Rail to Digital automated up to autonomous train operation

D11.3 – PoC of Perception System

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EXECUTIVE SUMMARY

This document presents the proof of concept carried out for AŽDs perception system. The goal of the task 11.3 was to operate an existing AŽD perception system in shadow mode on an SBB Xem 181 vehicle. These vehicles are used in demanding environmental conditions in the perimeter of the Gotthard Base Tunnel (currently longest railway tunnel in the world) and the Ceneri Base Tunnel. Data was collected in continuous shadow mode during routine movements and in predefined test cases.

For the perception system, a sensor set of RGB camera, thermal camera and LiDAR were installed on both sides of the vehicle. A privacy-by-design pipeline applied real time detection and blurred faces and license plates before recording. Between 22.10.2025 and 29.12.2025, approximately 350 hours of recording were collected over 48 operating days. This resulted in a total of 4.4 TB of data. Triage identified approximately 13% (0.5 TB) as corrupted (mainly due to power interruptions), 47% (2.0 TB) as irrelevant (for example uneventful idling or obstructed views), and 40% (1.7 TB) as retained for evaluation.

Key findings for the trial are:

- **Sensor robustness under real conditions:** Across all operating days with wide temperature ranges (external temperature from -2.9 °C up to 33.4 °C) and rapid changes (for example -2.9 °C to 19 °C in four minutes), no sensor degradation was observed. The operation in the tunnel environment (dust, humidity) didn't have a lasting effect on the sensors.
- **Individual sensor strengths and limits:** The RGB camera offered mostly useful images but was "blind" at tunnel portals due to high brightness changes and of limited use in total darkness. The thermal camera reliably identified people but lost the ability to render the environment due to the uniform temperature in the tunnel. The LiDAR provided consistent spatial and intensity context, with reflectivity-based visualization clearer for human reviewers near walls.
- **Sensor fusion / sensor redundancy**: During RGB camera exposure transitions (for example at the portal of the tunnel), the LiDAR and thermal camera preserved situational awareness. It appears that obstacles on the track remained distinguishable with the use of LiDAR, and people were reliably visible on thermal imagery. The trial clearly demonstrated the importance of sensor redundancy / sensor fusion in such cases.

The overall trial was successfully executed. The system remains on the vehicle until summer/autumn 2026. This allows to extend data collection and may take also harsher winter conditions into analysis. Due to operational reasons, not all test cases could be executed. They could be compensated with the data collected in shadow mode.

Overall, this experiment provided invaluable data for the further development of the sensory system. Although the testing period in this specific environment was limited, the findings from task 11.3 significantly enrich the ongoing sensor development also being conducted in other configurations (for example in WP46 with Faiveley and AŽD on regional line).

ABBREVIATIONS AND ACRONYMS

AŽD	Automatizace Železniční Dopravy
CBT	Ceneri Base Tunnel
CNN	Convolutional Neural Network
CPU	Central Processing Unit
DDP	Deliverable Development Plan
ETCS	European Train Control System
EN	European Norm
ERJU	Europe's Rail Joint Undertaking
FoV	Field of View
GBT	Gotthard Base Tunnel
GDPR	General Data Protection Regulation
GPU	Graphics Processing Unit
HD	High Definition (camera)
HDD	Hard Disk Drive
HDR	High Dynamic Range
I/O	Input/Output (direction signal)
LiDAR	Light Detection and Ranging
MIC	Maintenance and Intervention Center
NAS	Network Attached Storage
PoC	Proof of Concept
R2DATO	Rail to Digital automated up to autonomous train operation
RGB	Red, Green, Blue (camera)
SBB	Schweizerische Bundesbahnen (Swiss Federal Railways)
SSD	Solid State Drive
TB	Terabyte
UIC	International Union of Railways
WP	Work Package
ZUB	Zugbeeinflussung (CH specific automatic train protection)

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1 INTRODUCTION

Task 11.3 “PoC of Perception System” is part of R2DATO WP11 titled “Prototype development of perception system”. The aim of the mentioned work package is the detailed design, development and validation of the perception system defined in the Perception Architecture and System Specification in WP6.3 (deliverable D6.3).

Tasks 11.1 and 11.2 focus on the specification of datasets and the development and validation of such a perception system.

Task 11.3 focuses on an existing perception system / sensor set from AŽD. The exact description of this task is mentioned in the Grant Agreement:

> *“Perception activity will be performed in Gotthard Base tunnel area in shadow mode using regular traffic of maintenance vehicles. The aim is to collect and evaluate perception data from different weather conditions and to evaluate performance and collect requirements from these regular runs.”*

As stated above, task 11.3 explicitly does not develop a new system or perform requirements engineering. The focus relied on testing an existing sensor set provided by AŽD under challenging environmental conditions such as high temperatures and fluctuations, high humidity, different lighting or fog.

The system consists of a camera, a thermal camera, and a LiDAR sensor installed on each side of the vehicle. These components were integrated into a maintenance vehicle (Xem 181) and operated in shadow mode in the Gotthard Base Tunnel (GBT) area to collect representative operational data without affecting regular operations. In addition to the shadow mode data collection, a set of predefined test cases was executed as well.

The collected datasets were transferred regularly to AŽD. The subsequent analysis phase covered data quality assessment, detection performance, sensor failure and operational impacts.

C2 - Intern

1.1 SCOPE

Over the duration of the project, the scope of task 11.3 was refined. The evolution of the project was tracked and described in various amendments.

The proof of concept focuses on testing an existing AŽD perception system in shadow mode during regular maintenance operations in and around the Gotthard and Ceneri Base Tunnel. Task 11.3 is clearly distinct from the other WP11 tasks. Task 11.3 does not develop or validate a new system. In addition, defining a formal requirements evaluation is also not the intention of the task.

The focus is on operational system trials of the sensor set (camera, thermal camera, LiDAR) under challenging environmental and operational conditions, combined with data collection and performance assessment. The trials are conducted on the Xem 181 maintenance vehicle, operating between the Maintenance and Intervention Centers (MIC) in Erstfeld and Biasca.

It is limited to a continuous shadow mode recording alongside predefined field test cases. The primary focus of the PoC is the Gotthard Base Tunnel perimeter.

1.2 PROJECT RELATIONS

The activities provided in task 11.3 follow activities in task 11.2 and are complementary to testing in WP46 on regional line. Results and experience from this task will be used in further perception system development.

1.3 RESEARCH METHODOLOGY

The objective of the data collection was to obtain a large, diverse dataset. Therefore, the evaluation was based on collecting data in shadow mode to assess data quality, performance and robustness under representative operational and environmental conditions. In addition to the continuous shadow mode data acquisition during the operational runs a set of predefined test cases was performed to enhance the data. On the one hand, this approach offered a large dataset and on the other hand, to test specific scenarios that do not occur often in regular operations.

All data from the perception system's SSD array were uploaded to the NAS at AŽD and sorted into three categories: specific test cases, relevant shadow mode recordings (for example from pedestrians or objects near the train), and irrelevant recordings (for example nighttime idling). Irrelevant recordings were excluded.

For shadow mode analysis, periods with notable weather were prioritized. Synchronized RGB, LiDAR and thermal images were crosschecked to find people and objects. The sensor signal quality was subjectively assessed. All events were classified as typical or anomalous and checked for impacts from transient weather, sudden changes, or sensor degradation, e.g., exposure to harsh winter environments and the specific conditions of the Gotthard Base Tunnel (GBT).

For specific test cases, the evaluator assessed and logged the data quality into a structured table according to the parameters defined for each specific test scenario.

Further information can be found in chapter "5.2 - Methods of analysis".

2 BASICS FOR THE PROOF OF CONCEPT

2.1 USED VEHICLE

The vehicle used for the trial is a service vehicle of the type ”Xem 181” (X: service vehicle, em: electric traction unit with pantograph and diesel motor). Within SBB, this type of vehicle is referred as a so called “base vehicle” and is mainly used for maintenance and service work in the area of the Gotthard Base Tunnel (GBT) as well in the area of the Ceneri Base Tunnel (CBT) - see also chapter “2.3.2 - Operational use and scenarios”. In total, there were 13 base vehicles built for SBB. In addition to that, there are 17 special non-powered wagons such as the mobile maintenance gates, modular and basket wagons [1].

The following table indicates general parameters of the base vehicles:

Parameter	Value
Number	99 85 9181 001 - 013
Type	Maintenance / Service vehicle
Year of manufacture	2016 - 2017
Manufacturer	Harsco Rail

Table 1: General parameters of the Xem 181

Figure 1: Used vehicle Xem 181 - 99 85 9181 001

2.1.1 Technical details

The Xem 181 is a four-axle traction unit with two bogies and four electrically driven and water-cooled traction motors. The energy supply for the main circuit is provided either from the overhead line with 15 kV / 16.7 Hz or from an underfloor-mounted diesel power pack. For every bogie there is a propulsion converter available. The vehicles are equipped with an automatic draw/push coupling and buffers. They can be coupled without restrictions to vehicles with UIC coupling and buffer devices. The Xem 181 is multi-traction capable. Additional technical parameters can be found in the following table [1]:

Parameter	Value
Vmax	100 km/h
Total weight max.	85 t
Length (buffer)	22000 mm
Axle load	22.5 t
Automatic train protection	ETCS L2 Baseline 2.3.0d ZUB 262ce
Power	550 kW (diesel) / 1080 kW (electric)
Wheel diameter	920 mm

Table 2: Technical parameters of the Xem 181

The vehicle has a single driver's cab. A remote control is available and can be used on the vehicle or in the near range of the vehicle. In addition to the engine room, the vehicle is equipped with a loading platform including a crane and a workshop module [1].

The vehicle is built up as follows:

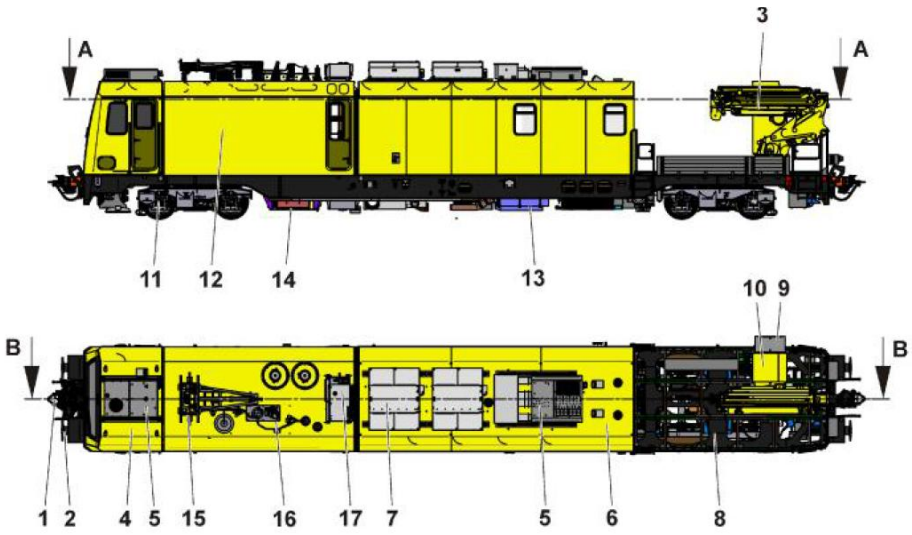

Figure 2: Side and roof view of vehicle Xem 181

1. Coupler	2. Crash-buffer	3. Crane PR220
4. Driving cab	5. Air conditioner	6. Workshop module
7. Brake resistor	8. Loading area	9. Control station crane
10. Auxiliary driving cab	11. Bogie	12. Engine room
13. Powerpack	14. Transformer	15. Pantograph
16. Main circuit breaker	17. Compressor	18. Work basket (crane)

Table 3: Description of parts from vehicle Xem 181

2.2 LOCATION OF THE VEHICLE

For maintenance and servicing work in the GBT (Gotthard Base Tunnel) and CBT (Ceneri Base Tunnel), the so-called “Maintenance and Intervention Centers” (MIC) have been established. These are the main bases for personnel, vehicles, and materials required for work in the tunnels. There are two Maintenance and Intervention Centers: One is located at the north portal of the GBT in Erstfeld, while the other is at the south portal in Biasca. The vehicles are stationed at one of these locations depending on operational needs. Figure 3 shows the two MIC located in Erstfeld (north) and Biasca (south). The red line indicates the 57.09 km long GBT.

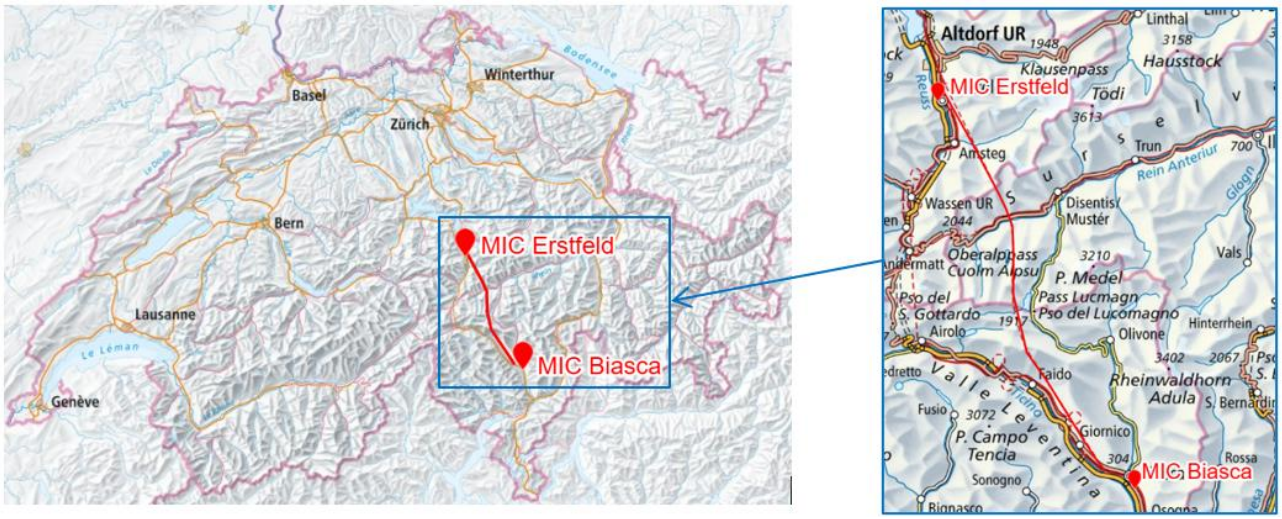

Figure 3: Location of MIC Erstfeld and Biasca [2]

2.3 OPERATIONAL USE

2.3.1 Gotthard and Ceneri Base Tunnel

The vehicles are mainly used for maintenance services in the GBT and CBT tunnels:

GBT – Gotthard Base Tunnel

The Gotthard Base Tunnel is currently the longest railway tunnel in the world. The north portal of the tunnel is in Erstfeld (460 m above sea level), and the southern portal is located in Bodio (322 m above sea level). The tunnel is 57.09 km long. There are two single track main tubes with interconnecting cross-passages. In addition, there are two access points via service tunnels in Sedrun and Faido.

CBT – Ceneri Base Tunnel

The Ceneri Base Tunnel is in the south of Switzerland. It connects Camorino on the north side with Vezia on the south side. The length of the tunnel is 15.4 km. Like the GBT, there are two single track main tubes with interconnecting cross-passages.

2.3.2 Operational use and scenarios

Usually, the following procedure for a week is applicable for the GBT/CBT:

- *Tuesday to Thursday:*
  The Xem 181 vehicles are primarily parked at one of the MICs, where minor service is performed. In addition, several individual transits between the two MICs are scheduled. The vehicles are also prepared for the shift on the upcoming weekend.

- *Friday:*
  Final preparations for the tunnel shift are complete. The day also serves as a buffer in case any technical issues arise with the vehicle.

- *Saturday and Sunday evening/night:*
  Maintenance work in the GBT/CBT is carried out primarily at night.

- *Monday:*
  The vehicles are serviced and cleaned after the work shift in the tunnel.

Work shifts in the tunnel

For the shift in the tunnel, several compositions are combined. A composition consists of an Xem vehicle and several coaches. Up to four compositions could be combined. The movement from the MIC into the tunnel is a diesel-powered train journey, as the overhead catenary wire is typically switched off. To access the tunnel, the composition must be moved through the public area, this might involve passing several train stations. As soon as the first workstation is reached, one composition is decoupled. The train journey continues to the next workstation afterwards. This process is repeated until the final workstation is reached with the front-composition. At the various compositions, maintenance activities such as the flushing process or the maintenance of electrical systems are then executed. Finally, the compositions are joined together again and leave the tunnel.

Individual transit movements

Additionally, to the maintenance work in the tunnel, there are regular transit movements between Erstfeld and Biasca. For example, it is possible that in Biasca more vehicles are needed for maintenance work shifts. Due to the high frequency of traffic in the GBT, the transfer is done via the Gotthard mountain route. This route includes several tunnels as well as steep ascents and descents.

2.4 ENVIRONMENTAL CONDITIONS

The vehicles are used in a diversified and challenging environment for testing the perception sensor set. The following overview gives an indication of these conditions.

Erstfeld

Erstfeld, located on the north side of the GBT, has a mild mountain climate with clear alpine influences that is typical for central Switzerland. Summers tend to be mild, while winters are colder caused by the surrounding mountains. Foehn wind could generate warm conditions and dry the air. Rainfall occurs throughout the whole year, during the winter there is a lot of snow possible. There are noticeable climate differences between the valley and the surrounding mountains/slopes, as they have for example different sun exposure.

Biasca

Biasca is located on the south side of the GBT, and its climate is warm and mediterranean influenced. Summers are hot and sunny with more than 30 °C, while winters remain mild. Biasca has one of the warmest Winters in Switzerland. Foehn-wind could also generate brief warm and dry conditions.

Tunnel

Inside the tunnel, temperatures can rise to 40 °C despite active ventilation and climate-control systems. When outside temperatures fall to around -15 °C to -20 °C, temperature differentials up to 60 °C can develop in a short time. Relative humidity typically remains moderate at around 70%. Additional to these conditions, dust and dirt accumulation can be also observed.

Environmental conditions for the PoC

The actual environmental condition during the shadow mode data collection and for the specific test are described in chapter “5.3.1 - Environmental conditions and observations”.

2.5 REQUIREMENTS FOR THE TEST SYSTEM

To enable the trial of the system with the Xem 181 vehicle, several prerequisites and requirements had to be met. They were defined and specified by the vehicle responsible and communicated to the project team.

2.5.1 General restrictions and requirements

Topic	Description	Justification
Interaction with operational staff	For the trial it was mandatory that the personnel at no time of their everyday work were disturbed by the system. Neither the driver nor the staff in the tunnel nor the maintenance personnel should be required to interact with the perception system.	The system was operated in shadow mode. Therefore, no actions by operational staff were required. Maintenance and system checks were performed by the project team.
GDPR	As cameras were used for the trial, the privacy for the operational staff had to be ensured. This also applied to vehicle license plates that may appear within the camera's field of view.	Faces and license plates were anonymized. See also chapter "3.1.3.1 - Visual stream anonymization" for more details.
Safety relevant modification	It had to be assessed whether the installation constituted a safety relevant modification of the vehicle. If yes, the change would have to be reported to the appropriate authorities.	An internal SBB assessment was conducted for the installation. The assessment concluded that the modification is non-substantial and therefore does not require new permission. This assessment is classified as "internal" and will not be published.
Publication	Because cameras are used for the trial, all involved and affected stakeholders had to be informed.	All relevant stakeholders like train drivers, team leaders, maintenance personnel, etc. were informed personally. As the vehicle also could operate in public areas, a corresponding announcement was published. This announcement was created in coordination with AŽD.

Table 4: General restrictions and requirements

2.5.2 Technical restrictions and requirements

Topic	Description	Justification
Power management	Power was provided via an electrical distribution box (3×230 V, 1×400 V, 16 A). Energy requirements must be coordinated with SBB. The power supply may be interrupted or shut off at any time.	Energy consumption was in the range of 700 W, with a maximum peak of 1000 W. Power loss interruption was considered, see also chapter “3.1.4.2 - Controlled archival rotation policy”.
Technical concept	The system must be designed for challenging operational conditions. It is exposed to high temperatures, dust and dirt, and strong vibrations in the tunnel environment. The following standards and regulations must be complied with for the installation: - EN 45545-1:2013 - EN 45545-2:2020 - EN 45545-5:2013+A1:2015 - EN 50121-3-2:2016 - EN 61373:2010 - EN 50153:2014 - EN 50125-1:2014 - EN 50155:2022	The technical concept was developed together with AŽD taking the operational conditions into account. Before the installation, it was verified that the respective standards and regulations were met.
Direction detection	It was requested to have a signal available, which represents the selected direction of the vehicle to reduce the amount of data. The signal must be provided via an available digital I/O signal. The signal must be connected without any feedback.	The concept was discussed and considered with AŽD. Using relay between the I/O signals allowed non-reactive implementation.

Table 5: Technical restrictions and requirements

3 DESCRIPTION OF USED SYSTEM

3.1 GENERIC OVERVIEW OF THE USED PERCEPTION SYSTEM

3.1.1 Deployment architecture and hardware configuration

The deployed core system operates as a high-throughput rail-mounted data acquisition platform engineered for continuous, reliable data capture in demanding onboard rail environments.

Computer hardware specifications

The processing backbone is anchored by an *Intel Core i9-13900E 24-Core CPU*, selected specifically for its capability to manage numerous concurrent data streams, handle complex sensor initializations, and oversee synchronous operations across the entire sensor suite. Graphical acceleration and parallel computing tasks are offloaded to two *Nvidia RTX A4000* GPUs. These are instrumental in accelerating computationally intensive tasks, namely real-time video encoding and high-speed neural network inference required for anonymization. Persistent data archival is managed by a high-performance four *Kingston DC600M 3.84 TB SSD* array, providing both the necessary total capacity and the required write endurance and speed for parallel data logging within the rail deployment.

Figure 4: Computer unit in the vehicle

Sensor suite and connectivity

Two identical systems were installed on the vehicle, one at the front and one at the rear side. Each system integrates a diverse array of sensors, all connected via a robust ethernet network backbone to ensure synchronous, high-bandwidth data transfer:

1. **Lucid Vision TRT162S-C with 8mm lens** (RGB camera - one each side) [3]
    - FoV: ~85°
    - Resolution: 16 MP (5320 x 3032)
    - Operating temperature: -20 °C to +55 °C
    - Operating humidity: 20% to 80%
    - IP rating: IP67
    - Grade: Industrial grade

2. **Livox Avia** (3D LiDAR - one each side) [4]
    - FoV: ~70°
    - Detection range: ~ 450 m @ 80% reflectivity
    - Laser wavelength: 905 nm
    - Operating temperature: -20 °C to +65 °C
    - IP rating: IP67
    - Grade: Industrial grade

3. **FLIR Boson 640** (Thermal camera - one each side) [5]
    - FoV: ~50°
    - Resolution: 640 x 512
    - Operating temperature: -40 °C to +75 °C
    - Solar protection
    - IP rating: IP67
    - Grade: Automotive grade

4. **Papago 2TH ETH** (Thermometer for environmental monitoring - one outside the window) [6]
    - Thermal sensor limits: -55 °C +125 °C
    - Operating temperature: -20 °C to +70 °C
    - IP rating: IP30

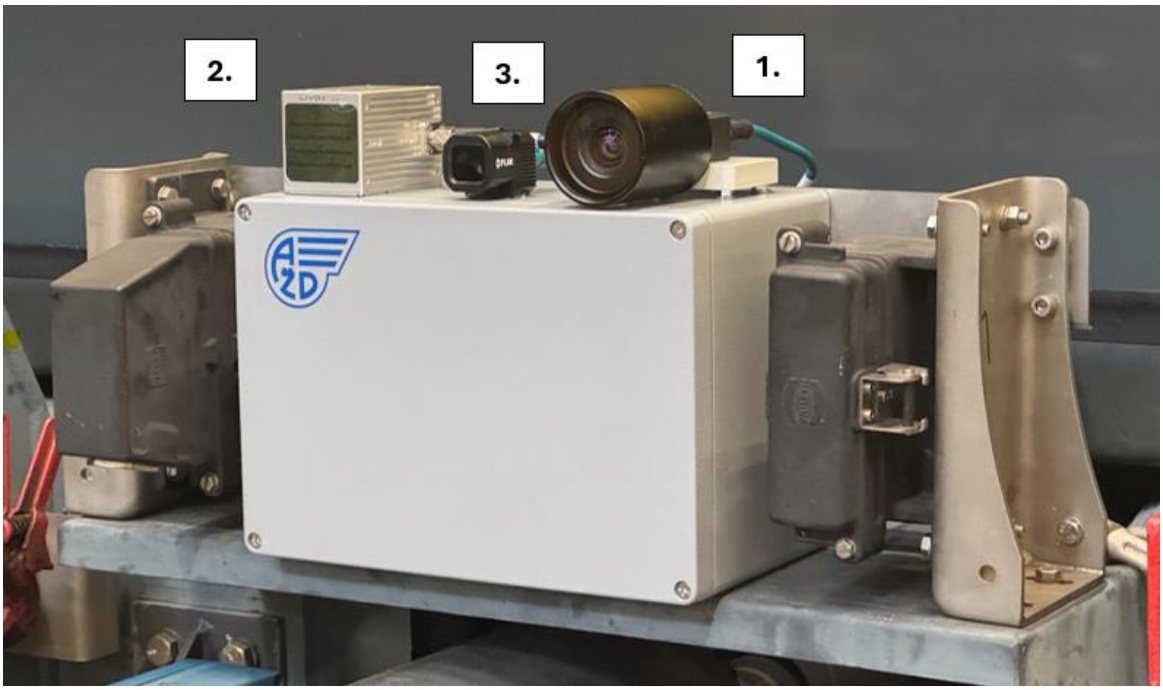

Figure 5: Perception system / Sensor unit

3.1.2 Autonomous operation and directional initialization

The system is designed for autonomous operation, initiating its primary logging loop immediately upon connection to the train's electrical power supply and depending on the selected direction. A critical prerequisite is the identification of the current train direction. This information triggers a deterministic initialization of the corresponding directional sensor suite (front or back), ensuring only relevant data streams are activated and recorded. Data is persistently archived into newly created, timestamped, and directionally labeled directories (note: at this stage of the trial there is no georeferenced information collected).

3.1.3 Data Processing and privacy-by-design pipeline

The software implements distinct, high-efficiency processing pipelines tailored for each sensor type:

3.1.3.1 Visual stream anonymization

The RGB camera data is routed through a mandatory privacy pipeline. Acquired images are immediately processed by an onboard convolutional neural network (CNN) optimized for real-time inference to perform face and license plate detections. The solution for blurring is an in-house implementation of AŽD and is based on CNN training on a random sample from the “Open Images Dataset”. The resulting detection bounding boxes are used to define regions that are instantaneously subject to irreversible digital blurring applied directly to the original image data. This strict procedure ensures anonymity over collected public data, adhering to robust privacy-by-design and regulatory compliance standards before the anonymized images are subsequently encoded into video archives.

3.1.3.2 LiDAR data archival

Each LiDAR unit continuously streams high-frequency spatial data, generating 2400 discrete data points - each consisting of *X, Y, Z* coordinates and reflection intensity value - every 10 milliseconds (100 Hz). This raw data is efficiently serialized and written directly to a dedicated binary file. The serialized format preserves the integrity of the raw measurement structure, enabling high-fidelity post-processing, such as the creation of dense 3D point clouds or synthesized environmental videos, by leveraging auxiliary configuration metadata (e.g., desired output density or frame rate).

3.1.3.3 Thermal and environmental streams

The thermal cameras acquire images similarly to the visual stream but bypass the detection and anonymization pipeline, as thermal data generally falls outside the scope of personal privacy identification. The acquired thermal imagery is directly encoded into a video format. Concurrently, the thermometer performs periodic environmental monitoring, saving both indoor and outdoor temperature readings to a separate, time-stamped text file at one-minute intervals.

3.1.4 Archival and robustness management

3.1.4.1 Dynamic load balancing strategy

Data persistence is optimized through a “dynamic load balancing strategy” across the four SSD units. Before the creation of any new data folder, the software queries the available free capacity on all four SSDs. The drive exhibiting the highest percentage of available free space is dynamically selected as the destination for the new data archive. This uniform data distribution maximizes the lifespan and utility of the SSD array, delays reaching a full-disk state, and ensures optimal write performance by avoiding the utilization of single, highly fragmented drives.

3.1.4.2 Controlled archival rotation policy

Data recording is subject to controlled termination and continuation protocols to safeguard against data loss:

1. **Controlled rotation (timeout):** A crucial periodic archival rotation policy is implemented with a fixed time limit (currently 30 minutes). Upon expiration of this timeout, the system executes a safe data finalization protocol for the current directory, closes all open files, and seamlessly initiates logging into a new archive folder. This strategy is essential for crash recovery, ensuring that the maximum window of data vulnerability to an unexpected power disconnection or system failure is limited to the preceding 30-minute block.

2. **Controlled switchover (direction change):** An external trigger signaling a change in train direction immediately initiates a controlled shutdown of the current recording session, performs the sensor suite switchover (front to back or vice versa), and commences logging into a new, directionally updated archive folder.

3. **Uncontrolled interruption:** The system acknowledges the inherent risk of an immediate and sudden power disconnection, which results in the interruption of active write operations and may lead to the corruption of the final, unclosed data file.

3.2 INSTALLATION OF THE SYSTEM ON THE VEHICLE

3.2.1 Preparation and timeline

The installation of the system was done in three steps. The first step was to develop a cabling concept, the second the installation of the cables, and the third to install the system (sensors, processing unit, mechanical parts, etc.).

The cabling concept was developed on 08.05.2025 based on the on-site measurements done by SBB. This concept was discussed and approved by the relevant people in charge of the vehicle. Based on this concept, the required cable lengths were defined and communicated to AŽD.

All cables were then sent from AŽD to SBB. These cables were installed by SBB between 16.09.2025 and 17.09.2025, and everything was prepared for the final installation. From 21.10.2025 to 23.10.2025, AŽD installed the system in collaboration with SBB in the MIC Erstfeld, which was then tested and approved by the responsible authorities for the vehicle.

3.2.2 Cabling concept

To ensure the cabling to be executed efficiently and correctly, a concept for the cabling had to be developed [7]. All cables outside the vehicle must be placed in a protective hose. It was decided to combine the sensor cables from the front and rear part of the vehicle and route them in a separate protective hose. This approach allowed efficient and straightforward cable routing. The cables could not be routed through the vehicle itself due to space constraints, so they had to be fixed externally without violating the profile area. The window at the workshop area was designated as the entry point to the vehicle. To define the best way for the cabling route, a mockup hose was used as indicated in Figure 6 indicated.

Figure 6: Definition of cabling route

The complete cabling concept was checked by the vehicle responsible and approved afterwards.

The cabling included the following:

- Front end: Camera, thermal camera and LiDAR including power supply to the processing unit
- Rear end: Camera, thermal camera and LiDAR including power supply to the processing unit
- Digital I/O for direction detection signals to the processing unit
- Temperature sensors outside of the vehicle to the processing unit

The detailed overview can be found in chapter “8.1 - “Overview system installation”.

3.2.3 Installation of cables

The cabling concept allowed the precise definition of the dimensions for the cables. During this period, also the cabling for the direction detection was prepared. All cables were supplied by AŽD, while SBB organized the protective hose and all assembly materials. The entire cabling could be completed within two days. The cables were properly routed to the designated location, as shown as an example in Figure 7.

Figure 7: Example picture for final cabling outside of the vehicle

A bigger challenge was to insert the protective hoses into the vehicle, as only the window at the workshop could be used. Additionally, special fastening clips had to be glued to the vehicle, since no other fastening options were available. A non-flammable wooden cover was made and fitted to the window with holes drilled for entry the protective hoses. An additional hole was drilled between the entrance for the protective hose for the temperature sensor. Everything was sealed in a further step. Figure 8 shows the final installation of the vehicle entrance for the cables:

Figure 8: Cable routing and entrance into the vehicle

The cabling for the front part had to be routed primarily outside the vehicle, while the rear cabling could mostly run beneath the loading platform.

3.2.4 Installation of the system

Three days were used for installing the system. The vehicle was located in the workshop at MIC Erstfeld during this period. AŽD installed the mechanical and electrical components in collaboration with SBB. The installation proceeded without major problems and could be carried out as planned. Minor modification could be solved immediately without any impact on the timeline. After the installation, the team in charge of the vehicle approved the installation. The following image shows the position of the system, where the left image shows the frontside and the right image indicates the backside of the vehicle.

Figure 9: Position of perception system (left: frontside / right: backside)

The system was installed between two connectors. These connectors are rarely used in operational applications. The plugs are used for the train bus when the automatic train coupling is not functioning, requiring the train bus to be connected manually. Therefore, it was no problem to use these mechanical parts for installation. The system does not affect the personnel in everyday use and does not violate the profile area.

4 TEST CONCEPT FOR THE SYSTEM

There are two approaches for testing the sensor set and collecting data:

- Testing in operational use / collecting data in shadow mode
- Specific test cases

4.1 SYSTEM IN SHADOW MODE

The main focus for the PoC was to test the system in operational use and to collect data in shadow mode. In this context, shadow mode means that there is no interaction between the perception system and another system installed on the vehicle, apart from the power supply and the direction detection. Furthermore, the train driver also has no interaction with the perception system.

4.2 SPECIFIC TEST CASES

Besides collecting the data in shadow mode, it was decided to execute specific test cases. These test cases were defined and aligned with the task participants and based on previous test experiences with perception systems. Due to vehicle availability, personnel resources, and test-site constraints, it was necessary to adapt the defined tests for the current situation. This section describes in detail the executed test scenarios and frame conditions.

4.2.1 Test location

The test location for executing the defined cases was outside of the MIC in Erstfeld. There is a large area beside the workshop hall. There are several tracks for parking and the preparation of vehicles. It was possible to use track A12, as shown in the following schematical plan indicated.

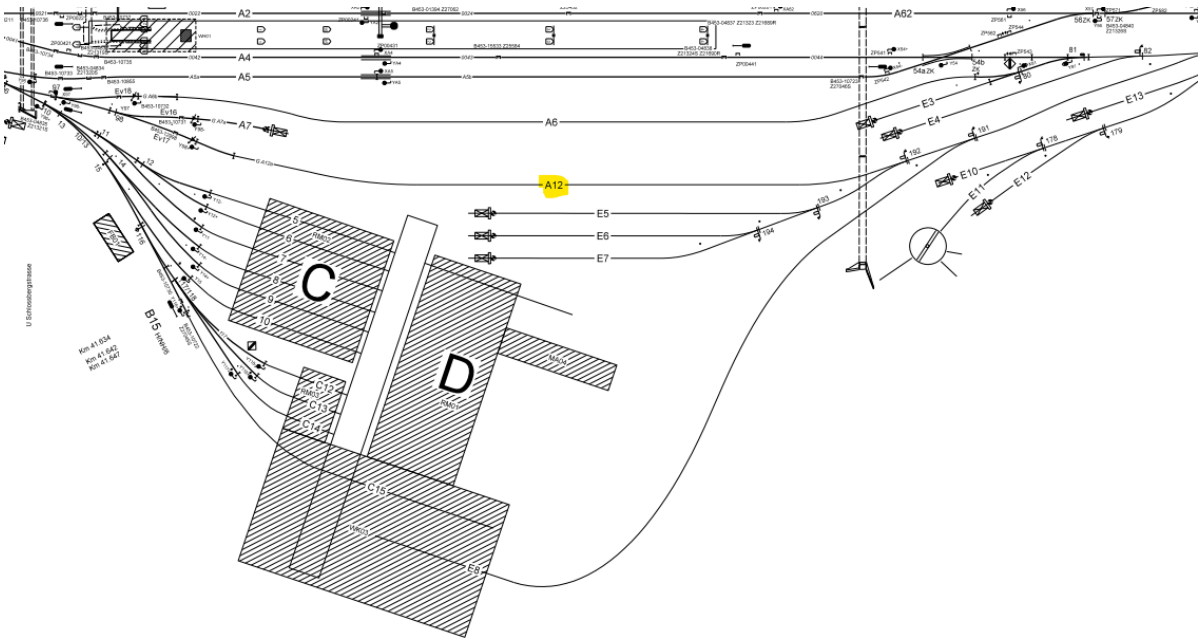

Figure 10: Track overview in MIC Erstfeld

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Track A12 has a length of approximately 380 m. There is a restriction to drive at a speed of 10 km/h. The following pictures indicate the area and track A12 [8].

Figure 11: Test area in MIC Erstfeld

It is important to note that, for operational reasons, the full length of the track could not be used, as other vehicles occupied certain sections.

4.2.2 Test cases

The following section describes the predefined test cases within the task. Results and findings are included in chapter “5.3 - Insights and findings”. All test cases were executed in static mode only. The test case approaching the buffer stop was performed dynamically. The test objective for all test cases was to detect the object or person.

4.2.2.1 Person in profile area

#	Test case	Description
1.1	Person on the track	A person is located directly in front of the vehicle. The person starts to walk along the track until the end of the maintenance area. Variants: With or without high-visibility vest.
1.2	Person near the profile area	A person is located in front of the vehicle. The person starts to walk beside the track until the end of the maintenance area. Variants: With or without high-visibility vest.
1.3	Person approaching the profile area	The person is located outside the railway profile area of the vehicle (approx. 20m, 50m, 100m, 150m, 200m). The person starts to walk towards the track. Variants: With or without high-visibility vest.

Table 6: Test case person in profile area

The test cases were executed also with a high-visibility vest. It was decided that test case #1.2 does not need to be executed several times, as it provides no further insights.

Example image of the test carried out:

Figure 12: Example picture for test case - person on the track

4.2.2.2 Object in profile area

#	Test case	Description
2.1	Object on the track	The object is placed at a predefined location (20m, 50m, 100m) on the track. Used objects: – Brake shoe – Car – Bicycle – Trolley – Buffer stop – Red stop sign – Cardboard box / cardboard box with reflecting material – Stone
2.2	Object near the track	The object is placed at a predefined location (20m, 50m, 100m) near the track. Used objects: – Car – Bicycle – Trolley – Cardboard box / cardboard box with reflecting material – Stone
2.3	Object approaching the profile area	The object is approaching the track (20m, 50m, 100m). Used objects: – Car – Bicycle – Trolley
2.4	Object is located halfway up the vehicle in the profile area	An oblong object is positioned in the track area halfway up to the vehicle. This test simulates an object (for example a crane boom) in front of the vehicle.

Table 7: Test case object in profile area

Remark: There was no possibility of carrying out test case #2.4. The test approach was used from tests case #3.1 and #3.2. The gate was opened halfway (static state), which then reflected the object located halfway up the vehicle in the profile area.

Example image of the test carried out:

Figure 13: Example picture for test case - object on the track (trolley)

4.2.2.3 Opening and closing the gate

#	Test case	Description
3.1	Opening the gate from the maintenance hall	The vehicle is located in front of the gate of the maintenance hall at a predefined position (10m, 30m). The closed gate will be opened. Variants: The gate stops at a certain point; the gate is open at 2/3.
3.2	Closing the gate from the maintenance hall	The vehicle is located in front of the gate of the maintenance hall at a predefined position (10m, 30m). The open gate will be closed. Variants: The gate stops at a certain point; gate is closed at 2/3.

Table 8: Test case opening and closing the gate

Example image of the test carried out:

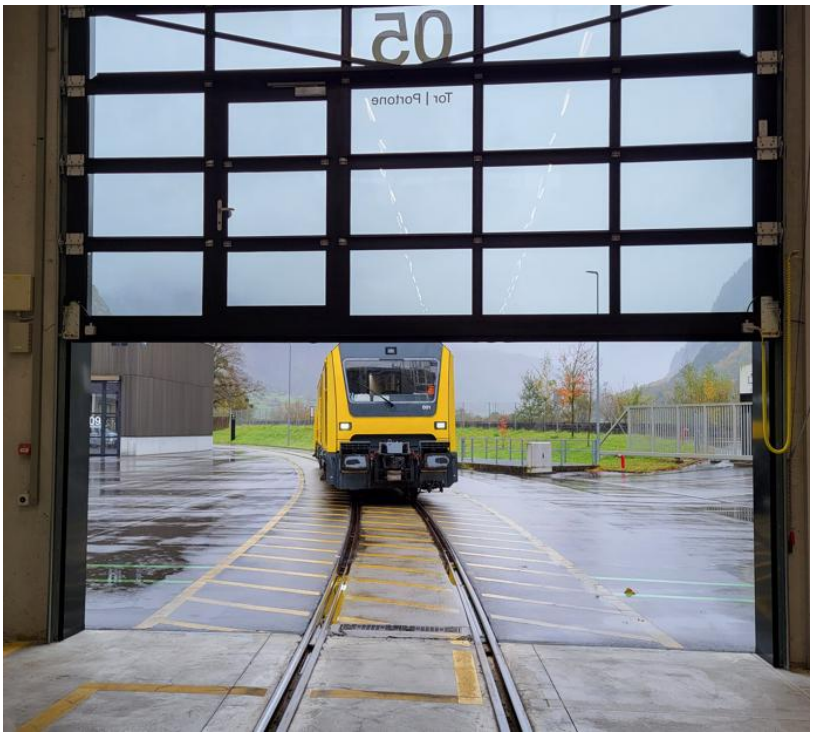

Figure 14: Example picture for test case - opening the gate

4.2.2.4 Specific test cases related to LiDAR

#	Test case	Description
4.1	Disturbance caused by external LiDAR	An external LiDAR is positioned in front of the built-in LiDAR sensor from the vehicle.
4.2	Reflecting surfaces	The vehicle is approaching a buffer stop with reflecting end indication.

Table 9: Test case related to LiDAR

Test case #4.1 could not be executed due to missing external LiDAR and will be performed at a later stage.

Example image of the test carried out:

Figure 15: Example picture for test case - reflecting surface (buffer stop)

4.2.2.5 Specific test cases related to the thermal camera

#	Test case	Description
5.1	Fire detection	A fire (volcano / firework) is lit at a predefined position (40m in front of the vehicle).
5.2	Direct sun exposure to the thermal camera	Sunlight is pointed directly at the thermal camera using a mirror.

Table 10: Test case related to thermal camera

Test case #5.2 was not explicitly executed, as it was covered during the data collection phase in shadow mode.

Example image of the test carried out:

Figure 16: Example picture for test case - fire detection

5 COLLECTED DATA & ANALYSIS

Data collected during both the shadow mode and specific test cases were recorded onto the SSD array as described in chapter “3.1.4 - Archival and robustness management”. Two interchangeable sets of disks were utilized for this purpose. While one set was installed in the testing vehicle for active data acquisition, the other was kept ready for rotation. The disk sets were exchanged at regular intervals, either when the storage capacity was reached or as part of routine maintenance procedures. Once exchanged, the disks containing the recorded data were sent to AŽD.

At AŽD, the data were transferred to a *QNAP TS-864eU-8G NAS* equipped with four 16 TB *Seagate IronWolf Pro* HDDs. The storage system was designed to be scalable up to eight disks if necessary, providing sufficient capacity for both archival and data analysis. After the transfer to the NAS was complete, the disks were reinitialized and sent back to SBB for subsequent use.

5.1 OVERVIEW OF COLLECTED DATA

Sensor data from vehicle Xem 181 were evaluated for the collection period from 22.10.2025 to 29.12.2025. During that period the vehicle was in operation for a total of **48 days**.
A total of **4.4 TB** of data were produced, this collected data represents approximately **350 hours of recording**.

5.1.1 Data classification

The data was manually categorized into four distinct groups:

- **Corrupted data (13% / 0.5 TB):** Recordings from trips that were not terminated correctly, resulting in unreadable files.
- **Irrelevant data (47% / 2.0 TB):** Includes trips where the sensors faced a coupled wagon, or recordings lacking objects of interest or significant conditions.
- **Data for evaluation (40% / 1.7 TB):** Recordings containing journeys with relevant objects that were not pre-screened.
- **Data of interest: (7% / 0.3 TB)** Specific records selected from the "data for evaluation" category that feature significant situations for detailed analysis. Selection was made based on inspection of the HD stream and on temperature analysis.

5.1.2 Data distribution by sensor type

The collected dataset, totaling **4.4 TB**, originated from various sensors installed on the vehicle. The following overview summarizes the specific contributions of each device to the overall data volume:

- **Visual data (HD camera):** This sensor generated the largest portion of the dataset, representing approximately **47%** of the total volume.
- **Spatial data (LiDAR):** The LiDAR system contributed **45%** of the data, providing critical point-cloud information.
- **Thermal imaging:** The thermal camera produced **8%** of the total data volume, primarily used for identifying persons.
- **Environmental telemetry:** Although the temperature sensors recorded data every minute, their contribution to the total volume was negligible (under **0.001%**) due to the small size of text-based logs.

5.2 METHODS OF ANALYSIS

The data recorded on the perception system's SSD array were uploaded to the NAS at AŽD. During a preliminary assessment, the dataset was categorized into three groups: data from specific test cases, relevant data from shadow mode (recordings containing pedestrians or objects near the train), and recordings with no relevant content (e.g., footage from nighttime idling while awaiting morning departure). The latter were excluded from further processing.

For the data selected for further analysis, the raw LiDAR data were converted into human-interpretable imagery. Two synchronous images were generated: the first used a color-coded scheme to represent the distance of each point from the front of the train, while the second used colors to interpret the reflectivity (intensity) of the detected objects.

Data from the thermal and environmental stream were processed to facilitate human evaluation. The original records, which contained weather parameters measured at one-minute intervals, were aggregated for each 30-minute recording session. This summary included minimum and maximum values as well as the variance (spread) of the data, allowing evaluators to more easily identify significant or anomalous weather conditions. Further evaluation was conducted manually, using separate procedures for shadow mode and specific test case data.

For shadow mode analysis, the evaluator first identified periods with significant weather conditions and prioritized the review of recordings from those intervals. By cross-referencing synchronized feeds from the RGB camera, LiDAR, and thermal camera, the evaluator searched for relevant events, such as the presence of persons or objects near the train. A subjective assessment of signal quality from individual sensors was then performed. The evaluator documented instances that were either typical or anomalous and analyzed whether data quality was compromised by immediate ambient conditions, sudden environmental changes, or permanent sensor degradation resulting from long-term exposure to harsh winter environments and the specific conditions of the GBT.

For specific test cases, the evaluator assessed and logged the data quality into a structured table according to the parameters defined for each specific test scenario. An example of the table can be found in chapter “8.2 - Test case evaluation”. The results and findings from the specific test cases are incorporated into the overall findings and described in the following chapters.

Human evaluation was utilized in this instance as a resource-saving measure. A full-scale automated object detection system is already being tested under WP46. The objective of this WP was specifically to determine the impact of a different environmental setting on the performance and reliability of the sensors used.

5.3 INSIGHTS AND FINDINGS

5.3.1 Environmental conditions and observations

During the testing period, the following temperatures were recorded:

- **Internal vehicle temperature:** 5.3 °C to 52.9 °C
- **External temperature:** -2.9 °C to 33.4 °C
- **Max. temperature change within 4 min (external):** -2.9 °C to +19.0 °C

Observations:
The test conditions remained within the specified operating limits of all sensors used in the perception system.

The vehicle speed was not logged during the test campaigns. However, the vehicle used has a maximum operating speed of 100 km/h. Throughout the testing activities, no adverse effects attributable to vehicle motion were observed in the acquired sensor data or in the overall performance of the perception system.

Scene illumination varied over a wide range of environmental conditions, including direct sunlight, backlit scenarios, tunnel sections illuminated only by low-level emergency lighting, and nighttime outdoor conditions. Illuminance levels (lux) were not measured during the tests.

The most significant and abrupt changes in lighting conditions occurred during transitions between brightly sunlit areas and tunnel environments. These transitions were intentionally included in the test scenarios to evaluate sensor robustness under rapidly changing illumination conditions. No operating conditions exceeding the specified limits of the deployed sensors were encountered during the tests. A summarized impact of different environmental and operational conditions can be found in chapter “8.3 - Impact of environmental and operational conditions to sensors”.

While the train was in service, the weather conditions were not as extreme as originally anticipated (mild winter for the observed period). Because of tight deadlines and the R2DATO project’s end date, data from an additional winter season could not be evaluated. Those future winter recordings will still be processed for internal use by the task participants. In addition, no observable sensor degradation occurred during the monitored period.

5.3.2 Analysis of rapid temperature fluctuations

- **Temperature spike:** On 22.11.2025 at 23:39, the system recorded the fastest external temperature rise from -2.9 °C to 19 °C within just 4 minutes.
- **Sensor resilience:** No adverse effects or negative impacts on sensor performance were observed because of this extreme thermal shock.
  Thermal camera limitations: Regardless of the rate of temperature change, the characteristics of the tunnel remained consistent: the internal surfaces reached a near-uniform temperature, causing the thermal camera to provide a less distinct image of the train's surroundings compared to outdoor conditions.

5.3.3 Documentation of sensor output

The following chapter presents the sensor outputs, shown as different samples.

General sensor visualization overview

Figure 17 and following images consist of different sections:

- **Upper image section:**
  - **Left side:** Displays interpreted data from the **thermal camera**.
  - **Right side:** A log of the recorded **internal and external temperatures**, captured at one-minute intervals.
- **Middle image section**: Shows interpreted **LiDAR** data. These point clouds are visualized in two ways:
  - **Left side:** Points are color-coded based on the **measured distance** from the front of the train.
  - **Right side:** Points are color-coded according to the **reflectivity** of the detected object/point.
- **Lower image section:** Displays the raw feed from the **HD camera**.

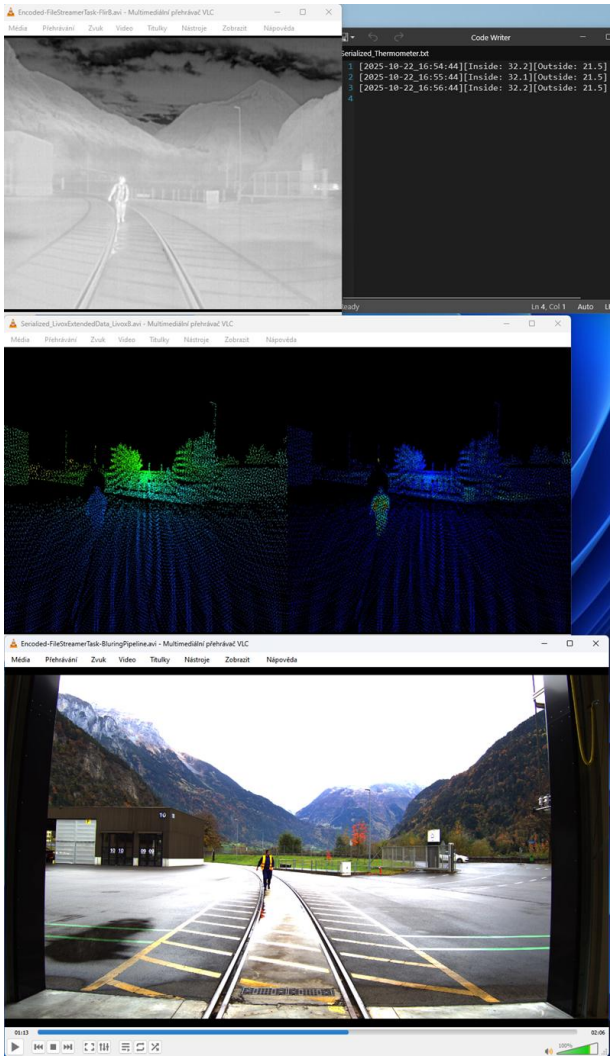

Figure 17: Sensor visualization overview

GDPR compliance and data privacy

- **Automated anonymization**: In accordance with privacy requirements, the system automatically detected faces and vehicle license plates within the HD camera recordings.
- **Real-time processing:** Recognized faces (Figure 18) and license plates (Figure 19) were blurred in real-time before the data was stored on the disk.

Figure 18: Blurred face

Figure 19: Blurred license plate

- **Computational efficiency:** To facilitate real-time processing, a mechanism was selected that prioritized being resource-efficient and time-sensitive.
- **Algorithm performance:** The applied algorithm occasionally produced "false positives", applying blur to incorrect areas - such as text or labels on the side of the train or building- that were misidentified as license plates as in Figure 20 indicated.
- **Operational impact:** These minor technical imperfections did not diminish the system's core capability to identify potential obstacles on the track.

Figure 20: False positive blurred license plate

LiDAR data processing and storage

- **Software transformation:** The presented LiDAR data were generated through a software conversion of the raw LiDAR sensor data.
- **Visual representation:** A video representation was created from these data to facilitate human interpretation.
- **Storage impact:** Because this video representation was similar in size to the original raw data, the total volume of stored data increased by approximately **1.7 TB**.

HD camera exposure and environmental transitions

- **Automatic exposure control:** The HD camera was set to automatic exposure.
- **Contrast observations:** In several instances, this resulted in high-contrast images, most notably in mountainous areas where clouds appear overexposed.
- **Operational visibility:** Despite these contrast variations, the track and its immediate surroundings remained clearly visible throughout most of the recordings.
- **Tunnel transitions:** A specific exception occurred during the rapid transition between open landscapes and the tunnel interior (both entry and exit).
- **Sensor redundancy:** During the brief intervals of exposure adjustment, data processing must rely on other sensors that are unaffected by lighting changes to compensate for the camera's temporary "blindness". Another option to consider is to use HDR cameras with wider dynamic range.

This effect described above is visualized in Figure 21:

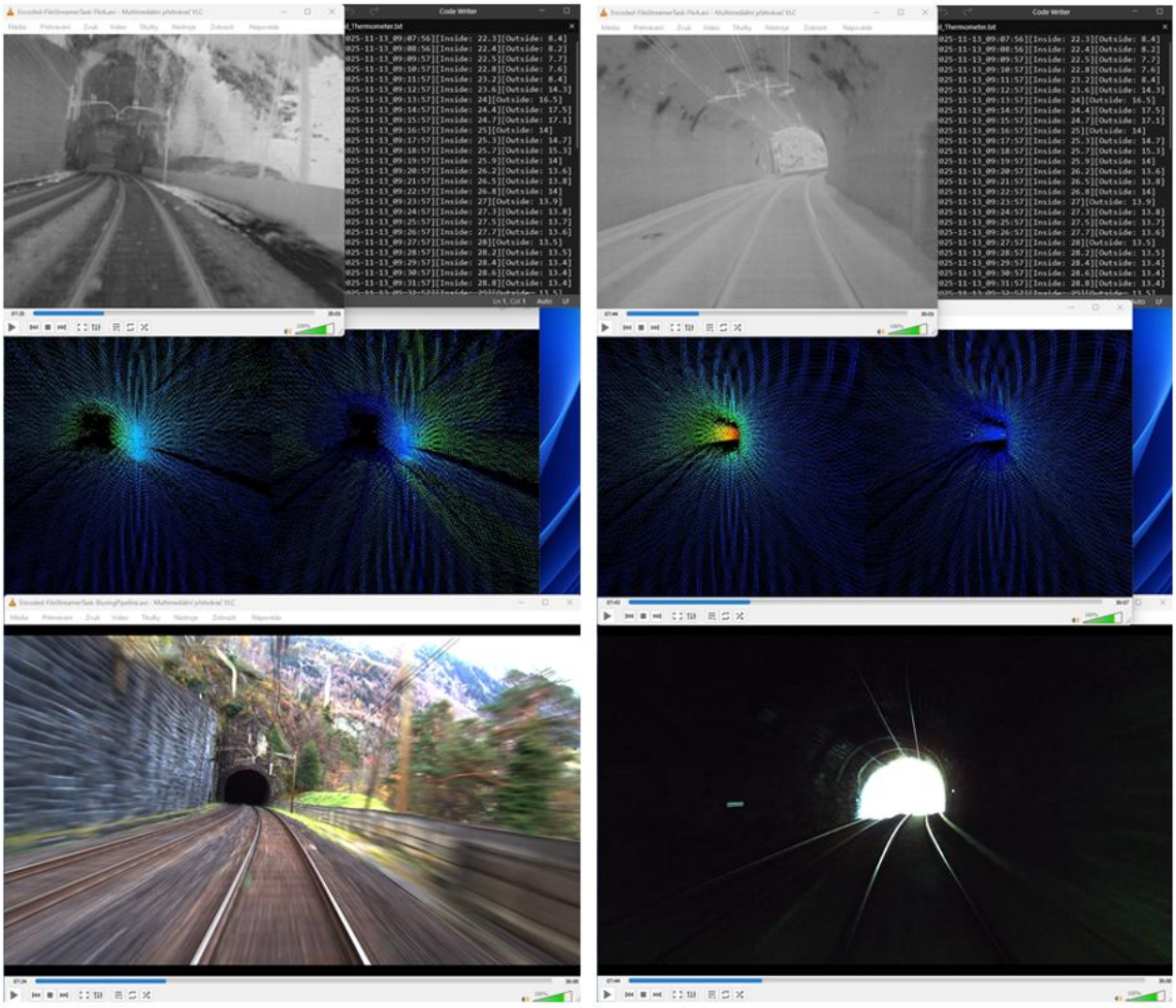

Figure 21: Rapid transition between open landscapes and tunnel interior

LiDAR data interpretation and visualization

The following analyses are related to Figure 22, Figure 23 and Figure 24.

- **Point cloud human interpretation:** The effectiveness of LiDAR data is highly dependent on how the point cloud is interpreted and visualized (see for example Figure 22).
- **Reflectivity vs. human perception:** For the human eye, visualization based on reflectivity (intensity) appears much clearer and more intuitive for general orientation.
- **Detection challenges in tunnels:** In distance-based visualizations, highlighting a person within a tunnel is difficult for a human observer. **The reason is that the difference in distance between a person moving along the wall and the tunnel wall itself is very small**, resulting in minimal visual contrast (see Figure 23 and Figure 24).
- **Machine processing advantages:** Unlike the human eye, automated machine processing can evaluate both properties - **distance and reflectivity** - simultaneously and with significantly higher sensitivity.
- **Obstacle contrast:** While subtle for humans, any obstacle located directly on the track (in the most dangerous location) remains highly detectable even by humans and much better by the system due to the contrast provided by the open space behind it (see also Figure 26).

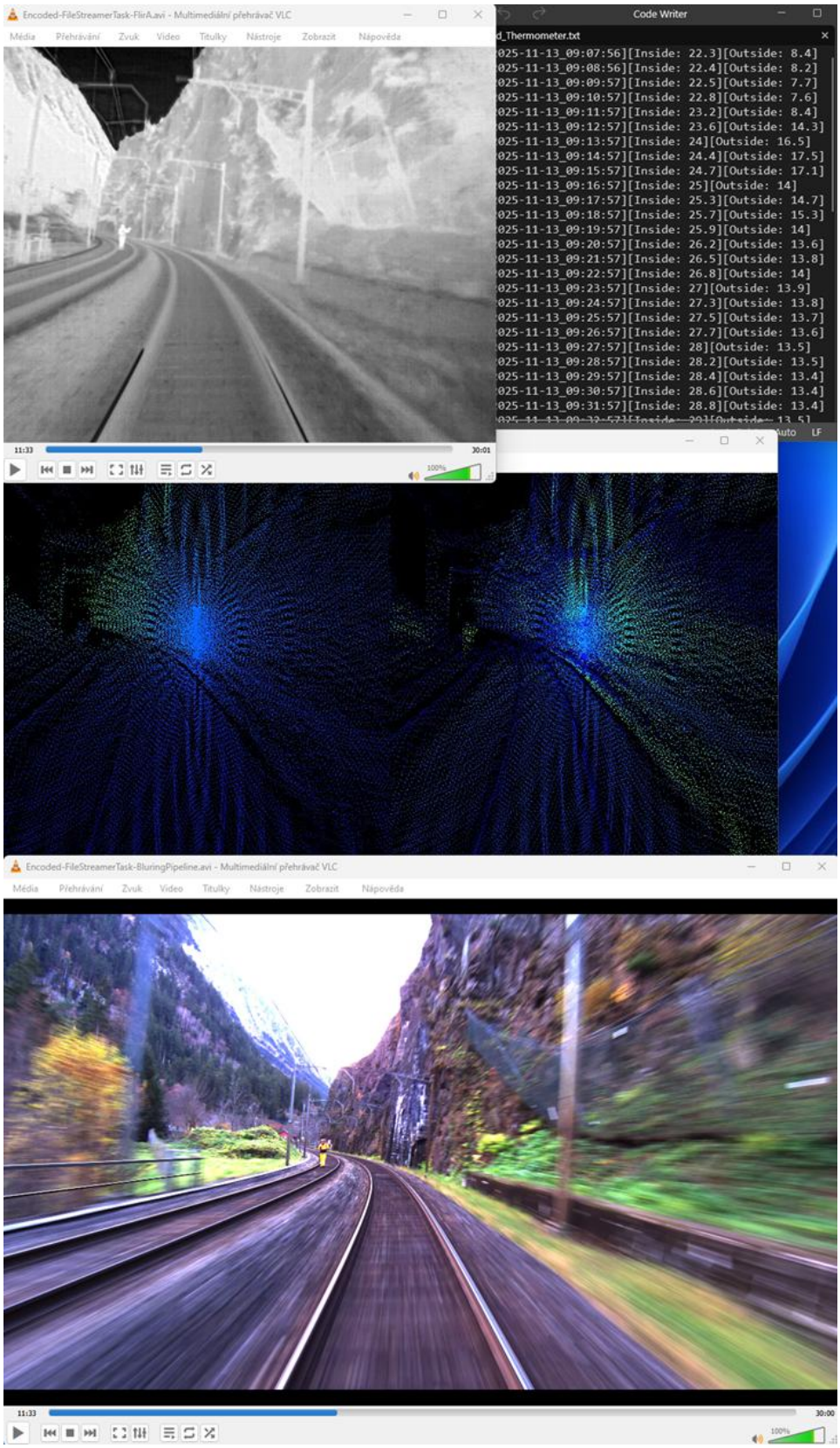

Figure 22: Person along the track

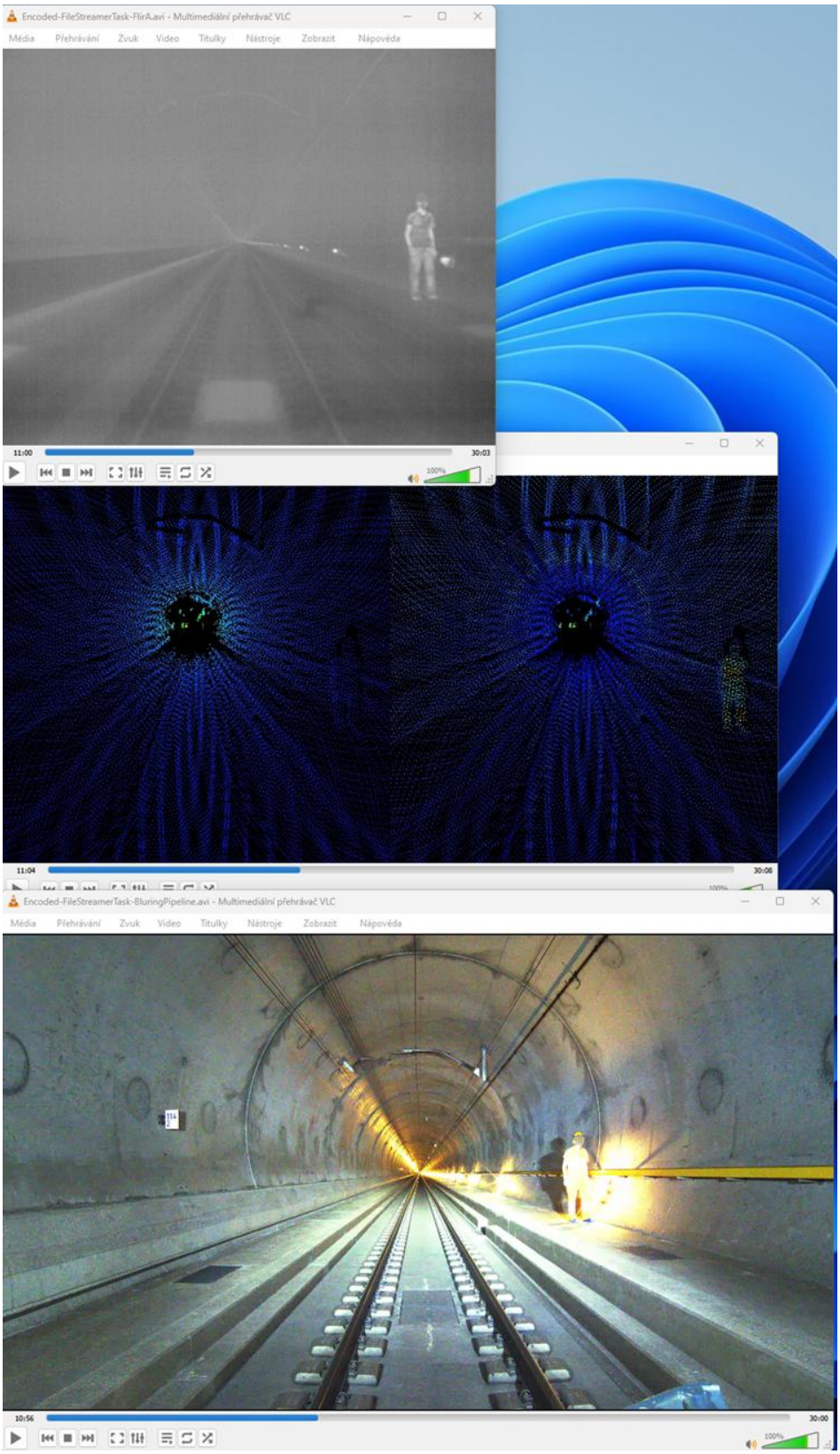

Figure 23: Person in the GBT

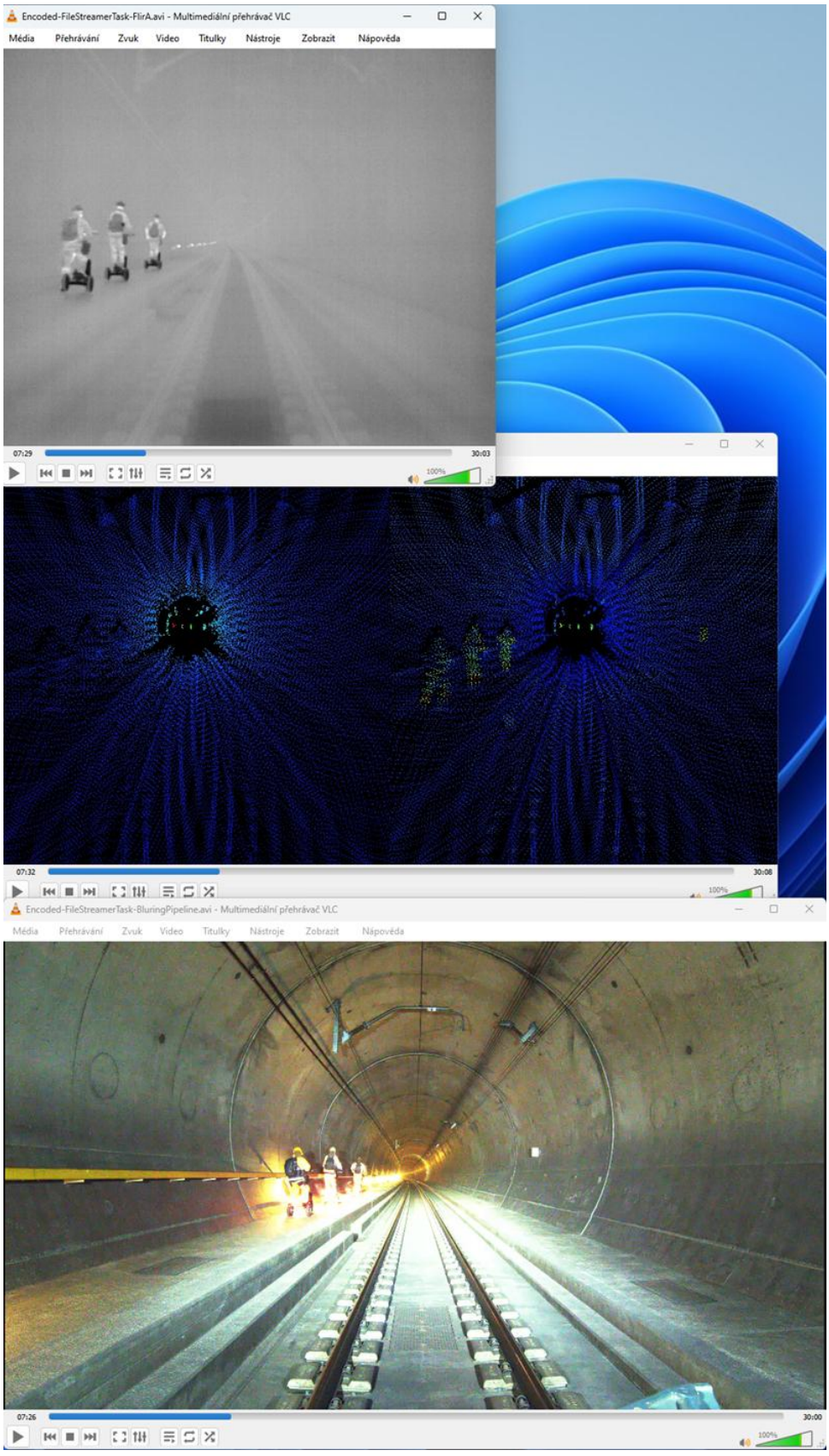

Figure 24: People in the GBT on scooters

Thermal analysis: tunnel environment vs. outdoor conditions

The following analyses are related to Figure 24 and Figure 25.

- **Thermal uniformity in the tunnel:** As demonstrated in the provided imagery, identifying the specific geometry of the tunnel's interior using the thermal camera becomes difficult deep underground. This is because all surfaces (walls, catenary, and infrastructure) reach a nearly uniform, stable temperature of approximately **21 °C**.
- **Visibility of personnel:** In contrast to the uniform background, people remain highly distinct and clearly visible on the thermal feed due to their body heat.
- **Comparative analysis:** For comparison, refer to the nighttime image captured at the tunnel approach (recorded on 22.11.2025 at 23:41). At that time, the external temperature was approximately **2.2 °C**, providing a much higher thermal contrast compared to the stabilized conditions inside the tunnel.

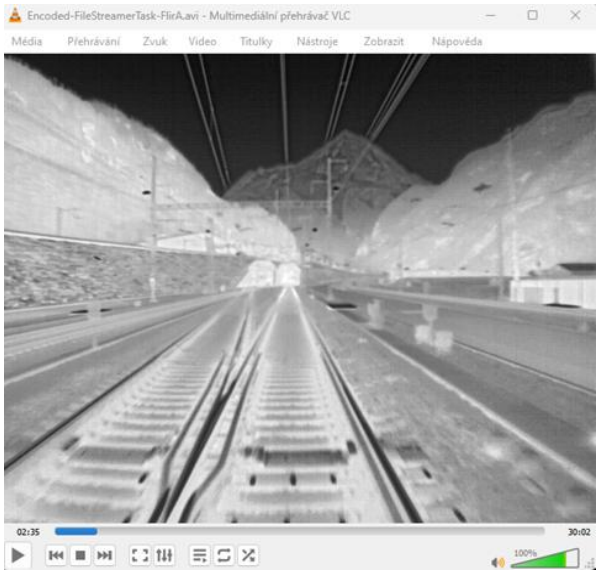

Figure 25: Contrast of thermal camera in open environment

Obstacle detection and spatial contrast

- **Strategic positioning:** For the purpose of evaluation, the detection of a person is significantly enhanced when they are positioned in the center of the track. Obviously, this is also the most dangerous where they can be located.
- **Visual background:** Against the backdrop of the long, otherwise empty expanse of the tunnel, a person creates a distinct silhouette and clear data signature for the sensors.
- **Environmental note:** In this specific test scenario, the ambient temperature was approximately **21 °C**, providing a specific thermal context for evaluating the contrast between the person and the tunnel environment (see for example Figure 26).

LiDAR shadowing and point cloud visualization

The following analyses are related to Figure 26.

- **Point cloud perspective:** To improve visual clarity for the human eye, the point cloud is rendered from a slightly elevated, overhead perspective.
- **Shadowing effect:** The black areas visible immediately behind the people are caused by "shadowing." These represent zones where the LiDAR pulses did not penetrate because they were obstructed by individuals.
- **Data interpretation:** These "blind spots" are a natural result of the line-of-sight measurement and confirm that the persons are effectively reflecting the sensor's signal and can be also used for LiDAR data evaluation.

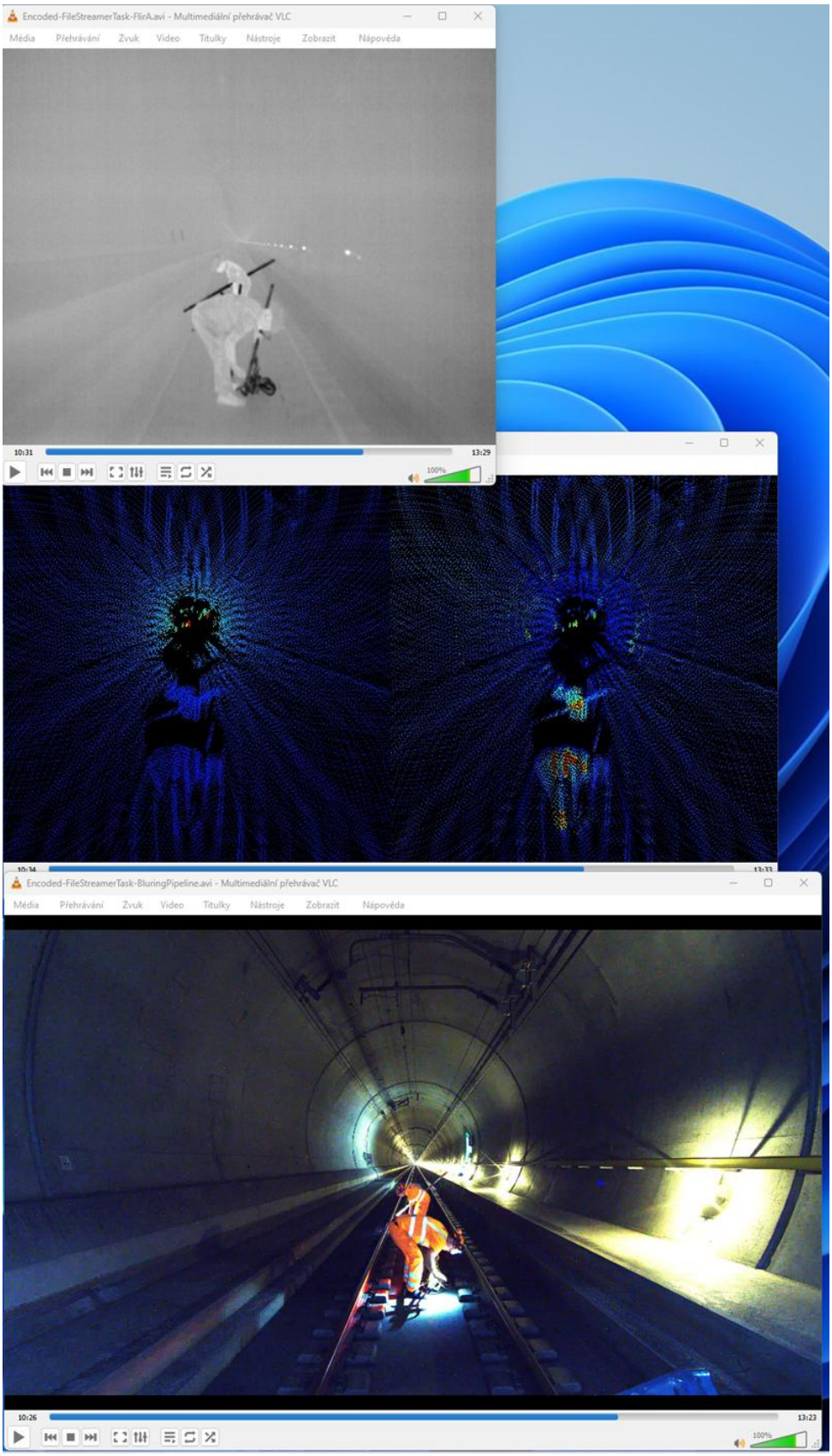

Figure 26: Maintenance work on the track in the GBT

Field of view comparison

The following analyses are related to Figure 27.

- **Sensor coverage analysis:** To compare the field of view and spatial coverage of the individual sensors, the following image is provided.
- **Visual comparison:** This visualization illustrates how the different sensor types (HD camera, LiDAR, and thermal camera) overlap and complement each other, ensuring comprehensive monitoring of the track and its surroundings.

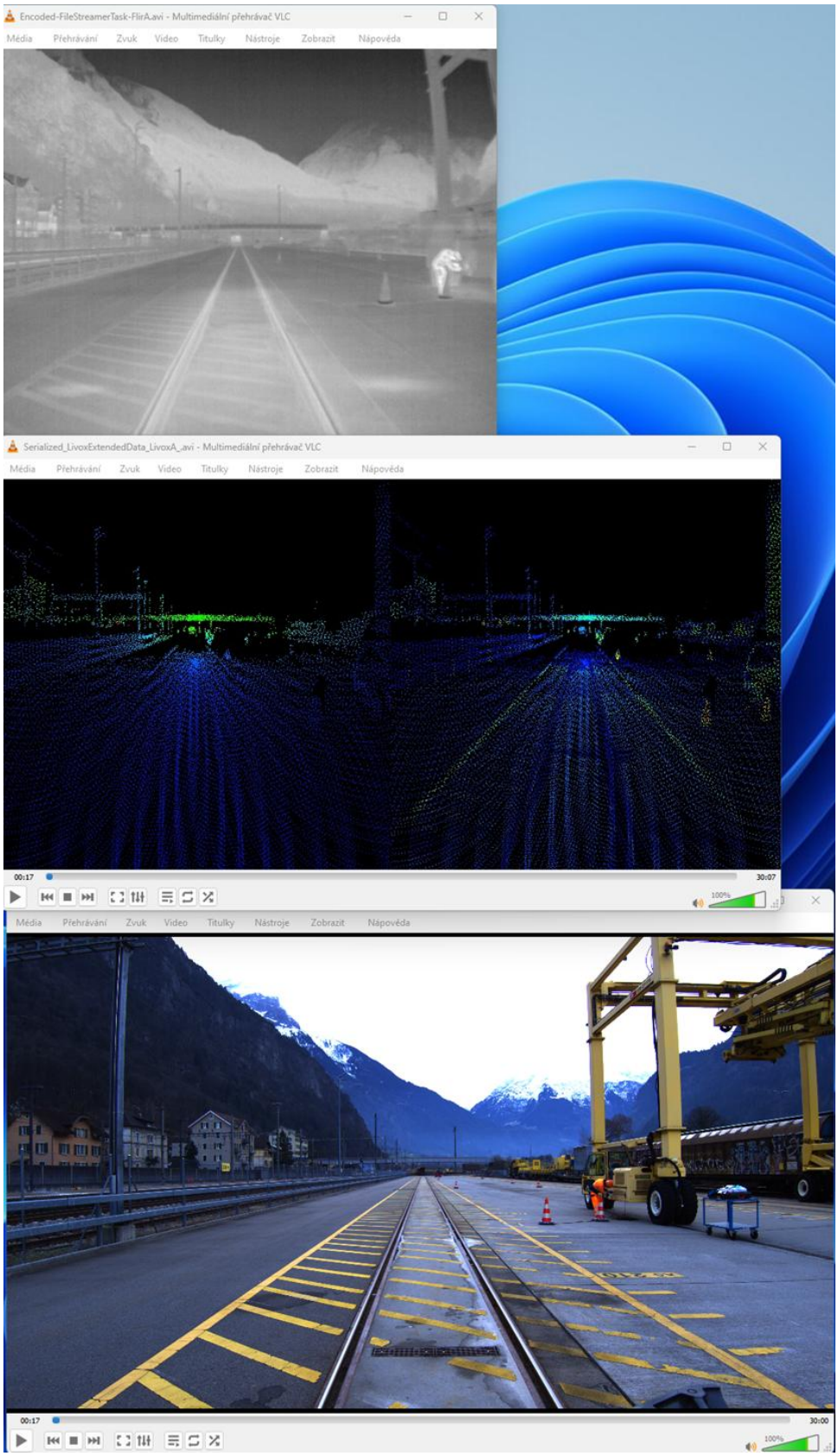

Figure 27: Person repairs the crane in MIC Erstfeld

5.3.4 Collected requirements in context of task 11.3

As already described, task 11.3 aims to investigate the operational applicability of the existing sensors and to document their strengths and limitations under real-world conditions. In line with the scope, defining a formal requirements list is not the intention of the task. Instead, this subsection consolidates requirements-relevant findings from the observed performance during the trial for further requirement engineering.

- **Sensor fusion at tunnel portals:** The RGB camera experienced brief “blindness” during exposure transitions at tunnel portals. The sensor combination / fusion logic should compensate the RGB camera exposure adjustments to preserve detection performance at all times.
- **Darkness and tunnel operation:** Under dark conditions, the RGB provides limited information. For night/tunnel operation, people detection can be supported by a thermal camera while objects on the track are reliably covered by LiDAR. It has to be considered that if surrounding surfaces approach a uniform temperature, the thermal camera’s ability to distinguish the train’s surroundings is reduced compared with outdoor conditions.
- **Tunnel walls:** Distance-based visualizations made people near walls hard to spot. An automated machine process can evaluate the surrounding with higher sensitivity and shall therefore be considered for the fusion logic.
- **Environmental robustness (temperature):** Rapid temperature changes did not degrade the function of the used sensors. System design should account for the operative operational ranges and thermal transition rates of the target environments.
- **Degradation:** During the whole period, no sensor degradation occurred. Additional protective measures should be taken into account depending on the application to sustain long-term reliability.

6 CONCLUSIONS

6.1 GENERAL SUMMARY

The aim of the task 11.3 was to demonstrate a proof of concept by operating an existing perception system from AŽD in shadow mode on an SBB Xem 181 vehicle within the GBT and CBT perimeter. The focus relied on evaluation of perception data under challenging operational and environmental conditions without developing a new system. A perception system that consists of an RGB camera, a thermal camera, and a LiDAR was used for the trial. The opportunity to test alternative sensor types was utilized to broaden the developers' expertise. Furthermore, gaining experience with specific environments (for example in tunnels) where AŽD had limited prior exposure proved to be highly beneficial.

The perception system was successfully installed on the vehicle. Data could be collected as planned in shadow mode and with specific test cases. Between 22.10.2025 and 29.12.2025, approximately 350 hours of recording were collected over 48 operating days. This produced around 4.4 TB of data. Data triage classified approximately 13% (0.5 TB) as corrupted, 47% (2.0 TB) as irrelevant, and 40% (1.7 TB) as usable for further evaluation. Reflected on the sensor contribution, around 47% of the volume came from the RGB camera, 45% from LiDAR, and 8% from the thermal camera. Environmental monitoring reported internal temperatures from 5.3 °C to 52.9 °C and external temperatures from -2.9 °C to 33.4 °C. Rapid temperature changes were also observed in the data. There was a change from -2.9 °C to 19 °C within four minutes with no observed influence on sensors efficiency.

The RGB camera provided useful imagery in most conditions but experienced brief “blindness” during tunnel transitions, mitigated though not eliminated by headlights. In total darkness, the RGB camera provided reduced information, while normal tunnel ambient light still enabled track visibility. The thermal camera proved highly effective for identifying people, especially outside or at tunnel portals. The recognition of the scenery was reduced inside of the tunnel, because all surfaces (walls, catenary, and infrastructure) reach a nearly uniform, stable temperature. Ambient temperatures inside the tunnels approaching human body temperature were not observed. Therefore, the effectiveness of the thermal camera under such conditions could not be evaluated. If such conditions occur, detections from other sensors must be used to compensate for the thermal camera’s limitations. The LiDAR delivered consistent spatial context and intensity data.

The objectives for the task were fulfilled in general. Data could be collected (in shadow mode and within specific test cases) and multisensory behavior within different conditions was assessed. The trial clearly demonstrated the importance of sensor redundancy / sensor fusion at tunnel portals. LiDAR and thermal streams preserved situational awareness during RGB exposure shifts. In addition, obstacles on the track remained distinguishable with LiDAR, people were reliably visible by the thermal camera. During the whole period, no sensor degradation occurred.

Overall, the trial provided invaluable data for the further development of the sensory system. Although the testing period in this specific environment was limited, the findings from task 11.3 significantly enrich the ongoing sensor development also being conducted in other configurations (for example in WP46 with Faiveley and AŽD on regional line).

HDR cameras can be evaluated for use in challenging environments, such as tunnel entrances and exits. It will be necessary to continue the evaluation in regional line environment (the focus of AŽD development) to check effective distance for obstacle recognition. Thermal cameras are not part of the current configuration used by AŽD on regional lines, as their application was previously deemed unnecessary for the standard operating environment. However, for night-time operations and tunnel transits, they appear to be a suitable tool for enhancing the capabilities of the AŽD sensor suite.

The collection of data in shadow mode continues until summer/autumn 2026.

6.2 SPECIFIC SUMMARY

During the monitored period and under the observed weather conditions, **no sensors showed visible signs of damage or any other degradation**. However, specific sensors demonstrated certain limitations in particular use cases.

HD camera

- **Low-light performance:** As expected, the HD camera provided reduced to minimal information in total darkness. In our case, this occurred only when the train was stationary in the depot or inside a tunnel and therefore had no impact on the actual operational performance of the sensor system.
- **Tunnel lighting:** Even with tunnel lights switched off, there was sufficient ambient light for the HD camera to remain functional.
- **Lighting transitions:** The camera experienced temporary "blindness" during rapid lighting changes when entering or exiting tunnels.
- **Mitigation:** While the use of headlights minimized the duration of these blind spots, it did not eliminate them. During those intervals, the other sensors provided sufficient data to compensate for the HD camera’s limitations.

Thermal camera

- **Personnel identification:** Despite initial uncertainty regarding its performance in the tunnel, the thermal camera proved highly effective for identifying people.
- **Environmental rendering:** In open environments, the camera clearly captured the train's surroundings. However, after approximately three minutes of travel inside the tunnel, it lost the ability to render the environment due to the uniform temperature of the walls, catenary, and tunnel infrastructure.
- **Test limitations:** It is still unverified whether a train left stationary in the tunnel for an extended period would thermally blend into its surroundings.

LiDAR

- **Data dimension:** LiDAR provides a four-dimensional description of space (3D coordinates + reflectivity).
- **Visualization strategy:** To facilitate human interpretation, a parallel 2D visualization was used: one interpreting distance through color and the other interpreting reflectivity.
- **Tunnel challenges:** Detecting objects positioned very close to the tunnel walls proved more difficult than in open spaces. For human analysis, reflectivity-based imaging was found to be more effective in these scenarios.
- **Obstacle Detection:** Since obstacles on the track are backed by open space, the contrast remains sufficient for reliable detection. Furthermore, machine processing point clouds significantly exceeds the interpretive capabilities of the human eye.

Open points for further research

Based on the evaluated data and the results of task 11.3, the following research topics, amongst others, require further investigation:

- **Deduction of specific requirements for perception system design:** Depending on the intended application and the use case of the system, a specific set of requirements can be elaborated.
- **Necessary sensor set:** It has to be investigated which sensor types and configurations are required and identified which is the optimal sensor combination for a target use case.
- **Tunnel gates:** The effect of temporary “blindness” at tunnel portals is a recurrent event in combination with the RGB camera. Besides mitigation options like sensor fusion strategies or HDR cameras, a trackside solution could also be considered to monitor the tunnel portal and provide information to an approaching vehicle.
- **Testing in harsh winter conditions:** Data collection occurred during a mild winter period and harsh conditions did not occur**.** Within the remaining time of data collection, such conditions might be covered. Otherwise, it has to be further analyzed.

7 REFERENCES

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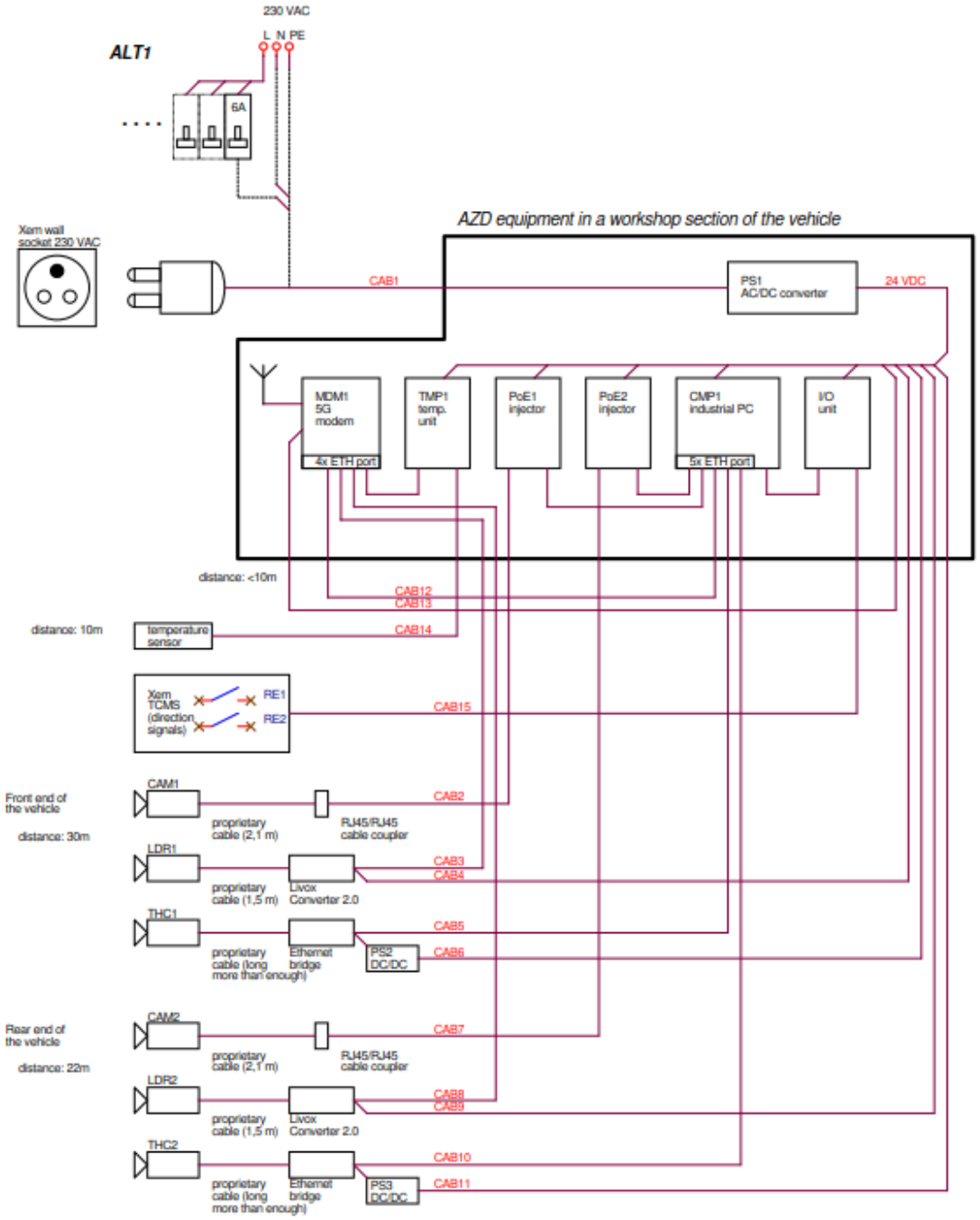
8 APPENDIX

8.1 OVERVIEW SYSTEM INSTALLATION



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8.2 TEST CASE EVALUATION

Date and time	23.10.2025 / Afternoon
Location	Erstfeld / Track A12
Weather	Changed from cloudy to partly cloudy to rain
Temperature	19 °C down to 13 °C

The numbers indicate object/person visibility on the sensor streams. Classification scale:

- 1 - Easily identifiable
- 2 - Identifiable
- 3 - Difficult to identify
- 4 - Very difficult to identify
- 5 - Hard to identify / not reliably identifiable

#	Test case name	Weather condition	Sensor	10 m	20 m	30 m	40 m	50 m	60 m	70 m	80 m	90 m	100 m	140 m	150 m	200 m	250 m
	Person in profile area with high-visibility vest (including on the		Camera		1			1					1		2	3	3
			LiDAR		1			1					1		3	3	4
1	track and approaching the profile	cloudy	Thermal camera		1			1					1		3	3	4
	Person in profile area without high-visibility vest (including on the		Camera		1			1					1		2	3	3
			LiDAR		1			1					1		3	3	4
2	track and approaching the profile	cloudy	Thermal camera		1			1					1		3	3	4
			Camera	1	1	1	2	3	4	4	4	5					
			LiDAR	5	5	5	5	5	5	5	5	5					
3	Brake shoe	cloudy	Thermal camera	1	1	3	4	4	5	5	5	5					
			Camera		1			1					1	1		2	
			LiDAR		1			1					1	2		3	
4	Car	cloudy	Thermal camera		1			1					1	2		3	
			Camera		1			2					2				
			LiDAR		1			2					3				
5	Bicycle - standing	partly cloudy	Thermal camera		1			2					3				
			Camera		2			3					3		4		
			LiDAR		2			2					4		4		
6	Bicycle - laying	partly cloudy	Thermal camera		1			3					4		4		
			Camera					1					2				
	Bicycle - approaching (with		LiDAR					1					4				
7	person)	partly cloudy	Thermal camera					1					4				
			Camera	1				1					3		4		
			LiDAR	1				2					4		5		
8	Red stop sign	partly cloudy	Thermal camera	1				3					5		5		
			Camera		1			2					3				
			LiDAR		1			2					3				
9	Trolley	partly cloudy	Thermal camera		NA			NA					NA				
			Camera		2			2					3		3		
			LiDAR		1			1					2		2		
10	Stone	rainy	Thermal camera		3			5					5		5		
			Camera				1										
			LiDAR				1										
11	Fire (smoke was visible)	rainy	Thermal camera				1										
			Camera	1		1											
			LiDAR	1		1											
12	Opening and closing the gate	rainy	Thermal camera	1		1											
			Camera		1			1					2				
			LiDAR		1			2					3				
13	Approaching buffer stop	rainy	Thermal camera		1			3					4				
			Camera		1			2					2		2		
			LiDAR		1			1					1		3		
14	Cardboard box - non reflecting	rainy	Thermal camera		1			5					5		5		
			Camera		2			2					3		3		
			LiDAR		1			1					2		2		
15	Cardboard box - reflecting	rainy	Thermal camera		3			4					5		5		

8.3 IMPACT OF ENVIRONMENTAL AND OPERATIONAL CONDITIONS TO SENSORS

This appendix summarizes the impact of different environmental and operational conditions on the performance of the deployed sensors. A detailed discussion of the observed performance degradation mechanisms is provided in chapter “5.3 - Insights and findings”.

The numbers indicate visibility on the sensor streams. Classification scale:

- 1 - Easily identifiable
- 2 - Identifiable
- 3 - Difficult to identify
- 4 - Very difficult to identify
- 5 - Hard to identify / not reliably identifiable

Conditions	RGB camera	Thermal camera	LiDAR
Sunny	1	1	1
Cloudy	1	1	1
Sharp backlight	4	1	1
Abrupt changes of lightning conditions	5	1	1
Low thermal contrast	1	4	1
Low distance contrast	1	1	3
High speed with low level lightning	3	1	1