A Deep Learning-based Anomaly Detection System for Railway Equipment

Michele Bevilacqua (RFI), Walter Didimo (UniPG), Alessandro Eugeni (UniPG), Fabrizio Montecchiani (UniPG), Giovanni Spinelli (RFI)

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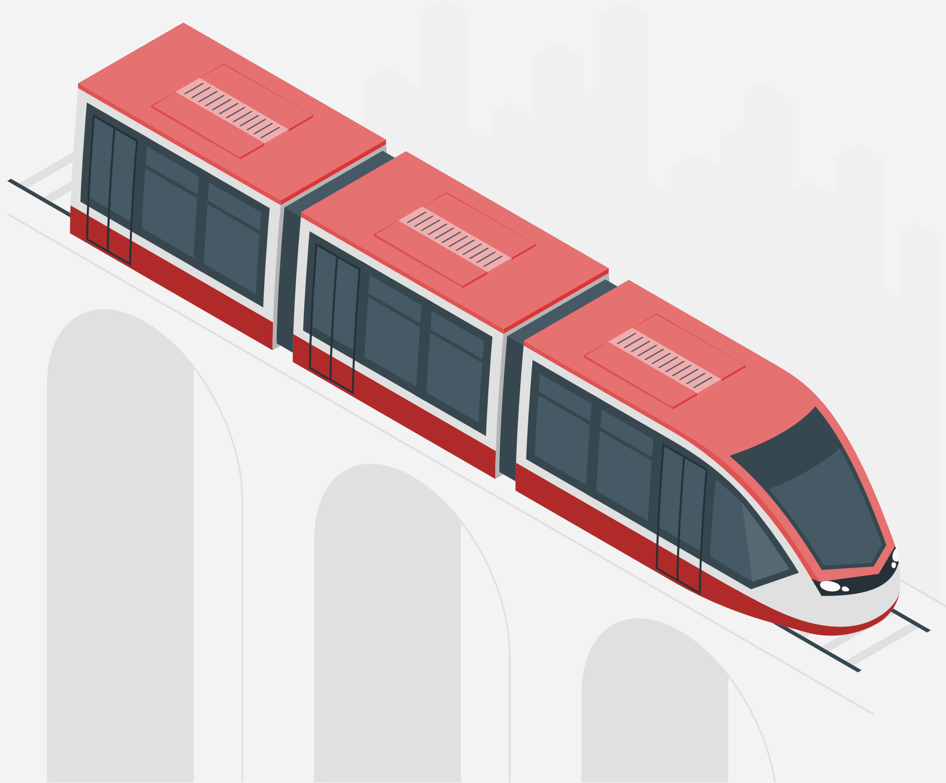
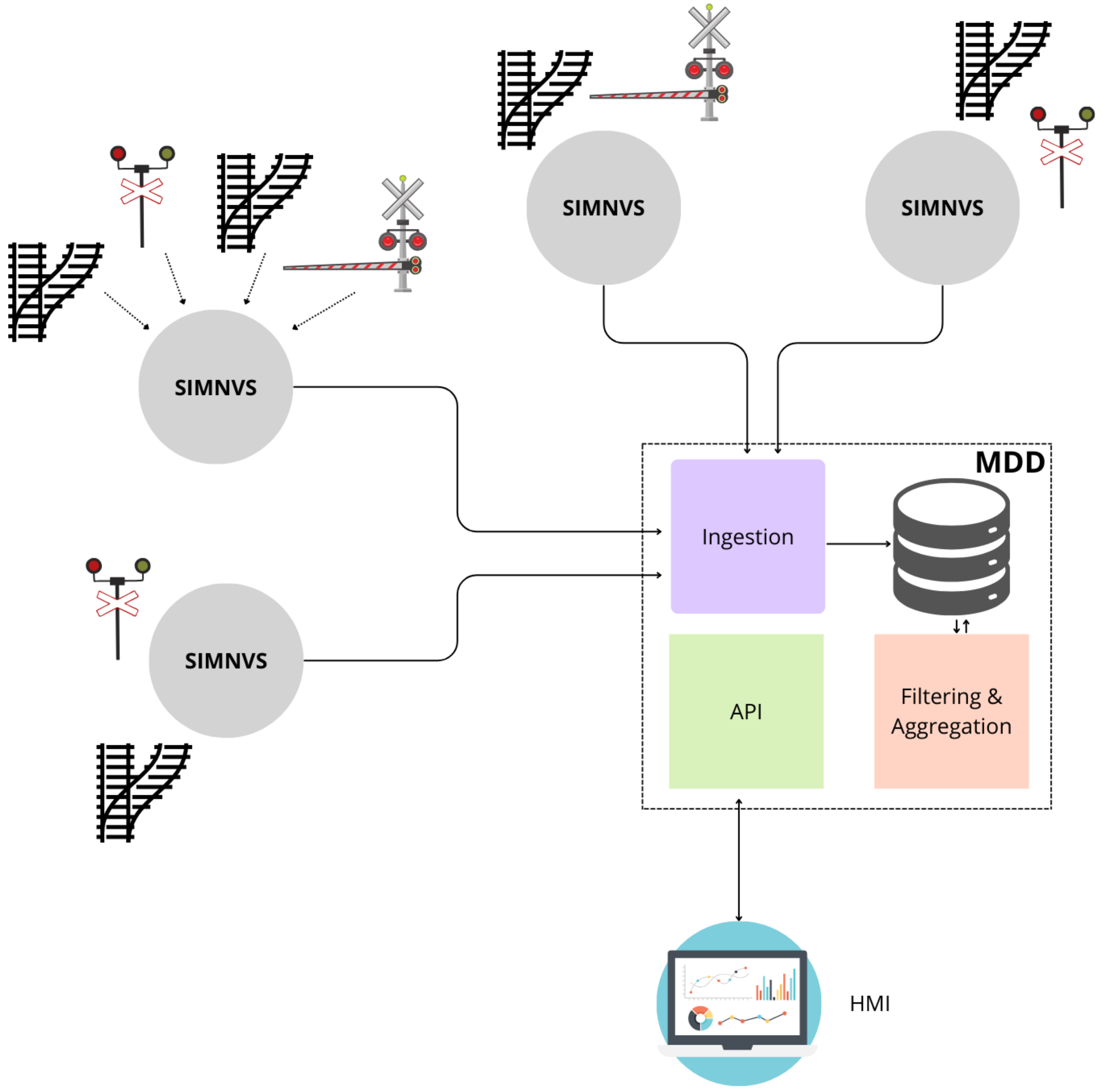


ITA DATA 2025

Context

- Established collaboration between RFI and CINI.
  - Our research is embedded in a larger project aimed at developing a software platform to ingest, store, and analyze diagnostic data from the railway network.



Motivation

- In 2024, for high-speed trains:
  - 57% of delays caused by infrastructural problems
  - 3.16 billion euros lost due to delays for companies and travelers

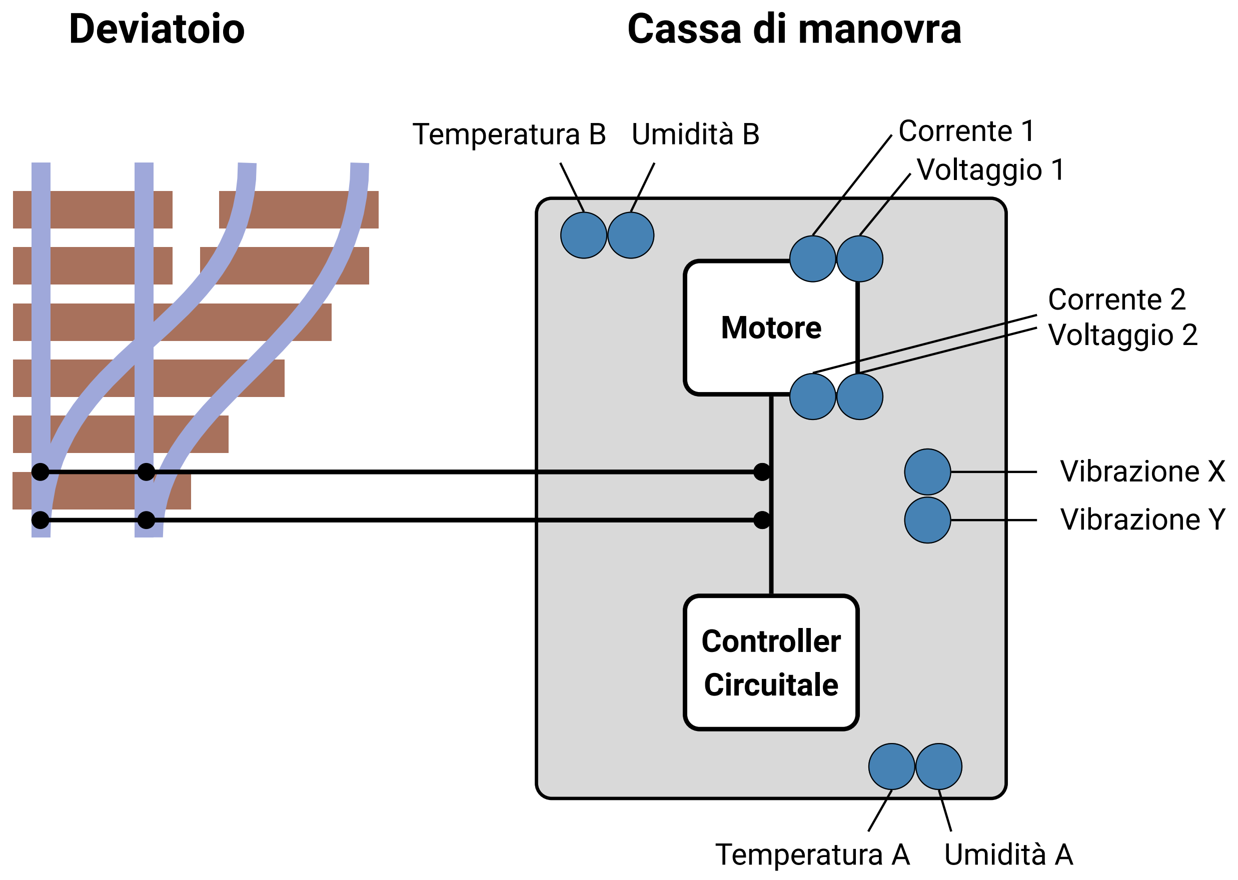
Sources: RFI, Unimpresa

Contribution

- We focus on a specific type of device, namely railway switches
  - critical assets: faults can freeze train lines

- Objective: develop a data-driven solution for predictive maintenance of railway switches

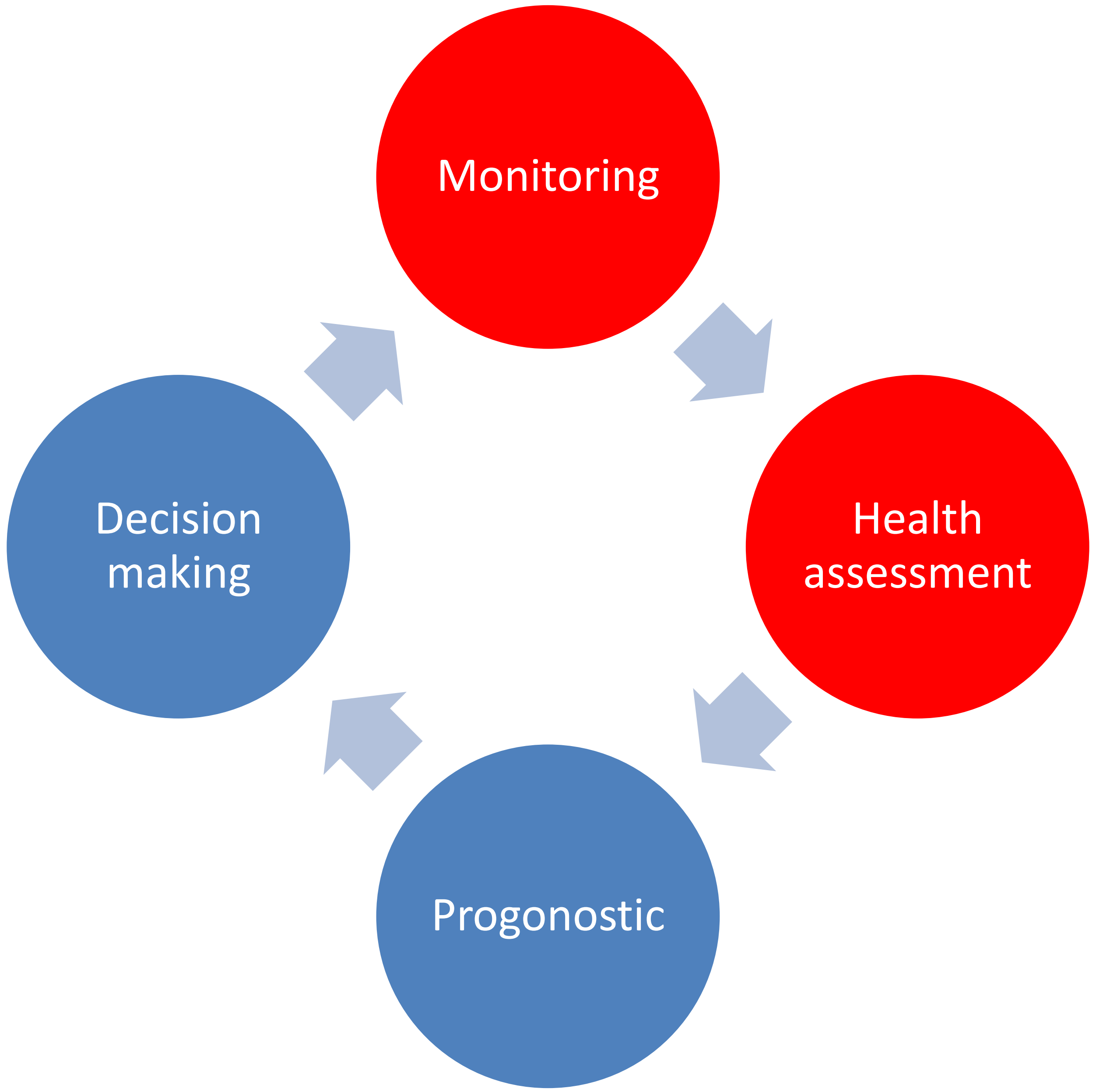
- Twofold contribution:
  - Original methodology for the creation of a hybrid dataset (real and synthetic data), with various degradation levels.
  - Thorough experimental evaluation of SOTA deep-learning models to extract a health indicator index of a railway switch.



Condition-Based Maintenance (CBM)

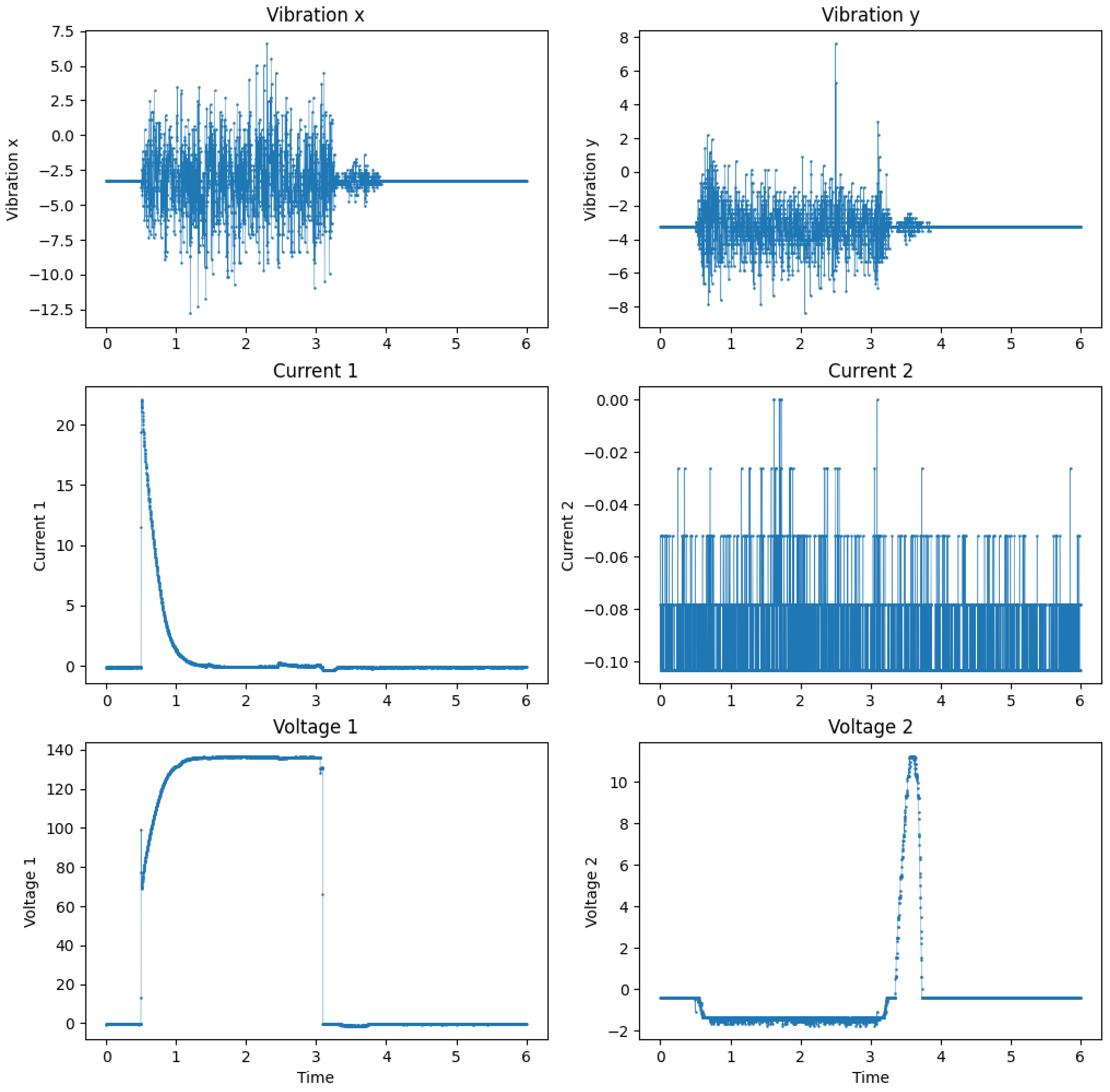
- Maintenance based on asset health, rather than periodic schedules
  - Focus on health assessment

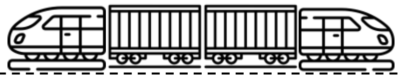
- Data-driven approaches avoid explicit modeling of physical assets



Collecting the Real dataset

- Sensors: current, voltage, vibration, temperature, humidity
- Real dataset:
  - 153 maneuvers (time series)
    - 116 normal
    - 37 abnormal
  - Anomalies injected via mechanical resistance (friction)
    - Simulates aging or absence of lubricant of the physical asset.





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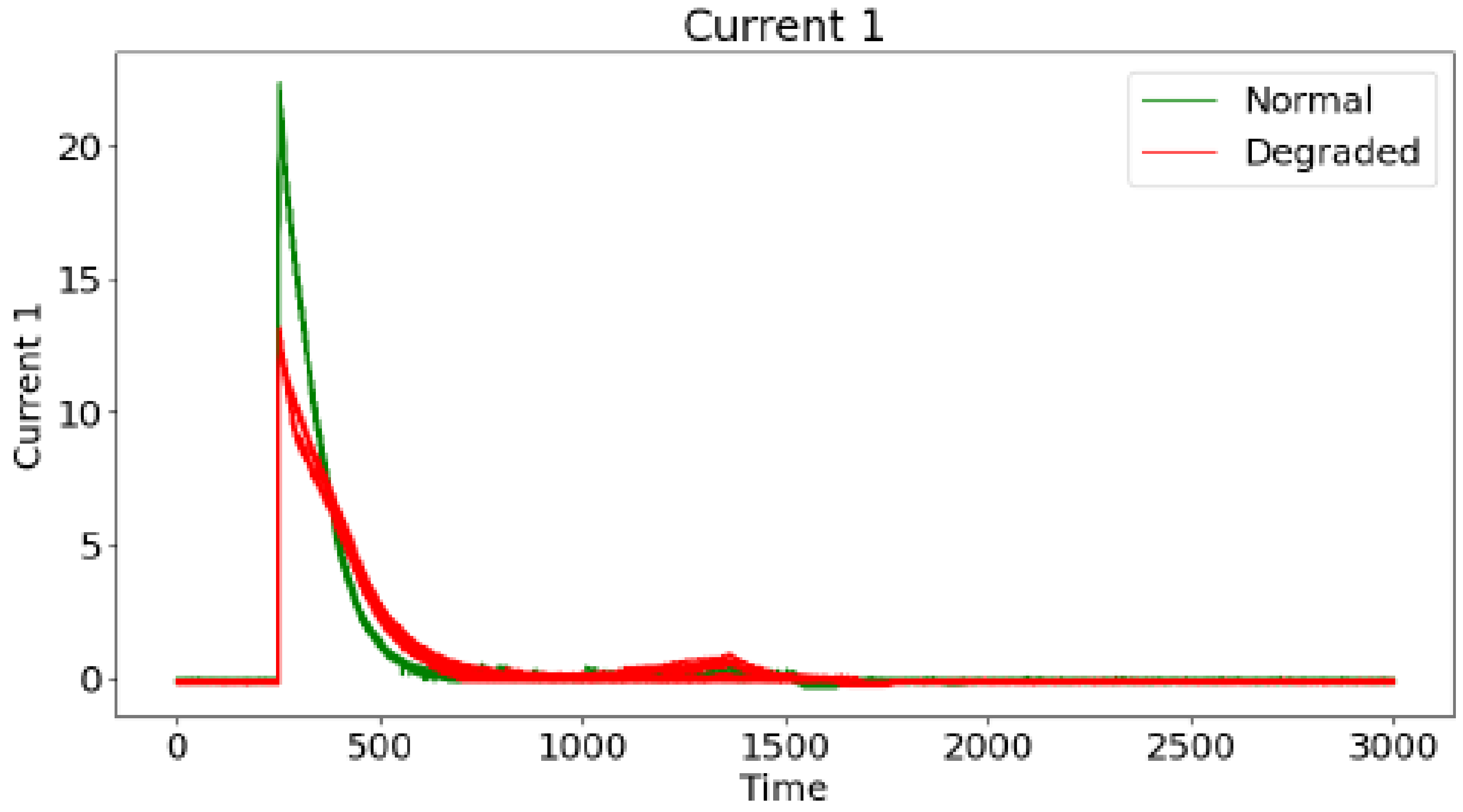
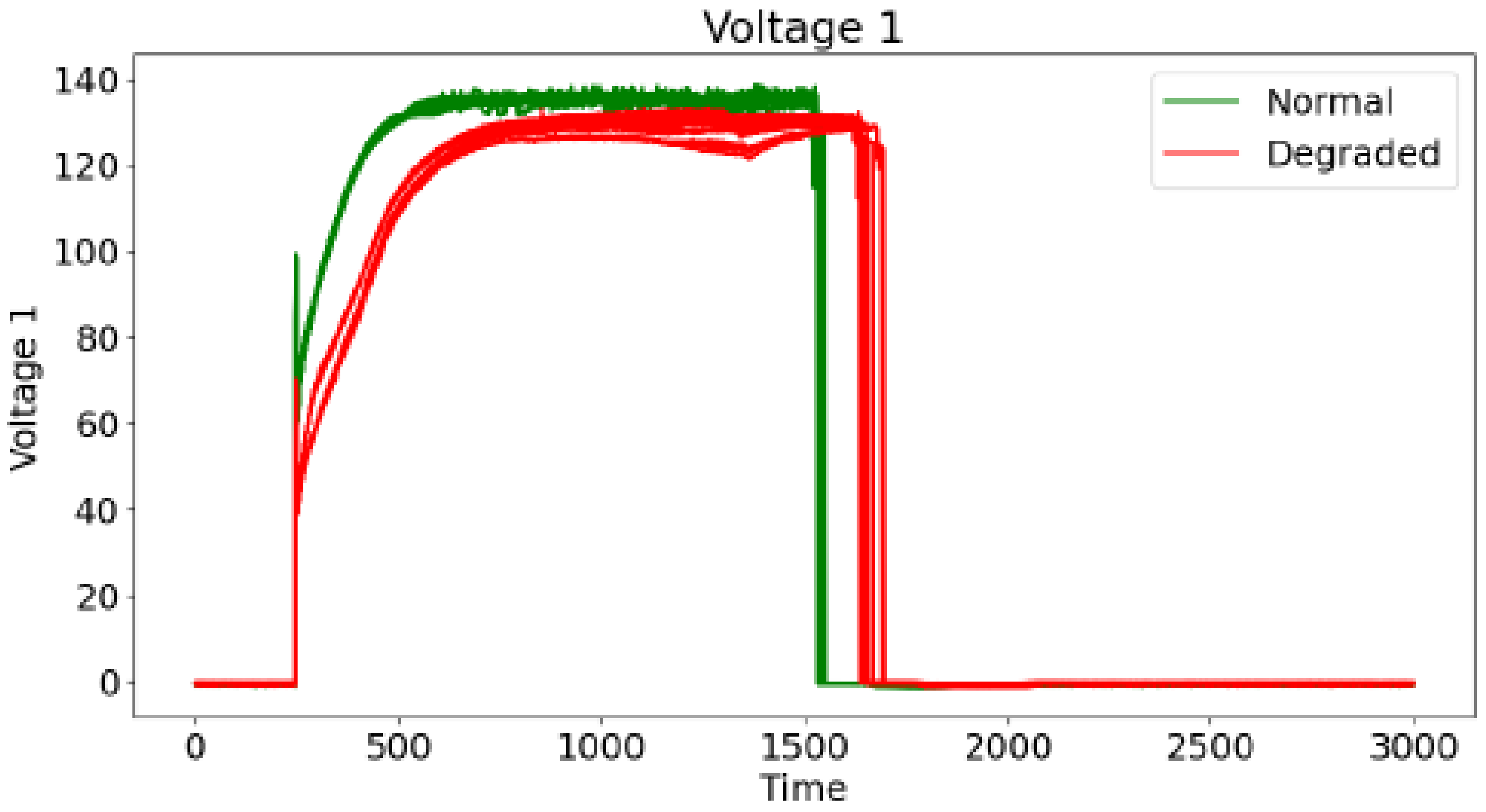
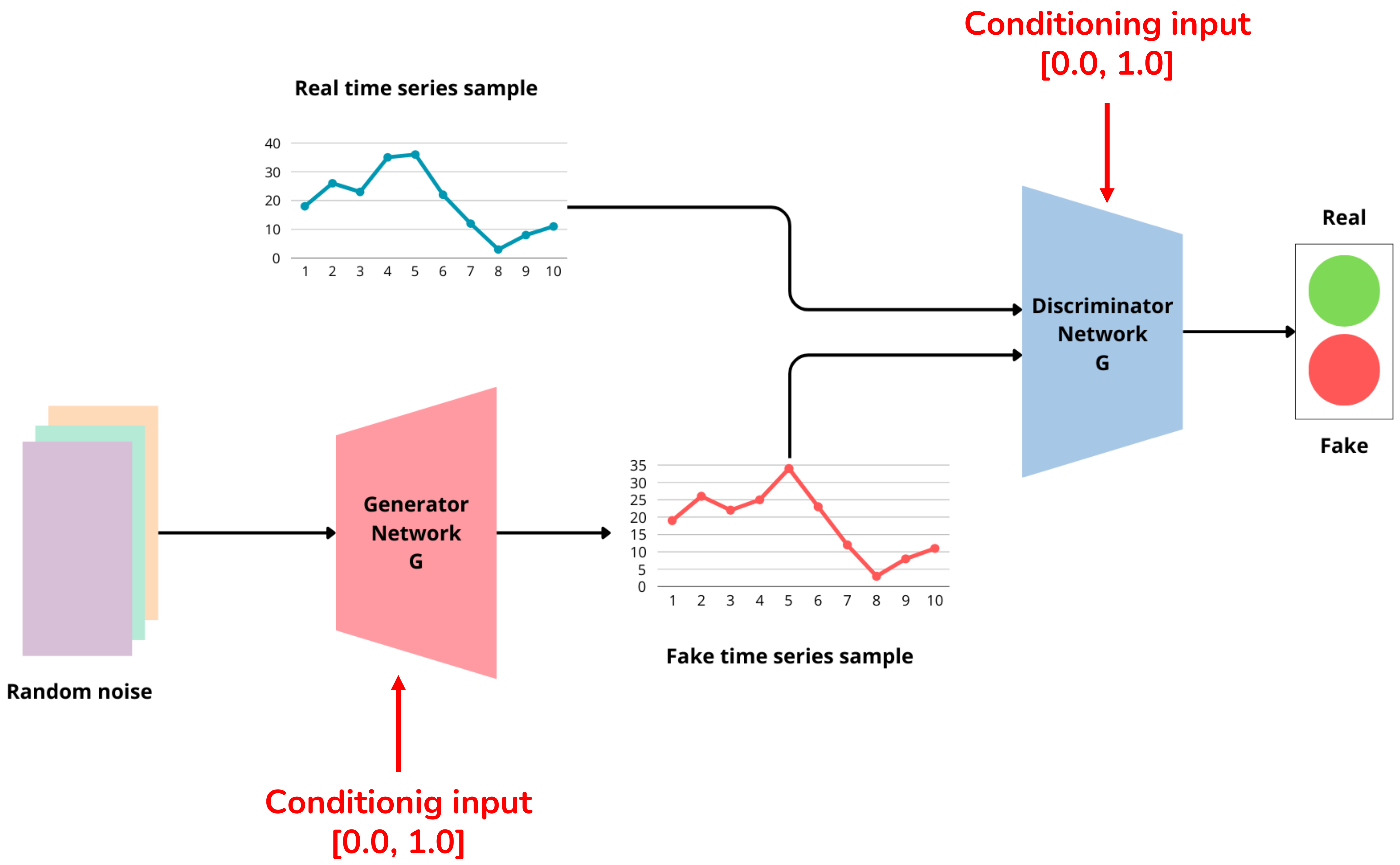




Computing synthetic data

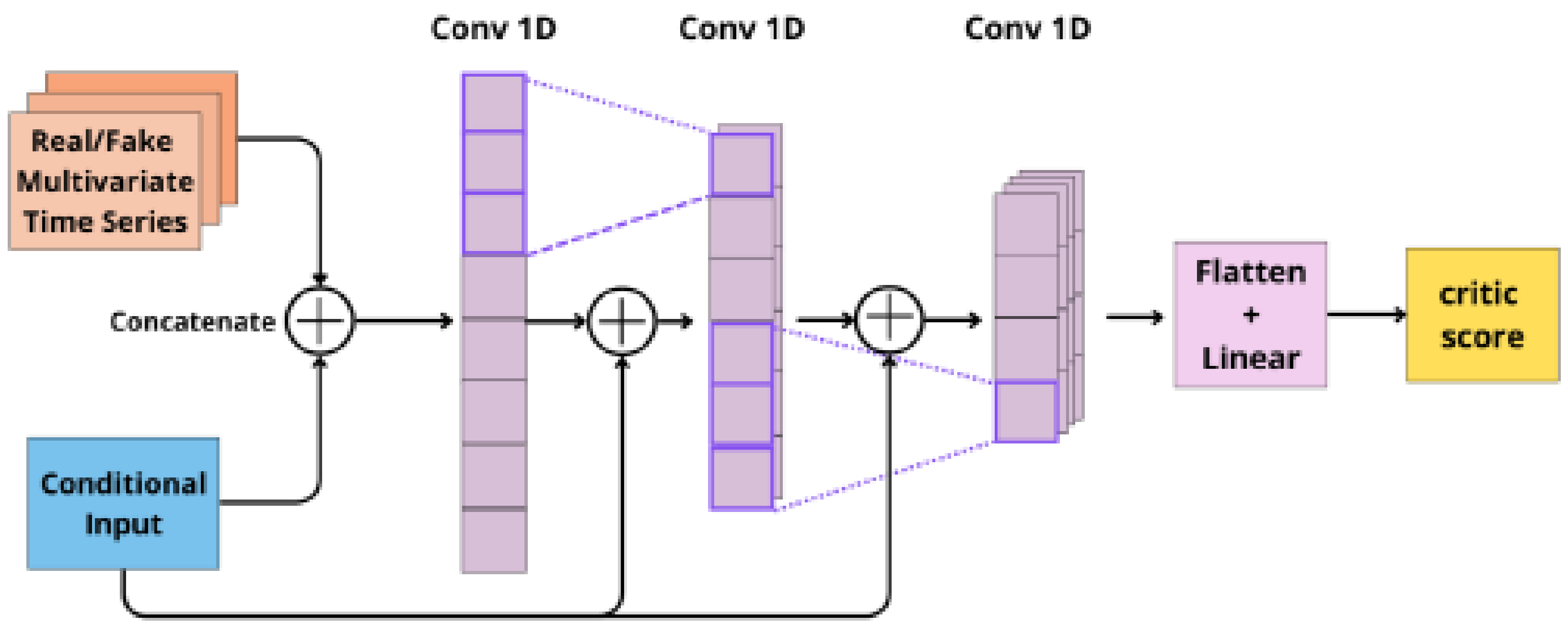
- Issues of real dataset:
  - small,
  - only extremal behaviors

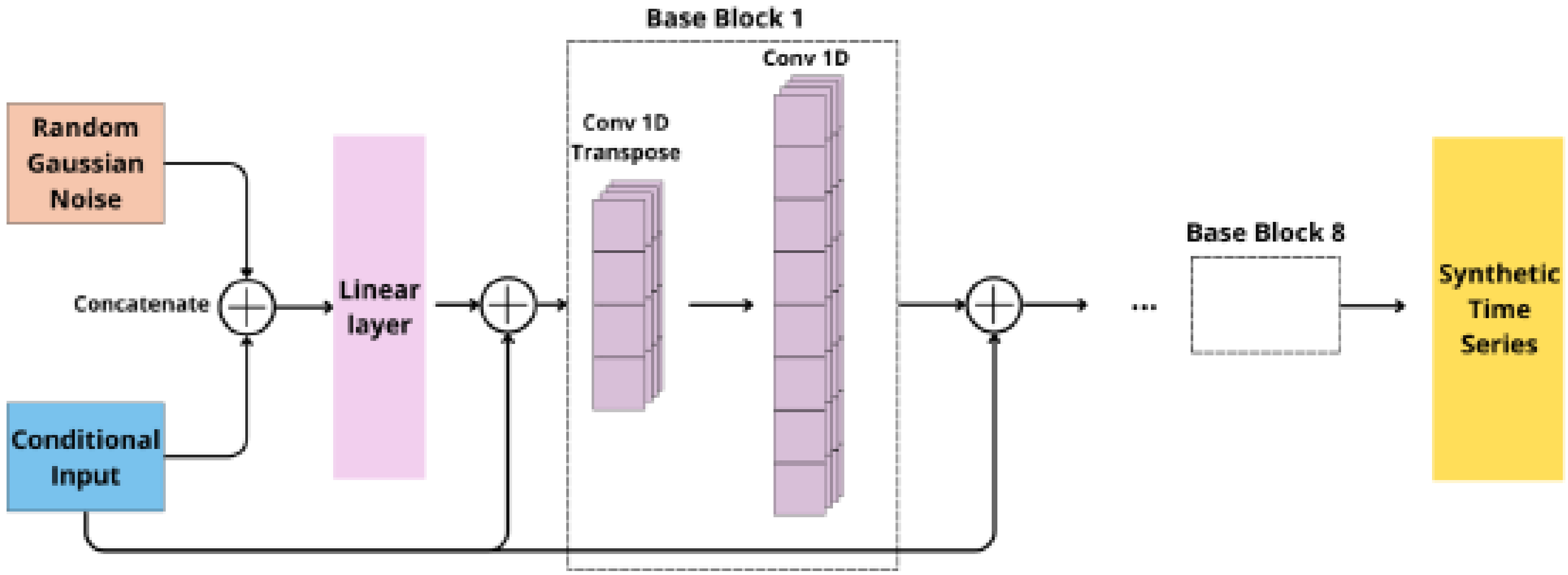
- Solution:
  ad-hoc GAN architecture to deal with multiple degradation levels
  (0.1 → 0.9)



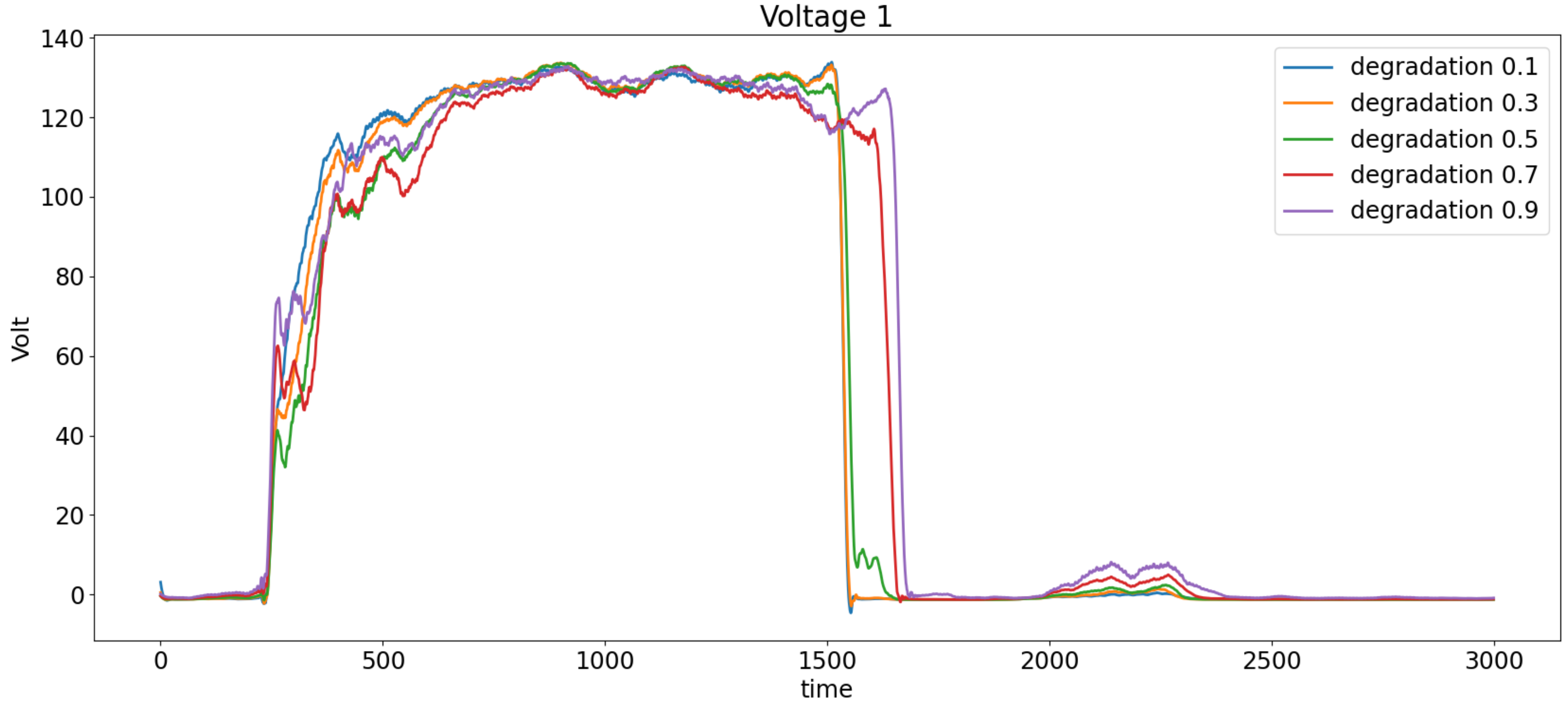
Conditional Wasserstein GAN with Gradient Penalty

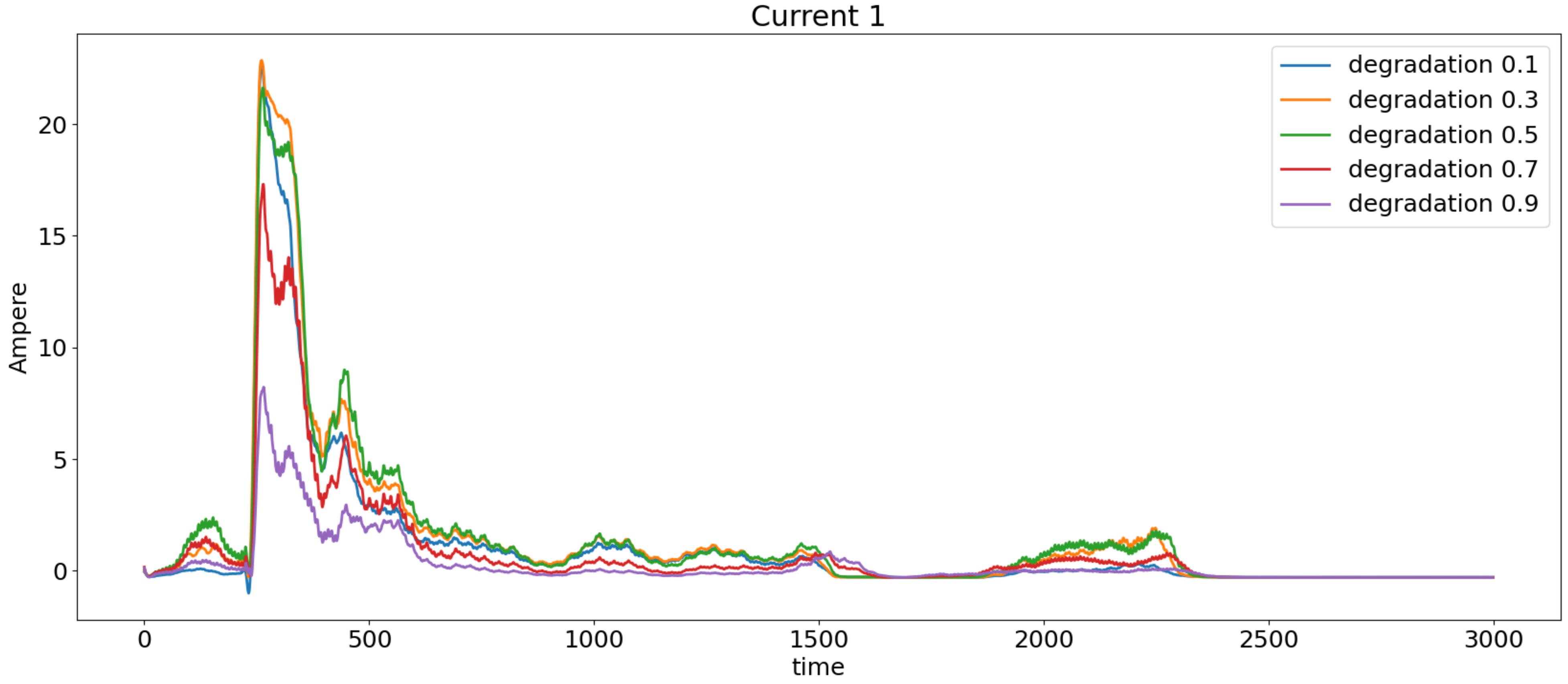
- More robust training with fewer chances of mode collapse
- Conditioning input to interpolate between extremal behaviors





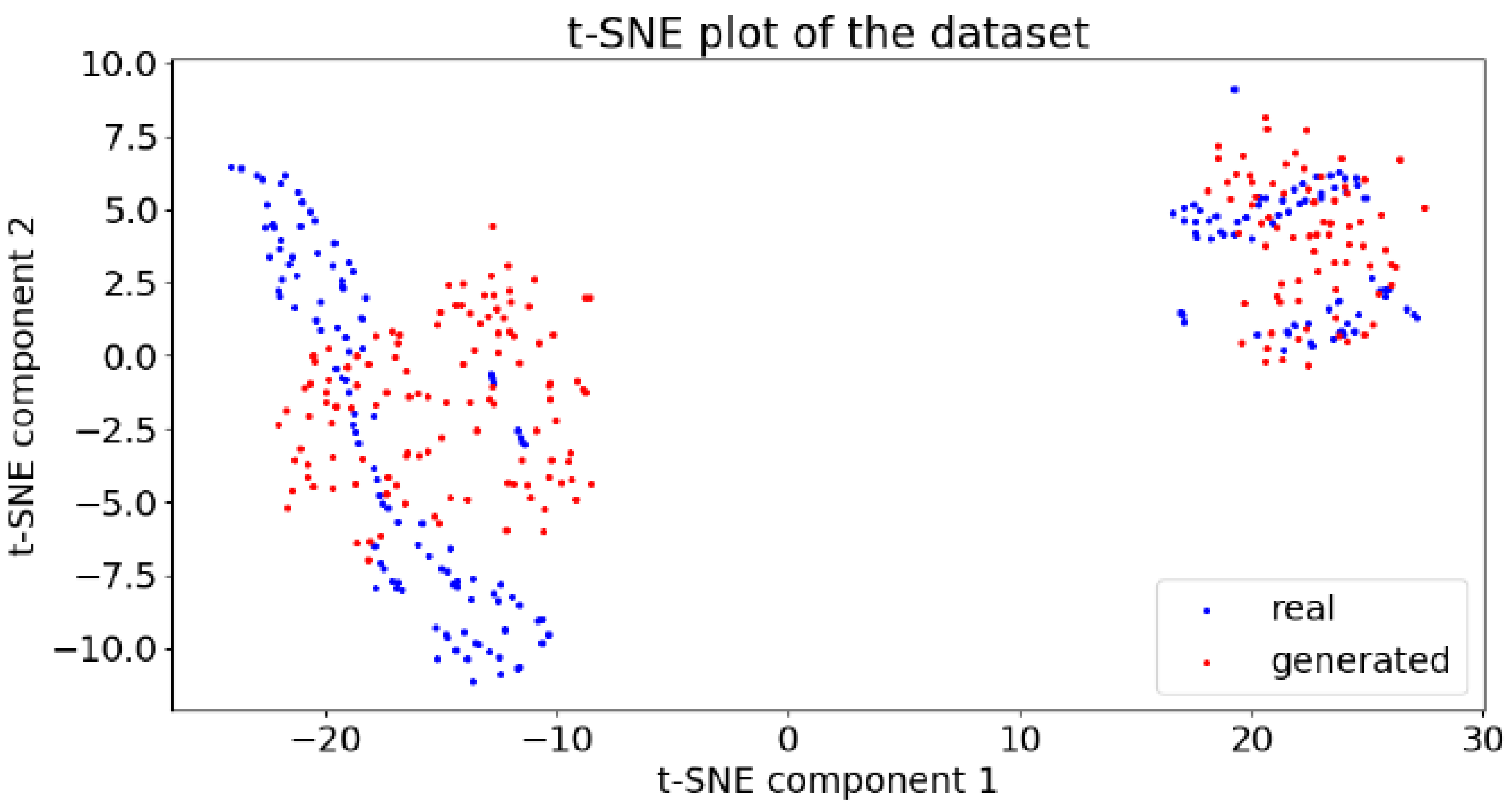
Synthetic dataset (1,250 maneuvers)





Validation

- t-SNE plot
  (reconstruction of the real dataset)
- Train-Synthetic Test-Real (omitted)
- Discussions with RFI engineers

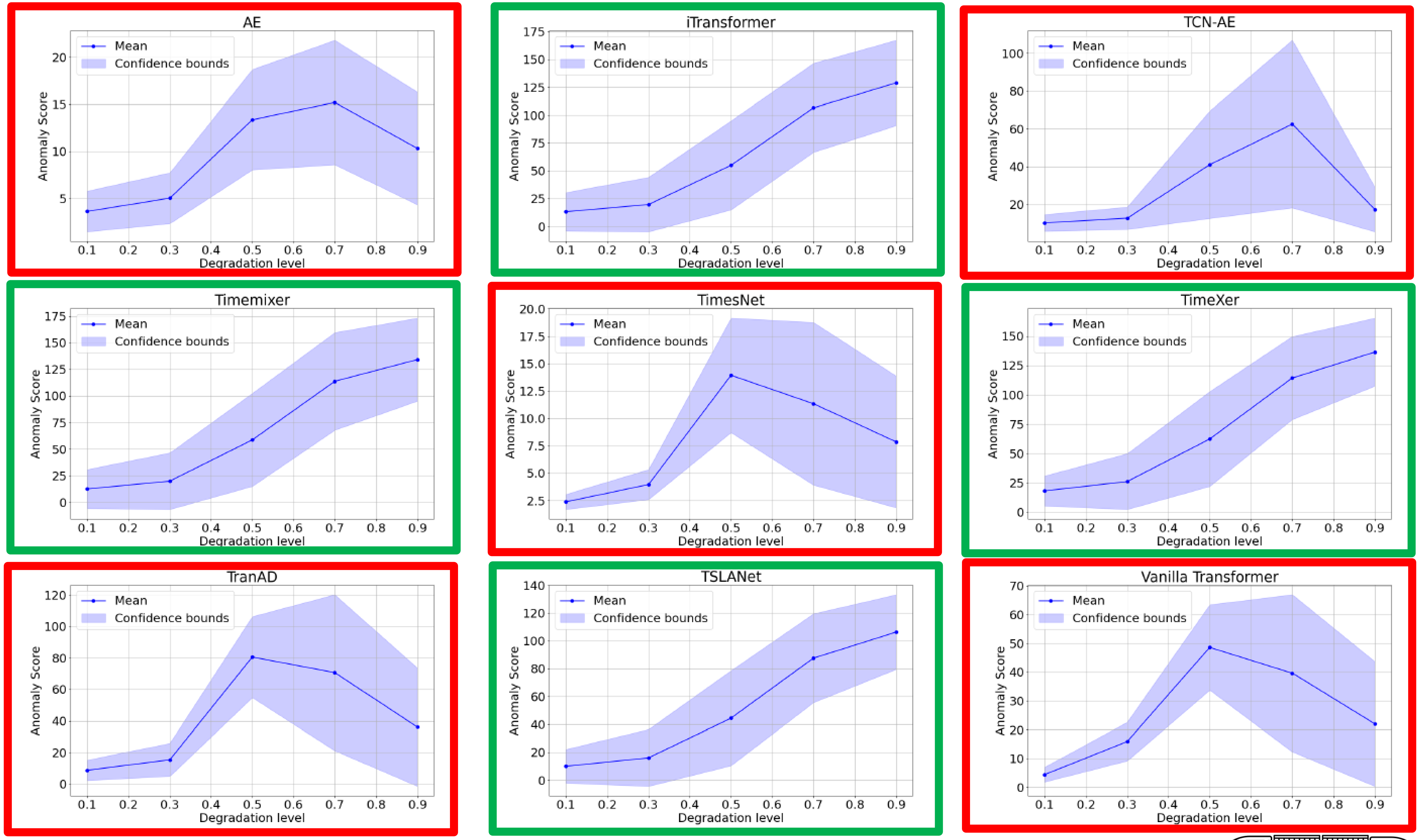


Health indicator index

- Approach: we use the mean square error (MSE) of SOTA reconstruction-based DL models
  - Standard approach when dealing with time-series

- Candidate models identified through a preliminary analysis:
  - iTransformer (transformer encoder-only)
  - TimeMixer (fully MLP with scale decomposition)
  - TimeXer (transformer encoder-only)
  - TSLANet (convolutional neural network)
  - TranAD (transformer + GAN)
  - TimesNet (based on ResNet)
  - Baselines:
    - AutoEncoder
    - Vanilla Transformer

Results



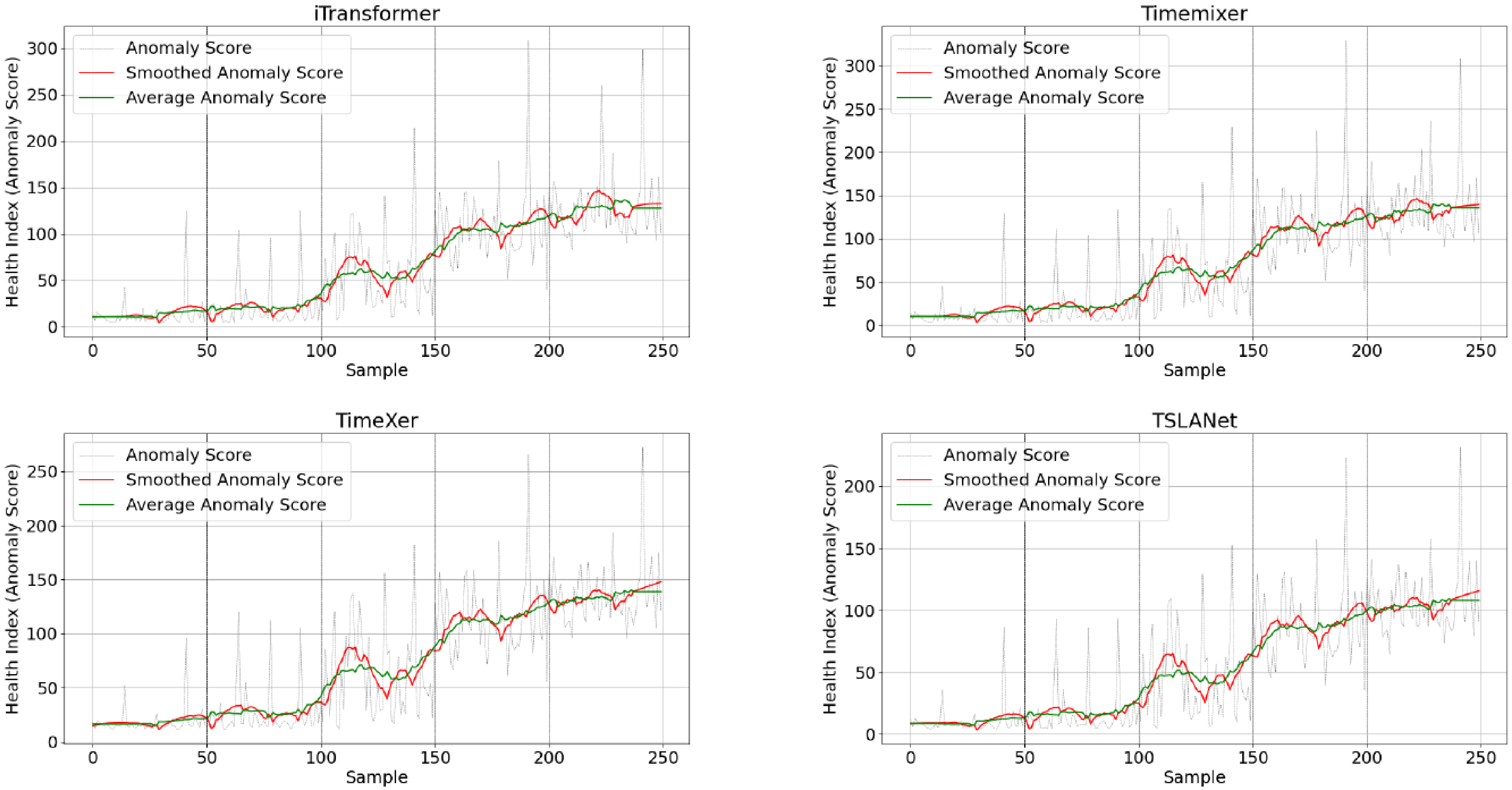
Training performed on common laptop --Ryzen 7 6800HS CPU, 32 GB of RAM, Nvidia GeForce 3050

Results

- Robust & monotonic trends achieved by:
  - iTransformer, TimeMixer, TimeXer, TSLANet

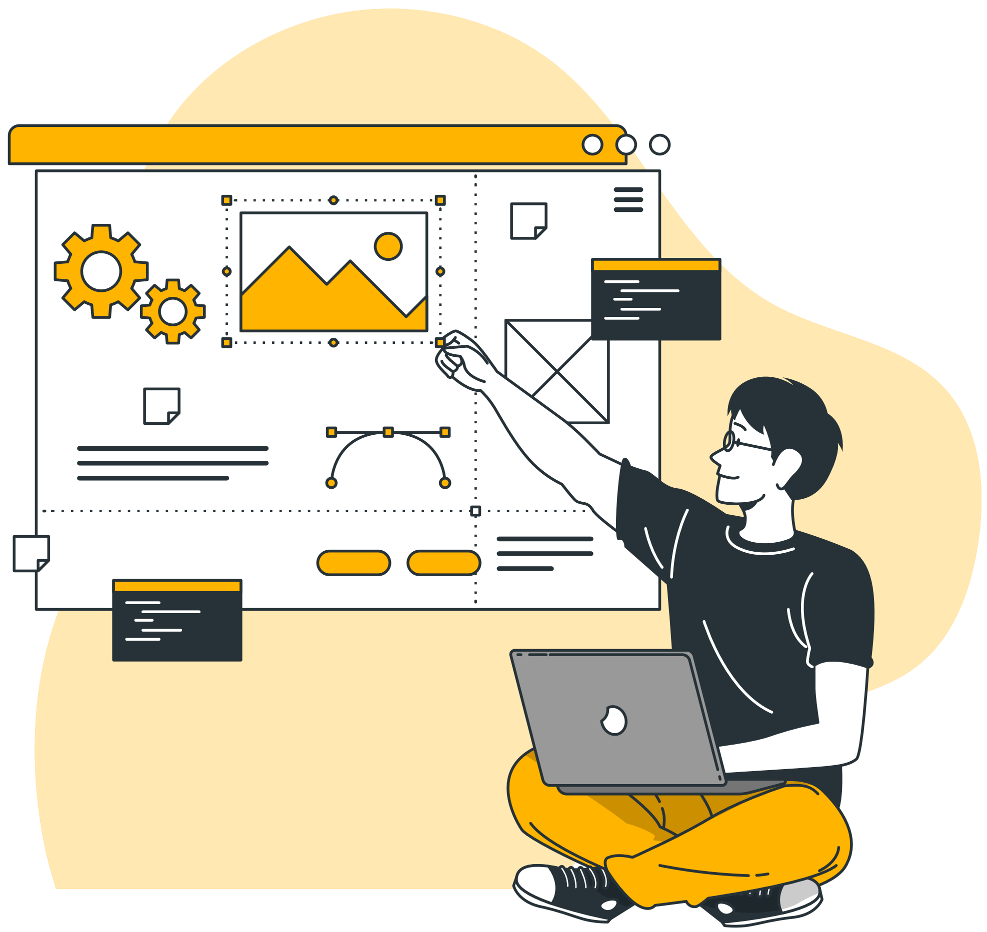
- All other models achieved inconsistent results

Health index evolution over the samples:
The degradation level is 0.1 for the first maneuver and is incremented by 0.2 every 50 samples.



Future work

- More general dataset and include exogenous variables
- Run-to-failure data collection,
- Estimation of remaining useful life (RUL),
- Work on explainability of models



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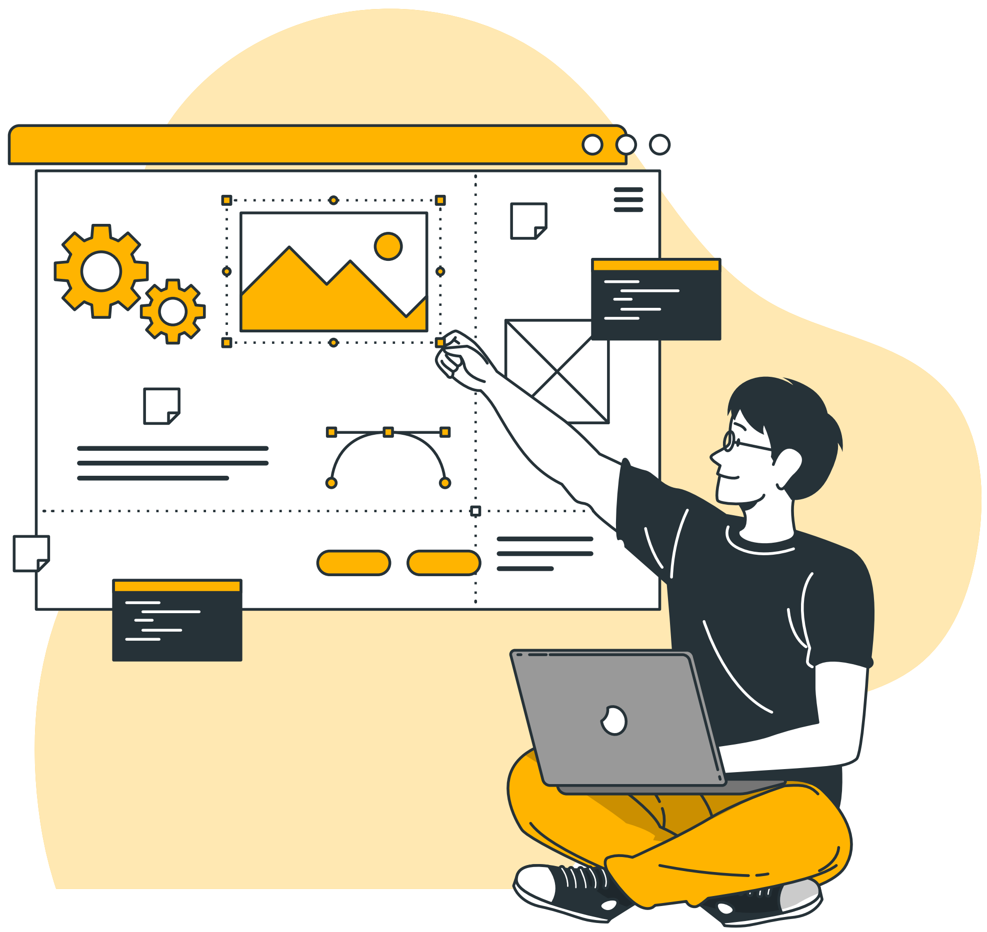

THANK YOU FOR YOUR ATTENTION!