Lorenzo De Donato

Deep Learning for Railway Safety and Maintenance: Methodologies and Applications

Tutor: Prof. Valeria Vittorini
co-Tutors: Prof. Carlo Sansone,
Prof. Francesco Flammini (Linnaeus University, Sweden)

Cycle: XXXVI Year: Third

Background information

- **MSc degree**: Computer Engineering
- **Research group/laboratory**:
  - Laboratorio Sicurezza Sistemi Informatici
  - Pattern analysis and Intelligent Computation for mUltimedia Systems
- **PhD start date**: 01/11/2020 | **End date**: 31/10/2023
- **Scholarship type**: funded by CINI, partially on the H2020 Shift2Rail project "RAILS – Roadmaps for AI integration in the rail sector", G.A. n.881782.
- **Period abroad**: Linnaeus University (Växjö, Sweden), 01/09/2022 – 22/12/2022
- **Cooperation**: partners of the RAILS project:

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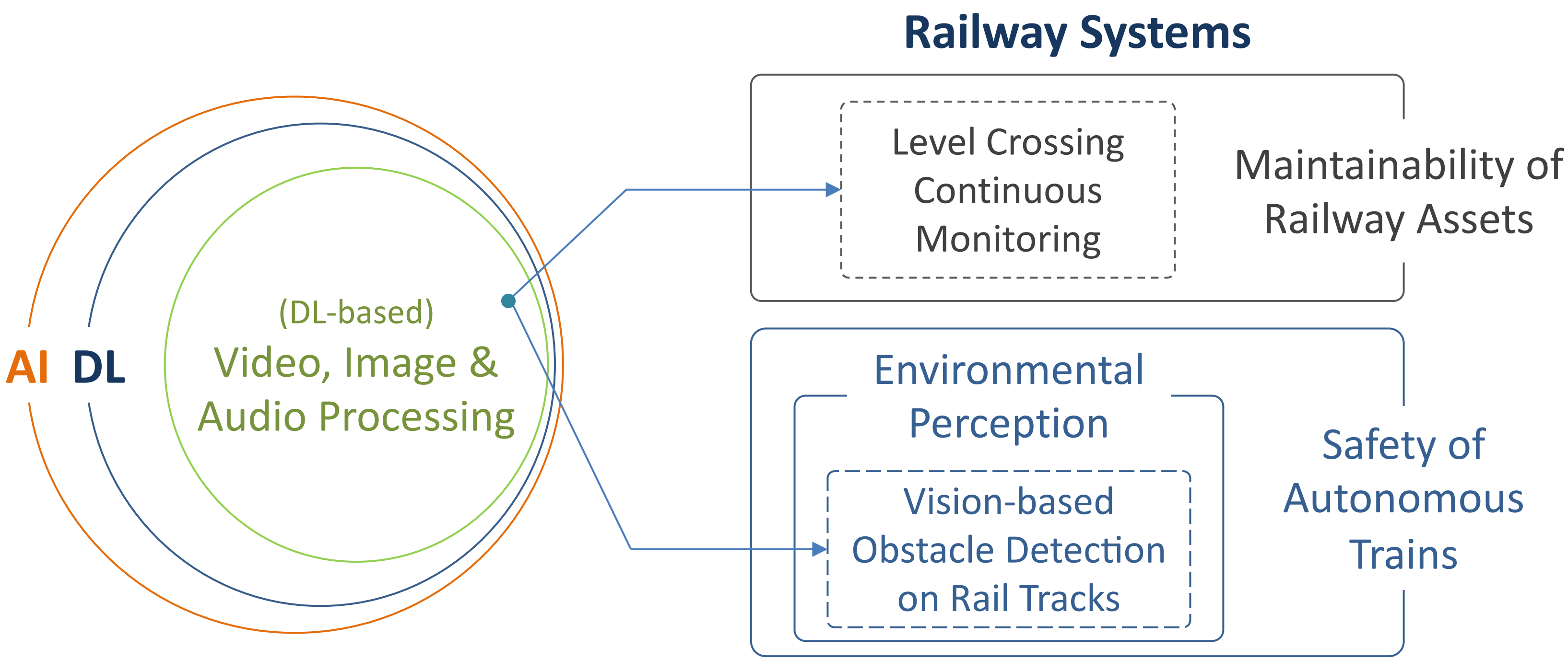
Summary of study activities

- **8 Courses.** The latest include:
  - Neural Networks and Deep Learning
  - Using Deep Learning properly
- **41 Seminars** with the aim of acquiring knowledge on AI, Deep Learning, Computer Vision, and Railway Systems.
- **10 Conference/Workshops.** I presented research results in the form of oral presentations, conference papers, or short papers at almost all of them. The latest include:
  - “Big Data Conference 2022”, Kalmar, Sweden, 2 December 2022. Poster Presentation.
  - “Europe’s Rail 2022 Innovation Days”, Online, 7-9 December 2022. Oral Presentation.
  - “RAILS Final Workshop & Roadmapping Event”, Online, 30 May 2023. Organization and Oral Presentation.
  - “MATLAB Academic Forum for Research and Teaching”, Online, 27 September 2023. Invited to give an Oral Presentation.

Research area(s)

Investigate the potential of Deep Learning for audio-video analysis leveraging data from cost-effective and non-intrusive sensors, with a focus on Railway Safety and Maintenance applications.



Research results

Methodological:

- Definition of guidelines for the introduction of AI in autonomous train driving
- Definition of DL Modular Architectures for:
  - Vision-based *Obstacle Detection on Rail Tracks through On-board Cameras*.
  - *Level Crossings Continuous Monitoring through Cameras and Microphones*.

Experimental:

- Implementation of DL approaches for:
  Rail Tracks Segmentation, Anomaly Detection on Rail Tracks, Warning Bell Classification, and Protective Barrier Motion Extraction.
- Development of two virtual railway scenarios in RoadRunner and Unreal Engine.
- Construction of four datasets, two of which have been published on Zenodo[1,2].

1. https://zenodo.org/records/7924875
2. https://zenodo.org/records/7945412

Research products [1/2]

[P1]	N. Bešinović, L. De Donato, F. Flammini, R.M.P Goverde, Z. Lin, R. Liu, S. Marrone, R. Nardone, T. Tang, V. Vittorini, *Artificial Intelligence in Railway Transport: Taxonomy, Regulations and Applications,* **IEEE Transactions on Intelligent Transportation Systems,** vol. 23 (9), pp. 14011-14024, 2021, DOI: 10.1109/TITS.2021.3131637.
[P2]	R. Tang, L. De Donato, N. Bešinović, F. Flammini, R.M.P. Goverde, Z. Lin, R. Liu, T. Tang, V. Vittorini, Z. Wang, *A Literature Review of Artificial Intelligence Applications in Railway Systems,* **Transportation Research Part C: Emerging Technologies,** vol. 140, pp. 103679, 2022, DOI: 10.1016/j.trc.2022.103679
[P3]	L. De Donato, F. Flammini, S. Marrone, C. Mazzariello, R. Nardone, C. Sansone, V. Vittorini, *A Survey of Deep Learning Applications to Railway Maintenance by Audio-Video Analytics,* **IEEE Access,** vol. 10, pp. 65376 - 65400, 2022, DOI: 10.1109/ACCESS.2022.3183102.
[P4]	L. De Donato, S. Marrone, F. Flammini, C. Sansone, V. Vittorini, R. Nardone, C. Mazzariello, F. Bernaudin, *Intelligent Detection of Warning Bells at Level Crossings through Deep Transfer Learning for Smarter Railway Maintenance,* **Engineering Applications of Artificial Intelligence,** vol. 123, pp. 106405, 2023, DOI: 10.1016/j.engappai.2023.106405.
[P5]	L. De Donato, R. Dirnfeld, A. Somma, A. De Benedictis, F. Flammini, S. Marrone, M. Saman Azari, V. Vittorini, *Towards AI-assisted digital twins for smart railways: preliminary guideline and reference architecture,* **Journal of Reliable Intelligent Environments,** vol. 9, pp. 303–317, 2023, DOI: 10.1007/s40860-023-00208-6.
[P6]	R. Dirnfeld Túrocy, L. De Donato, A. Somma, M. Saman Azari, S. Marrone, F. Flammini, V. Vittorini, *Integrating AI and DTs: Challenges and Opportunities in Railway Maintenance Application and Beyond,* **SIMULATION**, **Accepted**, 2023.

Research products [2/2]

[C1]	F. Flammini, L. De Donato, A. Fantechi, V. Vittorini, *A Vision of Intelligent Train Control,* **International Conference on Reliability, Safety, and Security of Railway Systems (RSSRail 2022),** Paris, France, Jun. 2022, pp. 192-208, Springer, DOI: 10.1007/978-3-031-05814-1_14.
[C2]	R. Dirnfeld, L. De Donato, F. Flammini, M. Saman Azari, V. Vittorini, *Railway Digital Twins and Artificial Intelligence: Challenges and Design Guidelines,* **European Dependable Computing Conference (EDCC). Dependable Computing - EDCC 2022 Workshops,** Zaragoza, Spain, Sept. 2022, pp. 102-113, Springer, DOI: 10.1007/978-3-031-16245-9_8.
[D]	L. De Donato, V. Vittorini, F. Flammini, S. Marrone, Vision-Based Obstacle Detection on Rail Tracks, *Dataset*, Zenodo, 2023. DOI: 10.5281/zenodo.7924875, https://zenodo.org/records/7924875
[D]	L. De Donato, V. Vittorini, F. Flammini, S. Marrone, Level Crossing Warning Bell (LCWB) Dataset, *Dataset*, Zenodo, 2023. DOI: 10.5281/zenodo.7945412. https://zenodo.org/records/7945412
[B]	L. De Donato, R. Tang, N. Bešinović, F. Flammini, R.M.P. Goverde, Z. Lin, R. Liu, S. Marrone, E. Napoletano, R. Nardone, S. Santini, V. Vittorini, *Artificial intelligence in railways: current applications, challenges, and ongoing research,* In H. Dia (Ed.), **Handbook on Artificial Intelligence and Transport**. Edward Elgar Publishing, October 2023.
[R*]	R.M.P. Goverd**,** L. De Donato, T. Ruifan, F. Flammini, Z. Lin, R. Liu, *Report on identification of migration strategies and roadmaps for AI integration in the rail sector,* **Deliverable D5.3 of the RAILS Porject** https://rails-project.eu/downloads/deliverables/

C: International Conference Papers | D: Datasets | B: International Book Chapter

R*: I co-authored **12** (most of) RAILS Deliverables, five of which have been finalised or addressed this year.
Here is reported only the last one.

PhD thesis overview

Objective

Develop solutions for the effective application of DL in safety and maintenance applications with a focus on autonomous train driving and railway assets monitoring.

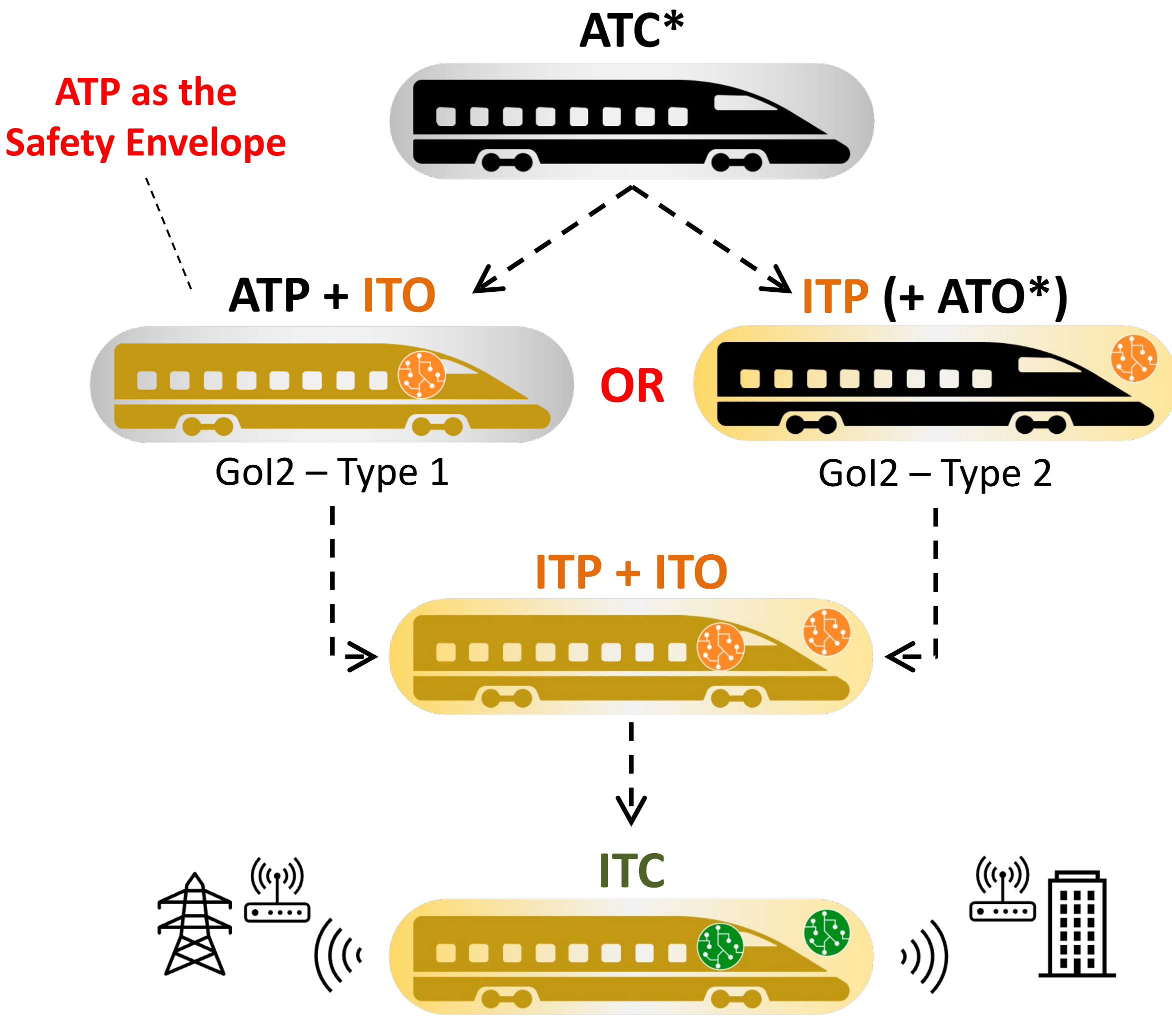
Main Challenges for DL (include)

- Lack of ad-hoc standards
- Instability/explainability of DL approaches
- Lack of suitable datasets to train and test DL models

Opportunities

- Support the shift from automatic to autonomous trains.
- Support the shift from on-field/scheduled inspections and corrective maintenance to online monitoring and predictive maintenance.

PhD thesis: A Vision of Intelligent Train Control
Grades of Intelligence (GoI)



GoI 1
Limited / No Autonomy

GoI 2:
Partial Autonomy

GoI 3:
Full Autonomy

GoI 4:
Full Autonomy in
Fully Connected Environment

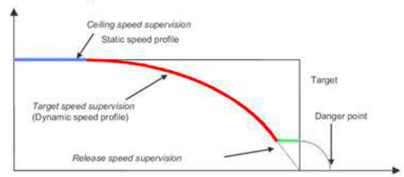
* If / where present

PhD thesis: A Vision of Intelligent Train Control
ATP as the Safety Envelope for ITO

Automatic Train Protection

acting as a SAFETY ENVELOPE to ATO/ITO by ensuring train interdistance, train and route integrity, etc.

Requires connection with signalling system



SIL4

Energy Optimisation

Capacity Optimisation

Comfort Optimisation

Intelligent Train Operation

adding ”smartness”, learning and adaptation to traditional ***A****utomatic* ***T****rain* ***O****peration*

ATP unavailability or partial supervision

Intelligent Train Protection

using AI to replace/support ATP

SIL?

Obstacle Detection

Signal Recognition

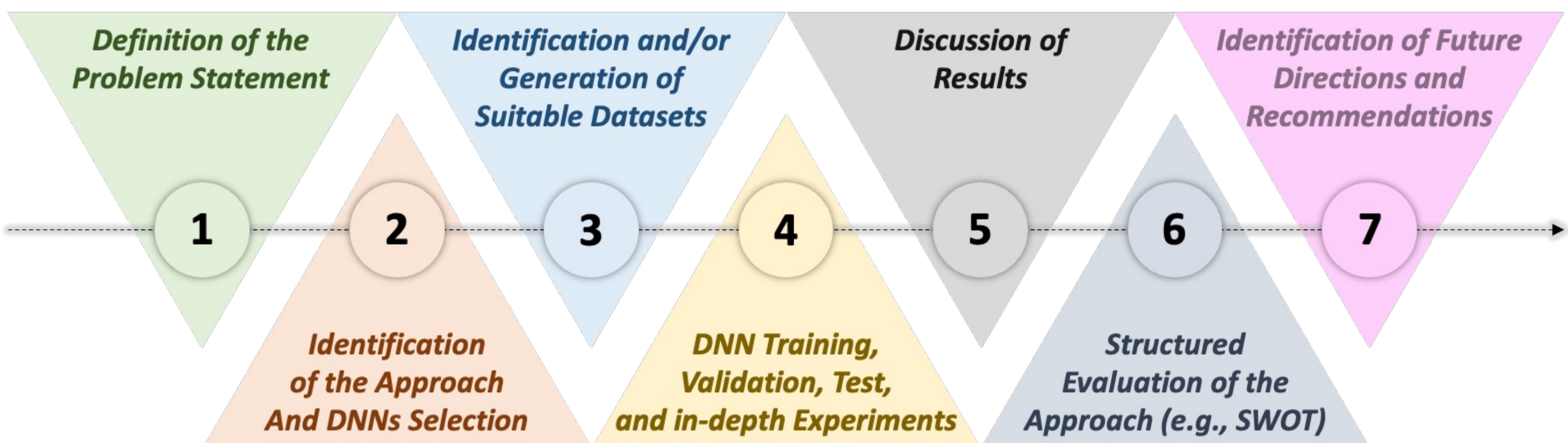
information technology electrical engineering itee PhD

PhD thesis: Case Studies

Case Study 1:
Vision-based Obstacle Detection on Rail Tracks

Case Study 2:
Level Crossings Continuous Monitoring through Audio/Video Data

Methodology for Deep Learning applications:



PhD thesis: Case Study 1 (Steps 1-3)

Problem
Identify any possible obstacle (known and unknow) laying on rail tracks ahead the train while exploiting only cameras.

Objective
Exploit the peculiarities to address rail tracks identification and anomaly detection

Identified Peculiarities
Fixed and pre-determined Train Path

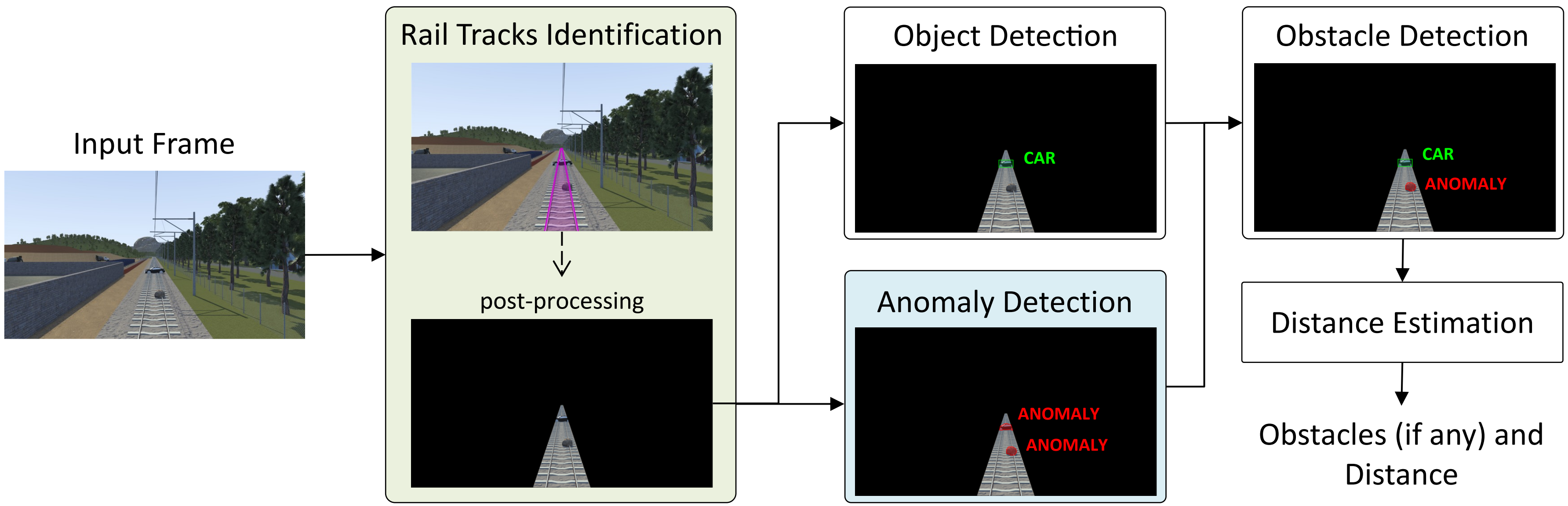
Main (beforehand) Issues
Data Availability
Data Labelling

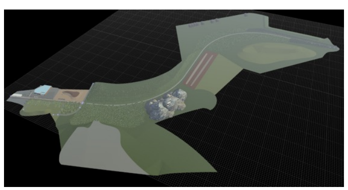
Exploited Solutions and Tools
Modular Approach
Transfer Learning / Self-Training
RoadRunner, Unreal Engine

Developments
Virtual Railway Environments
Semi-Automatic Labelling (Self-Training)
Semantic Segmentation (U-Net)
Anomaly Detection (VQ-VAE)

Datasets
RailSem19 (Transfer Learning)
Synthetic Data from Virtual Scenarios

PhD thesis: Case Study 1 (Step 4)





Semantic Segmentation (U-Net)

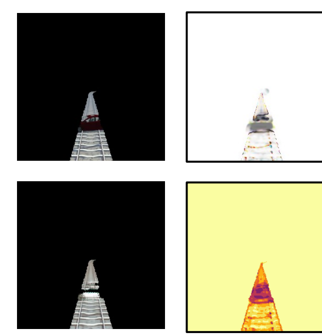
Simulated Scenario + Augmentations (9600 samples)

Dice Score: 0.9993 ~ 20.6 ms

Image Reconstruction (VQ-VAE)

U-Net’s Outputs

SSIM Score: 0,9887 ~ 38.9 ms



information technology electrical engineering PhD

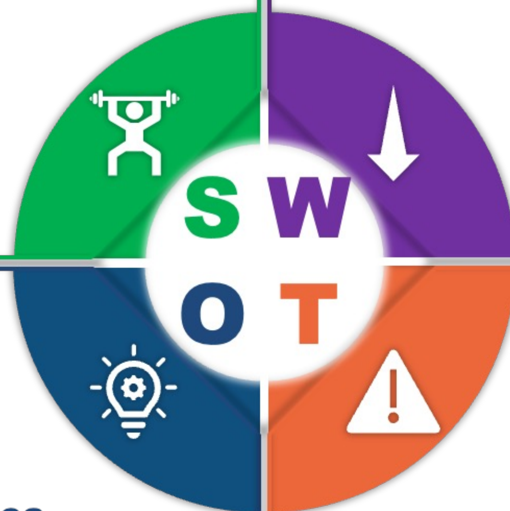
PhD thesis: Case Study 1 (Steps 5-7)

Strengths

Increment of the Coverage
★ Modularity
Redundancy
Scalability
Cost-effectiveness

Weaknesses

Long-range Anomaly Detection
Long-rage Segmentation
Computation Time
False Positives and Noise



Opportunities

Self-Training
Transfer Learning
Explainable AI
★ Domain-Specific Characteristics
★ 3D Editors and Simulators

Threats

Explainability
Instability
Certifiability

★ Recommendations for future developments

PhD thesis: Case Study 2 (Steps 1-3)

Problem
Move from scheduled inspections to continuous monitoring adopting non-intrusive and cost-effective sensors.

Objective
Exploit the peculiarities to address
LC components monitoring

Identified Peculiarities
LCs subdividable in components,
Fixed cameras,
Warning bell with different sounds

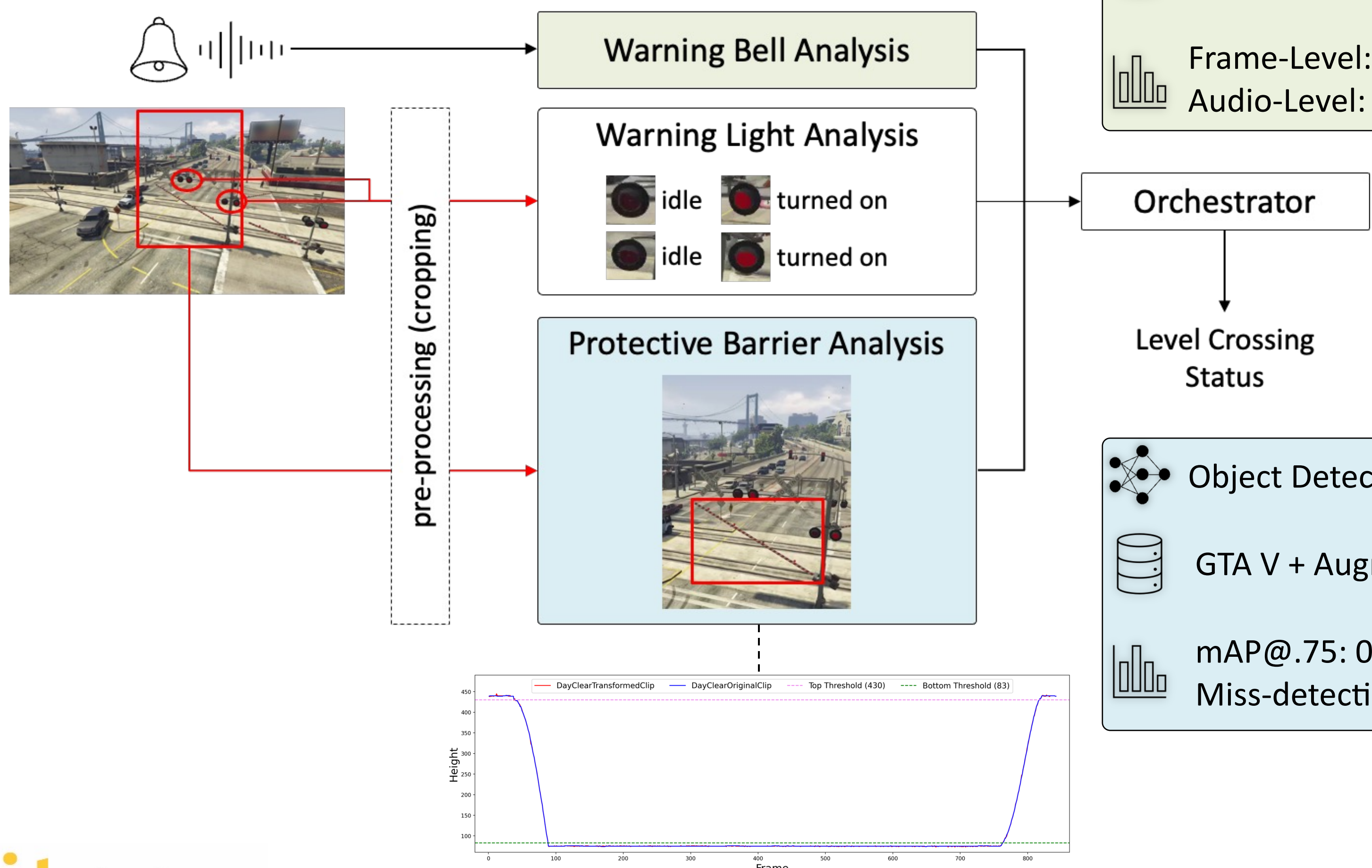
Main (beforehand) Issues
Data Availability
Data Labelling

Exploited Solutions and Tools
Modular Approach
Transfer Learning
YouTube, Grand Theft Auto V

Developments
Three-class Classification (U-Net)
Anomaly Detection (VQ-VAE)

Datasets
AudioSet, YouTube (Audio Data)
Synthetic Data from GTA (Video Data)

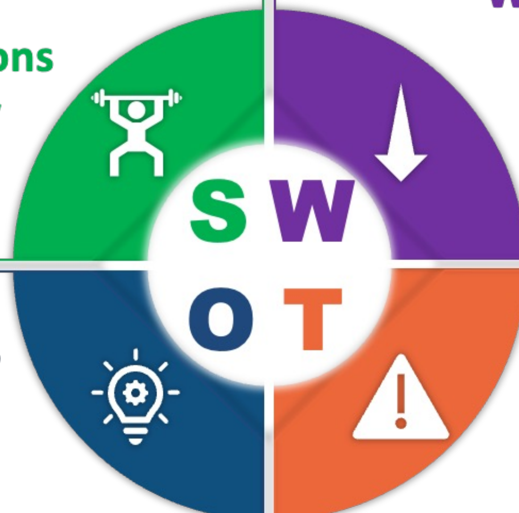
PhD thesis: Case Study 2 (Step 4)



- Three-Class Classification (VGGish)
- AudioSet / YouTube (1180 Audios)
- Frame-Level: 92.48%
  Audio-Level: 97.37%
- 1.13 ms

- Object Detection (YOLOv5)
- GTA V + Augmentations (17760)
- 10.36 ms
- mAP@.75: 0.995
  Miss-detection rate <0.7

PhD thesis: Case Study 2 (Steps 5-7)



Strengths

Non-Intrusiveness, Cost-Effectiveness
Technology Re-usability
Dual-Usability
Robustness to Miss-classifications
Modularity and Adaptability
Processing Time
★ Realisation of Digital Twins

Weaknesses

Warning Bell Analysis Module's
Robustness to Noise
and Granularity

Opportunities

Already Installed Cameras
★ Real-life Simulators
Online Collections
Data Augmentation
★ Transfer Learning

Threats

Weather Conditions
Environmental Noise
LCs Diversity

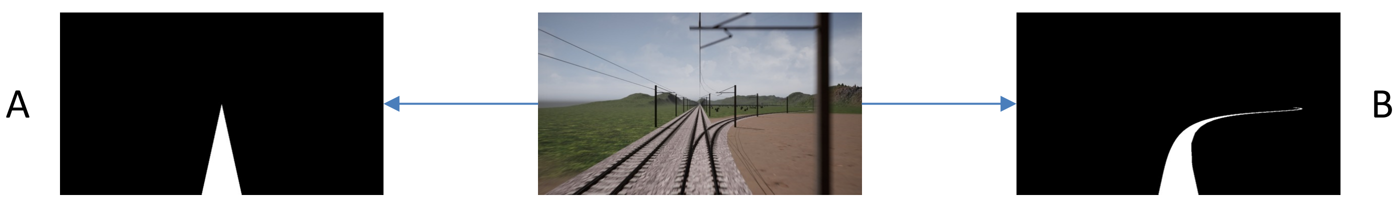
★ Recommendations for future developments

Conclusions

- The adoption of DL in safety railway scenarios raises concerns in terms of certifiability but also introduce opportunities in enhancing current applications. Both the aspects have been analysed in the thesis.

- On the one hand, the rail sector is strictly regulated by safety standards and one of the paramount challenges concerns the certifiability of AI systems. In this context, high-level guidelines have been introduced towards the introduction of AI in fully autonomous trains including the concept of *Safety Envelope.*

- On the other hand, experiments highlighted what DL could open for in the context of environment perception and non-intrusive monitoring. Worth highlighting are:
  - The role that 3D Editors and Real-Life Simulators could play in *"Ad-hoc and Suitable"* datasets generation for the development of DL strategies and PoCs.
  - The value of Domain- and Problem-specific characteristics in the facilitation of the tasks DL systems should address. *A "very easy" question*: which mask should the model predict?



Modular architecture exploiting these aspects have been proposes which, compared to the known state-of-the-art, apport innovative hints and solutions for rail tracks identification, anomaly detection on rail tracks, and level crossing non-intrusive and continuous monitoring.