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FP5TRANS4M-R
Transforming Europe's Rail Freight

D18.1

Test Report for Powerline PLUS Technology

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1 Executive Summary

The main objective of Work Package 18.1 was to test the most important automated FDFT functions (DAC4 and DAC5) on the basis of the Powerline PLUS Train Backbone in a real operating environment and under actual operating conditions using a prototype test train.

To this end, a test and trial system was set up based on the DAC4EU test train and the requirements and specifications of the EDDP and ERJU FP5-TRANS4M-R available to date.

With regard to the applications below, the FDFT functions were further developed on the basis of existing components and systems:

- Automatic brake test:
  - The already approved PJM system was integrated into the DAC, whereby:
  - The data for this system was no longer transmitted via LORA, but via the PTB Backbone in compliance with EDDP.
  - The system is powered by the train power system.
- Uncoupling device:
  Voith and HSLU implemented and tested a prototype system for uncoupling both by means of pushbuttons on the side of the wagon (DAC4) and remotely (DAC5) from a tablet. Data transmission is EDDP-compliant via the PTB Backbone and a consist internal communication system.

No systems that would have enabled integration were yet available during the processing period for equipping mainline locomotives and shunters for the digital freight train. The "locomotive functionalities" were therefore installed in a covered freight wagon, which was permanently integrated into the test formation. For this reason, the test runs and shunting tests were carried out with existing SBB Cargo mainline or shunting locomotives.

In the period from 13 February 2023 to 8 December 2023:

- 16 days were spent on installation and conversion work.
- Static and coupling tests were carried out in Lupfig on 10 days.
- Shunting tests were carried out at various locations on 8 days.
- A total of 4’211 kilometres were covered on 20 days of test runs.

Four automated train functions were tested:

- Train composition (wagon sequence and orientation)
- Automatic brake test
- Train composition detection
- Automatic uncoupling (remotely using a tablet or by pushbutton)

The results show that these functions work resiliently and reliably based on the PTB communication system with data transmission via the train power cable and its spring-loaded contacts in the e-couplers, including the new e-coupler prototypes from Voith and Knorr-Bremse.

Data transmission errors only occurred in a few cases when passing over Euroloops (wayside system part of ETCS). Corresponding analyses of the causes have been initiated.

The electrically actuated uncoupling using the pushbutton installed on the wagon worked reliably during the tests, but the installed full digital freight train (FDFT) "Prevent Coupling" function proved to be unsuitable for the shunting hump in the specific tests as the reset of "Prevent Coupling" by means of a light sensor led to incorrect behaviour of the system due to external influences / reflections from the track environment.

These results represent great added value for the development of the DAC and the FDFT. They will now be fully utilised in ongoing developments in the EDDP, in the ERJU FP5-TRANS4M-R project and in CENELEC standardisation. The delivery of Work Package 18.1 can serve as a basis for the further technical specification of the FDFT. The test results were also used to make a decision in favour of the e-couplers concept.

All conversion work, static, shunting and running tests were carried out without any damage to "man or machine".

Although the test campaign carried out in 2023 provided many insights into the applicability of "Power Line Communication" in the future digital freight train and although the mechanical, electrical and electronic components installed were also tested for their operational and technical suitability in rail freight transport, many additional development and test steps are still necessary before a final, approvable and verifiable solution can be developed.

Keywords: Test train, train backbone, technology

2 Abbreviations

Abbreviation / Acronym	Description
ABT	Automated Brake Test, digital solution for the brake test operation
CCU	Central Control Unit, central control and monitoring unit on a vehicle
DAC	Digital Automatic Coupling
DAC4EU	Digital Automatic Coupling for Europe, European consortium of freight train operators and wagon keepers
EDDP	European DAC Delivery Programme
ERJU	Europe's Rail Joint Undertaking
ETCS	European Train Control System
FDFT	Full Digital Freight Train
FDFTO	Full Digital Freight Train Operations
GA	Grant Agreement
HMI	Human Machine Interface, tablet or similar device for displaying data and controlling commands
HSLU	Lucerne University of Applied Sciences and Arts
LORA	LoRA, Long Range radio communication technology
PLC	Powerline Communication Technology
PLUS	Power Line Data Bus
PTB	Powerline Plus Train Backbone
TTD	Train Topology Detection

3 Background

The FDFTO test train was based on the mechanical, pneumatic centre buffer coupler (DAC2, mechanical and pneumatic Scharfenberg coupler type 10) currently used in Switzerland. Technologically, this test train is based on Powerline Plus technology, which forms the Powerline Train Backbone for the test train.

PTB is a backbone data network for the FDFT that enables the reliable transmission of Ethernet/IP data packets between the locomotive and all wagons in the train via the 400 VAC train power cable. The PTB communication system follows the specifications of the digital automatic coupler (DAC) Type 4/5 and the system architecture for the FDFT.

The starting point was to implement the DAC functions of the "Basic Package" defined by EDDP for the prototype test train. In addition to the pneumatic/mechanical connection, this also includes the power and data connection. Based on this, the following FDFT functions could be implemented for the test train:

- Train composition (wagon sequence and orientation)
- Automatic brake test
- Train composition detection
- Automatic uncoupling (remotely using a tablet or by pushbutton)

For this application, some of the systems and components were completely rebuilt or had to be adapted to the new requirements. The systems and components were manufactured or customised by the project partners and installed on the test train. During the time taken to process the work package, it was possible for the systems and components to be further adapted and optimised by the project partners in charge with the help of the test results that had been obtained in the meantime.

Regarding the extension to the DAC4 (additional power and data transmission via the DAC) further trials were carried out as part of the work package on:

- The e-coupler (fixed head) from Voith
- The e-coupler (movable head) from Knorr-Bremse and Voith (one pair each)
- The PTB technology (Powerline PLUS Train Backbone)

While there are already advanced specification proposals for some FDFT functionalities, no solutions had yet been proposed for others. The implementation of this work package therefore not only demonstrated the integration of systems that are ready and approved for volume production, but also highlighted and tested the technical feasibility and benefits of the systems and their respective implementation variants.

4 Objective

This document has been created to provide the report for Work Package 18.1 of FP5 based on the realized field tests with the Powerline Plus Technology. The main objective of the work package was to obtain results regarding the fulfilment and robustness of the most important automated train functions with the Powerline PLUS train backbone. The report includes the results of the FDFT functions with PTB of stationary, shunting and driving tests in a real operating environment under real operating procedures.

Based on the foundation provided by the EDDP WP1 SG 3, Powerline PLUS is one of two shortlisted communication technologies for the data backbone of the future freight train. The primary focus from FP5 will be on the technology SPE, due to the limited resources in the project and the challenging time plan. As none of the technologies has been fully tested and qualified in the target environment and to minimize the risk in the project, it´s recommended to continue the development and testing with both technologies, meanwhile in parallel. As SPE is an industrial standard and supporting the Ethernet train bus (ETB) IEC 63175 it's the preferred solution. Anyhow there is a risk that SPE might not fulfil the requirements of FDFTO with the DAC it is beneficial to pursue also the Powerline PLUS solution within FDFTO as a fall-back solution. Another outcome of EDDP is that both technologies in their current state bear several further optimizations which must be realized first in order to explore the full potential of each technology. Then the adequate field test (train) platform must be defined, components purchased and realized / installed, test procedures and cases must be defined, etc. To have comparable and sophisticated test results, both solutions will be implemented on the functional identical test-train-environment. This would be followed by the test campaigns. Based on experience from DAC4EU, it must be assumed that a large number of such tests must be carried out in order to arrive at a statistically robust assessment of reliability. If Powerline PLUS will be selected instead of SPE it needs to be further pursued, in this WP an interoperable Powerline plus based DAC communication systems, will be brought to a higher maturity (TRL8), and integrated into ERJU demonstrators. The aim is to provide standardized interoperable set of solutions. The functionality and performance shall be demonstrated and validated against the requirements and documented in test-reports for interoperability readiness. Mechanical, electrical, and software integration into rail vehicles shall be made possible by providing integration instructions and required documentation of the individual components and sub-systems (TRL8).

4.1 Task description

Task 18.1 started in month seven and the results of the task are included in this document. The following table gives the direct match of the task definition from the proposal with the output and a link to the section where more details can be found.

This task includes the planning, definition, preparation, installing on the selected test train(s), conductance of tests and processing of the test results for Powerline PLUS.

The test train(s) were selected by the WP leader who will also be responsible for the overall test procedures, permits, authorization, etc. and the coordination between the partners in alignment with the overall test planning in WP13 and the execution in WP14. The industrial partners in this task prepared the Powerline PLUS technology for such tests and participate in the tests. This includes - participation in the definition of the required appropriate field tests - further optimization / adaptations of the Powerline PLUS technology for such tests - purchasing of the components required for the testing on the field test (train) platform - installation of such components on the test platform - participation in the conduction of the field tests - participation in the analysis of the test results / providing all the related test reports. The decision if Powerline PLUS will be further pursued will be made in the consortium steering committee in case that SPE will not satisfy the FDFTO requirements.

	Task definition GA (Task 18.1)	Output of WP18.1
Task 18.1	planning, definition, preparation, installing's on the selected test train(s), conductance of tests of the test results for Powerline PLUS	Chapter 5-10

Figure 1: Task definition GA

4.2 Outline of deliverable 18.1

Section 1-4: Summary, Abbreviations, Background & Objective

Section 5: Organisation and Execution

Section 6: Test-Cases

Section 7: System Concept Prototype Test Train

Section 8: Risk Analysis and Installation

Section 9: Test Execution

Section 10: Test Results

Section 11: Conclusions

Section 12: References

Section 13: Appendices

5 Organisation and Workflow

Under the leadership of SBB Cargo and the HSLU, the organisation of Work Package 18.1 was carried out from the following companies:

- SBBC, SBB Cargo AG
- HSLU, Lucerne University of Applied Sciences and Arts - Central Switzerland
- VOI, VOITH SE & CO. KG
- PLC-TEC, PLC-TEC AG
- PJM, PJ Monitoring GmbH

Information on the method and progress in the work package for current and upcoming work was exchanged in regular meetings held every two weeks.

The results achieved were checked after each series of tests. If necessary, the systems and components were adapted by the project partners in charge and then subjected to a new series of tests.

6 Test-Cases

A particular focus of the trials was on testing the reliability of the FDFT functions in real operations. The reliability of FDFT functions under the harsh operating and environmental conditions is one of the greatest challenges for the success of the FDFT.

In addition, the following components and functionalities were tested for suitability in operations:

- Prevent Coupling function
- Mechanical function of the e-coupler
- Data and power transmission of the different e-coupler variants

Table 1 shows an overview of the FDFT functions to be tested in this project, including the additional functions of the PTB.

Operational process	FDFT function	Role of the communication system	Add-on features of Powerline PLUS
Train composition detection	*Train composition detection*: - Determination of the wagon sequence and orientation of each wagon - Creation of a logical addressing scheme	Establishing a communication connection of all nodes via the train bus Based on this, the communication of electronic systems can be implemented in the FDFT, and further cross-system or system-specific initialisation functions can be carried out.	Detection of the correct wagon sequence and orientation using the PLUS Train Topology Detection Protocol
Brake test	*Automatic brake test:* - Functional tests of the braking system on a newly formed or modified train composition using electronic support	Transmitting the signals of the automatic brake test of each wagon via the train backbone to the locomotive. Ensuring that the control variables for the brake are transmitted to all wagons and lead to the necessary measures.	
Train run: Monitoring the train and wagon systems	*Train Integrity Monitoring:* - Automatic monitoring of train integrity	Cyclical transmission of signals between the last wagon and the locomotive via the train backbone.	Train integrity monitoring using the PLUS TOKEN Protocol
Shunting at the service point or in the marshalling yard	*Uncoupling and activation/deactivation of "Prevent Coupling":* Uncoupling of wagons or groups of wagons - by means of pushbuttons on the side of the wagon (DAC4.5) and/or - remotely (locomotive, tablet, shunting hump computer in the marshalling yard)	Transmission of signals between the DAC control units and the uncoupling actuators in the coupler heads via the train backbone	

Table 1: Primary FDFT functions

Table 2: Extended FDFT monitoring functions
shows further monitoring functions relevant to operation of the FDFT.

Operational process	Monitoring function	Role of the communication system	Add-on features of Powerline PLUS
Train run	Monitoring and control of the 400 V power supply, including insulation resistance, etc.	Transmission of monitoring system data between wagons and locomotives	
	Communication system (backbone, wagons, locomotive)		
	In-situ monitoring of the train power system for detecting damage to electrical contacts	Transmission of status data from each wagon via mobile communication to the railway undertaking's cloud/maintenance centre	Detection of incipient damage from changes in the long-term behaviour of the Powerline PLUS signal

Table 2: Extended FDFT monitoring functions

The trials also included testing a new and innovative method for automatic in-situ monitoring of the behaviour of the Powerline PLUS signal over longer periods of time for the:

- detection of incipient damage to the electrical contacts in the e-couplers caused by the mechanical loads and friction processes during shunting and train runs – as the basis for a condition-based / predictive maintenance system
- localisation of earth faults

This procedure was developed by the HSLU in a parallel project and integrated into the tests.

7 System Concept of Prototype Test Train

In this chapter the basic concept and design of the prototype test train is presented.

Details on implementation are listed in Appendix 13.

7.1 Composition and Equipment

Some of the systems and components for use in rail freight transport had to be completely rebuilt or adapted to the new requirements. The systems were manufactured or customised by the project partners and installed on the test train.

An architecture for a test system – the prototype test train – was developed and iteratively refined and improved during the course of the project. This work was based on:

- the task description stated in Section 4
- the architecture and concepts for the power and communication systems (backbone, wagon) promoted in TRANS4M-R
- the available components of a basic system (wagons from SBB Cargo already equipped with DAC2 couplers from Voith and the WaggonTracker ABT system from PJM)

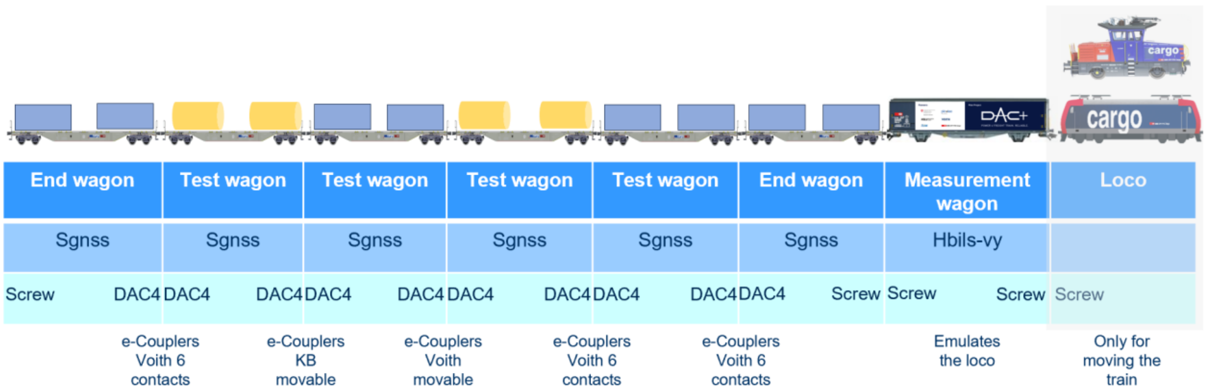


Figure 2: Composition of prototype test train

The final version of the test composition is shown in Figure 2 and consists of:

- 4 test wagons (Sgnss) each with:
  - DAC2 Scharfenberg couplers integrated on both sides (Voith)
  - WaggonTracker ABT (PJM)
- 2 intermediate/adapter wagons (Sgnss) with:
  - DAC2 Scharfenberg coupler integrated on one side (Voith)
  - Screw coupler on one side

- WaggonTracker ABT (PJM)

- equipment and measurement wagon (Hbils-vy equipment and measurement wagon) that emulates the locomotive (contains the locomotive components of the power and communication system)

The locomotives used are not integrated into the test system.

A two-phase 400 VAC power system is implemented on the test train in accordance with EDDP specifications. A two-phase, twisted power cable was used for the train power cable.

The communication system design was based on PTB in such a way that it complies with the IEC 61375 Train Communication Standard TCN from passenger transport (see Figure 3)

Figure 3: IEC Train Communication Network Architecture

The train backbone is realised with PLC / Powerline PLUS via the train power cable and its electronic contacts in the e-coupler. There are backbone nodes in the wagons and the locomotive, i.e. PTB nodes as a connection between the backbone and the wagon communication network.

7.2 Power and Communication Layout

The fundamental architecture of the wagon systems was based on the modules shown in Figure 4 (corresponding to the concepts from TRANS4M-R to date):

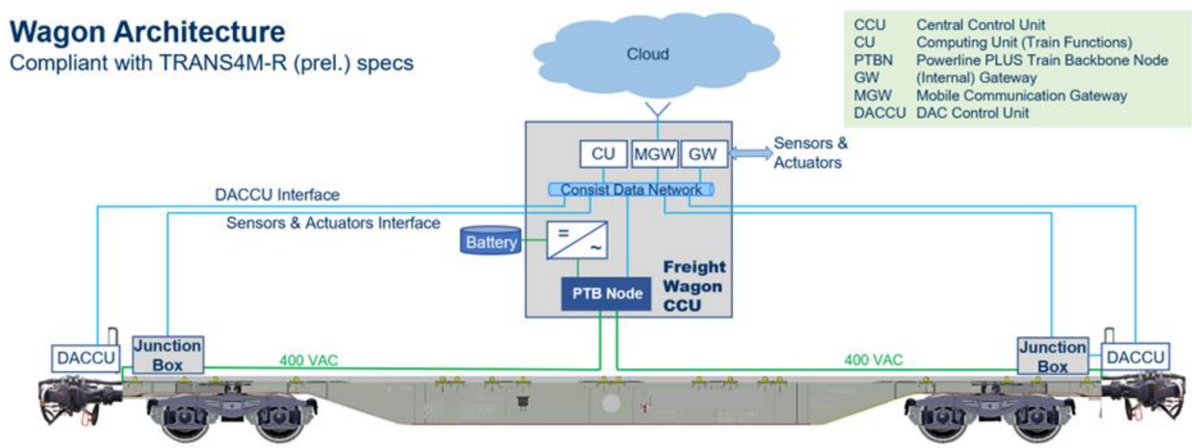


Figure 4: Architecture of the PTB wagon power and communication system

The following modules were installed for the wagon power and communication test system:

- DAC4 couplers with e-couplers and uncoupling actuators
- Wagon central control unit (CCU, also known as the on-board unit, OBU) as a central control and monitoring unit on the wagon comprising:
    - wagon power system with AC-DC converters for the wagon power supply with battery, uninterruptible power supply (UPS)
    - communication system with
        - PTB node (connection to the backbone)
        - interfaces to gateways (4G mobile communication, control units such as DACCU, sensors / actuators, computer unit)
    - computer unit for the applications / FDFT functions
- Junction box (end of wagon position) for connecting the 400 V power cable from the e-couplers with the power cable to the CCU
- DAC control unit (DACCU) for controlling the coupler actuator system

7.3 Test System Layout

Figure 5 shows the set-up of the test and intermediate wagons. The DAC components were only installed on one side of the intermediate wagons.

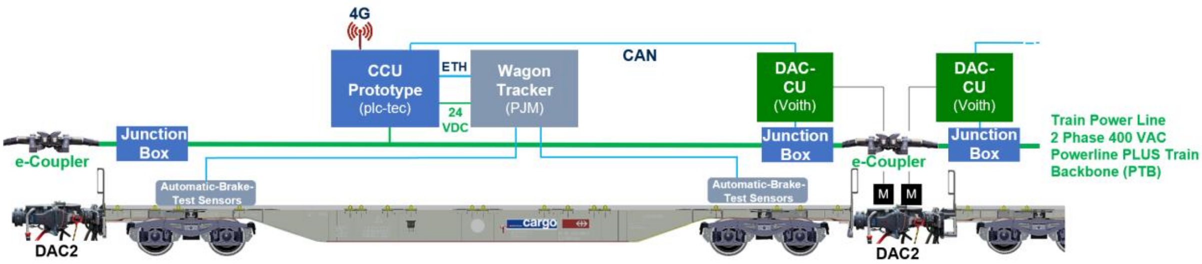


Figure 5: Wagon test system set-up

The set-up consists of the following main components (for details see Appendix 13.1):

- DAC2 (Voith)
- E-coupler for coupling the train power cable between the wagons (Voith and Knorr-Bremse)
- 400 VAC power cable (Studer Cables)
- WaggonTracker ABT (PJM)

- Central control unit (CCU) prototype (HSLU/plc-tec)
- Junction box prototype (HSLU)
- "DAC Control Unit" coupler control unit (DACCU) prototype (Voith)

7.4 Measurement Wagon Layout

There are still many unanswered questions regarding the integration of the locomotive into the overall FDFT system. This also applies to the interfaces for the power and communication system.

Up to now, SBB Cargo has only had locomotives with hybrid couplers (automatic coupler / screw coupler) and without electrical components. In addition, the use of locomotives in test operation is very time-consuming and costly. The operational test concept was therefore designed from the outset to ensure that:

- "standard" SBB Cargo locomotives are only used for mainline runs or shunting operations and are not integrated into the test system
- the functions of the locomotive are emulated in an additional wagon modelled on the DAC4EU test train

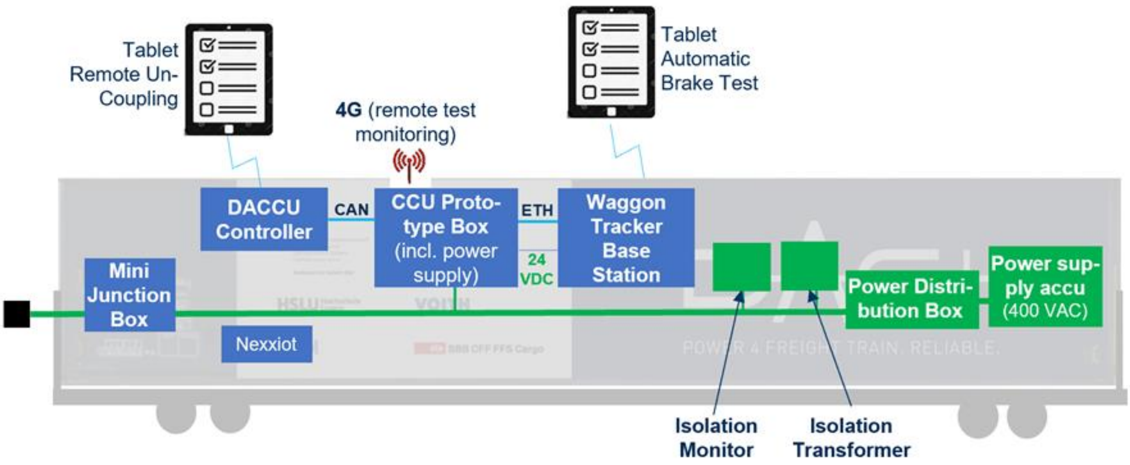


Figure 6: System set-up Components in the equipment and measurement wagon

The measurement wagon is a fully enclosed and lockable wagon. Figure 6 shows the set-up of the test system, which was installed in the measurement wagon with the following key components (see Appendix 13.1.2):

- Power supply and monitoring systems for 400 VAC
- Gateway for the automatic brake test
- DACCU controller for controlling uncoupling via a pushbutton on the wagon or via tablet

7.5 Test and Measurement Systems

To achieve the test objectives in terms of system reliability, a large number of sensors and measuring devices were integrated into the DAC+ test train to continuously record synchronised data and correlate measurements with events during train runs (see Table 3). The data is partially pre-processed in each wagon in the CCU prototype and then transmitted via 4G from each wagon to the cloud and to a central database for further analysis. At all times there is a digital image of the power and communication system of the entire train in this database – even when the train is stationary, during night, over weekends, etc. Further information can be found in Appendix 13.1.3.

System / Device / Measurement	Item	Analysis
400 VAC power system	Per wagon, dependent on time in each case: Voltage V, current I, active power P, apparent power S, reactive power Q, cos phi, frequency, real energy, apparent energy, energy supplied, energy consumed, max. and min. voltage, as well as time of max. / min. voltage	Power system statistics • Voltage / current statistics • Cos phi statistics • Resistance
	Monitoring of the insulation resistance (over time) from the locomotive/equipment and measurement wagon; voltage L1-L2, L1-PE, L2-PE, detection of faults, e.g. earth faults	Statistics on the occurrence of earth faults, correlation of earth faults with insulation monitoring data to determine the possible cause, correlation of resistance with weather, ...
Communication system (PTB)	Performance measurement such as packet error rates, latency, network bandwidth, etc.	
GPS	Precise UTC time, GPS location recording, speed relative to the ground	• Creation of the route on a map for each day of test runs • Correlation of the location and train speed with other data (moving vs. stationary train)
Video camera on the equipment and measurement wagon	Synchronised recording of the journey to enable tracking of events (meeting another train, tunnel, sparks from the pantograph, tight curves, points, ...)	Correlation of other measurement/test data with events in the train run (e.g. crossing points, meeting another train, curves, ...)
Video camera on one DAC (GoPro)	Synchronised monitoring of DAC/e-coupler movements: • Observation of the movement of the measurement scales on each DAC relative to each other. • Measuring the movement of each DAC relative to each other using video content analysis techniques.	
3D acceleration sensors	On both e-couplers in order to record three-dimensional relative accelerations and correlate them with train encounters, tight curves, etc.	
DC resistance of the e-coupler contacts	DC resistance – measured when running – across the two free current contacts in Voith's static coupler between two coupled junction boxes	• Statistical analysis of DC resistance measurements • GPS/test run videos are used to correlate changes in DC resistance with external events
E-coupler micro-interruptions	Detection and number of micro-interruptions within a timeframe	• Probability of micro-interruptions, distribution vs. time • Duration of micro-interruptions

		• Correlation of micro-interruptions to external events (e.g. passing over electrical infrastructure devices)

Table 3: Additional measuring and testing devices

8 Risk Analysis and Installation

Before the systems and components of the prototype test train were installed and tested, a risk assessment was carried out in accordance with SBB specifications.

In addition to technical considerations, the aspects of employee protection, hazards due to high voltage or incorrect and unauthorised use of components and systems, as well as the influences on the environment/infrastructure were also considered.

On the basis of the assessment, technical adjustments were made and operational specifications/measures were defined for operating the prototype test train.

The results of these considerations were operational guidelines for:

- the static and shunting tests
- the test runs

The specifications for operating the test train were adopted in scripts and checklists for the test personnel. This also included the processes for commissioning and decommissioning the test composition.

As the Sgnss test wagons used already the automatic coupler and the equipment for the automatic brake test, the following work still had to be carried out during the course of the project:

- In November 2022 by CT-X on behalf of SBB Cargo:
    - Installation of the various electronic boxes, cabling and power supply.
- In December 2022 / January 2023 by HSLU:
    - Procurement of all components of the power and communication system as well as the measurement and test systems.
    - Development and integration as well as laboratory tests (in the HSLU Virtual Train Test Lab) of all these components.
    - Installation of the components in the test wagons and the equipment and measurement wagon
- End of January 2023 by certified SBB inspection experts:
    - Acceptance of the electrical installations.
- From February 2023 until autumn 2023 by HSLU:
    - Procurement, laboratory tests and installation of additional systems and components.
- In Q2/2023 by PJM:
    - Customisation of the components of the WaggonTracker system and their testing in the HSLU Virtual Train Test Lab
- End of July 2023 by PJM:
    - Installation of the customised WaggonTracker systems on the test wagons.
- End of June 2023 by Voith:

    - Installation of the DACCU system on the test wagon
- Beginning of August 2023 by Knorr-Bremse:
    - Installation of a pair of e-couplers (movable head)
- Mid-September 2023 by Voith:
    - Installation of a pair of e-couplers (movable head)

9 Test Execution

The following section briefly describes the details of the test environment, test planning and the execution of the static, coupling and shunting tests as well as the test runs.

9.1 Test Environment

SBB Cargo looked for a suitable siding to ensure access to the test composition for inspection and conversion work as well to as the power supply during stabling and also to provide a certain level of security against vandalism.

The siding of the KIBA company in Birr/Lupfig (Aargau/Switzerland) was rented for this purpose in 2023.

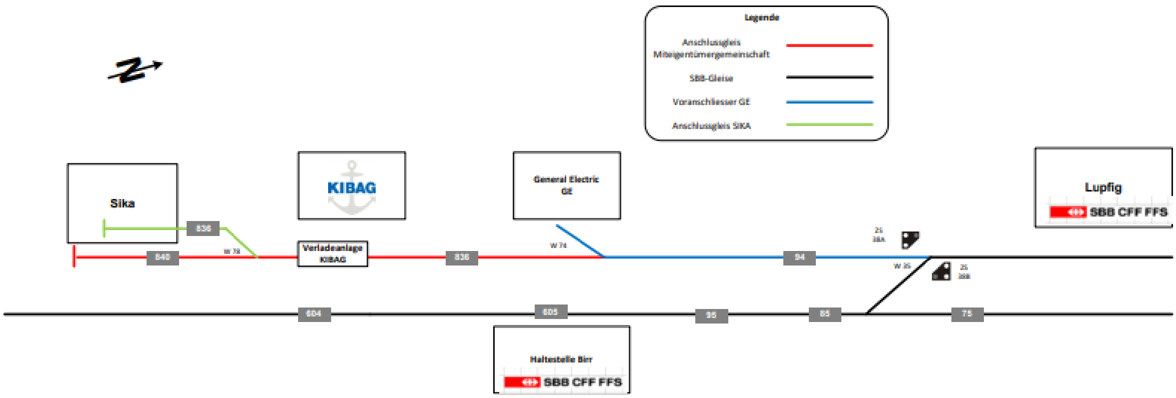


Figure 7: Lupfig track plan

The test composition was positioned so that the measurement wagon was near the freight terminal and could be connected to the external 400 VAC power supply there. The test wagons were parked to the south (Othmarsingen) of the freight terminal.

Tracks 836 and 94 were also used for static and simple coupling tests.

9.2 Test Planning

The test programme was defined by the work package teams and included two days for shunting tests and two days of test drives per month. The individual test days were then planned in detail by SBB Cargo. For this purpose, a detailed daily programme was drawn up and the required personnel and traction resources, train paths and track requirements were ordered and reserved in accordance with standard operational processes. This was followed by preparation of the tests using a script containing all the information necessary for the test day.

9.3 Static and Coupling Tests

In order to test the basic functions of the hardware and software, static and coupling tests were performed in Lupfig. This was done in 10 days for the static and coupling tests.

9.4 Shunting Tests

The shunting test days mentioned in Table 4 were held in Dottikon, Wildegg and Basel Marshalling Yard (Basel MY).

Location	Test days	Contents
Dottikon distribution substation	2	Normal shunting processes
Wildegg	1	Coupling / uncoupling in tight curve radii
Basel MY	1	Normal shunting
Basel MY	4	Basel MY I and Basel MY II shunting hump operation

Table 4: Overview of shunting test days

9.5 Test Runs

A total of 20 test run days were carried out as part of 10 one-week campaigns, covering a total distance of *4'211 kilometres* (Table 5)

Test Drive #	Date	Route	Distance / km
1	09.03.23	Lupfig – Brugg – Zürich Vorbahnhof – Ziegelbrücke – Linthal	236
2	10.03.23	Lupfig – Brugg – Zürich Vorbahnhof – Ziegelbrücke – Linthal	237
3	06.04.23	Lupfig – Basel RB – Olten RB	181
4	04.05.23	Lupfig – Basel RB – Olten RB	181
5	05.05.23	Lupfig – Basel RB – Olten RB	182
6	08.06.23	Lupfig – Rotkreuz – Erstfeld – Göschenen - Biasca	358
7	09.06.23	Lupfig – Rotkreuz – Erstfeld – Göschenen - Bodio	364
8	17.07.23	Lupfig – Rotkreuz – Erstfeld – Göschenen - Biasca	360
9	18.07.23	Lupfig – Rotkreuz – Erstfeld – Göschenen - Biasca	359
10	10.08.23	Lupfig – Basel RB – Olten RB	180
11	11.08.23	Lupfig – Basel RB – Olten RB	180
12	31.08.23	Lupfig – Luzern - Horw/HSLU	178
13	07.09.23	Lupfig – Basel RB – Olten RB – Basel KH	134
14	08.09.23	Basel KH – Lupfig	65
15	05.10.23	Lupfig – Niederglatt	89
16	06.10.23	Lupfig – Basel RB – Olten RB	181
17	23.10.23	Lupfig – Basel RB – Olten RB – Basel RB	123
18	10.11.23	Basel RB – Olten RB – Basel RB – Lupfig	123
19	07.12.23	Lupfig – Bern - Brig	410
20	08.12.23	Lupfig – Niederglatt	90
		Total Distance	4'211

Table 5: Overview of test runs

10 Test Results

The test results are categorised as follows in this section:

- Data acquisition and analysis
- Performance
- FDFT functions
- Components

10.1 Data Acquisition and Analysis

The sensors and measuring devices installed in the prototype test train were used for the performance tests described in Section 10.2. In addition, diagnostic data was collected from the power and communication system. This resulted in a large amount of data. This data was acquired by an industrial PC in the CCU prototype and partially pre-processed there. Data was then transferred to a database in the back office via the Internet using a mobile communication gateway (MCG) (Figure 8).

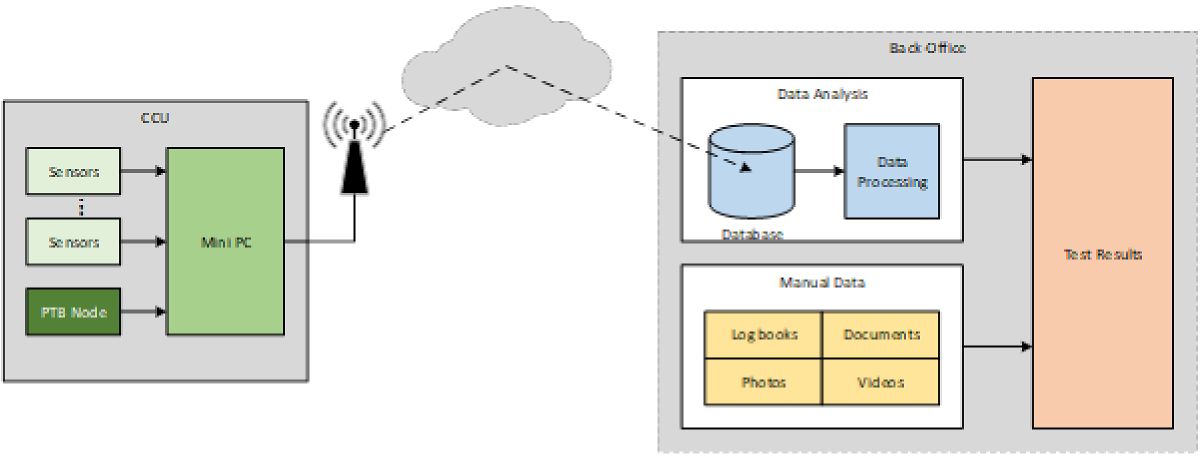


Figure 8: Data acquisition and analysis system

In addition, during the test phases, the tests were documented manually using a predefined report with logbooks, reports, photos and videos.

In order to identify reciprocal influences, e.g. meeting another train or driving over hard points or through a tunnel, and a sudden increase in the packet error rate, the data was recorded synchronously. For example, GPS data is used to determine the geographical position at any point in time, while video recordings could provide information about the surroundings, e.g. stations, nearby trains or whether the train is passing over hard points. The analysis then identified correlations between the performance of the communication system at a certain point in time and environmental influences.

Here are two examples:

- During the first test run, it was found that the message error rate was much too high in comparison with laboratory tests. Using the sensors on the train, the fault was then pinpointed to one of the CCU prototype boxes on one wagon and to a specific power connection there. This was checked and the fault was quickly found (insulating material in a terminal).
- During one test run, an above-average number of message errors were observed over a period of a few seconds. The data showed that the train was travelling through Faido station at this time. Further analyses revealed that a Euroloop transmitter was installed there, which caused electromagnetic impacts on the prototype systems that were being used.

10.2 Performance Criteria

10.2.1 Power System

The tests focuses on the two aspects of reliability and safety of the power system. Reliability is primarily influenced by the reliability of the power contacts within the e-couplers, while the safety aspect is aimed at preventing earth faults, i.e. the insulation behaviour of all components involved (e-couplers, power cables, boxes, etc.).

10.2.2 Communication System

There are several performance metrics that are relevant in the context of a communication system. The key performance indicators are:

- **Message error rate**
  The underlying communication protocol in PTB has a token-based medium-access scheme. A token loss can be regarded as an end-to-end message loss. Therefore, the token loss rate corresponds to the end-to-end message loss rate.
- **Message latency**
  The cycle time determines the intervals at which messages can be sent. The resulting message latency is directly related to the cycle time. The PLUS token protocol has an asymmetrical traffic pattern, i.e. the traffic from the master to the slaves has a shorter cycle time than the traffic from the slave to the master. As the PLUS token protocol is a deterministic protocol, the expected cycle time can be calculated in advance. The cycle time may be extended in some cases as a result of token losses.

The key performance indicators depend on several parameters. The most important of these are:

- **Number of wagons**

  The number of wagons determines the number of communication nodes, but also the length of the train. As it is not possible to reach the end of the train directly with PLC, the PTB protocol relies on forwarding. The longer the train is, the more often a message has to be forwarded, or technically speaking, there are more hops. This has an influence on both the message error rate and the latency. As each individual hop involves a message error probability and a latency, a higher number of hops increases the message error rate probability and the latency for the entire train.

- **Forwarding distance**

  The forwarding distance is a parameter that controls how many nodes a message skips before it is forwarded. For example, with a forwarding distance of four, four nodes are skipped before forwarding from the fifth node takes place. Selecting a greater forwarding distance reduces the number of hops required to reach the end of the train, which reduces the probability of an end-to-end message error and the latency. However, since the communication range is physically limited, selecting too great a forwarding distance leads to the probability of a message loss per hop that is too high to maintain reliable communication. Selecting this parameter is therefore a compromise between performance and reliability.

10.3 FDFT Functions

The test results achieved with the prototype test train are listed below for the following FDFT functions:

- Train composition detection
- Automated brake test
- Train integrity monitoring
- Automatic uncoupling

10.3.1 Train Composition Detection

Train composition detection is based on the PTB Train Topology Detection (TTD) protocol. The protocol was tested as part of shunting tests with changing topologies. Both the wagon sequence and the orientation of the individual wagons were detected correctly in all tests.

Figure 9 shows an example of the TTD output with the detected wagons in their sequence, their wagon UIC number ("Wagon ID" column) and their orientation ("Ori" column). In this case, the detection of 7 wagons took *390 ms*.

```
#########################        PTB Status       #########################

TTD Status                     :        COMPLETE
TTD Sequence No.               :               1
TTD Duration [ms]              :             390

Topology Size                  :               7
Displayed Entries              :               7

Train Integrity Check Status   :               1
Train Integrity Compromised    :               0
Train Integrity Counter        :               0

Transmitted Allocation         :          259215

--------------------------------------------------------------------------
Entry   Addr     Wagon ID            Ori   Master   MPD [ns]   Rcvd Alloc
--------------------------------------------------------------------------
    0   0x001    21 85 237 0 487-0     A        1          0            0
    2   0x002    81 85 456 5 052-0     B        0        170       258969
    3   0x003    81 85 456 5 091-8     A        0        305       259018
    5   0x004    81 85 456 5 078-5     A        0        460       259009
    4   0x005    81 85 456 5 075-1     A        0        605       259039
    1   0x006    81 85 456 5 119-7     B        1        800       259027
    6   0x007    81 85 456 5 095-9     A        1        970       221772
--------------------------------------------------------------------------
```

Figure 9: TTD output of train topology

10.3.2 Automatic Brake Test

The customised WaggonTracker systems for the ABT, including the provision of the HMI and the updated software, were installed in calendar week 30 of 2023.

This is the ABT volume production system from PJM, which has been extended to include a communication module for this purpose so that the brake test can be carried out via the Powerline Backbone (instead of the LORA wireless system). In this way the ABT was integrated into the PTB.

Immediately after installation, the ABT was successfully carried out by means of an HMI via "Leading Consist". The data was transmitted via PTB to the six test wagons. All test cases were passed.

No further tests were carried out after that as the data interface for the services used to transfer the train list was being overhauled.

Figure 10 shows the ABT application on a mobile device. The HMI of the ABT system visualises the brake status data and the operator checks that status is correct according to the brake testing process.

Figure 10: ABT process step – preparing for brake test

10.3.3 Train Integrity Monitoring

Train integrity monitoring is based on the detection of communication losses in the PTB communication system. When designing the system, a compromise must be found between response time and false alarm rate. If the threshold is set too low, sporadic, short-term failures can falsely trigger an alarm. If the threshold is set too high, a loss of train integrity will be recognised too late. This delay in the response time is called the train integrity threshold. The correct triggering of train integrity events was also tested in shunting tests. Robustness and false alarm behaviour were tested during test runs. The train was never uncoupled at any time during the test runs.

The train integrity threshold was set to *250 ms* for the test runs. The current working hypothesis is that the requirement for the communication system recognises a train integrity event within *1,000 ms*. Therefore, the train integrity threshold of *250 ms* was chosen as a conservative approach to ensure a robust solution to fulfil the *1,000 ms* requirement.

32 out of 33 test runs were completed without a single train integrity fault alarm. The first and only train integrity fault alarm occurred during the morning test run on 7 December 2023. The reason why the train integrity monitoring was triggered during this test run is still under investigation. It is suspected that the fault was erroneously triggered due to the local conditions as a train integrity fault alarm did not occur once during the long-term tests at the train's stabling location.

10.3.4 Automatic Uncoupling

With regard to the operational use of the DAC, the question arises, on the one hand, as to the technical suitability for the shunting hump and, on the other hand, as to whether the processes defined in Work Package 2 can be applied in shunting hump operation.

Following initial shunting hump tests with the DAC2 in operational use at SBB Cargo in 2021, Voith further developed the electrical uncoupling option using the DACCU prototype, data transmission via PTB, the actuator in the coupler head and operation using a pushbutton or tablet as well as the mandatory "Prevent Coupling" function, and implemented it on the prototype test train.

As part of the shunting hump tests carried out between 31 October and 3 November 2023 in the Basel marshalling yard, the uncoupling functions on the two different humps were thoroughly tested in terms of their functionality and suitability for shunting hump operations.

Considering the extreme complexity of the system with its mechanical components, sensors and actuators, electronics and software, the tests on this first prototype were very successful.

Normal uncoupling and coupling processes were tested without any significant problems. The shunting hump tests comprised an entire week of tests in a real environment and under realistic operating conditions. These tests were carried out in the Basel MY II gravity yard and on the hump in the Basel MY I hump yard.

The uncoupling and the simultaneous "Prevent Coupling" setting by means of the pushbutton worked with a high degree of reliability. Based on extensive tests, some minor points for improvement were identified with regard to the components of the automatic uncoupling, but also concerning the communication requirements for shunting operation. Up to now, communication has focussed on a static train configuration (train on open track) and less on dynamic configurations, as is the case in shunting operations. It also became apparent that the solution installed as a "proof-of-concept" to reset the "Prevent Coupling" function using a light sensor on the wagon and reflector plate in or next to the track area does not work reliably. Due to reflective objects on the track surface or at the side of the track (rail heads, masts or even reflective safety clothing), too many false activations were triggered, causing the "Prevent Coupling" function to be deactivated too early.

Furthermore, the fact that the uncoupling is currently controlled centrally by a "Leading Consist" has turned out to be a limiting factor. This results in operational restrictions, which is why alternative concepts should be sought. Nevertheless, the problems described above were resolved by adjustments during test operation, which meant that all the required functionalities achieved a positive test result.

Both interaction variants for uncoupling were also successfully tested. Namely:

- a pushbutton on the wagon
- remote uncoupling using a tablet

The pushbutton is currently the most important interaction interface, which therefore results in operational restrictions. The pushbutton forces the operator of the automatic uncoupling system to be located directly beside the vehicle, which offers a greater scope of action in the case of unforeseen events.

It must be emphasised here that the remote uncoupling solution is only a "proof of concept". For cybersecurity reasons, the connection between the tablet and the central control unit was established via WLAN. Due to its range, a WLAN connection has only limited suitability for shunting operations, as a train is usually significantly longer and the WLAN range is not sufficient. It is conceivable that the necessary systems for remote uncoupling will in future be integrated into the locomotive so that an engine driver can initiate uncoupling. In addition, remote uncoupling could also be triggered from a control centre, e.g. in a fully automated marshalling yard. As these applications are not yet possible with manual shunting, there are new requirements for the safety and integration of these systems, which must also be taken into account when defining the operational and technical requirements.

On the one hand, the shunting tests on the hump showed that the systems tested for the prototype application are well engineered and meet functional expectations. However, it was also found that certain operational processes (e.g. uncoupling by means of a pushbutton on the wagon) require different or new concepts that have not yet been included in Work Package 2. Finally, there are also other new operational scenarios that did not previously exist and need to be developed. The aim here is to define corresponding requirements in order to develop new concepts, such as the remote uncoupling, in a targeted manner.

Details of the tests are available in the test report on the shunting hump tests [1].

10.4 Components

10.4.1 E-coupler Variants

The analysis of the e-couplers focussed on the data and power transmission of the three e-coupler types available on the train. Experience was gained here regarding the reliability of the spring-loaded contacts or plug/socket contacts used.

In terms of mechanical functionality (folding control, plug connection, robustness, etc.), the focus was on the two new second-generation e-couplers with the movable head from Voith and Knorr-Bremse, as the Voith e-coupler with the static head, which was also installed on the prototype test train, will not be subject to further development.

In functional terms, the mechanics of both second generation e-couplers generally behaved with a high degree of reliability. The loads in test operation did not lead to any faults.

During the shunting and shunting hump tests in Basel MY, the folding mechanism of the Voith e-coupler malfunctioned, but this was easily rectified by applying grease.

On the Knorr-Bremse e-coupler, contacts jammed after just the first tests, and screws on the plug-in plate also worked loose. It was possible to solve these problems with simple modifications, and the two Knorr-Bremse e-couplers worked without any further faults during the subsequent tests.

In addition to the simple shunting tests and test runs, a test day was held specifically for the e-coupler on 5 December 2023 in Lupfig. The main focus here was on mechanical functionality in the case of horizontal and vertical offset of the coupling heads during the coupling process as well as on any resistance that may occur in power and data transmission via e-coupler. No mechanical or electrical malfunctions were detected in the e-couplers from Knorr-Bremse and Voith.

Details of the tests are available in the e-coupler test report [2].

10.4.2 Power Supply System

10.4.2.1 Power Interruptions

Long-term measurements were carried out both in the parked position and during test runs. The apparent power measurements were taken at 10-second intervals and did not show any failure in any of the test scenarios.

Several malfunctions of the battery-powered 400 VAC supply were observed during the test runs. However, these power failures had no impact on wagon performance as each wagon unit has its own battery-backed, uninterruptible power supply (UPS) which can compensate for power failures lasting several hours.

The e-coupler provided by Knorr-Bremse experienced a few incidents with jammed electrical contacts. The solution implemented in the form of spring-loaded contacts resulted in jamming of the contact parts so that no galvanic contact was made. Thanks to contact redundancy, however, no current interruption was measured. This problem did not occur with the e-couplers provided by Voith.

10.4.2.2 Micro-interruptions

Micro-interruptions are interruptions of very short duration, ranging from nanoseconds to milliseconds. Micro-interruptions were measured using a measuring platform, CouplerSense, specially developed by HSLU. It comprises measuring circuits and electronics as well as a microcontroller for capturing and storing data. CouplerSense is able to measure micro-interruptions of just a few hundred nanoseconds.

No micro-interruptions were measured for the new Voith e-coupler (movable head). On the old Voith e-coupler (fixed head), micro-interruptions were measured during a test run on 7 December 2023, with one interruption lasting *1.6 ms* and 8 interruptions lasting less than *10 μs* (Figure 11). Other than that, no other micro-interruptions were measured during the entire test period.

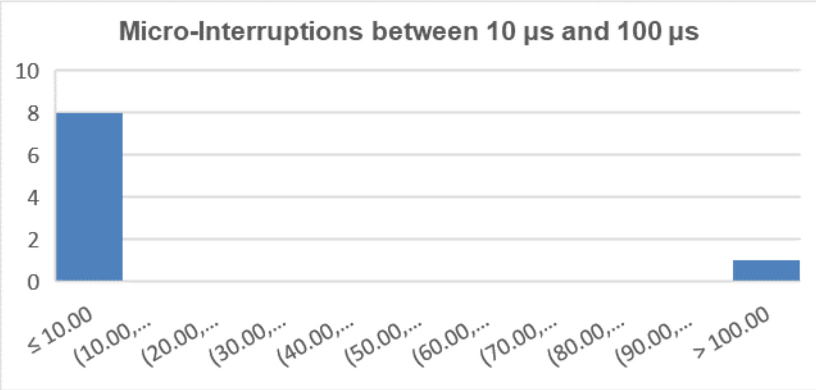


Figure 11: Micro-interruptions on Voith e-coupler (fixed head)

With the Knorr-Bremse e-coupler, 37 and 99 micro-interruptions were measured during the test runs on 5 and 6 October 2023. The interruptions lasted between several microseconds and several seconds (the longest interruption was *3.4 s*). However, it should be noted that the e-coupler was damaged during shunting tests in September. A visual inspection revealed that the plastic screws used to attach the contact holders to the housing were already broken (Figure 12, missing screw head, bottom left, September 8th. 2023). After Knorr-Bremse replaced the plastic screws with metal screws, no more micro-interruptions were measured on this e-coupler.

Figure 12: Damaged Knorr-Bremse e-coupler

10.4.2.3 Insulation Resistance

Insulation resistance was continuously monitored on the prototype test train using the measuring device (Bender isoRW685W insulation monitor) installed in the equipment and measurement wagon. Insulation resistance was measured both during test runs and during static long-term tests on the siding. Insulation resistance was in the range of *6 MΩ* during the period from March to August 2023. From August onwards, the value dropped several times, with the lowest measured value being *360 kΩ,* which is still above the assumed *300 kΩ*. This is very relevant with regard to possible hazards in terms of earth faults and therefore for physical safety. It is assumed that humidity influences insulation resistance, but not all rainy days caused a reduction in insulation resistance. One hypothesis is that a lot of installation work was carried out on the couplings from August onwards, meaning that the installations were exposed to the environment more frequently. Both the new Knorr-Bremse e-coupler and the new Voith e-coupler with movable head, as well as the automatic uncoupler, were installed. The extent to which the technical changes affected insulation resistance and why the value fluctuated significantly more afterwards cannot be answered at present.

It should be noted that these measurements are carried out on the entire train. In the event of reduced insulation resistance, it is still unknown where exactly the relevant and critical faults occur.

Salt tests were carried out with a measuring device for insulation resistance (Fluke 1663) on the Knorr-Bremse e-coupler and the new Voith e-coupler (movable head) in order to specifically stress the e-couplers with regard to insulation resistance. For this purpose, the e-couplers were disconnected from the 400 VAC power supply in order to specifically measure the insulation resistance of the e-coupler. Each e-coupler was sprayed three times with a water-salt solution and each time the insulation resistance was measured.

The Voith e-coupler initially had an insulation resistance of more than *1,000 MΩ*, which gradually fell to *80 MΩ*. The Knorr-Bremse e-coupler initially had an insulation resistance of *15 MΩ,* which fell to *6 MΩ* after the third exposure to salt water. This test showed that certain environmental conditions reduce insulation resistance, but the final measurements were still within the safe range. However, these are only initial tests that should be repeated in a larger and more systematic study in the TRANS4M-R.

10.4.2.4 On-board power supply for the wagons

The on-board power supply was loaded to a greater or lesser extent depending on the test case. The installed battery capacity was not always sufficient for the planned test campaigns and led to the cancellation of individual practical tests.

As the capacity of the on-board power supply depends directly on the installed loads and the operational FDFT functions, no conclusions can be drawn from the test train for the future dimensioning of the digital freight wagon.

10.4.3 Communication System

The results shown here are the message error rate and latency analysed across all test runs. As explained in Section 10.1.2, performance depends on several parameters. The results shown below are based on a train with 7 wagons and a forwarding distance between 2 and 4. Table 6 shows the complete statistics of PTB messages/tokens during all test runs performed.

Date	Test Route	Test Drive Duration (hh:mm:ss)	Forward Distance	PTB TOKENs Sent	PTB TOKENs Lost	PTB TOKEN Loss Rate
04.05.23	Lupfig – Basel RB – Olten RB	02:14:34	2	4'460'814	31	6.949E-06
04.05.23	Olten RB – Basel RB – Lupfig	03:47:45	2	2'810'003	76	2.705E-05
05.05.23	Lupfig – Basel RB – Olten RB	02:00:29	4	3'403'300	39	1.146E-05
05.05.23	Olten RB – Basel RB – Lupfig	02:26:26	4	4'149'048	70	1.687E-05
08.06.23	Lupfig – Rotkreuz – Erstfeld – Göschenen - Biasca	03:24:16	4	5'541'624	73	1.317E-05
08.06.23	Biasca - Göschenen - Erstfeld - Rotkreuz - Lupfig	03:06:21	4	5'294'820	50	9.443E-06
09.06.23	Lupfig – Rotkreuz – Erstfeld – Göschenen - Bodio	02:58:01	4	5'026'992	64	1.273E-05
09.06.23	Bodio - Göschenen - Erstfeld - Rotkreuz - Lupfig	03:22:15	4	5'707'842	53	9.285E-06
17.07.23	Lupfig – Rotkreuz – Erstfeld – Göschenen - Bodio	03:44:11	4	6'323'358	42	6.642E-06
17.07.23	Bodio - Göschenen - Erstfeld - Rotkreuz - Lupfig	03:12:50	4	5'445'550	122	2.240E-05
18.07.23	Lupfig – Rotkreuz – Erstfeld – Göschenen - Bodio	05:01:53	4	8'513'982	51	5.990E-06
18.07.23	Bodio - Göschenen - Erstfeld - Rotkreuz - Lupfig	03:09:30	4	5'355'270	58	1.083E-05
10.08.23	Lupfig – Basel RB – Olten RB	02:34:48	4	4'376'477	81	1.851E-05
10.08.23	Olten RB – Basel RB – Lupfig	02:39:45	4	4'510'854	631	1.399E-04
11.08.23	Lupfig – Basel RB – Olten RB	02:38:38	2	3'217'554	104	3.232E-05
11.08.23	Olten RB – Basel RB – Lupfig	02:20:49	2	2'819'430	318	1.128E-04
31.08.23	Lupfig – Luzern – Horw	03:06:55	2	3'798'312	3	7.898E-07
31.08.23	Horw – Luzern – Lupfig	02:31:48	2	2'962'462	5	1.688E-06
07.09.23	Lupfig – Basel RB	03:04:15	3	5'200'698	257	4.942E-05
07.09.23	Basel RB – Olten RB – Basel KH	01:15:21	3	2'165'616	142	6.557E-05
08.09.23	Basel KH – Lupfig	01:41:07	3	2'862'270	878	3.067E-04
05.10.23	Lupfig – Niederglatt	01:44:45	3	2'496'306	1	4.006E-07
05.10.23	Niederglatt – Lupfig	01:30:25	3	2'563'458	14	5.461E-06
06.10.23	Lupfig – Basel RB – Olten RB	02:34:21	3	4'362'890	19	4.355E-06
06.10.23	Olten RB – Basel RB – Lupfig	03:31:55	3	5'978'184	120	2.007E-05
23.10.23	Lupfig – Basel RB – Olten RB	02:41:01	3	4'105'222	8	1.949E-06
23.10.23	Olten RB – Basel RB	02:20:22	3	1'465'632	1	6.823E-07
10.11.23	Basel RB – Olten RB	01:23:51	3	2'380'290	9	3.781E-06
10.11.23	Olten RB – Basel RB – Lupfig	03:01:28	3	5'129'070	22	4.289E-06
07.12.23	Lupfig – Bern – Brig	03:22:14	3	5'442'759	133774	2.458E-02
07.12.23	Brig – Bern – Lupfig	03:28:08	3	5'911'788	19	3.214E-06
08.12.23	Lupfig – Niederglatt	01:32:15	3	2'628'480	12	4.565E-06
08.12.23	Niederglatt – Lupfig	01:49:34	3	3'101'911	9	2.901E-06

Table 6: PTB token statistics for test runs

The red row indicates a test run with exceptional events that led to high token loss rates. During the test run on 7 December 2023, there was a single event with an individual interruption in communication, isolated in terms of time. The cause of this incident is still being investigated.

In summary, the performance results for the communication system are as follows:

- **Message Error Rate**

  If the test drives without exceptional events (green rows) are taken into account, the average token loss rate is in the region of $2.5 \cdot 10^{-5}$. The exception to this is the event highlighted in red in Table 6.

- **Cycle time**

  As the PLUS token protocol is deterministic, the cycle time can be calculated in advance. The master cycle time, which corresponds to the cycle time with which messages can be sent from the locomotive to the wagons, is between *1.78 ms* and *2.23 ms* (for a forwarding distance of 3 and 4). These values describe the best case and worst case scenarios without token loss. The results of the test runs correspond closely with the expected values:

  - The median value is *2.13 ms*
  - The 90% percentile is *2.14 ms*
  - The 99% percentile is *2.27 ms*

  A certain deviation must be accepted as the time was not measured directly but was calculated using the tokens sent within the measurement intervals of *10 s*.

10.5 Summary of Performance

The performance analysis is mainly based on data collected during the test runs but also on data from long-term static tests in the parking position. Table 7 summarises the most important results of the entire test period in the prototype test train project. As neither the values for the message error nor the train integrity error alarms are currently specified, assumptions have been made.

	Tests	Target
Number of shunting days	18	18
Number of coupling cycles	1,342	1,200
Number of test runs	33	30
Total test distance	4,211 km	4,000 km
Total number of PTB messages sent during test runs	144×10^6	100×10^6
PTB message loss rate (during test runs, with the exclusion of the test drive on Dec 07, 2023)	2.5×10^{-5}	$<10^{-4}$ (assumed)
PTB train integrity false alarms (with 250 ms threshold)	7×10^{-7}	$<10^{-6}$ (assumed)
Insulation resistance	~ 6 MOhm	300 kOhm (assumed)

Table 7: Summary of test results

FDFT function	Powerline PLUS Train Backbone functions	PTB tests of various e-coupler prototypes		
		Voith Fixed head	Knorr-Bremse movable head	Voith movable head
Train composition detection	- Determining the sequence and orientation of all wagons using the PTB Train Topology Detection (TTD) protocol - Data transmission between the CCU in each wagon and the master tablet in the (emulated) locomotive via PTB	OK	OK	OK
Automatic brake test	- Data transmission between the PJM WaggonTracker box and the master tablet in the (emulated) locomotive via PTB	OK	OK	OK
Uncoupling	- Transmission of control and monitoring data between the Voith Coupling Control Unit (DACCU) and the Voith master tablet via PTB	OK	OK	OK
Train integrity monitoring	- Transmission of monitoring data between the last wagon and the master tablet in the (emulated) locomotive via PTB	OK	OK	OK

Table 8: Test results of the FDFT functions

The test results prove that the four main automated train functions based on the PTB communication system with data transmission via the train power line and its spring-loaded contacts function successfully and reliably for the e-coupler prototypes used, including the new ones from Voith and Knorr-Bremse (Table 8).

The tests for the PTB communication system showed very high performance in terms of the important variables of packet error rate (in the range of 10^{-5}, ratio PTB token sent to PTB token lost), false alarm rate for train integrity (in the range of 10^{-6}) and latency (in the low single-digit *ms* range) as a basis for meeting the communication requirements of the train functions. However, EDDP has not yet provided any quantitative specifications or requirements for the operation of the train functions or for the backbone communication system. However, it is expected that the ultimately specified communication requirements will be below the above values, so that PTB has a substantial reserve for meeting the ultimately expected requirements. This reserve suggests that PTB is a highly reliable and robust solution for the backbone.

Regarding the systems enabling the FDFT functions (e.g DACCU, ABT,...) based on PTB communication a conclusion for reliability and availability could not be generated with the prototype test train.

11 Conclusions

The results of Work Package 18.1 are of great benefit for the further development of the DAC and the FDFT. These results can achieve further impact with continued development in the EDDP, in the ERJU FP5-TRANS4M-R project and in the CENELEC standardisation, which is still in the initial stages.

The results to be achieved in Workpage 18.1 according to the Grant Agreement were expanded extensively during the course of the project. Based on the integration and implementation of the Powerline PLUS Train Backbone according to the Grant Agreement, further points could be worked on in WP18.1 and tested with the prototype train:

- E-coupler assessment
- FDFT functions DAC4 and DAC5 stage implemented
- Hump tests with DAC4 and DAC5 functions

The test results prove that the four main automated train functions based on the PTB communication system with data transmission via the train power cable and its spring-loaded contacts function steadily in the e-couplers currently in use, including the new e-coupler prototypes from Voith and Knorr-Bremse. However, it is also clear that the systems used do not yet conform to volume production status.

The tests for the PTB communication system showed very high performance in terms of the important variables of packet error rate (in the range of 10^{-5}, ratio PTB token sent to PTB token lost), false alarm rate for train integrity (in the range of 10^{-6}) and latency (in the low single-digit *ms* range) as a basis for meeting the communication requirements of the train functions. However, EDDP has not yet provided any quantitative specifications or requirements for the operation of the train functions or for the backbone communication system. However, it is expected that the ultimately specified communication requirements will be below the above values, so that PTB has a substantial reserve for meeting the ultimately expected requirements. This reserve suggests that PTB is a highly reliable and robust solution for the backbone.

Regarding the systems enabling the FDFT functions (e.g DACCU, ABT,...) based on PTB communication a conclusion for reliability and availability could not be generated with the prototype test train.

It should be emphasised that PLC technology made it possible to quickly implement and adapt the FDFT functions in the Powerline Train Backbone. Further work on industrialisation and achieving readiness for volume production will be carried out in Work Package 18.2.

The work in WP18.1 identified the following fields of action as further technical and operational challenges, which must now be included and subjected to further development in TRANS4M-R:

- Operating specifications for all uncoupling technologies (mechanical / electrical / local and network operated)
- Dimensioning of the on-board power supply regarding the power budgets with active and deactivated supply line (battery operation)
- Vehicle and entire train isolation concept: monitoring, fault reaction (warning / alarm / shutdown) and reaction thresholds.
- Micro-interruptions of the electrical power contacts (e-coupler) could be relevant for the design of the onboard power supply system
- Requirements for technical integration (mechanical / electrical)

Further challenges were the parallel progress and associated changes to the technical and operational framework from other work packages. Within Work Package 18.1 it was possible to take these dependencies into account as best as possible. In the overall context of TRANS4M-R, these interactions must be mastered methodically and through the project setup. Only with this step the foundation will be created for a systematic and consolidated development of a communication standard which all FDFT functions are based on.

12 References

[1] SBB Cargo, Aldo Smania, *Test report on hump tests, "24.02.26_Bericht DAC+: Ablaufbergtests_V1.0" (24.02.24_Report DAC+: Hump tests_V1.0),* February 2024.

[2] SBB Cargo, Aldo Smania, *Test report on e-couplers "Bericht DAC+: e-coupler tests 05.12.2023 in Lupfig (Report DAC+: e-coupler tests 05.12.2023 in Lupfig)",* December 2023.

13 Appendices

13.1 Technical Equipment

13.1.1 Test System Equipment

Fig.11.1 shows the wagon equipment implemented on the test and intermediate wagons (on some of the intermediate wagons only on one side).

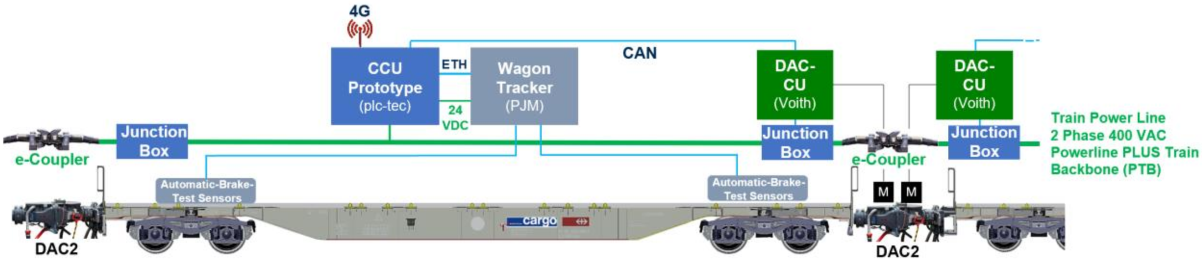


Figure 13: Wagon equipment

The technical equipment consists of the following main components:

a. DAC2 (Voith)

Scharfenberg couplers from Voith were already implemented on the Sgnss wagons supplied.

b. E-coupler for coupling the train power cable between the wagons (Voith and Knorr-Bremse)

Voith e-couplers with a second generation fixed head with 6 spring-loaded contacts (Figure 14) were installed for the initial tests. The reason for this was that a 3-phase 400 VAC system was being considered in the EDDP at the time the test system concept was drawn up, which would have resulted in 6 contacts in the e-coupler, taking into account the reversing symmetry of a wagon. Later, EDDP decided in favour of a 2-phase 400 VAC system. In the tests, only 4 of the 6 contacts were then connected to the power lines; the two unused contacts were used for other measurements.

Figure 14: Contact carriers and contacts of static e-couplers

The following were implemented as part of the testing of the new e-couplers with movable head (Figure 15):

- The Knorr-Bremse e-coupler at the beginning of August 2023
- The Voith e-coupler at the end of August 2023

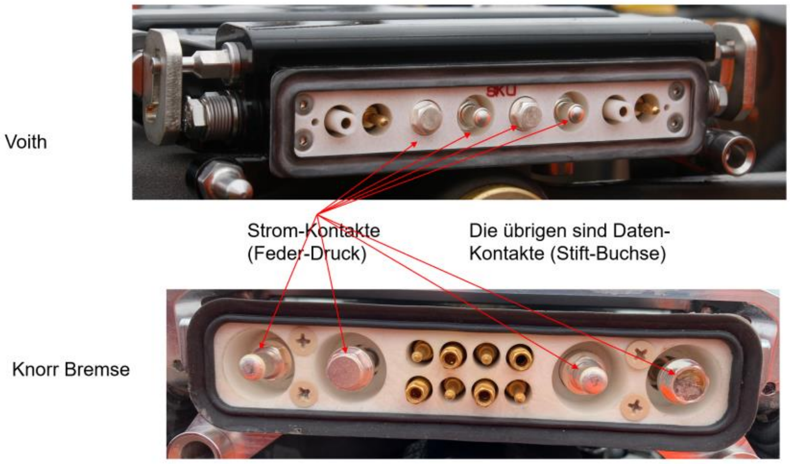


Figure 15: Contact carrier and contacts of e-coupler with movable head

Two new e-couplers were installed, leaving six of the old Voith e-couplers on the train. The new e-couplers from:

- Voith have 8 contacts, 4 of which are for the power line (spring-loaded) and 4 (pin / socket) for the data lines
- Knorr-Bremse also have 4 contacts (spring-loaded) for the power line and 8 (pin / socket) for the data lines

The PTB data was only transmitted via the current contacts.

c. 400 VAC Power Cable (Studer Cables)

One cable prototype (twisted, 2x$10\ mm^2$) from Studer Cables is used (equivalent to DAC4EU)

d. WaggonTracker ABT (PJM)

This system is already certified for the operational use at SBB Cargo. Until now:

- ABT communication from the WaggonTracker box has been implemented via a LORA wireless system from the wagon to the tablet
- the system has been powered by a wheel bearing generator

To realise the ABT FDFT function with PTB:

- the ABT data was transferred from the WaggonTracker box to the CCU prototype via an Ethernet interface implemented by PJM and then to the locomotive via PTB.
- the WaggonTracker box is powered via a 24 V DC interface (newly implemented by PJM) from the wagon power system in the CCU prototype.

In a further optimised wagon configuration, the WaggonTracker control system would probably be integrated into the CCU computer unit.

e. Central Control Unit (CCU) Prototype (HSLU/plc-tec)

Figure 16 shows the components of the CCU prototype:

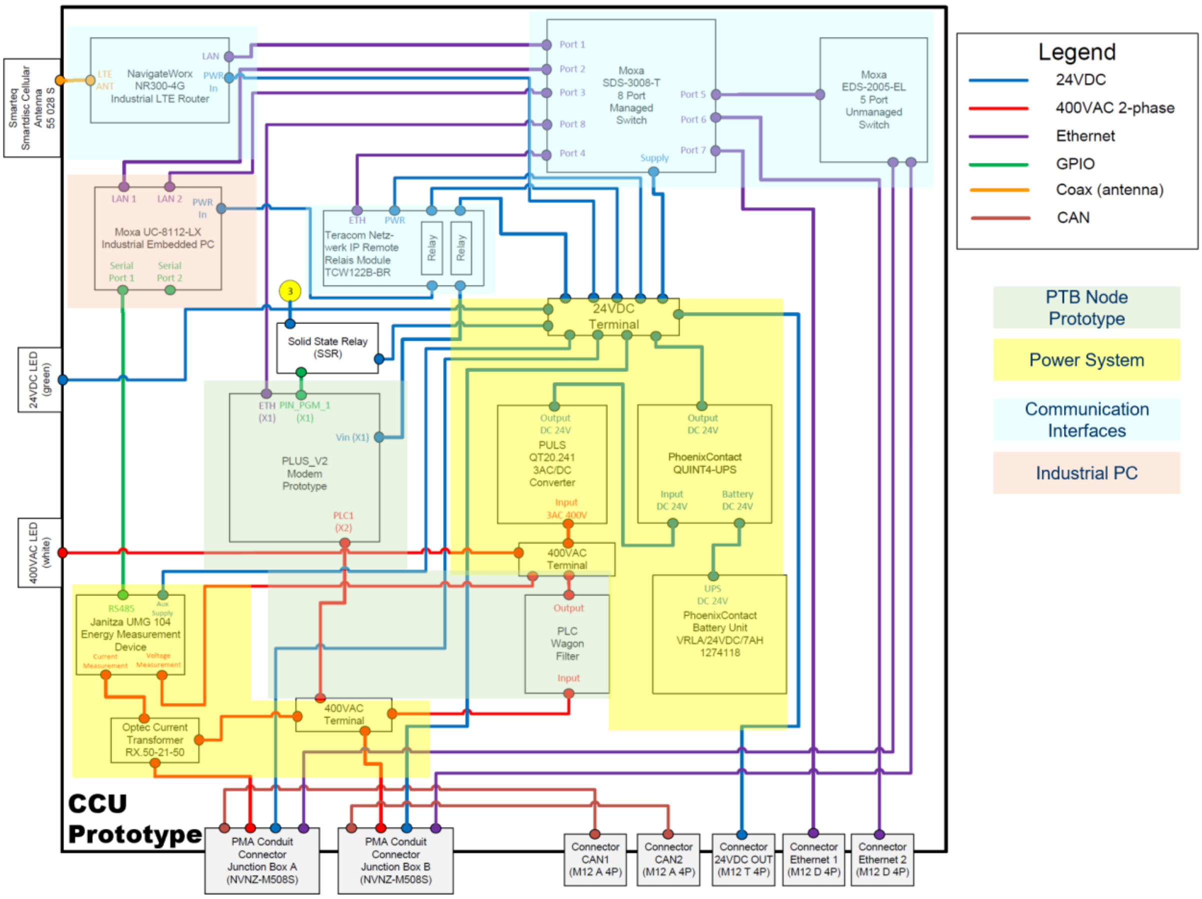


Figure 16: CCU prototype

- PTB node prototype
- Wagon power system:

- AC-DC converter (400 VAC - 24 VDC1)
  - Wagon battery for autonomous FDFT functions of the vehicle when no 400 VAC traction voltage is available, to be guaranteed during shunting for example.
  - UPS
  - Test devices
- Computer unit (industrial PC) for:
  - applications / FDFT functions: In a final architecture, this would include monitoring and control of the automatic brake test, which in our test system takes place separately in the WaggonTracker box.
  - Processing of measurement and test data
- Switches (Ethernet) and gateways (LTE/4G)
- Antenna (LTE/4G) for the transmission of measurement and test data from each wagon to the cloud and for subsequent back-office processing of the data

Figure 17 shows a photo of the contents of the CCU prototype box including the PTB node.

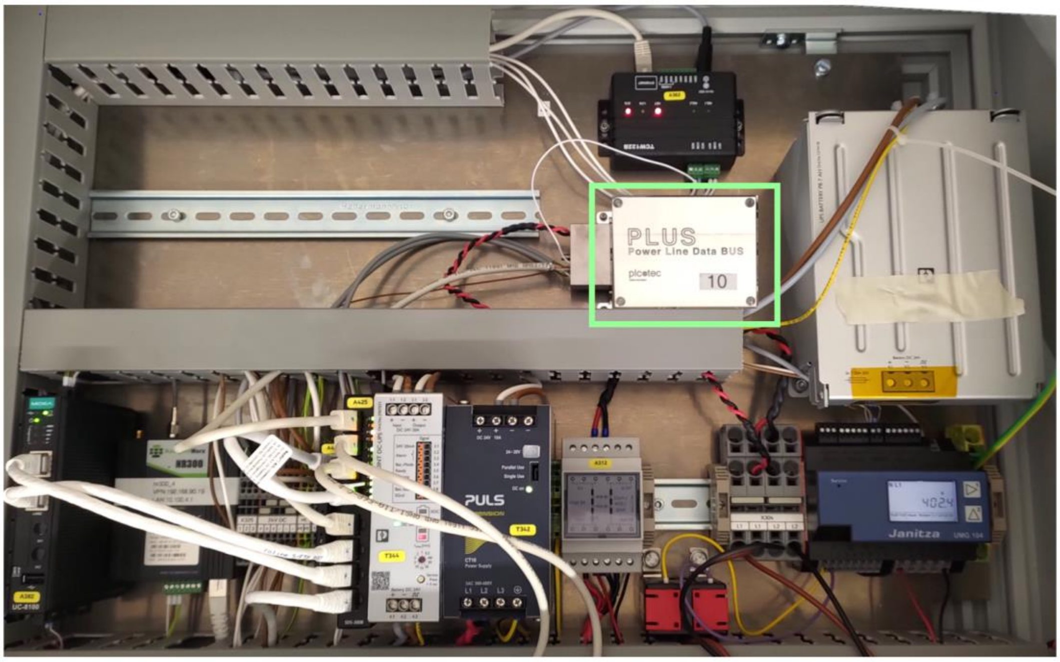


Figure 17: CCU prototype with PTB node

f. Junction Box Prototype (HSLU)

In the junction box, the power cables from the e-couplers are connected to the train power cable on the wagon. At the screw coupler ends of the two intermediate wagons,

[1] In the meantime, TRANS4M-R has specified the wagon voltage at 48 V DC. Corresponding developments for adaptation are currently underway at HSLU.

simplified "mini-junction boxes" connect the wagon/train power cable to a jumper cable in the equipment and measurement wagon.

g. Coupling Control Unit (DAC Control Unit DACCU) Prototype (Voith)

In the course of the project, Voith developed actuators for uncoupling wagons or wagon groups as well as prototypes for control units and integrated them into the architecture of the test system in collaboration with HSLU. This provides for one DACCU on each side of a DAC. Two uncoupling options were provided:

- Manual uncoupling command using a pushbutton at the end of the wagon
- Uncoupling command:
    - from the locomotive or close to the train, e.g. using a tablet
    - from the central unit of a yard management system

The existing architecture provides that the DACCUs are each:

- connected to the actuators with a control line
- connected to the CCU via a CAN interface in order to transmit the data between the DACCUs and a control unit via the PTB
- connected to the junction boxes for the power supply

This architecture was implemented on the test and intermediate wagons. The architecture for the uncoupling system is still not decided in TRANS4M-R and follows two different approaches:

- Uncoupling control via the backbone (via CAN or Ethernet) (Voith variant)
- Local control via separate discrete lines of the DAC.

A "Prevent Coupling" mechanism was implemented for the tests. The challenge here is that wagons/groups of wagons that have already been uncoupled might couple again before the hump. This was prevented by first mechanically preventing recoupling after uncoupling and then cancelling this mechanism at a certain point before the hump with an optical reflector system (sensor on the wagon near the DAC, reflector in the track bed).

13.1.2 Locomotive System Architecture

There are still many unanswered questions regarding the integration of the locomotive into the overall FDFT system. This also applies to the interfaces for the power and communication system. The following assumptions were made for this project based on the currently valid pre-specifications from EDDP:

- The locomotive must provide a 2-phase 400 VAC power supply.

- The total power for the train is 3 kW, which means approx. 60 W per wagon for a 50-wagon train.
- The insulation resistance of the entire train is monitored from the locomotive using special devices. It should be in the range above a few hundred kOhm.
- The data from the FDFT functions is transmitted to the locomotive and displayed there appropriately. This affects:
  - train list from train composition detection
  - display for the ABT
  - display of train integrity monitoring
  - display for uncoupling from the locomotive

Architecture and Integration of Locomotive Systems

With regard to equipping mainline and shunting locomotives for digital freight trains, there are no firm specifications for the power and data interfaces that could be used for the DAC+ project. In addition, providing a corresponding test locomotive would be very time-consuming and cost-intensive. The test concept was therefore designed so that:

- standard SBB Cargo locomotives can be used for mainline runs or shunting operations with the exclusive task of mechanically moving the train. Otherwise they are not integrated into the test system
- the functions of the locomotive were realised in an additional wagon similar to the approach chosen in the DAC4EU test train. In addition to the FDFT functions, other measuring devices for the tests are integrated in this wagon

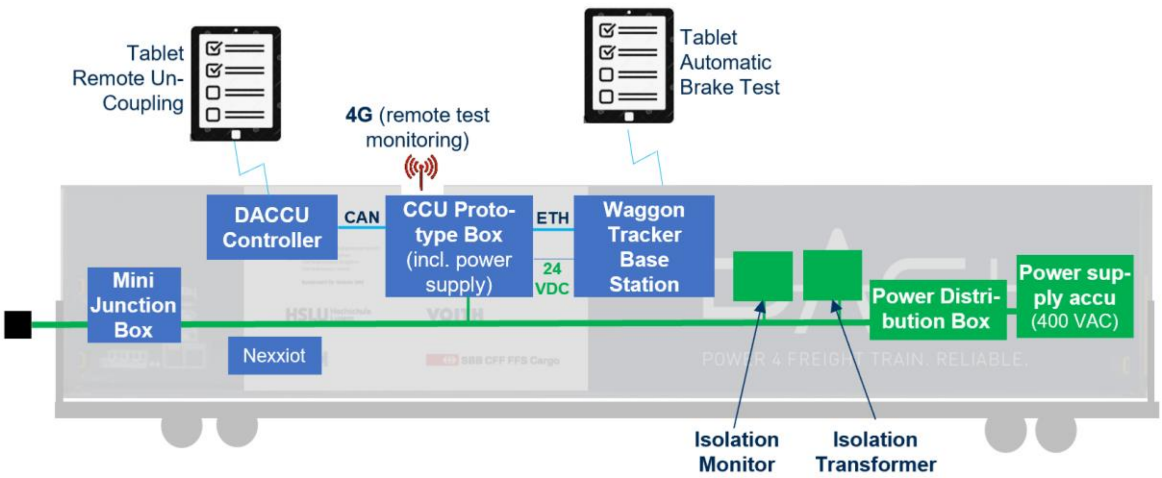


Figure 18: Equipment installed in the equipment and measurement wagon

The measurement wagon is a closed and lockable wagon on which the project logos are also displayed. Figure 18 shows the test equipment installed in the measurement wagon with the following main components.

a) Power supply including monitoring of the entire train with 400 VAC

- An external 400 VAC supply line was installed in the equipment and measurement wagon for static tests at the train's location in Lupfig.
- For the mainline runs and shunting operations, Ecocoach installed two EcoTrolley batteries (for redundancy reasons) [2] in the measurement wagon, see Figure 19, with a backup time of approximately one day.

Figure 19: EcoTrolley battery

- In the power distribution box, the power supply from the battery is connected to the train power cable and then via a mini-junction box (see above) and a jumper cable to the mini-junction box in the intermediate wagon.

b) Presentation of the data of the FDFT functions

- Automatic brake test (ABT): The 'base station' of the WaggonTracker system is located in the measurement wagon, i.e. the ABT data is transferred there from the wagons via PTB and transmitted via Bluetooth to the existing standard ABT tablet, where it is then displayed.
- Remote uncoupling: For uncoupling, there is a connection via PTB between the DACCUs in the wagons and the DACCU controller in the measurement wagon and via WLAN with a tablet developed by Voith, from which the uncoupling is triggered at the correct coupling points in or near the measurement wagon.

[2] https://eco-volta.com/ecopowertrolley/

13.1.3 Additional Test and Measurement Systems

To achieve the test objectives in terms of system reliability, a large number of sensors and measuring devices were integrated into the prototype test train (Tables 2 and 3) in order to continuously record time-synchronised data and correlate measurements with events during the train runs. The data is partially pre-processed in each freight wagon in the CCU prototype and then transferred via 4G from each wagon to the cloud and to a central database for further analysis. The database contains a digital image of the power and communication system of the entire train ("digital twin" concept) at all times – even when the train is stationary – so that the recorded behaviour of the insulation resistance can be called up in the event of corresponding weather conditions, for example. As well as being used for the test system in this project, this also provides a great deal of insight into how an FDFT system – which, even with optimally robust systems, is ultimately still likely to be relatively susceptible to faults due to the harsh operating conditions – can be monitored and provided with predictive maintenance from the back office.

HSLU has developed a new sensor system (*CouplerSense*) for measuring the electrical contacts in the e-couplers.

13.2 <u>Example of test report of a test drive</u>

13.2.1 Test Drive Info

All times referred in this document are in "Europe/Zurich" time zone otherwise specified.

Basic Info

Date:	06.10.2023
Route:	Lupfig – Basel RB – Olten RB – Basel RB – Lupfig
Duration:	06h 14m
Total Distance:	181.09 km

AM Session

Start Time, Place:	06:36:28, Lupfig
End Time, Place:	09:14:59, Olten RB

PM Session

Start Time, Place:	10:48:15, Olten RB

End Time, Place: 14:23:20, Lupfig

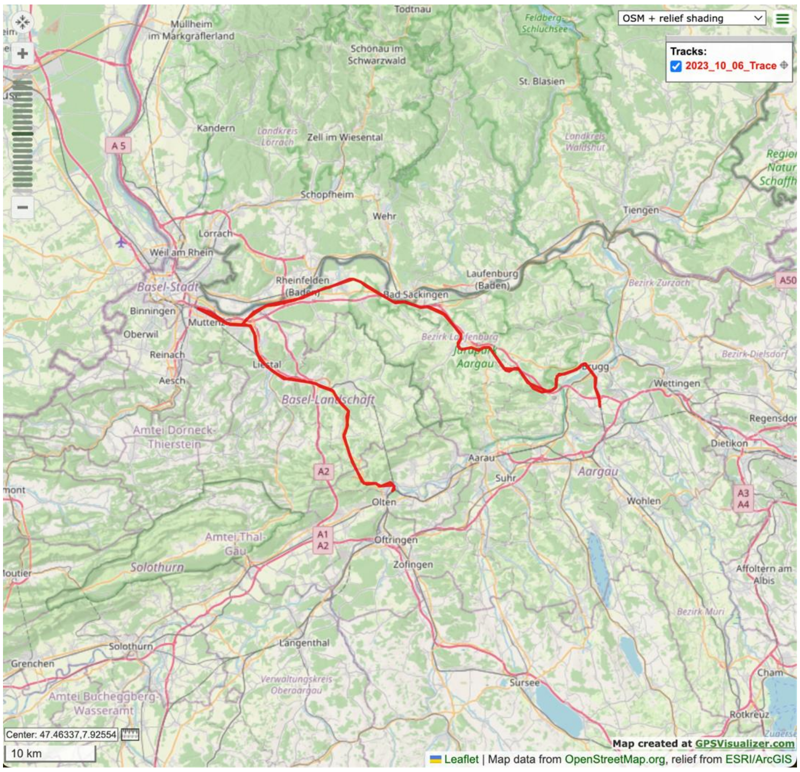


Figure 20: Test Drive Map

Special Notes

1. 400VAC power (and PTB) was routed over the bridge cable for both the KB and VOITH moveable head couplers so that CouplerSense measurements could be performed over all contacts of those couplers.
2. For the KB moveable head e-coupler, the screw heads of the contact carrier were broken – according to KB we should not decouple/couple these DAC.

13.2.2 Test Drive Train Topology

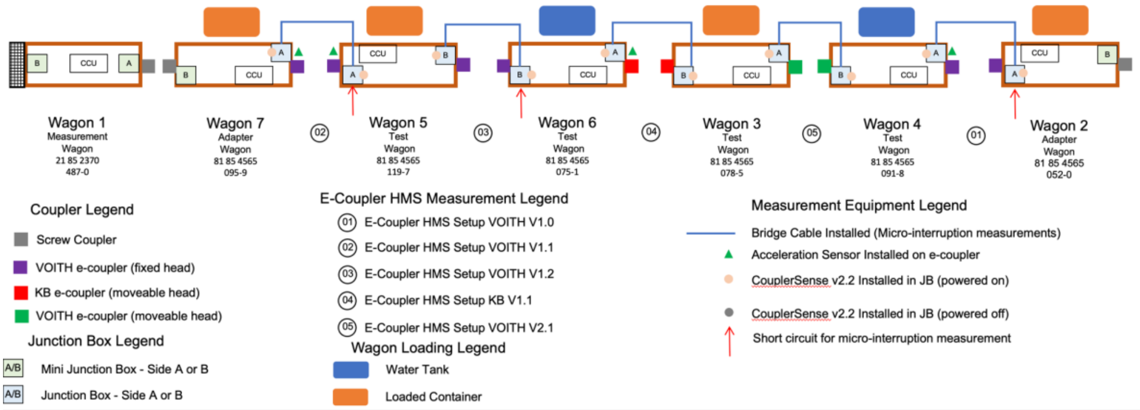


Figure 21: Test Drive Train Topology

13.2.3 Test Drive Features

Train Functions

- Train Composition Detection using PTB (wagon order/orientation)
- OTI monitoring with PTB
- Reliable train backbone communication with PTB
- Automated Brake Testing
- 2-phase 400VAC power system
- Ground fault detection / insulation monitoring – locomotive

Additional Monitoring Functions

- GPS (position/speed)
- Video camera (track)
- Video camera (DAC monitoring)
- E-coupler measurements (micro-interruptions/DC resistance/acceleration)
- Acceleration sensor (acceleration)
- PTB Gateway temperature

e-Couplers

- VOITH Fixed Head 6-power contact e-coupler
- VOITH Moveable Head 4-power contact / 4-data contact e-coupler
- KB Moveable Head 4-power contact / 8-data contact e-coupler

Train Composition

- Wagons 4 and 6 loaded with water tanks (77 tonnes per wagon)
- Wagons 2, 3, 5 and 7 loaded with weighted containers (80 tonnes per wagon)

13.2.4 GPS Data Profiles

Note that the times shown on the x-axis of the figures below are in UTC-time.

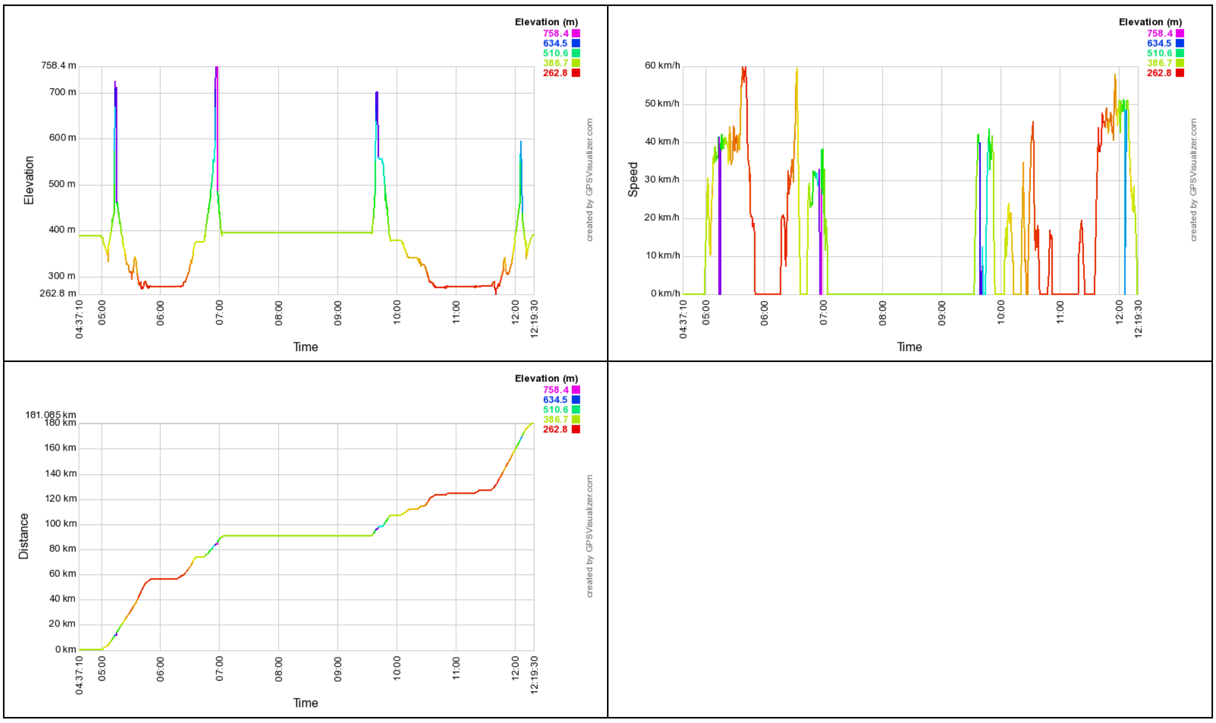


Figure 22: GPS Data Profile

13.2.5 PTB Train Composition Detection

The train composition was successfully detected.

```
###################### PTB Status ######################

TTD status                    : COMPLETE

Topology size                 : 7
Displayed entries             : 7

Train Integrity Check Status  : 1
Train Integrity Compromised   : 0
Train Integrity Counter       : 0

Transmitted Allocation        : 626

----------------------------------------------------------
Entry  Addr   Wagon ID     Ori Master  MPD [ns]    Rcvd Alloc
----------------------------------------------------------
0   0x001   0x051680b637    B   1   0       0
2   0x002   0x130ee98ae7    B   0   185     626
5   0x003   0x130ee98aff    A   0   320     626
1   0x004   0x130ee98ad3    B   0   503     626
4   0x005   0x130ee98ad6    B   0   638     626
3   0x006   0x130ee98ae3    B   0   785     626
6   0x007   0x130ee98abc    A   1   935     626
----------------------------------------------------------
```

Figure 23: PTB Train Composition Detection

13.2.6 PTB Transmission Analysis

Relevant PTB Configuration Parameters

TX_POW_SCL 38, FWD_DIST 3

PTB Statistics

	Test Route	PTB Tokens Sent	PTB TOKENs Lost	PTB TOKEN Loss Rate	Train Integrity Events	Train Integrity Threshold [sec]
AM Drive	Lupfig – Basel RB – Olten RB	4362890	19	4.355e-6	0	250e-3
PM Drive	Olten RB – Basel RB – Lupfig	5978184	120	20.073e-6	0	250e-3
Total		**10341074**	**139**	**1.344e-5**	**0**	**250e-3**

Table 9 PTB Transmission Analysis

TOKEN Loss vs. Network Hop

Most of the Token losses occurred between wagon 6 and 2, which was in the second hop for ping messages (transmissions from wagon 6 to wagon 2), and in the first hop for pong messages (transmissions from wagon 2 to wagon 6).

Analysis	Total	% Total
Lost TOKEN Ping Total	**14**	73.68%
Lost TOKEN Ping - 1st hop	4	28.57%
Lost TOKEN Ping - 2nd hop	10	71.43%
Lost TOKEN Ping - 3rd hop	N/A	N/A
Lost TOKEN Pong - Total	**5**	26.32%
Lost TOKEN Pong - 1st hop	5	100.00%
Lost TOKEN Pong - 2nd hop	0	0.00%
Lost TOKEN Pong - 3rd hop	N/A	N/A

Analysis	Total	% Total
Lost TOKEN Ping Total	**108**	90.00%
Lost TOKEN Ping - 1st hop	11	10.19%
Lost TOKEN Ping - 2nd hop	97	89.81%
Lost TOKEN Ping - 3rd hop	N/A	N/A
Lost TOKEN Pong - Total	**12**	10.00%
Lost TOKEN Pong - 1st hop	11	91.67%
Lost TOKEN Pong - 2nd hop	1	8.33%
Lost TOKEN Pong - 3rd hop	N/A	N/A

Table 10: Lost Token

<u>TOKEN Cycle Duration</u>

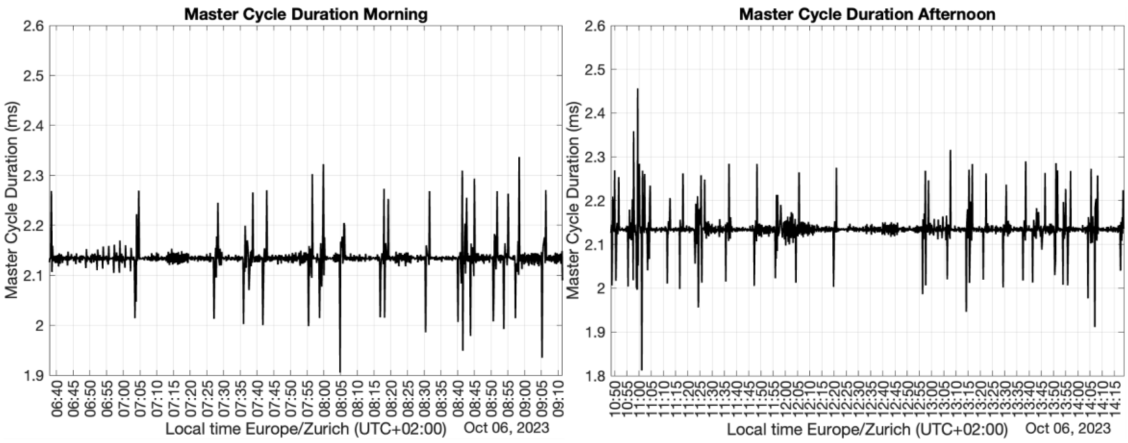


Figure 24: Token Cycle Duration

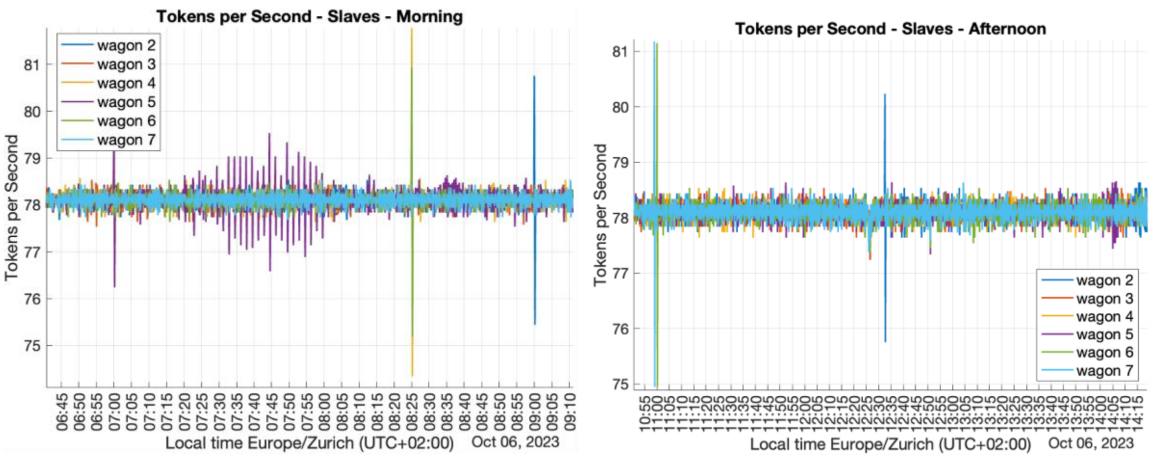


Figure 25: Token Cycle Duration

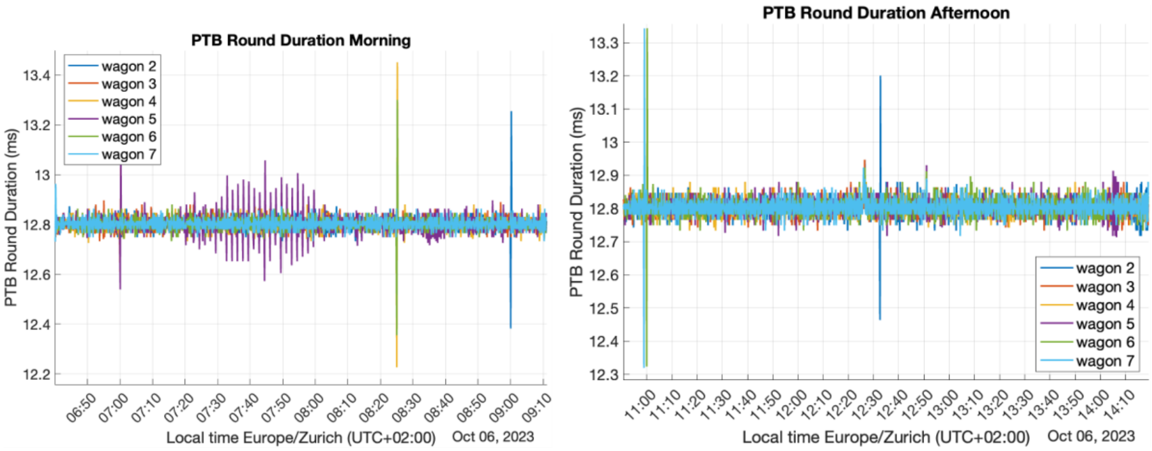


Figure 26: PTB Round Duration

<u>TOKEN Loss Standing vs. Moving</u>

Higher Token losses when the train is moving.

AM Ride

```
# ------------------------------------------------
# Statistics
# ------------------------------------------------
variable            Standing        Moving
time duration       01:00:18        01:32:43
TOKEN timeout       8               11
TOKEN LOSS HIST. 0  6               11
TOKEN LOSS HIST. 1  1               0
TOKEN LOSS HIST. 2  0               0
TOKEN LOSS HIST. 3  0               0
TOKEN LOSS HIST. 4  0               0
```

PM Ride

```
# ------------------------------------------------
# Statistics
# ------------------------------------------------
variable            Standing        Moving
time duration       01:48:50        01:39:51
TOKEN timeout       35              82
TOKEN LOSS HIST. 0  31              75
TOKEN LOSS HIST. 1  2               0
TOKEN LOSS HIST. 2  0               0
TOKEN LOSS HIST. 3  0               1
TOKEN LOSS HIST. 4  0               0
```

Figure 27: Token Loss Standing and Moving

<u>TOKEN Loss vs GPS Speed</u>

No appreciable correlation between token losses and train speed (measured via GPS).

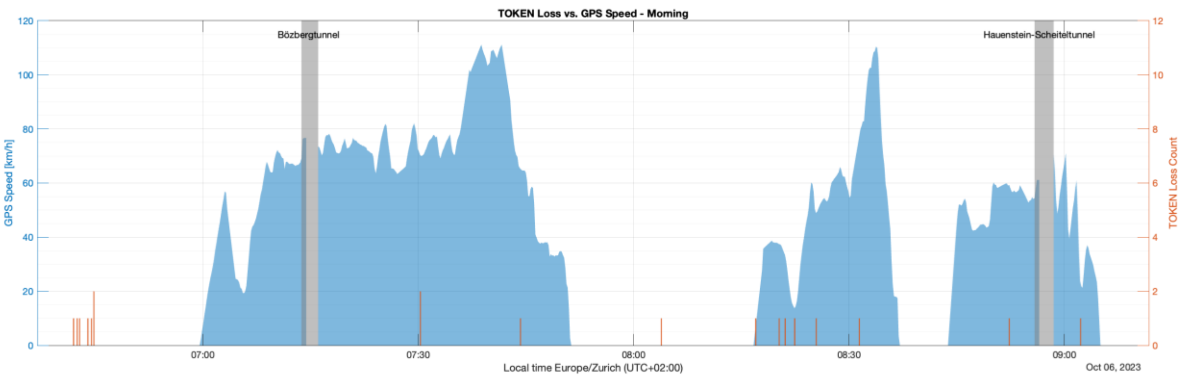


Figure 28: Token Loss with Train Speed I

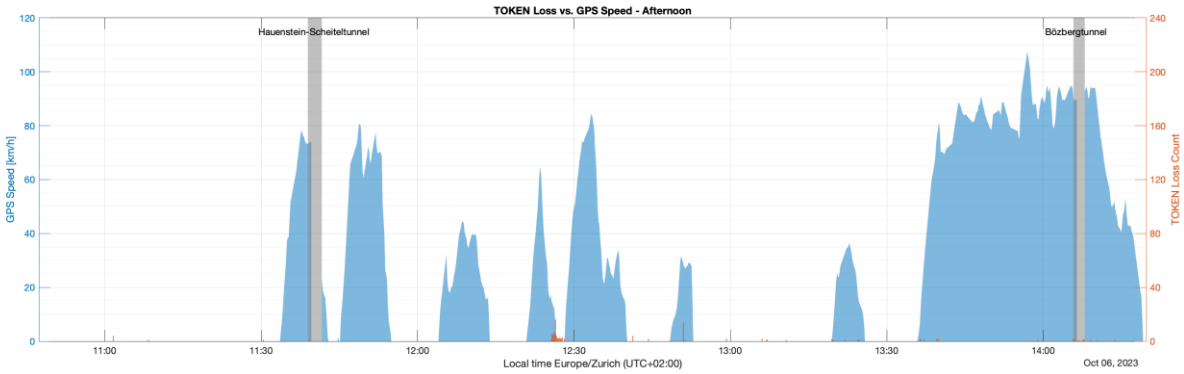


Figure 29: Token Loss with Train Speed II

<u>TOKEN Loss Event Analysis</u>

Event: 7 TOKENs lost in a row at 10:26:28

Analysis: High token losses event starting at (10:25:28) and lasting until (10:28:08). Axis camera observation shows the train braking at Liestal BHF. Then the train was standing still for about a minute while a passenger train passed next to. When the event ended the train was still accelerating to leave Liestal BHF. Euroloop at Liestal Nord (approx. at *950m* of the train standing position on a different track). (No GoPro video is available for this event)

13.2.7 Power System Analysis

The power monitoring unit is on side A in each wagon.

Day	AM/PM	Stat.	Apparent power (S) measured at each wagon						
			1	2	3	4	5	6	7
06.10.23	AM	mean	889,00	141,17	289,20	142,44	740,39	435,21	740,95
		var.	23969,72	714,06	2796,82	738,49	17041,55	6208,67	17234,68
		max.	1086,11	173,52	353,31	176,00	903,88	535,73	906,70
		min.	595,28	91,26	191,64	92,64	492,03	290,31	495,88
06.10.23	PM	mean	448,80	68,63	145,34	69,53	373,48	221,16	374,50
		var.	1393,79	29,69	102,96	28,22	855,83	252,12	807,40
		max.	586,41	130,29	196,10	121,51	468,00	300,82	464,17
		min.	403,10	60,24	130,51	61,64	337,69	199,44	338,50

Day	AM/PM	Apparent power (S) drawn per wagon							
		1	2	3	4	5&6	5	6	7
06.10.23	AM		142,44	146,01	146,76	305,73	152,87	152,87	148,05
06.10.23	PM		69,53	75,82	75,81	153,34	76,67	76,67	74,29

Table 11: Apparent Power

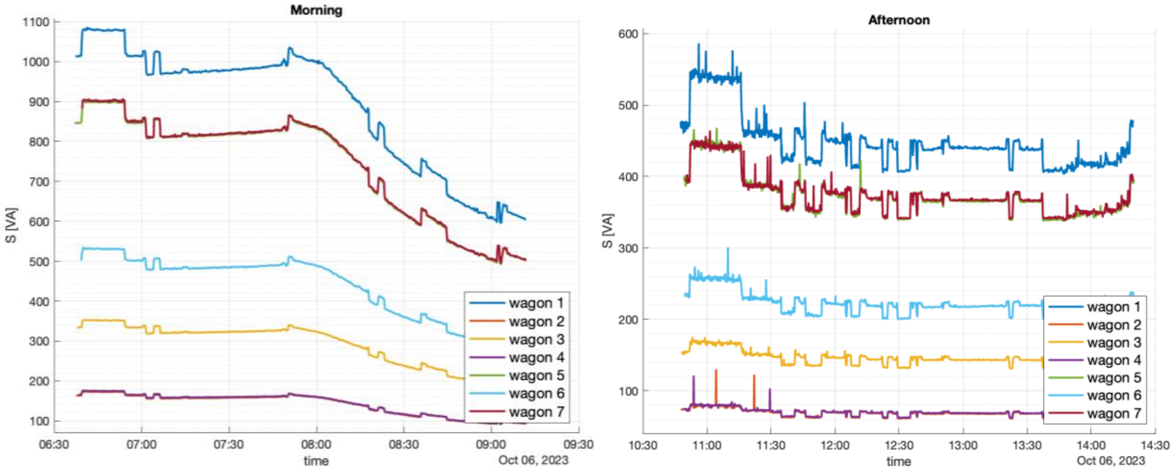


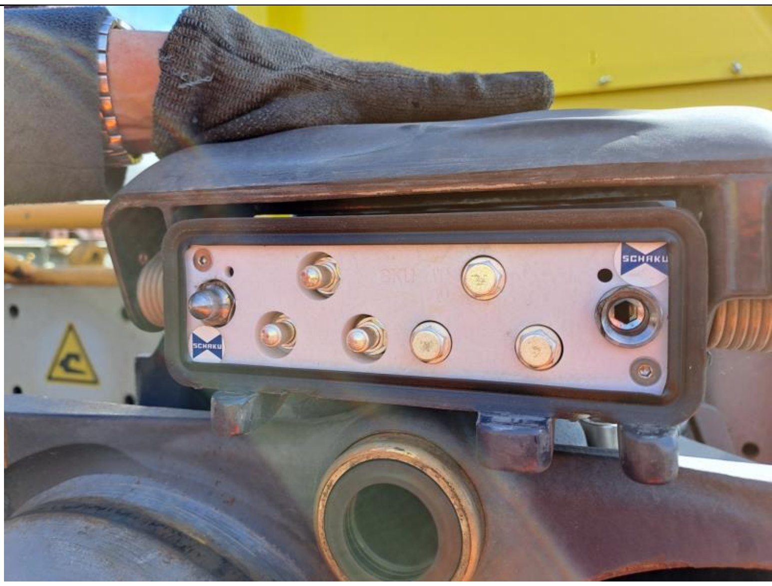
Figure 30: Power monitoring

13.2.8 e-Coupler Pictures

All photos have been made at the conclusion of the test drive.

E-Coupler 2A	

E-Coupler 3A	
E-Coupler 3B	No photo could be taken as the DAC could not be decoupled
E-Coupler 4A	

E-Coupler 4B	
E-Coupler 5A	
E-Coupler 5B	

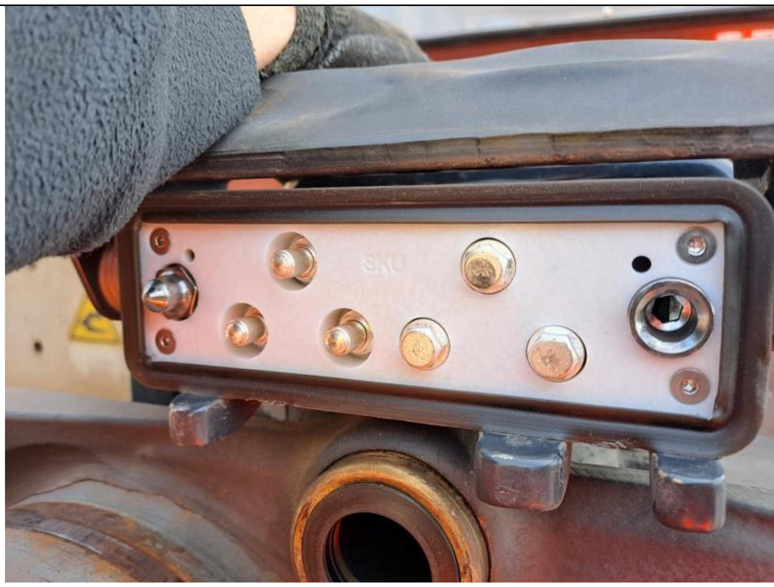
E-Coupler 6A	No photo could be taken as the DAC could not be decoupled
E-Coupler 6B	
E-Coupler 7A	

Table 12: e-Coupler Pictures

13.2.9 CouplerSense Measurements

Impedance Measurements

IMPEDANCE [Ohm]							
			10/6/23 AM			10/6/23 PM	
Measurement point	Type of contact	mean	var	max.	mean	var	max.
'imp_wag3_sideA'	data contact VOITH V2.0'	1.63	1.86E-05	1.67	1.66	5.25E-05	1.70
'imp_wag3_sideB'	power contact (10/11) KB V1.1'	1.43	8.55E-02	2.09	1.55	1.49E-01	8.35
'imp_wag4_sideA'	power contact (002/102) VOITH V1.0'	1.13	1.39E-05	1.17	1.13	1.86E-05	1.16
'imp_wag4_sideB'	power contact (003/103) VOITH V2.0'	1.12	3.11E-05	1.16	1.12	1.33E-05	1.16
'imp_wag5_sideB'	power contact (001/101) VOITH V1.2'	1.12	1.69E-05	1.16	1.13	1.58E-05	1.16
'imp_wag6_sideA'	data contact KB V1.1'	1.91	2.06E-05	1.95	1.96	1.03E-04	2.00
'imp_wag7_sideA'	power contact (003/103) VOITH V1.1'	1.12	3.17E-05	1.16	1.13	1.28E-05	1.16

Table 13: Impedance Measurements

Micro-Interruption Measurements

Micro-interruptions have only been detected on the e-couplers 3B/6A (KB e-couplers) on power pins 10&11. A total of 99 separate micro-interruptions have been measured.

Coupler KB V1.1, Power Contacts 10/11			
	No. of interruptions with duration (in ms) between t0 and t1		
	t0 (ms)	t1 (ms)	Count
	0,00	0,10	27
	0,30	0,60	5
	0,70	1,00	3
	1,00	2,29	10
	2,29	3,57	10
	3,57	4,86	5
	4,86	6,14	9
	6,14	7,43	4
	7,43	8,71	2
	8,71	10,00	2
	10,00	85,52	20
	85,52	161,05	2
total	0,00	161,05	99

Table 14: Micro-Interruptions

Acceleration Sensors

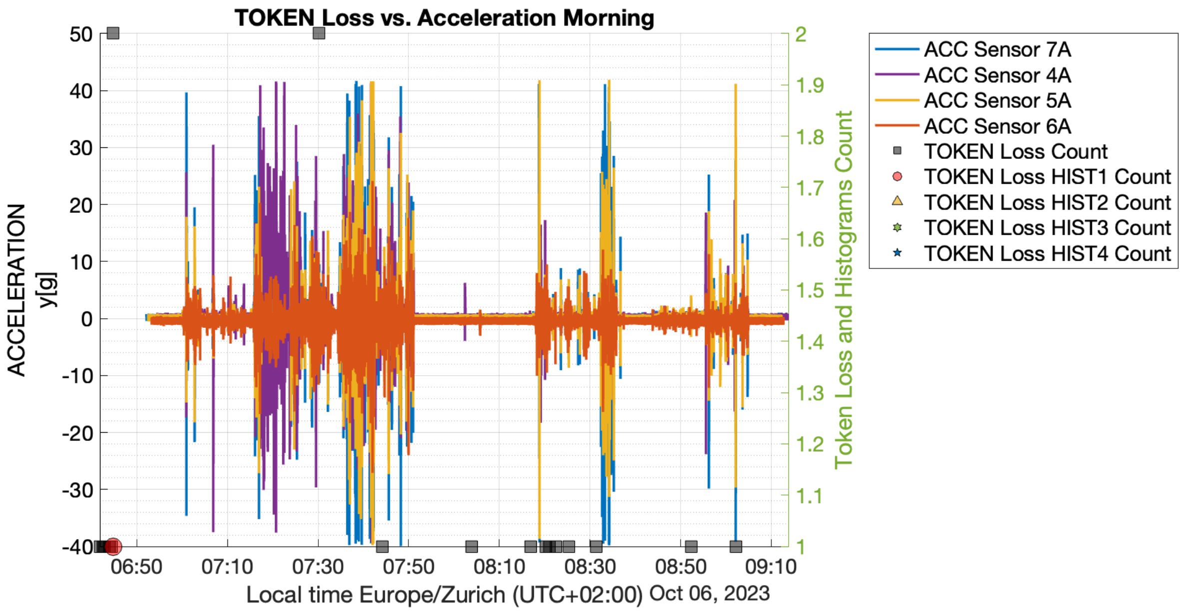


Figure 31: Token Loss Acceleration I

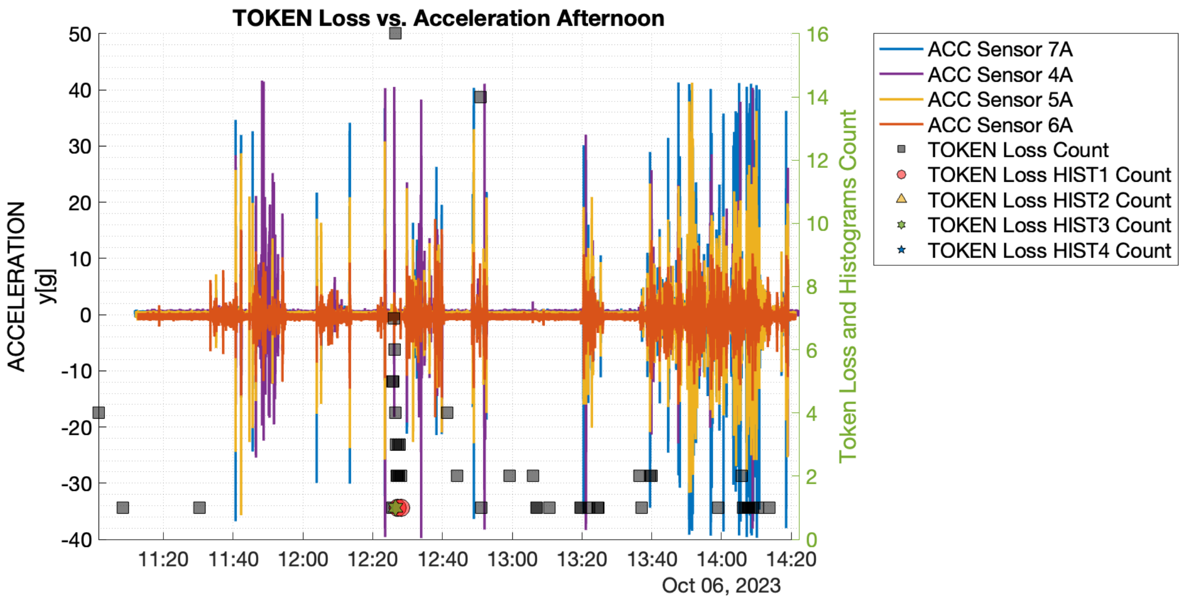


Figure 32: Token Loss Acceleration II

13.2.10 Insulation Resistance Measurements

Insulation Resistance Measurement

IMPEDANCE [MOhm]		
Day	6.10.2023	
Session	AM	PM
avg. insulation [MOhm]	6,31	6,30
std. insulation [MOhm]	0,02	0,02
avg. quality	100,00	100,00
insulation error	none	none
coupling system	ok	ok
coupling earth	ok	ok

Table 15: Insulation Resistance Measurements

<u>PTB Gateway Temperature</u>

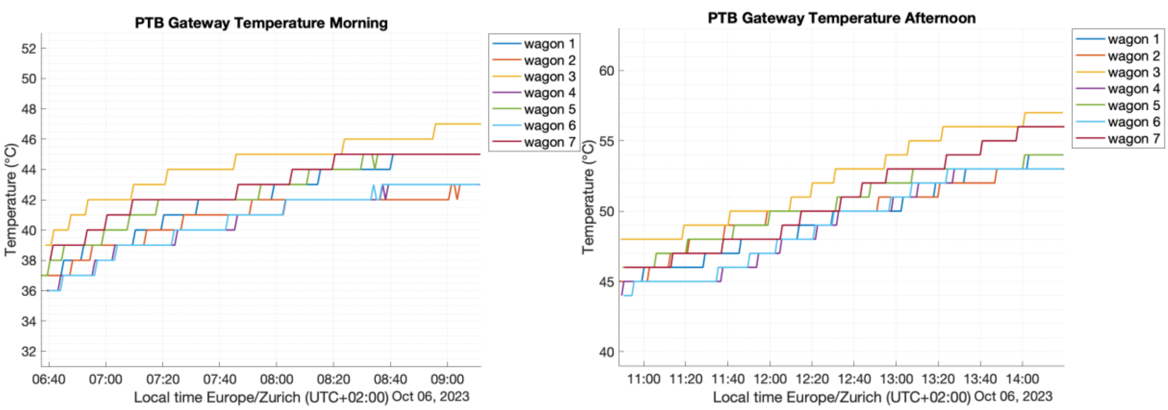


Figure 33: PTB Gateway Temperature

13.2.11 Summary of example test report

- Micro-Interruptions:
    - There were no micro-interruptions in any of the couplers.
- PTB Train Topology Detection
    - The wagon order and direction were successfully detected for all wagons using PTB-TTD.
- PTB Message Loss Rate:
    - Very high TOKEN loss rate (3.07e-4) with all tokens lost between wagon 6 and 2. The sudden increase in token losses may be attributed to a malfunctioning of the KB coupler after the screw heads broke at some point during the test drive. Photos of the e-coupler 3B depict this issue.
    - No correlation is found between token losses and the train speed. However, all the losses except 1 token, occurred while the train was in motion.
- PTB TOKEN Cycle Durations

- The TOKEN cycle duration for the master node is approximately *2.1ms*, whereas for the slave nodes, it is about *12.8ms*. An average of 78 tokens per second is allocated at slave nodes. The consistent timing indicates a high level of determinism in the PTB TOKEN protocol.

- PTB Onboard Train Integrity (OTI):
    - No train integrity events were detected by PTB.
- Other Measurements:
    - The apparent power shows a large variance, making it difficult to draw conclusions about the average power consumed.
    - The measured impedance from Junction Box to Junction Box over the VOITH power contacts is *1.13Ω*.
    - Average isolation resistance of *6.20MΩ* with a std. of *0.02MΩ*.

PTB Gateway temperatures range from *59°C* to *70°C*.