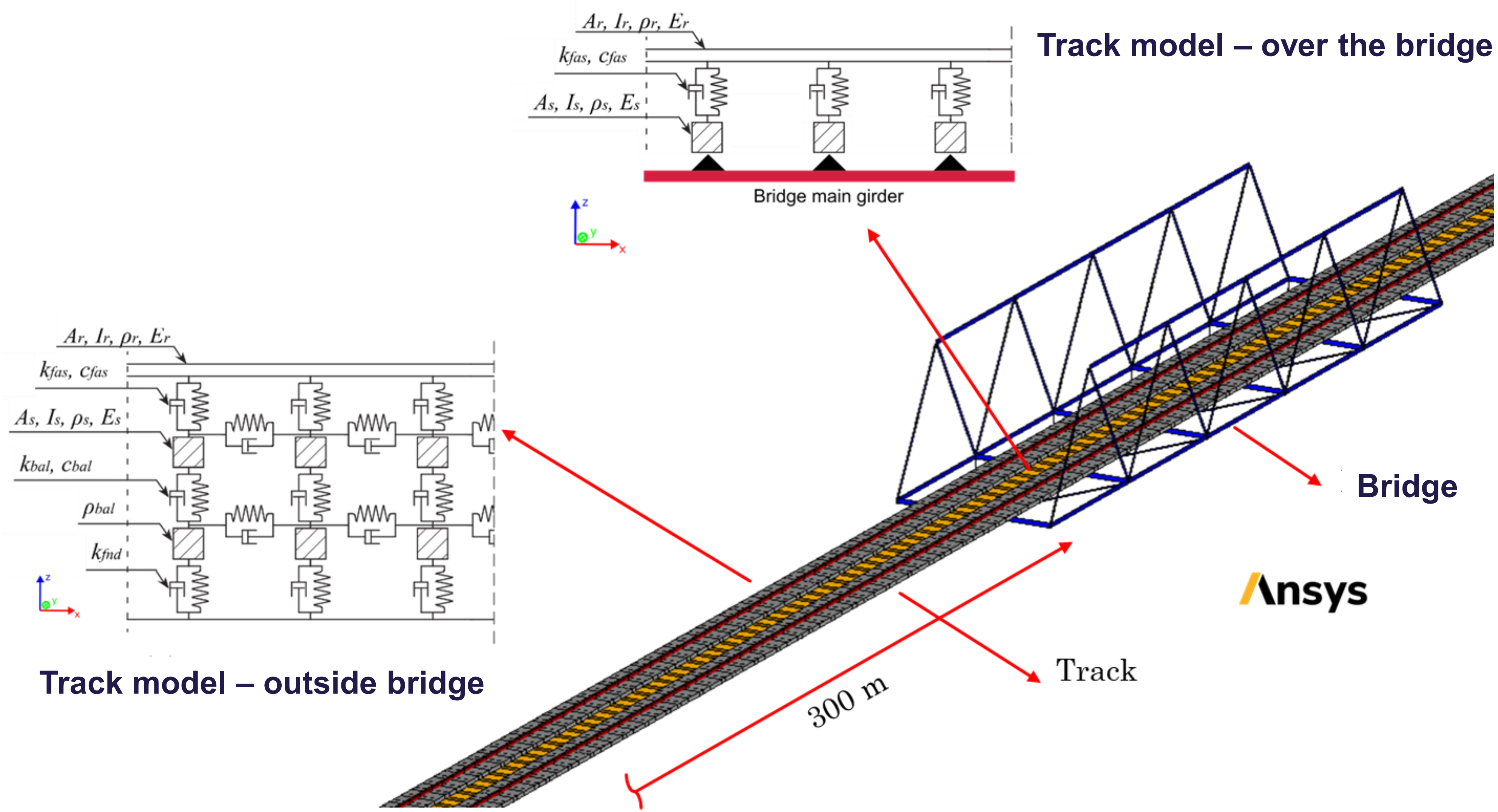
Numerical model

- 3D rigid body model
- Rigid bars: platform and axles
- Spring-dashpot assemblies: primary suspensions



3. Onboard monitoring systems

Degradation in a Warren truss bridge



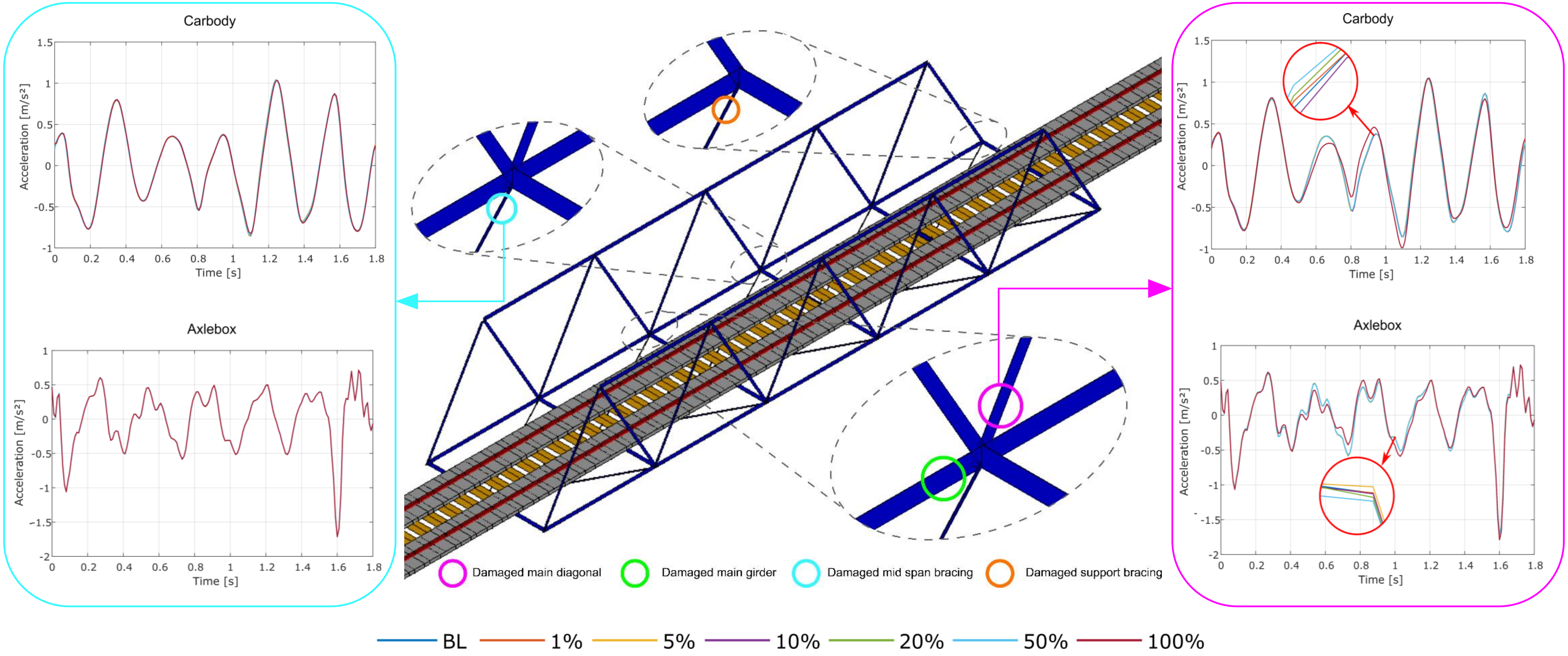
3. Onboard monitoring systems

Degradation in a Warren truss bridge

Condition	Baseline		Damaged
	Undamaged	Slightly damaged	
LAAGRSS type wagons	5	5	5
Speeds (km/h)	45/50/55	45/50/55	45/50/55
Irregularity profiles	2	1	1
Wagon mass variation (%)	90/95/100/105/110	90/95/100/105/110	90/95/100/105/110
Change in modulus of elasticity w/ temperature (‰)	975/1000/1025	975/1000/1025	975/1000/1025
Positioning accuracy (m)	±1	±1	±1
Measurement noise (%)	5	5	5
Damage severities (%)	-	< 0.5	1/5/10/20/50/100
Individually damaged elements	-	4	4
Number of simulations	90	1,260	1,080 (4x270)

3. Onboard monitoring systems

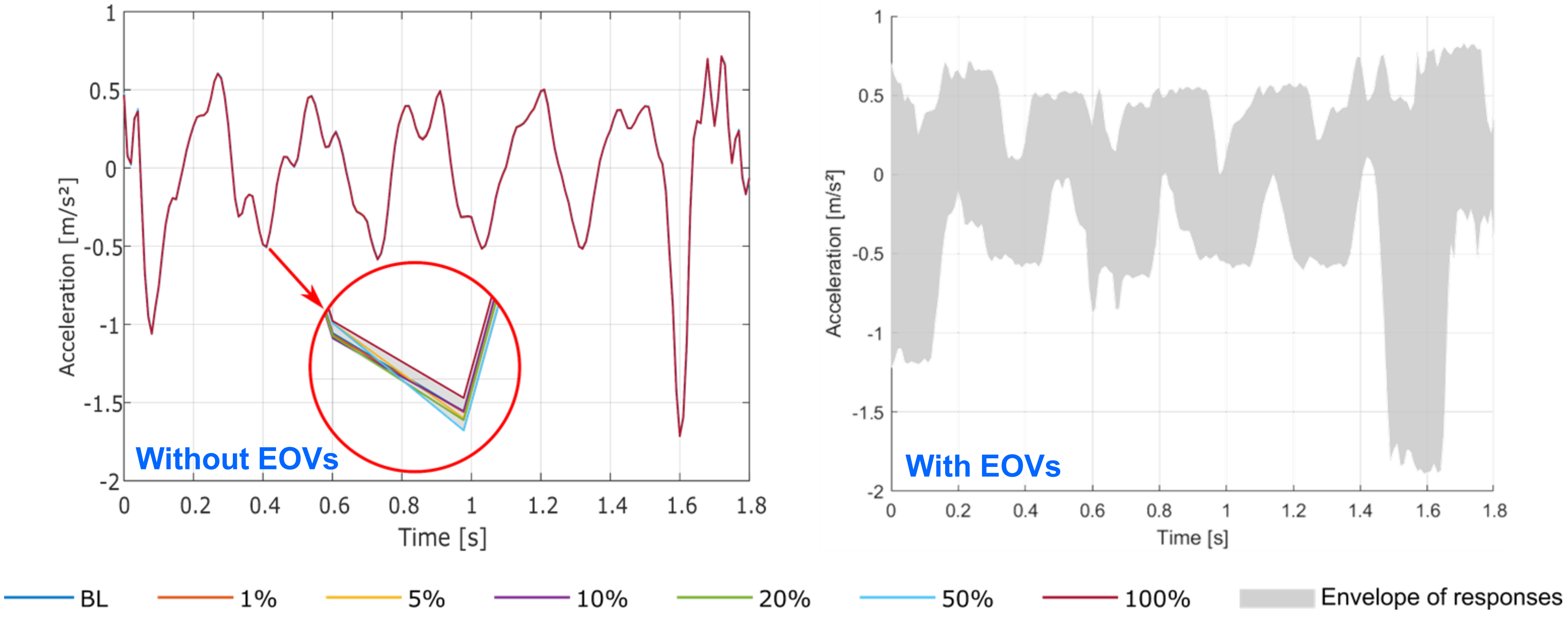
Degradation in a Warren truss bridge

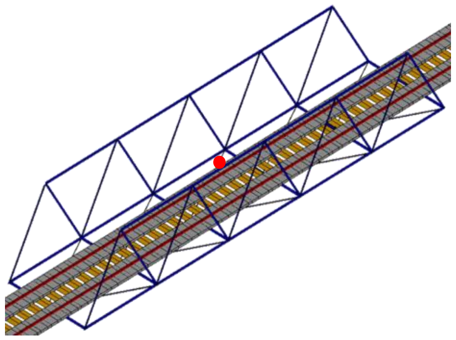


3. Onboard monitoring systems

Degradation in a Warren truss bridge

Challenge of removing the **influence of operational and environmental variabilities** from the carbody's dynamic response



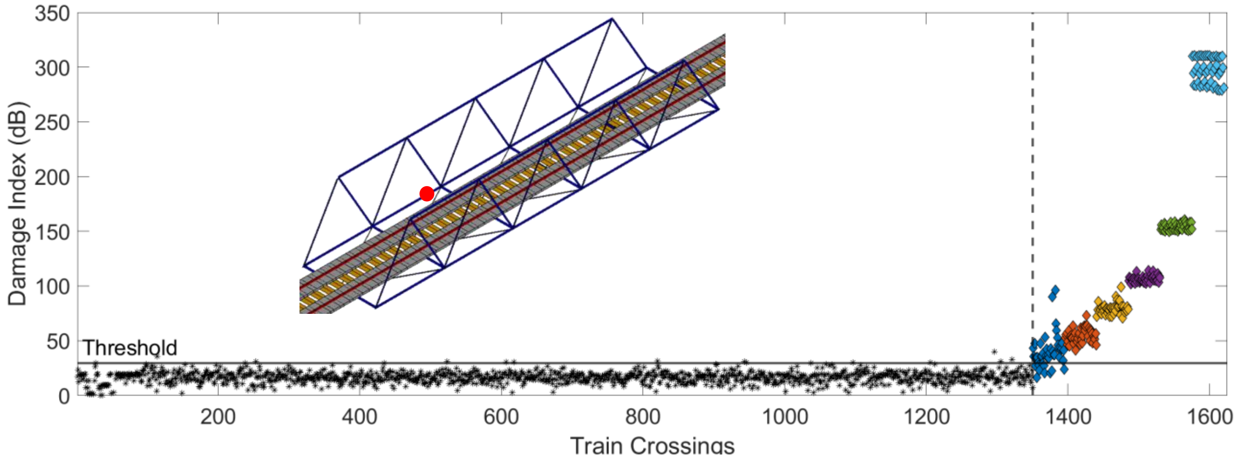


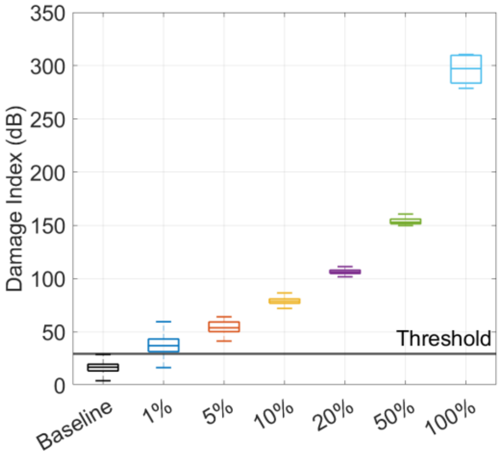
EOVs
- Train speed
- Irregularity profiles
- Wagon mass variations
- Temperature
- Positioning accuracy
- Measurement noise
- Manufacturing imperfections

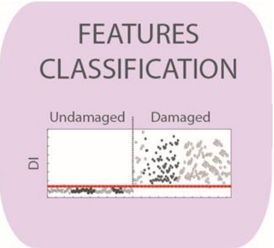
3. Onboard monitoring systems

Degradation in a Warren truss bridge

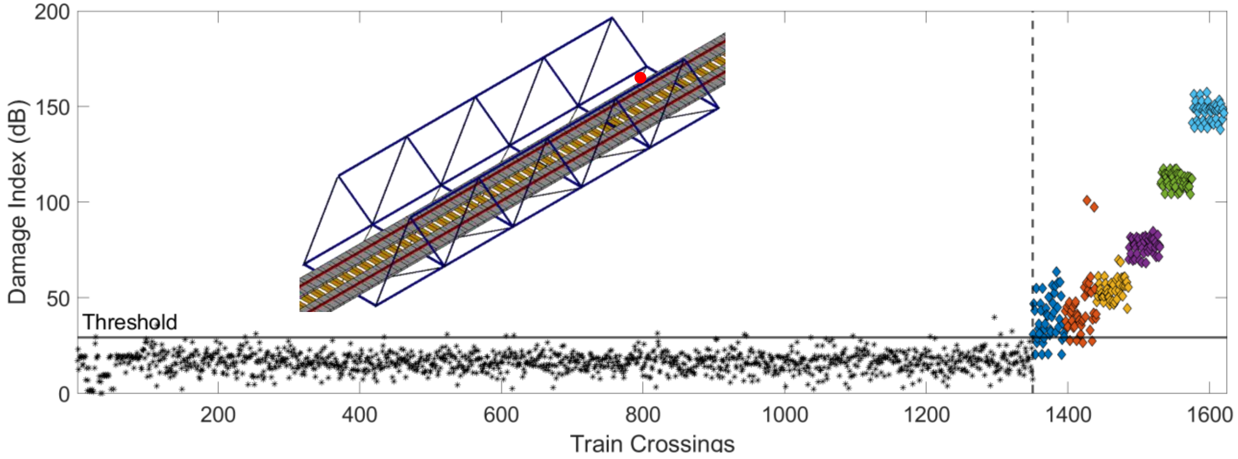
Damaged **main girder**

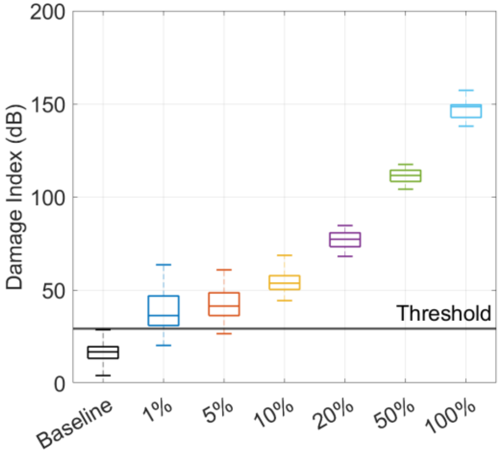






Damaged **support bracing**





3. Onboard monitoring systems

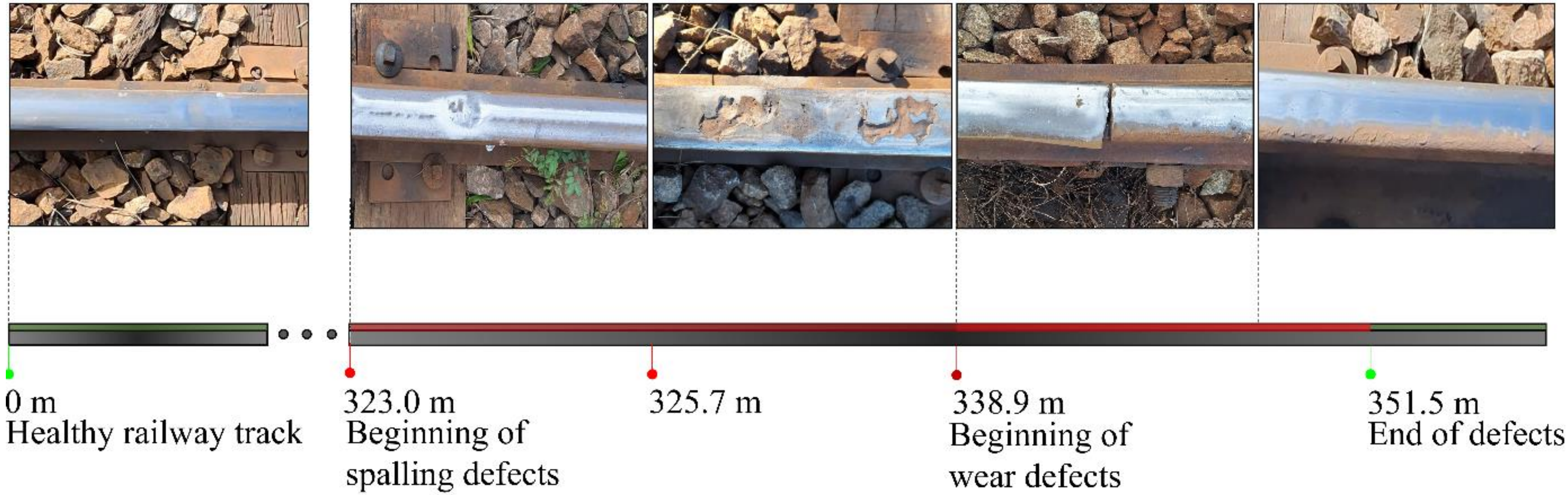
Track degradation in Ferrovia Tereza Cristina (Brazil)

Track information		
	General information	**Location:** South of Brazil **Built in:** 1953
	Track	**Gauge:** 1,000 mm **Sleepers:** Wooden **Foundation:** Ballasted track

3. Onboard monitoring systems

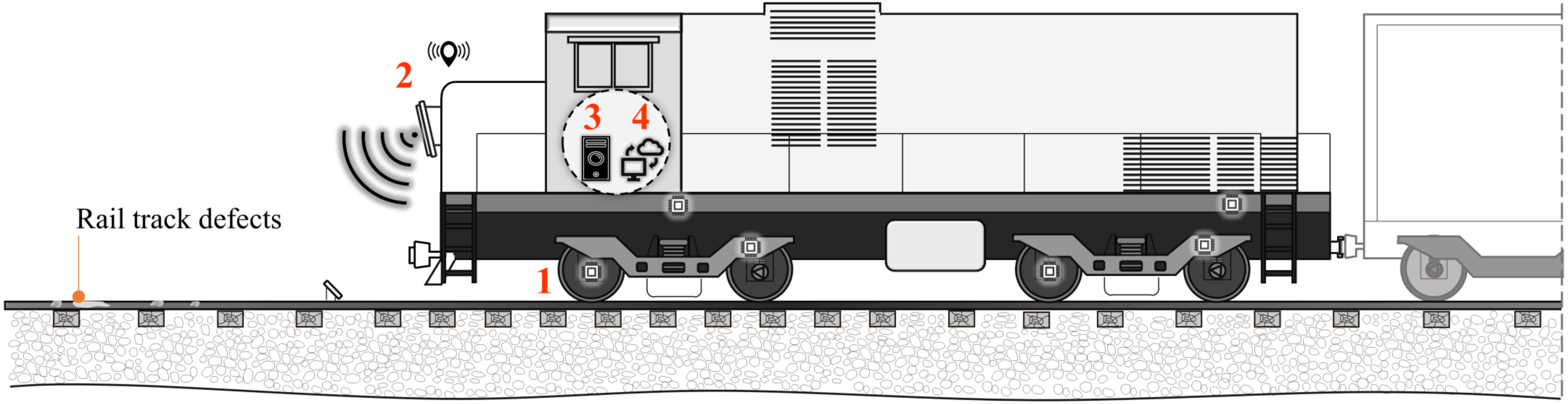
Track degradation in Ferrovia Tereza Cristina (Brazil)

Track damages



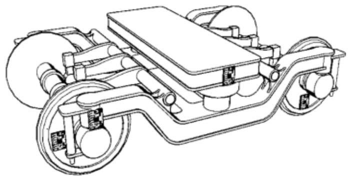
3. Onboard monitoring systems

Track degradation in Ferrovia Tereza Cristina (Brazil)



1. Sensors

- 12 uniaxial accelerometers
- Car body, bogies and axle box placements



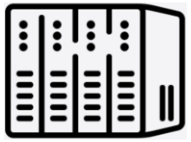
2. Trigger

- RFID

- GPS-based

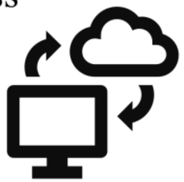
3. Data Acquisition

- Modular system inside of locomotive (16 channels)
- 1 kHz sampling rate



4. Communication

- 3G and Wi-fi antennas
- Cloud storage
- Remote access
- GPS tracking



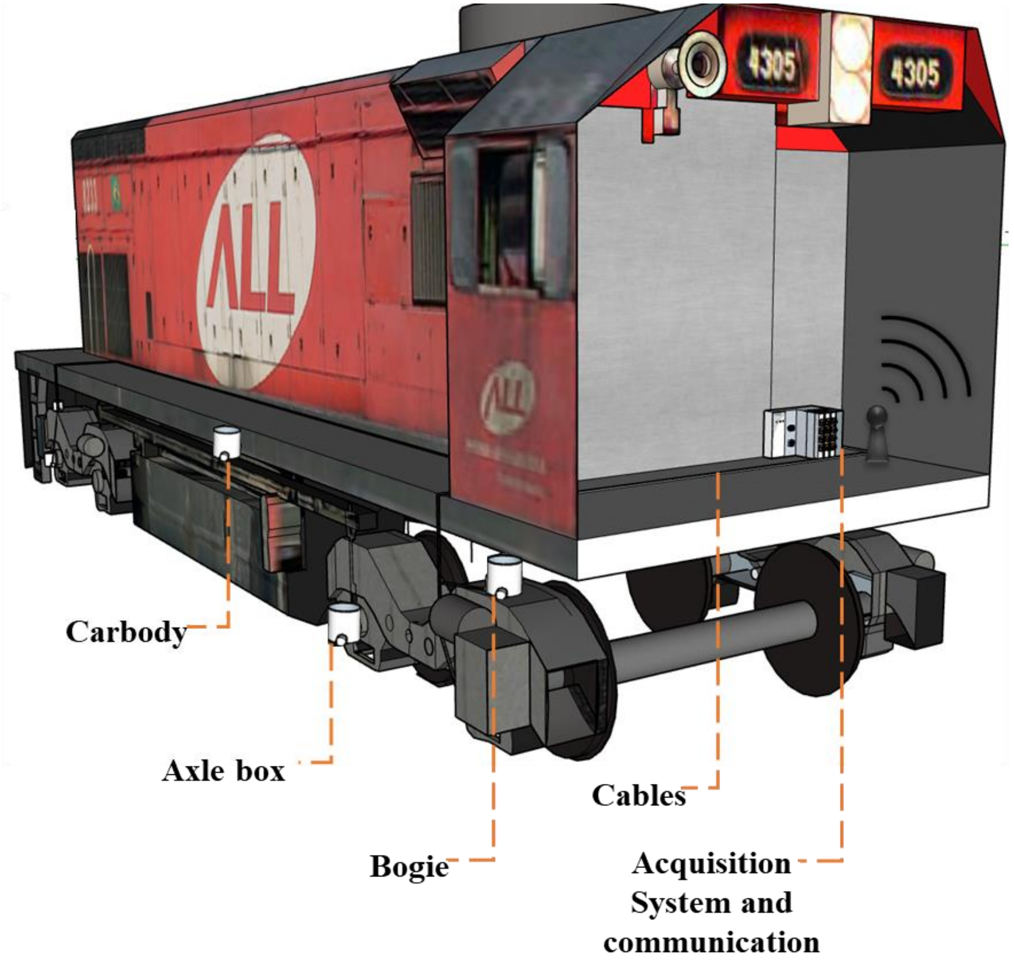
3. Onboard monitoring systems

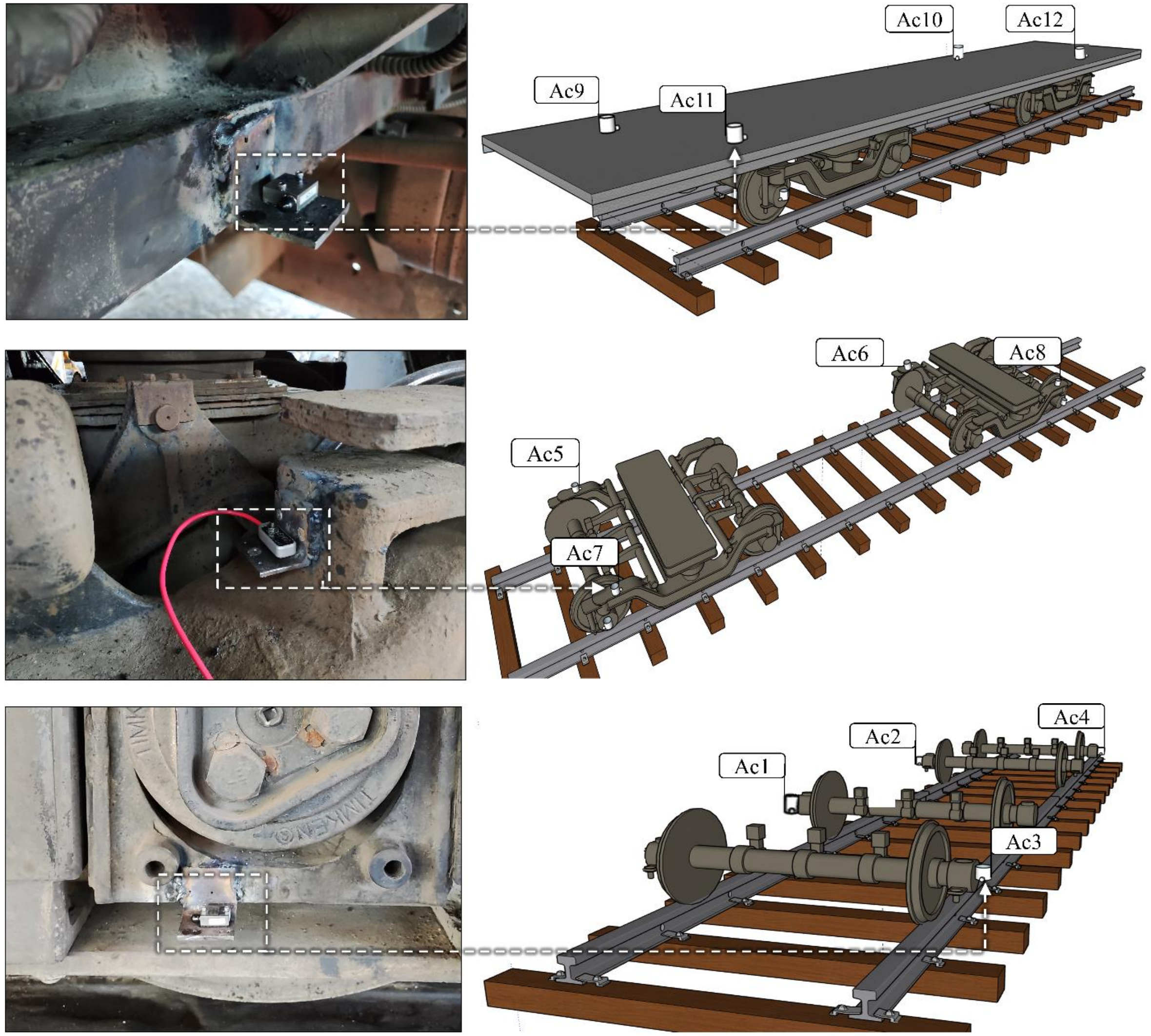
Track degradation in Ferrovia Tereza Cristina (Brazil)

3. Onboard monitoring systems

Track degradation in Ferrovia Tereza Cristina (Brazil)

Sensors





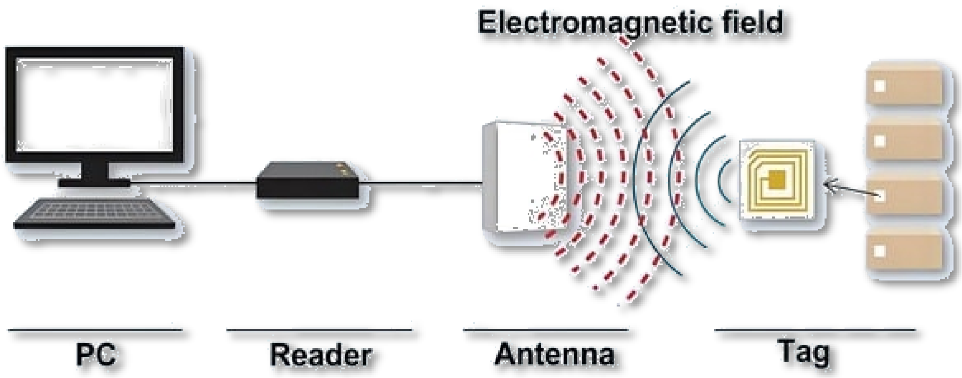
3. Onboard monitoring systems

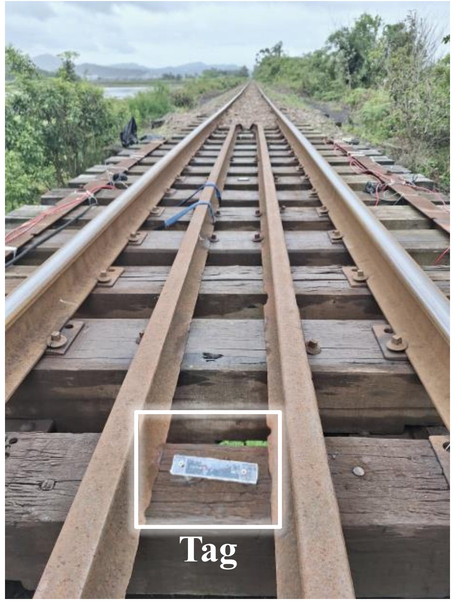
Track degradation in Ferrovia Tereza Cristina (Brazil)

Communication system: 3G Modem, WiFi antenna, cloud storage service & remote desktop service

Tracking system: GPS

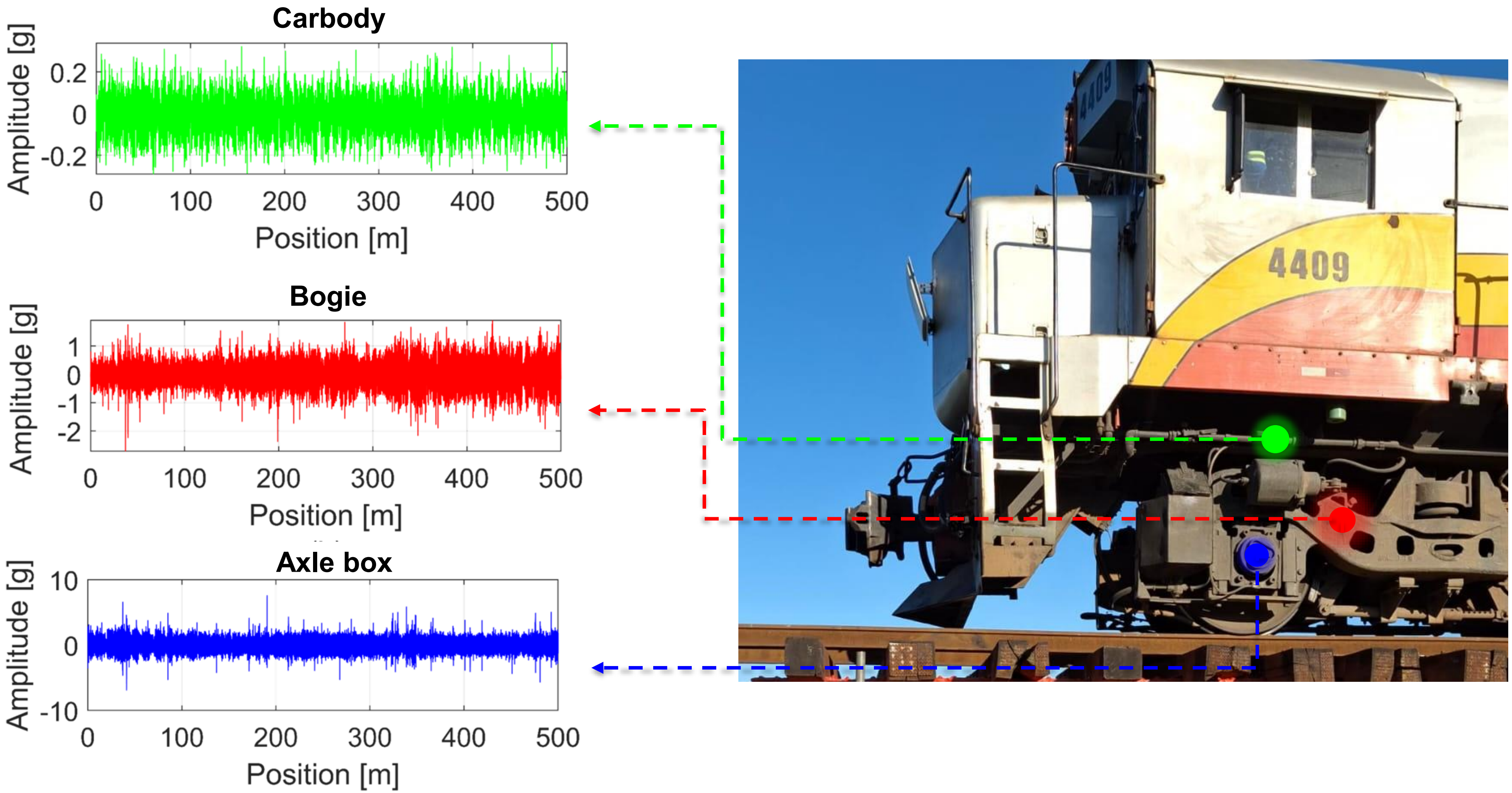
Trigger system: data logging & speed estimation





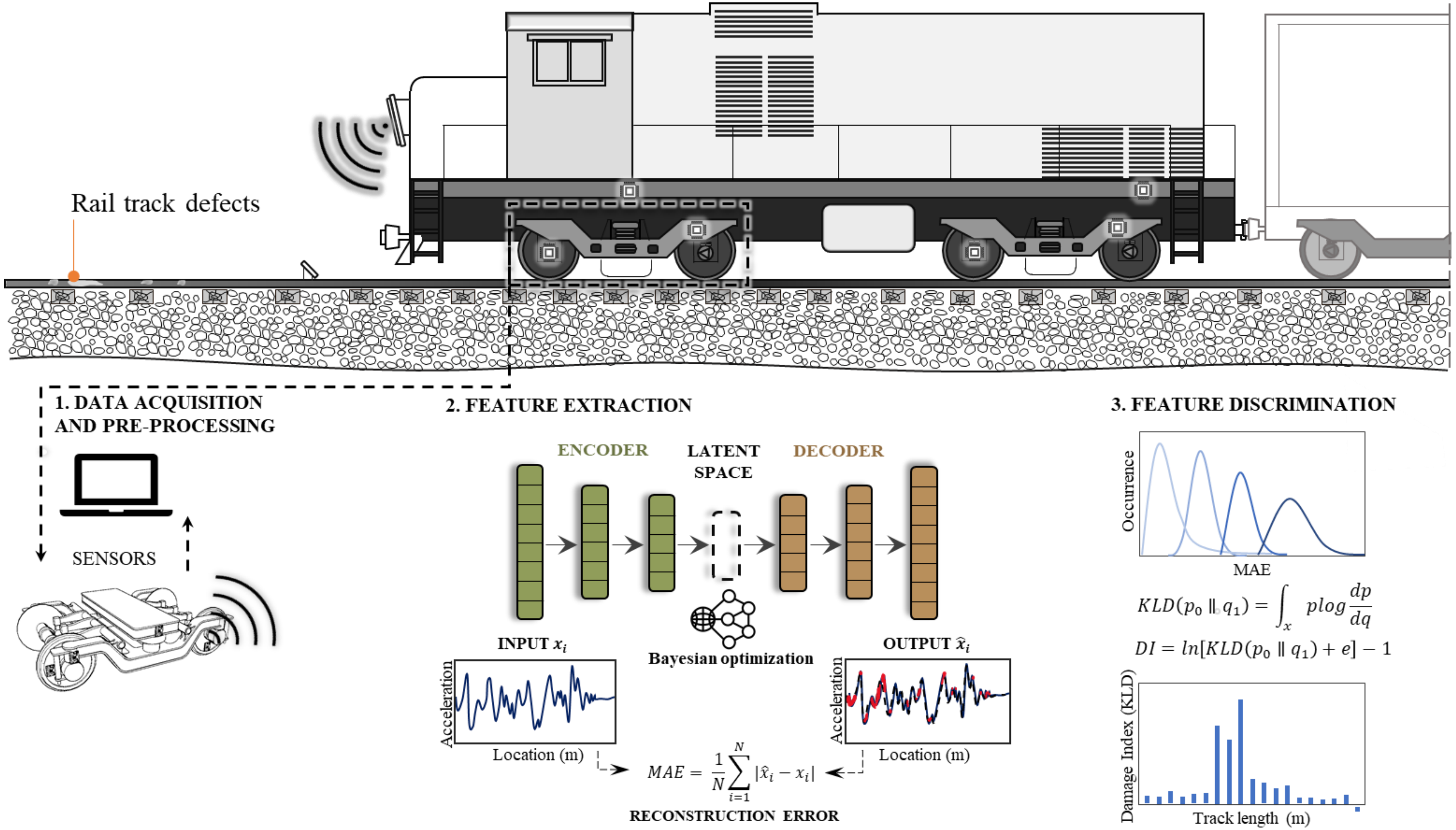
3. Onboard monitoring systems

Track degradation in Ferrovia Tereza Cristina (Brazil)



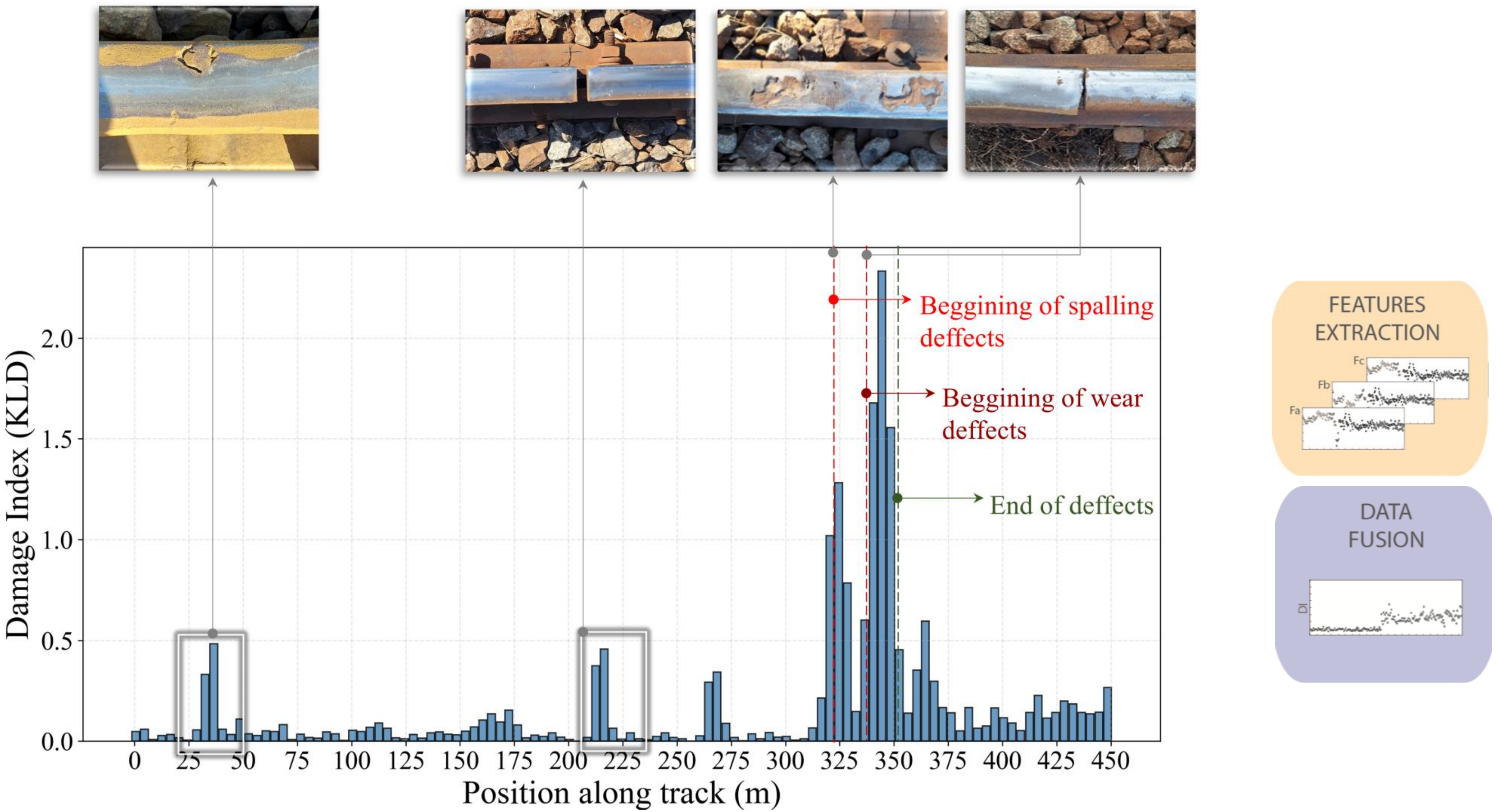
3. Onboard monitoring systems

Track degradation in Ferrovia Tereza Cristina (Brazil)



3. Onboard monitoring systems

Track degradation in Ferrovia Tereza Cristina (Brazil)



4. Wayside monitoring systems

Way4SafeRail project

Way4SafeRail project envisage the **design of a I2V wayside monitoring system** capable of:

i. assessing the **condition of the train wheels (flats and polygonization)** in operation, monitoring and categorizing their severity

ii. detecting situations of instability in railway circulation, particularly **unbalanced loads**

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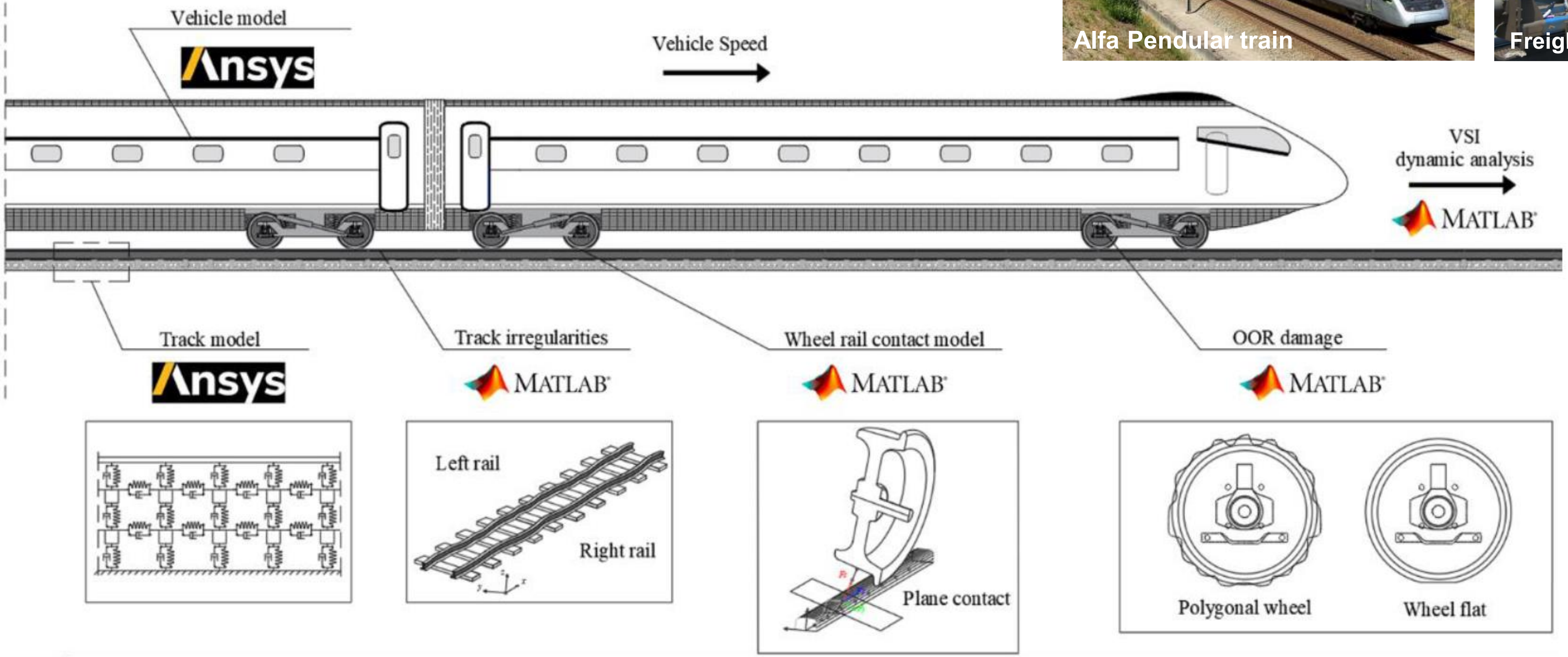
WAY4SAFERAIL project consortium

Train-track dynamic interaction

VSI | Vehicle-Structure Interaction



Models experimentally calibrated

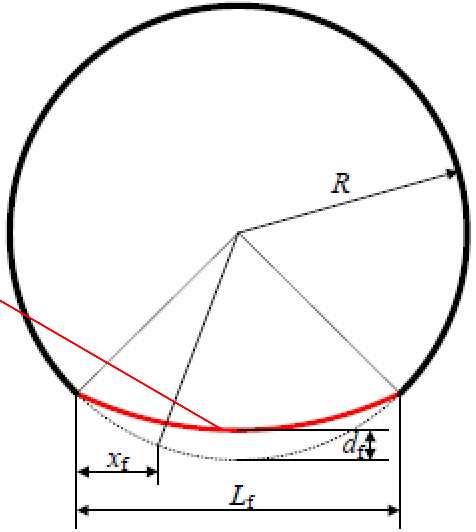
4. Wayside monitoring systems

Wheel flat

Wheel flat is a common tread defect mainly caused by repeated wheel/rail abrasion during the braking and the rolling of wheels over a long period of time.

(Ye et al., 2023).

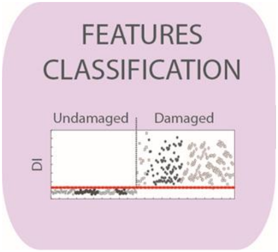
$$d_f = \frac{L_f^2}{16R}$$

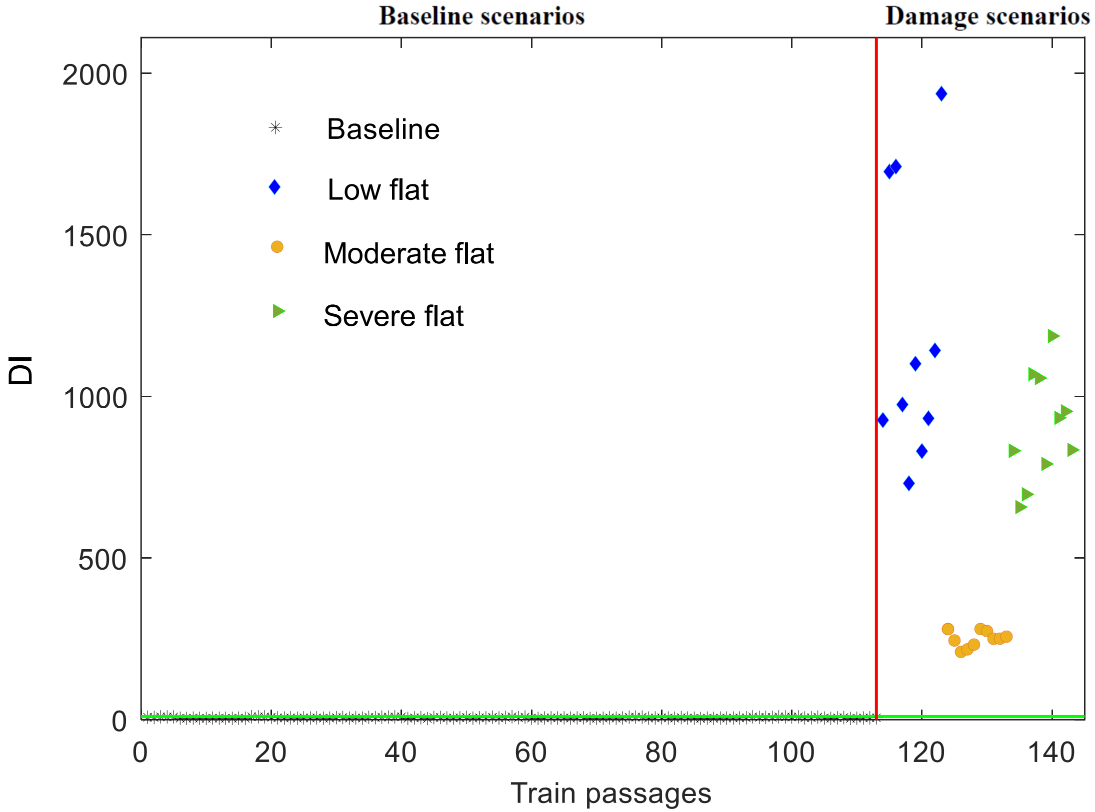


4. Wayside monitoring systems

Wheel flat

Wheel flat detection: Outlier Analysis using Auto Regressive model features

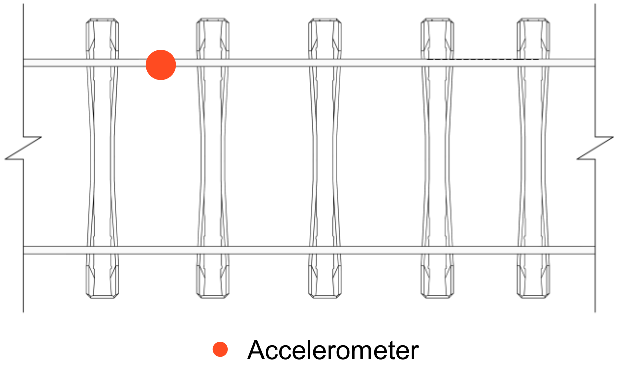




Accuracy: 100%

143/143

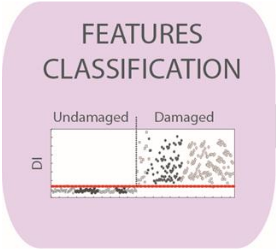
Optimized layout: 1 accelerometer

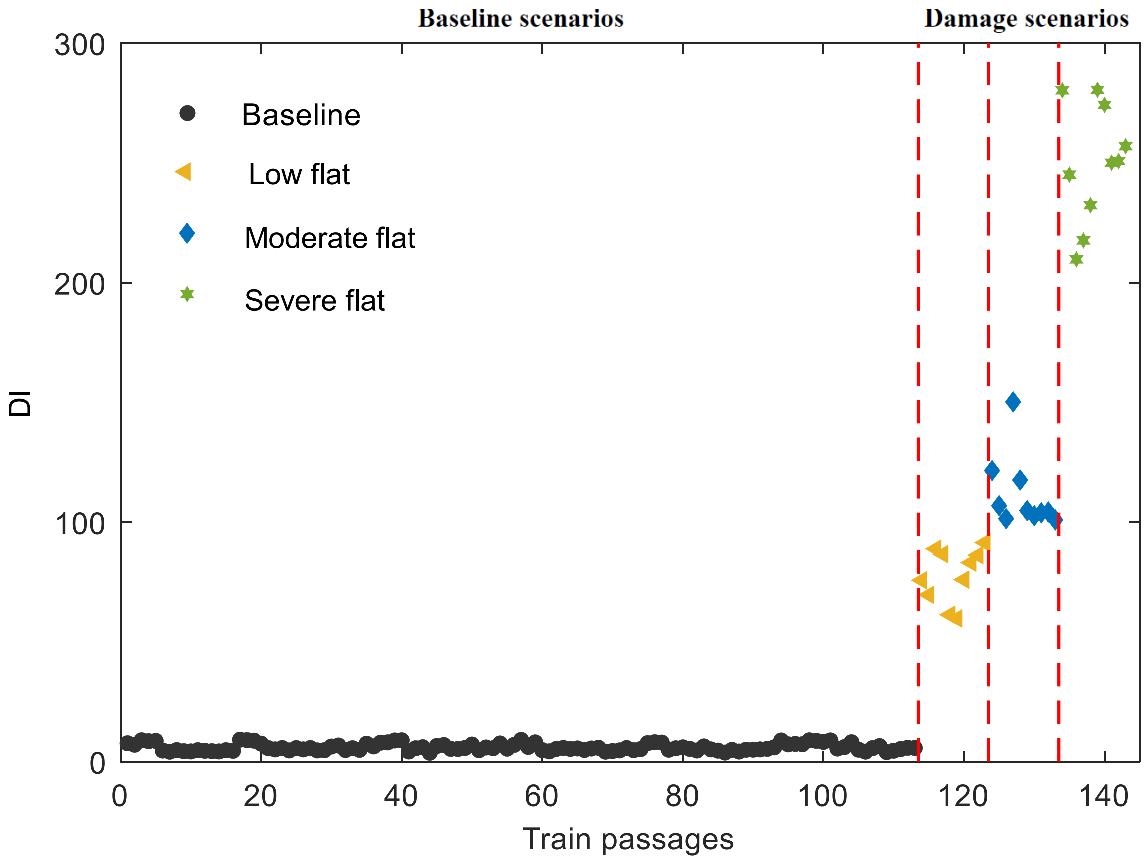


4. Wayside monitoring systems

Wheel flat

Wheel flat classification: Cluster Analysis using Auto Regressive model features

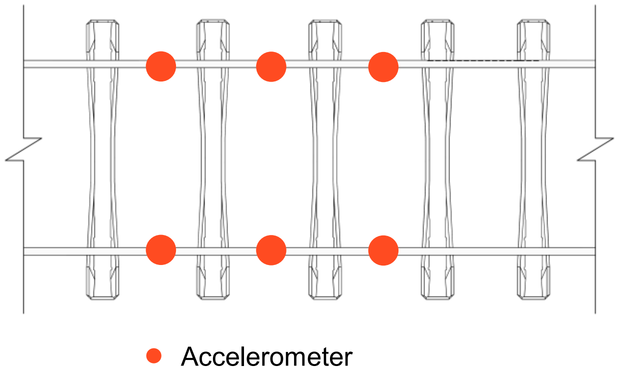




Accuracy: 100%

143/143

Optimized layout: 6 accelerometers



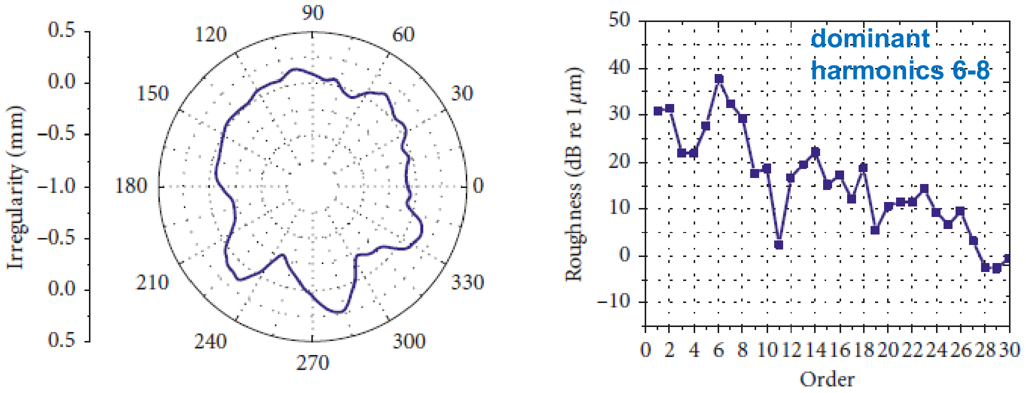
4. Wayside monitoring systems

Polygonal wheels

The **wheel polygonalization** is a periodic radial irregularity or wear around the wheel circumference with wavelength larger than 140 mm and amplitudes > 0.2 mm.

	Wavelength	Amplitude
Roughness	30-80 mm	10 µm
Polygonization	140 mm-one circle	>0.2 mm

(Peng, 2020)

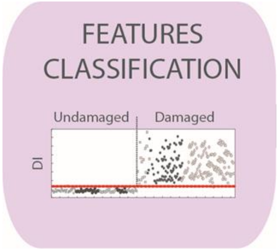


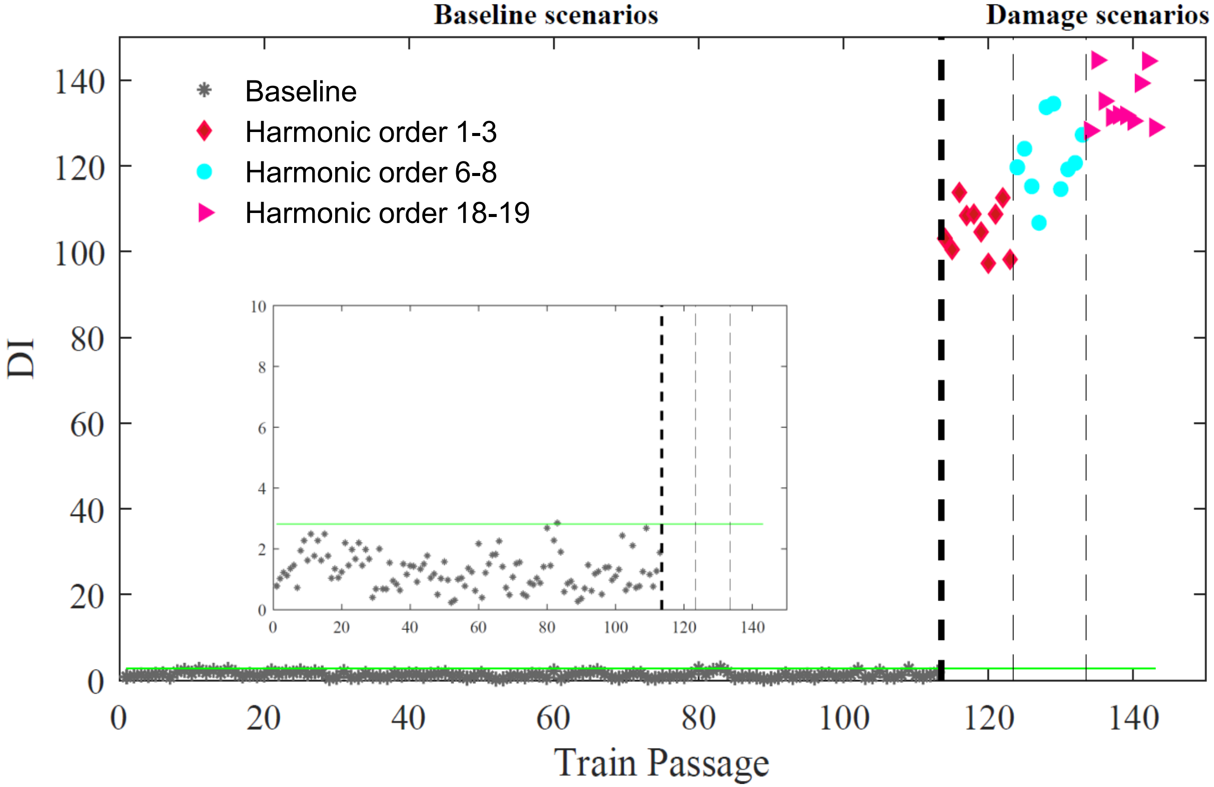
(Cai et al., 2019)

(Bogacz et al., 2016)

(Wu et al., 2020)

Polygonalization detection: Outlier Analysis using AutoRegressive eXogenous (ARX) model features



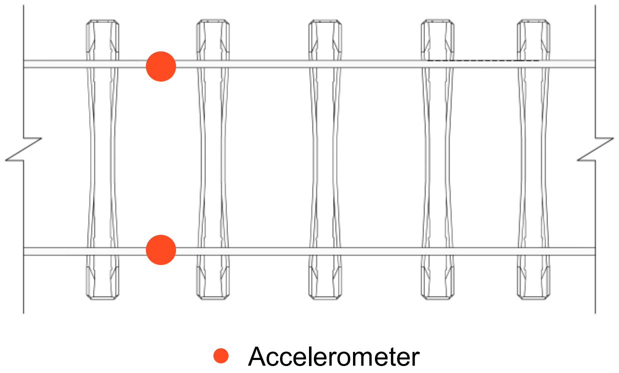


Accuracy: **99.3%**

142/143

1 false positive

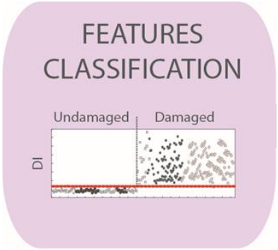
Optimized layout: 2 accelerometers

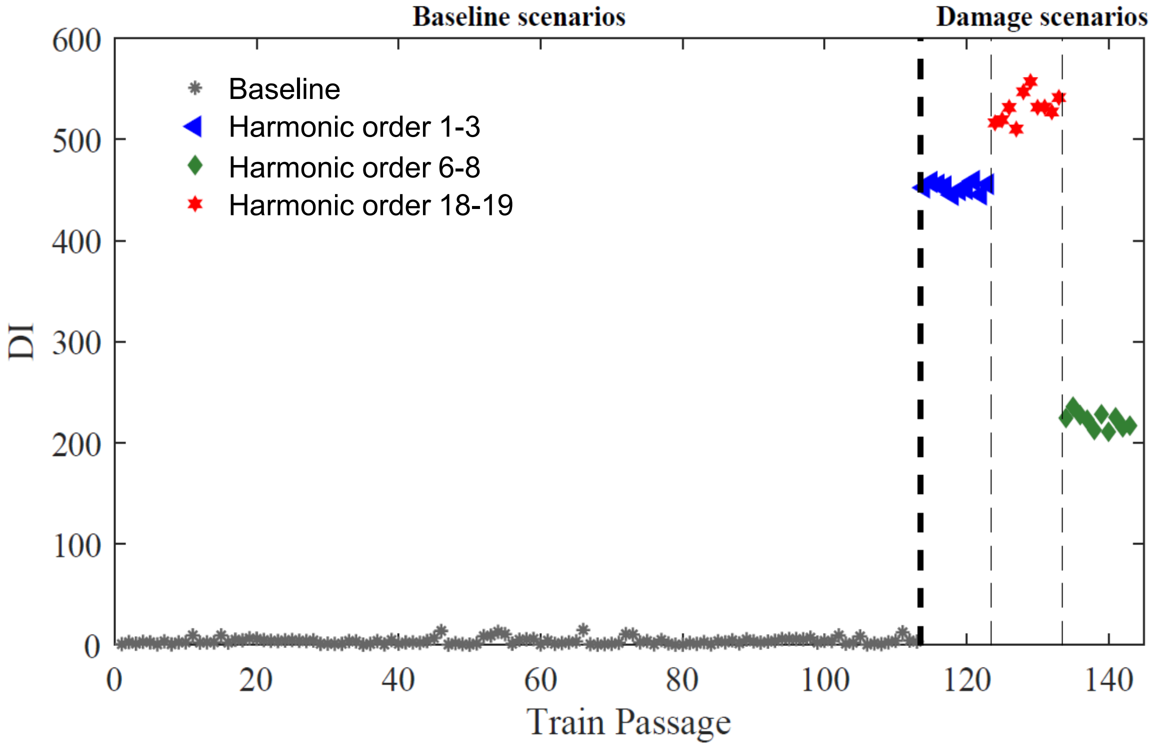


4. Wayside monitoring systems

Polygonal wheels

Polygonalization classification: Cluster Analysis using PCA & CWT model features

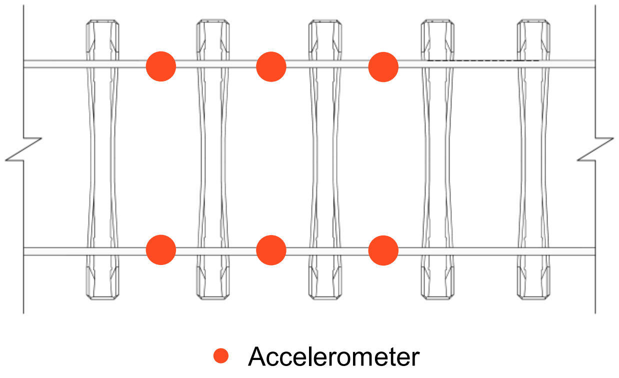




Accuracy: **100%**

143/143

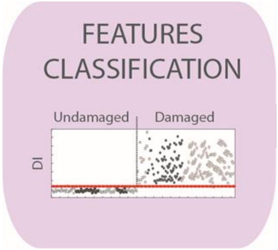
Optimized layout: 6 accelerometers

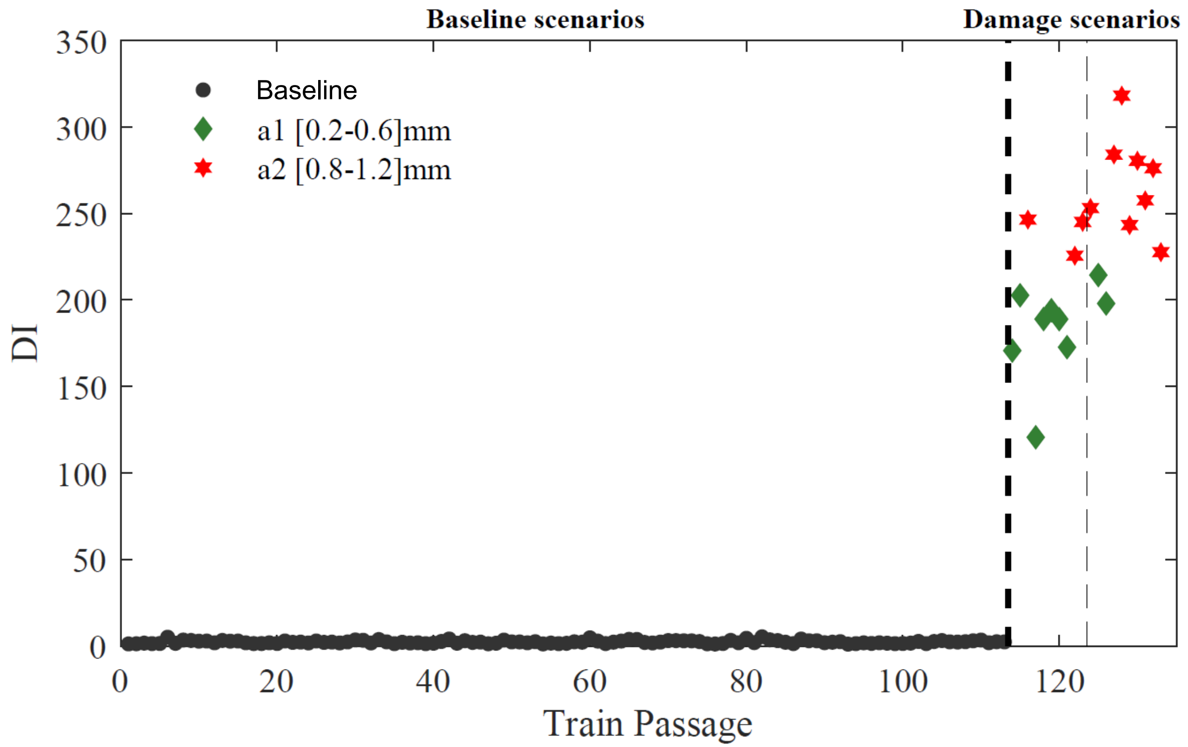


4. Wayside monitoring systems

Polygonal wheels

Polygonalization classification: Cluster Analysis using AutoRegressive eXogenous (ARX) model features

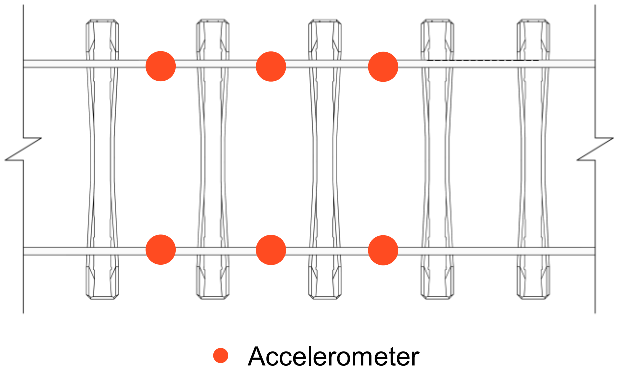




Accuracy: **96.2%**

128/133

Optimized layout: 6 accelerometers



4. Wayside monitoring systems

Unbalanced loads

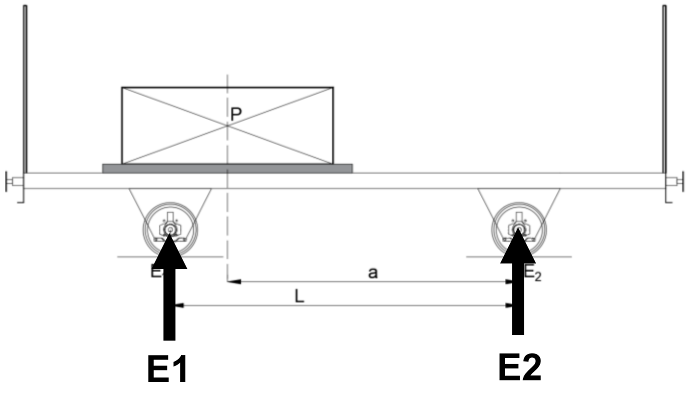
The presence of **unbalanced loads on freight trains** can potentially cause **higher levels of deterioration** or even the **failure of railway track components**, as well as **situations of risk of derailment**

For **2-axle wagons**: **ratio of 2:1** between the masses per axle

For **all wagons**: ratio of masses per wheel: 1.25:1

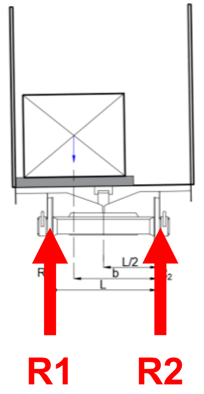
Longitudinal unbalances

E1 > 2 × E2

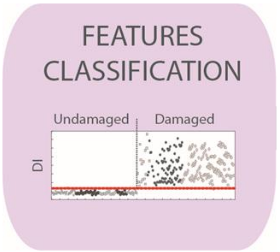


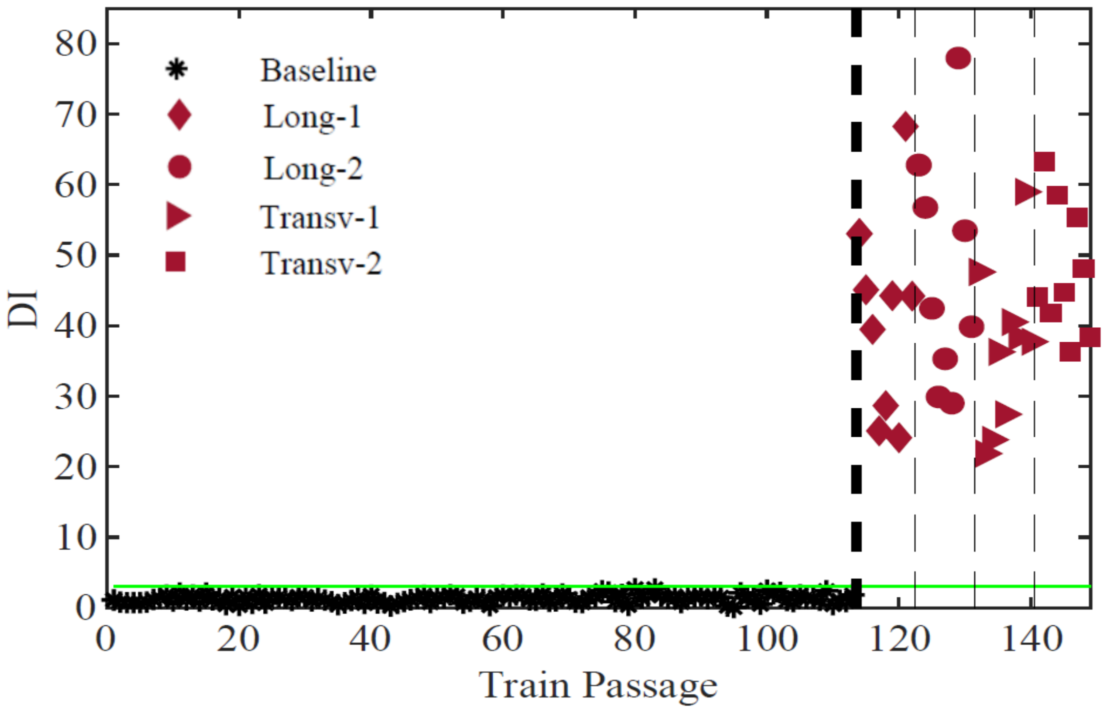
Transversal unbalances

R1 > 1.25 × R2



Unbalanced loads detection: Outlier Analysis using AutoRegressive eXogenous (ARX) model features





Accuracy: **98.7%**

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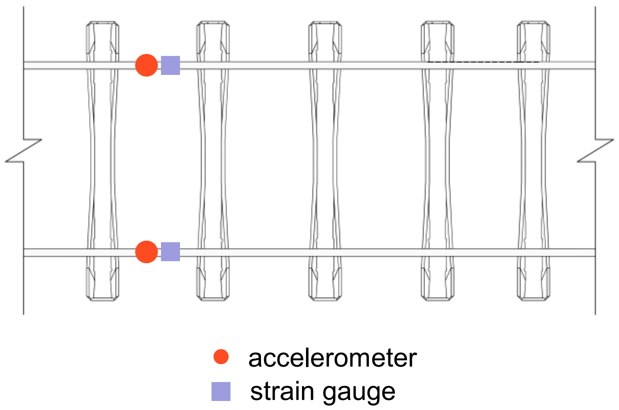
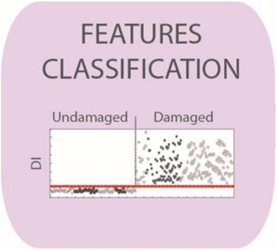
Optimized layout: 2 accelerometers + **2** strain gauges

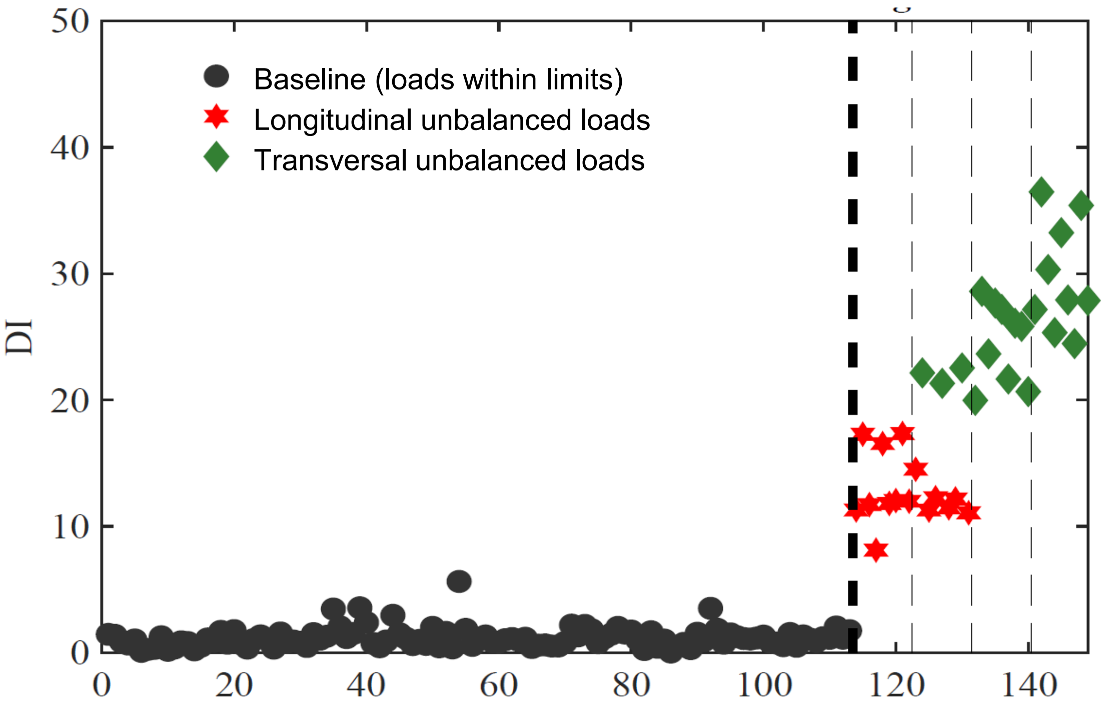


4. Wayside monitoring systems

Unbalanced loads

Unbalanced loads classification: Cluster Analysis using PCA features

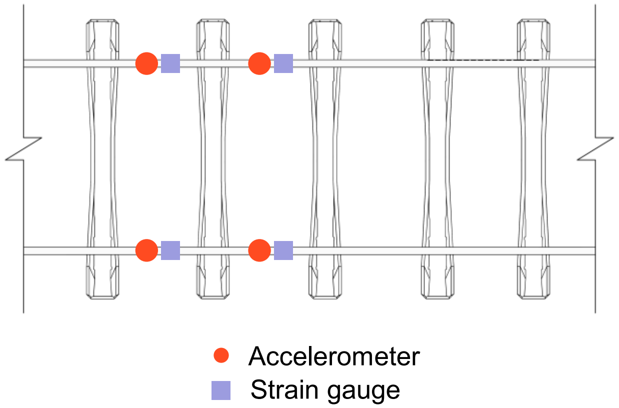




Accuracy: **98.0%**

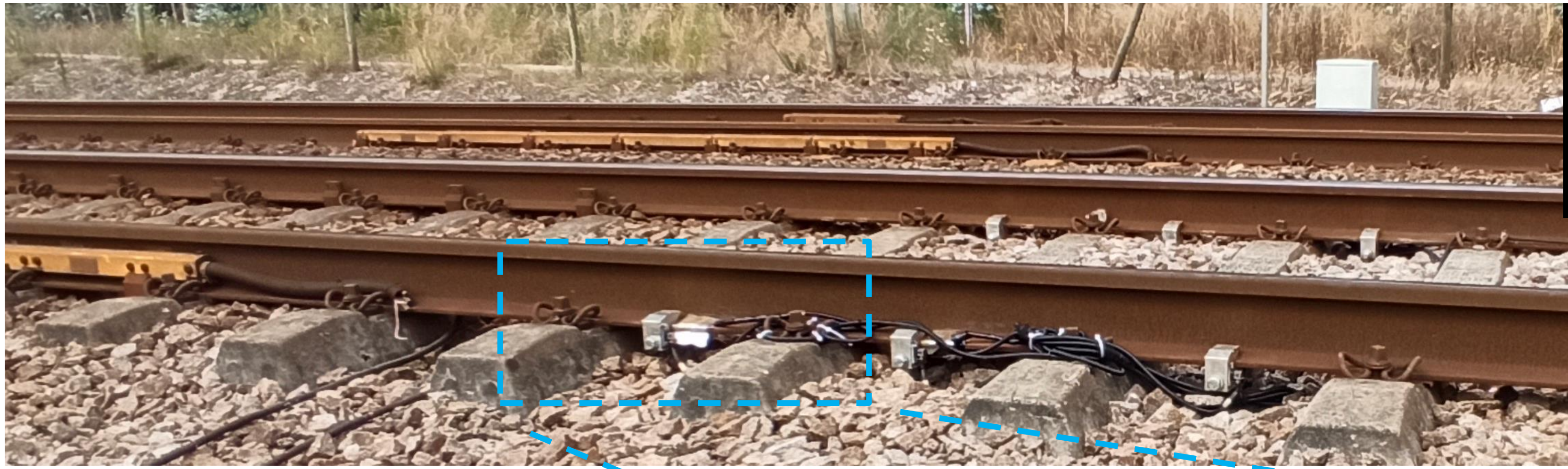
146/149

Optimized layout: **4** accelerometers +
4 strain gauges



4. Wayside monitoring systems

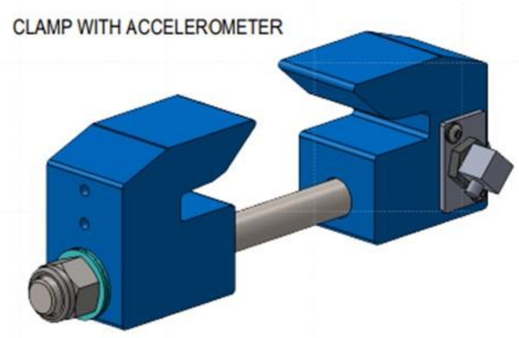
Experimental campaign



Experimental Proof-of-Concept
Location: Estarreja (Lisbon-Porto line)
Alfa Pendular train
Speeds between 140-200 Km/h

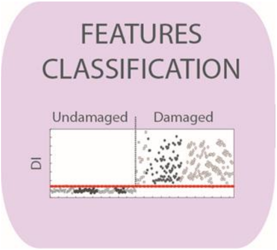
6 Accelerometer ICP
Model 356A02

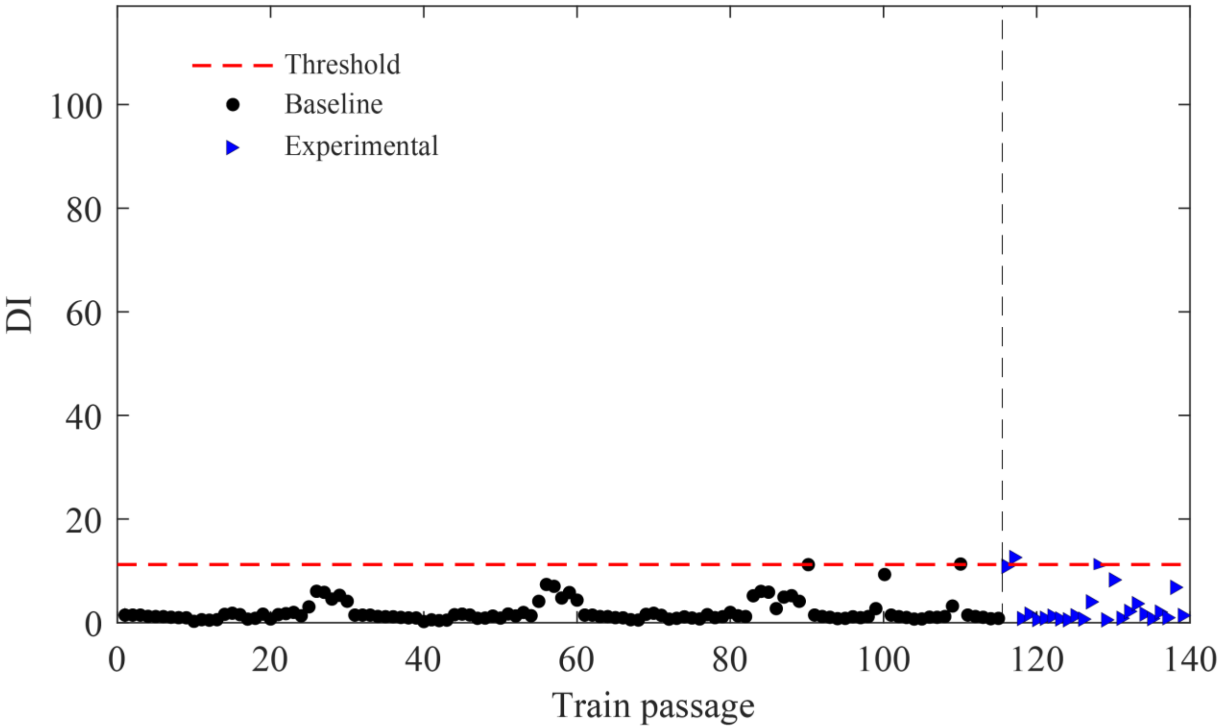
4 Strain Gages
LEA-06-W125E-350/3R

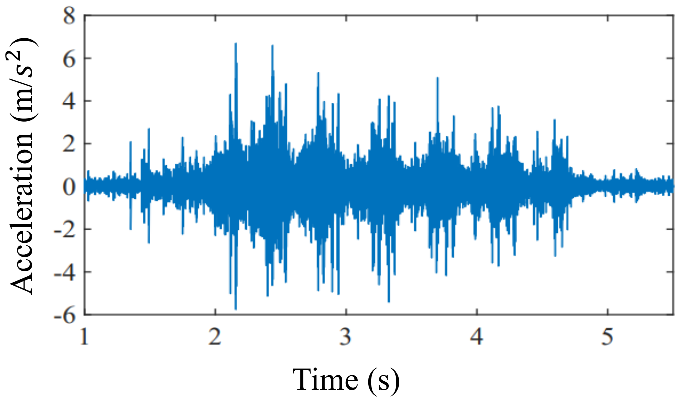


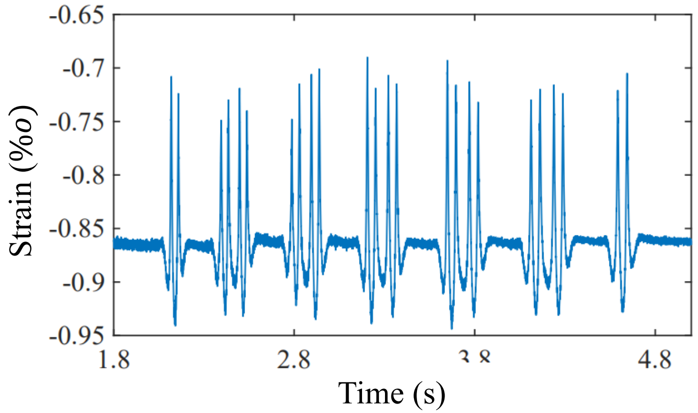
Experimental campaign

Polygonalization classification: real-time online procedure









Time (s)

5. Conclusions

- **AI-based condition monitoring** of railway infrastructures based on vibration data is an ongoing and challenging research topic, however, already constitutes an efficient and cost-effective health monitoring strategy.
- The most recent **damage identification methodologies** are based on advanced **feature extraction**, **data normalization** to remove the influence of EOVs, **multi-fusion** processes to enhance the sensitivity to damage, and damage **classification** based on statistical approaches.
- Most of the existing research is based on **numerical strategies** and the **experimental validation** of the proposed damage identification strategies are still ongoing. This is a key step to ensure that the methodology is robust and ready to address the complexities of real-world applications.
- The use cases presented in this work proved the efficiency of the proposed methodology on **onboard and wayside applications** under demanding operational scenarios, namely for bridges and track sections located on **freight and regular traffic lines**.
- In both cases the methodology had a very good performance in detecting and classifying **early-stage individual damages in bridge structural elements, detecting track defects** and **characterizing critical safety situations on moving trains**.
- Future works include upgrades on the methodology to properly localize the damages, as well as, working on multiple-damage scenarios. Also, the continuation/upgrade of experimental campaigns/results is a priority action.

Acknowledgements

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