

FP5DACTiVate

D5.1

Hybrid coupler for legacy locomotives

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1 Executive Summary

Keywords: DAC; legacy locomotive, SM42, ET22

Work Package 5 involves verifying the feasibility of installing DAC hybrid automatic couplers on the most common types of locomotives used by freight rail carriers in Poland, specifically the ET22 six-axle electric locomotive and the SM42 diesel shunting locomotive. It is important to note that both models exist in various configurations, ranging from classic versions to deep modernizations that significantly alter their technical parameters and physical appearance. The primary objective is to confirm the possibility of installing a hybrid coupler on both types of locomotives and, upon positive verification, to proceed with the installation and testing of a hybrid digital automatic coupler.

The preparation and implementation of coupling and uncoupling tests will utilize locomotives from the national carrier alongside wagons manufactured under other activities of the European DAC Delivery Programme (EDDP). These tests will focus primarily on mechanical force transmission, electrical power connections, and data transmission for digital systems. The key areas of focus include ensuring backward compatibility, enhancing operational safety, and improving overall efficiency in freight and shunting operations.

The tests will mainly concern mechanical force transmission, electrical power connection, and data transmission for DAC systems. Key areas include ensuring backward compatibility, enhancing operational safety, and improving efficiency in freight and shunting operations.

Work in the WP5 are divided into three tasks, of which:

Task 5.1 concerns work related to the preparation for the installation of a hybrid coupler on the SM42 locomotive. Its aim is to develop a standalone FDFT (Full Digital Freight Transport) system kit for the modernization of older locomotives. The specifications of the FDFT system set will be based on the specifications or results of the FP5-TRANS4M-R project and will include a Locomotive Control Unit (LCU), a hybrid-digital automated coupling system, an electric converter, and a Human-Machine Interface.

Task 5.2 assumes a detailed analysis of the possibility of integrating the DAC hybrid coupler on an older ET22 locomotive. This will allow to identify the scope of changes required to be made to this locomotive in the event of replacing the screw coupler with a

DAC hybrid coupler and will allow to assess the feasibility of such a locomotive modernization.

Task 5.3 covers the performance of functional tests on rolling stock equipped with DAC couplings and the preparation of the required documentation and achieved results.

Future Outlook, Challenges, and Strategic Benefits

1. Transition Period and Technical Compatibility

The primary challenge in implementing DAC is the "coexistence phase". During this period, wagons equipped with traditional screw couplers will operate alongside new DAC-equipped units. This will necessitate the strategic use of adapter wagons or hybrid couplers to maintain operational continuity across the European rail network.

2. Shift to Predictive Maintenance (Big Data)

The integration of the Data Bus across the railway cargo fleet will transform maintenance from a reactive to a predictive model. Real-time monitoring of axle temperatures, load distribution, and brake wear will allow for repairs to be conducted only when necessary, significantly reducing locomotive downtime and operational costs.

3. Environmental Impact and ESG Goals

The adoption of DAC is a cornerstone of the "Green Deal" in transport. By enabling the assembly of longer and heavier trains, DAC significantly reduces the carbon footprint per ton-kilometre. This efficiency makes rail a more competitive and sustainable alternative to long-haul road transport.

4. Enhancing European Competitiveness

As part of the Europe's Rail Joint Undertaking, the DAC project ensures that railway cargo carriers remains a key player in international transport corridors. Automation and digitalization are essential to eliminate technical barriers at borders, creating a seamless, high-capacity "Single European Railway Area".

2 Abbreviations & Acronyms

Abbreviation / Acronym	Description
AC/DC	Alternating Current / Direct Current
DAC	Digital Automatic Coupler
EDDP	European DAC Delivery Program
Interoperability	Coupling wagons between different suppliers
FDFT	Full Digital Freight Transport
FP5-DActiVate	Flagship Project 5 - DActiVate
FP5 TRANS4MER	Flagship Project 5 - TRANS4MER
GA	Grant Agreement
HMI	Human-Machine Interface
kW	Kilo Watt
LCU	Locomotive Control Unit
MAWP	Multi-Annual Work Programme
UIC	fr. Union Internationale des Chemins de fer - International Union of Railways
WP	Work Package

3 Background

The introduction of the Digital Automatic Coupler (DAC) represents a key technological enabler for the future of European rail freight, supporting higher levels of automation, operational efficiency, safety, and digitalisation. By integrating mechanical coupling, electrical power supply, and digital data transmission into a single interface, DAC provides the foundation for advanced train functions such as automated brake testing, train integrity monitoring, digital train composition, and condition-based maintenanceⁱ (EN 16019:2023).

Despite its strategic importance, the large-scale deployment of DAC faces a major challenge related to the existing fleet of legacy locomotives, which were designed long before automatic coupling concepts were envisaged. These locomotives remain essential for daily rail freight operations and cannot be replaced within a short or medium timeframe due to economic, operational, and organisational constraints. As a result, a transitional solution is required to ensure operational continuity while enabling progressive introduction of DAC-based technologies.

In this context, hybrid coupler solutions provide a pragmatic pathway for bridging conventional screw-coupled rolling stock and DAC-equipped wagons. Such solutions must ensure mechanical compatibility, reliable electrical power transfer, and data communication capabilities, while respecting the structural, spatial, and system limitations inherent to legacy locomotive platforms. At the same time, hybrid couplers must preserve interoperability across different operational scenarios, including shunting and mainline operations, and across multiple DAC supplier solutions.

Deliverable D5.1 addresses this challenge by establishing a technical baseline and feasibility assessment for hybrid coupler integration on representative legacy locomotives, with particular focus on the SM42 diesel shunting locomotive and the ET22 heavy electric mainline locomotive. The deliverable analyses the functional requirements, interface concepts, and key constraints associated with hybrid coupling on these platforms, without entering the domains of authorization procedures or functional validation.

By providing a structured technical foundation, Deliverable D5.1 supports subsequent

4 Objective/Aim

The objective of Deliverable **D5.1** is to provide a detailed technical assessment of **hybrid coupler solutions for legacy locomotives**, with particular emphasis on the **SM42 diesel shunting locomotive** and the **ET22 heavy electric locomotive**. The deliverable analyses coupling concepts that integrate **mechanical, electrical, and data interfaces**, enabling compatibility with both **Digital Automatic Couplers (DAC)** and conventional **screw coupler systems**.

The report evaluates the **technical capabilities, functional performance, and interoperability** of the proposed solutions, including their ability to withstand operational mechanical loads, ensure reliable power transmission, and support data communication between locomotives and rolling stock. By addressing the specific constraints of legacy locomotive platforms, Deliverable D5.1 supports a **gradual and interoperable transition toward DAC deployment**, while maintaining backward compatibility and operational continuity within existing rail freight operations.

4.1 Task Description

Task definition from GA (Task5.1)	Output of deliverable
Task 5.1 aims to deliver a standalone FDFT system kit enabling the retrofitting of a legacy locomotive to functionally demonstrate the feasibility of a Hybrid-DAC solution on at least one vehicle. The task also establishes the initial documentation set required to support future authorization activities. The FDFT system, aligned with the EDDP basic/starter package, is implemented on PKP's SM42 diesel shunting locomotive. All newly introduced technological components are based on specifications and results originating from the FP5-TRANS4M-R project. Within this task: • FTI provides the standalone Locomotive Control Unit (LCU), • VT supplies the Hybrid-DAC system, including the power supply and the	Deliverable D5.1 provides the technical and conceptual groundwork for Task 5.1 by delivering: – a technical description of hybrid coupler concepts applicable to the SM42 legacy shunting locomotive, including mechanical, electrical, and data interfaces; – an initial feasibility assessment of integrating a Hybrid-DAC solution on the SM42 platform, identifying structural, spatial, and system-related constraints; – a definition of functional expectations and operational use cases for shunting operations, serving as reference assumptions for later installation and testing activities; – an interface-level analysis supporting the integration of the FDFT system and EDDP basic/starter package, without entering detailed installation or validation procedures.

Task definition from GA (Task5.1)	Output of deliverable
Human-Machine Interface (HMI), • PKP is responsible for the mechanical and electrical integration engineering, as well as the coordination of all vehicle modifications and updates to the locomotive technical documentation, in close cooperation with FTI and VT.	These outputs establish the technical baseline upon which the physical installation, documentation updates, and demonstrator preparation activities of Task 5.1 are executed.

5 Reference Legacy Locomotive Platforms

5.1 SM42 Diesel Shunting Locomotive

5.1.1 Operational role

The shunting line locomotive SM42, which will participate in the Digital Automatic Coupler tests, belongs to the Polish carrier cargo. The carrier operates three distinct types of maneuver locomotives within this series: the SM42-6D (classic), 6Dg, and 6Dk.

For the purpose of the DAC project, the SM42-6Dg model has been selected.

Technical Adaptation of the SM42-6Dg for DAC:

Modular Architecture: Unlike the classic 6D version, the 6Dg features lowered engine hoods. The use of a modern, compact power unit has created additional internal space, which is essential for housing the control cabinets and converters dedicated to the DAC system.

Electrical Infrastructure: The 6Dg is equipped with an advanced electrical system based on the CAN bus. This significantly simplifies the integration of DAC controllers with the locomotive's master control system. Furthermore, its high-efficiency alternators provide the necessary power reserve for the coupler's electric actuators and data transmission lines.

Frame and Buffer Beam Design: The 6Dg's frame is reinforced at the front sections. The organized layout around the buffer beam allows for more efficient routing of the additional electrical harnesses and pneumatic lines required for full coupling automation.

HMI Integration: The modernized cabs in the 6Dg version feature digital displays. This allows for the integration of the "digital uncoupling" interface

5.1.2 Key technical characteristics

The SM42-6Dg is a modernized, four-axle diesel-electric shunting locomotive with a Bo'Bo' axle arrangement, specifically designed for heavy-duty marshalling and local freight operations. The vehicle features a modular body construction with lowered engine hoods and an elevated central cab, providing 360-degree operational visibility. Its power system is based on a 650 kW diesel engine integrated with a modern AC/DC transmission and a microprocessor-based control architecture with digital HMI displays. The locomotive is equipped with a high-capacity screw compressor unit and an efficient braking system, while its modernized internal layout and electrical infrastructure ensure high reliability and lower operating costs compared to the original version.

5.1.3 Integration constraints

Due to many variants and modernizations of this vehicle type any integration solutions developed may not be applicable to all SM42 locomotives in operation. The power

requirements of DACs and the need to enable power transfer to the train set through the couplers poses a challenge for the DAC integration electric supply. The SM42 locomotive was found to be restricted in terms of space and potential to deliver the power supply necessary to ensure the proper operation of the DACs. This also indicates potential challenges for the integration of other locomotive types. The native locomotive power supply is 400V AC 3 phase from its generator. The electrical elements required to adapt such a solution for DAC integration might make it necessary to make substantive changes to the locomotive frame and structure, which the proposed solution is aiming to avoid, as that would cause possible difficulty in ensuring the locomotive maintains its permissions to operate on the national rail network.

The mechanical integration requires an adapter which allows for limiting physical changes in the locomotive structure to a minimum in order to fit the DAC. There is no guarantee that such a solution is achievable for other legacy locomotive variants of SM42. This adaptation, with minor changes to the locomotive structure, does not necessarily scale up for use in other locomotives either. The necessary level of forces dissipation was achieved without using welding to fix the adapter to the locomotive head. This was partially to enable the removal of the adapter after the testing is complete. The DAC adapter was made using the standard S355JR type steel. Using a different material to reduce weight or cost might be possible depending on the steel type and its properties, as well as whether it is approved for use in rail vehicles. The conducted tests will indicate the feasibility of this solution. The resulting documentation describing the locomotive adaptation to DAC operation will only be verified using a single case as a basis for the concept and data. To ensure that the adaptation concept is safe and reliable for all locomotives of this type, further tests are recommended for other locomotives of the same type.

5.2 ET22 Heavy Electric Mainline Locomotive

5.2.1 Operational role

The ET22 locomotive is a heavy six-axle electric unit with a Co'Co' axle arrangement, constructed on a massive, welded steel frame designed to withstand extreme longitudinal forces. The locomotive's body consists of a high-capacity machine room housing the high-voltage cabinets, a central corridor, and two independent driving cabs located at both ends of the vehicle. The propulsion system is based on six DC traction motors, with three motors mounted on each of the two triple-axle bogies, providing a total continuous power output of 3000 kW. The electrical architecture includes a classic resistance-based starting system, high-speed circuit breakers for overcurrent protection, and two pantographs for current collection from the 3 kV DC overhead line. The pneumatic system is powered by high-output piston compressors supplying the main air reservoirs for the Oerlikon-type braking system and auxiliary equipment, such as sanders and horn signals. In modernized versions, the original electromechanical components are supplemented with

microprocessor-based control systems and digital HMI displays, significantly enhancing the diagnostic capabilities of the locomotive.

5.2.2 Load and system characteristics

The ET 22 series electric locomotive is a 6-axle CoCo locomotive running on 3000 V DC, designed for hauling freight trains.

Data:

- **Manufacturer:** PAFAWAG - Wrocław
- **Years of production:** 1969 - 1989
- **Production:** 1184 units
- **Axle arrangement:** Co'Co'
- **Supply voltage:** 3 kV
- **Number of pantographs:** 2
- **Number of cabins:** 2
- **Engine type:** EE 541
- **Number of engines:** 6
- **Engine power:** 6 x 500 kW
- **Continuous power:** 3000 kW
- **Hourly power:** 3100 kW
- **Starting type:** resistance
- **Travel controller positions:** 48
- **Shunt positions:** 6
- **Brake:** Oerlikon
- **Main compressor power supply:** 3 kV (from the mains)
- **Gear ratio:** 79:18
- **Maximum speed:** 125 km/h
- **Empty weight:** 120 Mg
- **Total length:** 19240 mm
- **Use:** freight trains

The ET22 series locomotive is based on two three-axle bogies. Each axle is powered by a single 500 kW EE541 motor, identical to the EU06 and EU07 locomotives. Torque is similarly transmitted to the wheelset via a single-sided gear train via Alstom flexible couplers. The bogie suspension is coupled and consists of springs connected by wishbones and coil springs resting on the ends of the leaf springs.

The bogies do not have a pivot pin. The body rests on the bogies via eight metal-rubber supports, which also constitute the second stage of the suspension. In the first series of vehicles (up to number 122), the body rested on rubber supports via beams and hangers. The disadvantage of this design was excessive vehicle stiffness and a tendency for the

locomotive to sway at higher speeds. For this reason, most of the "beam-frame" locomotives were scrapped or modernized during major repairs.

The body frame ends, designed to accommodate an automatic coupler, are connected to the bogies via horizontal, transverse hydraulic dampers. During the modernization, the ET22 locomotives were fitted with an inter-bogie coupler and wheel flange lubrication.

The locomotive body, including the frame, constitutes a welded, self-supporting structure. The interior is divided into five compartments. The outermost compartments contain the drivers' cabs. Two side corridors run along the remaining compartments. The engine compartments, located directly behind the driver's cabs, house the converters with the traction motor fans, compressors with accessories, and cabinets containing low-voltage equipment. These compartments also house the doors to the locomotive, eliminating them from the driver's cabs, improving driver comfort. The central section of the body houses the high-voltage compartment containing electrical equipment and starting resistors, which are cooled by five independently driven fans. Under the body frame, between the bogies, are the battery boxes, inductive shunts, and main air reservoirs.

6 Hybrid Coupler Concept and System Architecture

6.1 Definition of Hybrid Digital Automatic Coupler

The Voith Hybrid coupler consists of three main components: the coupler head, the coupler support, and the draw gear. The Hybrid coupler can be operated in DAC and UIC mode. Switching between these modes is done manually – after releasing the locking pin, the coupler head can be manually pivoted into the desired mode and then locked in this position. The coupler support holds the coupling in the correct alignment. The draw gear allows regenerative energy absorption of both tensile and compressive forces, as well as non-reversible energy absorption in the event of a crash. When coupled, the Voith Hybrid coupler establishes the mechanical, pneumatic, and electrical connections.

6.2 System Architecture Overview

6.2.1 Mechanical interface

The adapter was designed so that the hybrid DAC was mounted to the adapter alone, while the adapter was mounted to the locomotive head. The mounting was done using screws instead of welding. 12 screws were used for the adapter mounting and a further 8 for the DAC (Fig. 6.1).

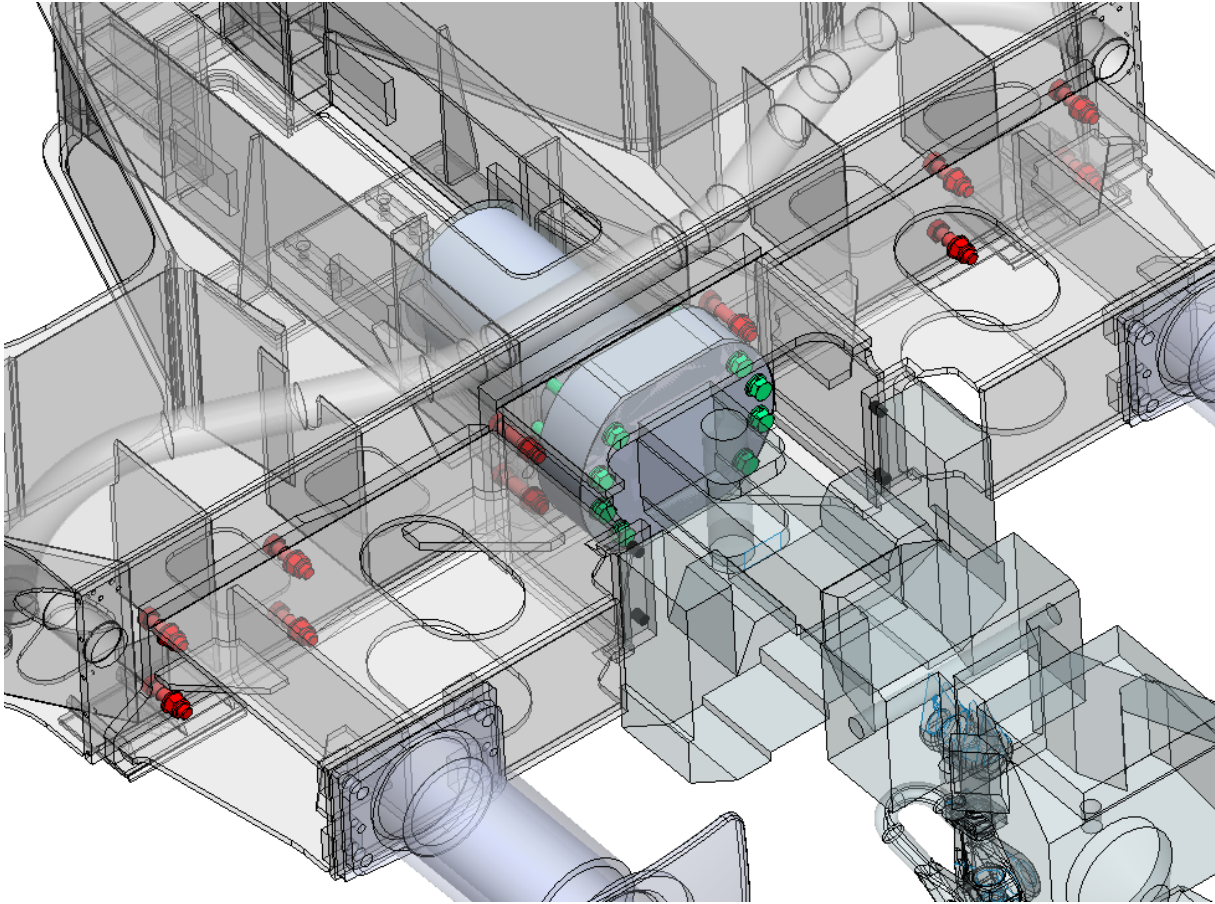


Fig. 6.1. Adapter and DAC mounting screws (red for adapter and green for DAC)

The overall adapter mounting to the locomotive frame was done using 12 hexagon head screws (M24x90-8.8-A-V4_ PN-EN ISO 4014 ⁱⁱ) along with self-locking nuts (M24-8-B-V4 _ PN-EN ISO 10512ⁱⁱⁱ) and washers (24-200HV-A2-V4_ PN-EN ISO 7089^{iv}), with 3 pairs of two on each side of the DAC. This was shown from the front side (Fig. 6.2) and from the back (Fig. 6.3).

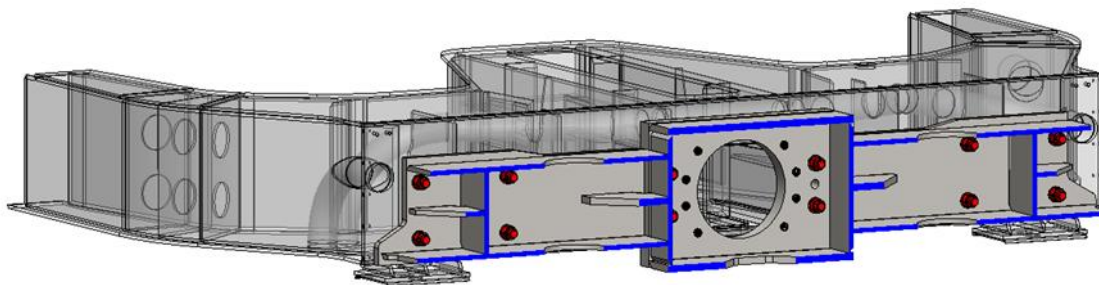


Fig. 6.2. Adapter to locomotive mounting screws setup from front

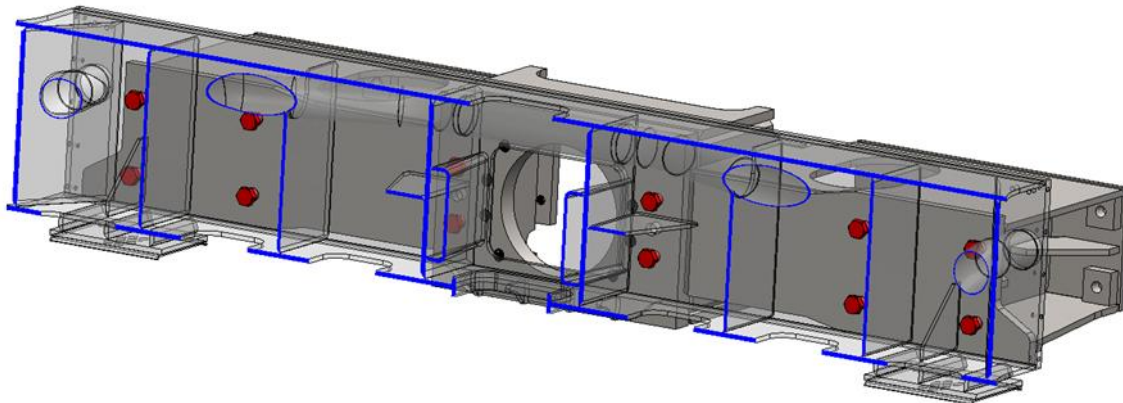


Fig. 6.3. Adapter to locomotive mounting screws setup from back

The connection between the hybrid DAC and the adapter was done using 8 screws (4 on each side). This required 8 hexagonal head screws (M24-180-10.9-B-V4 - PN-EN ISO 4014) along with 8 washers (24-200 HV-A4-V4 - PN-EN ISO 7089) and 8 spring washers (24 Z-V4 - PN-M-82008). This was shown from the DAC side (Fig. 6.4) as well as the locomotive side (Fig. 6.5).

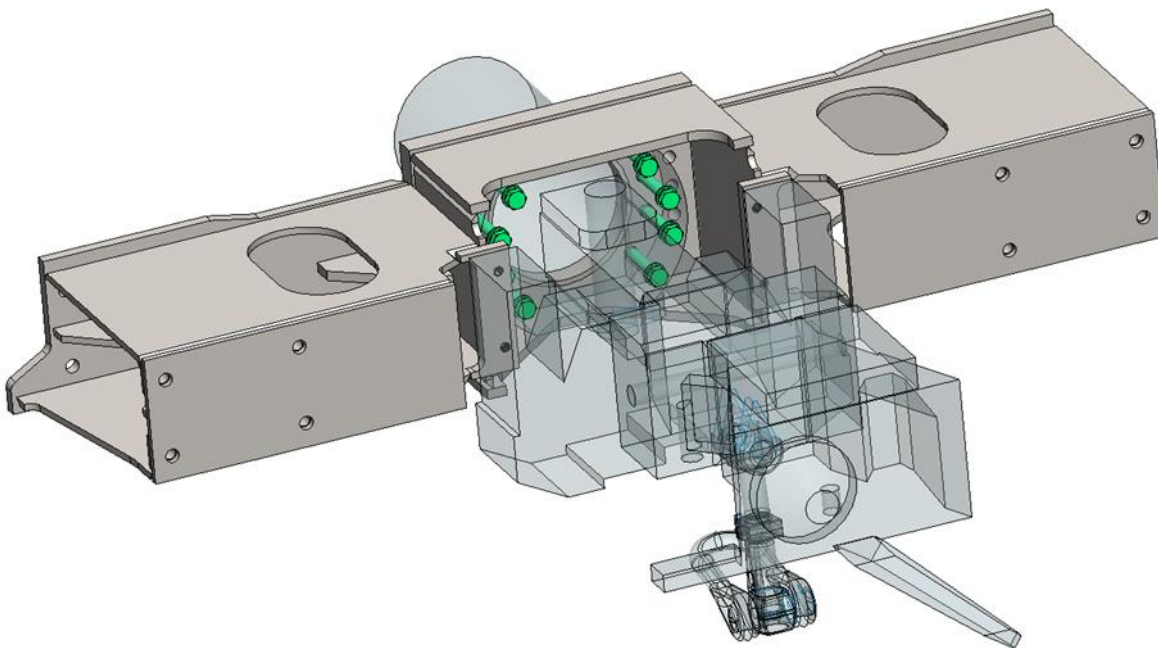


Fig. 6.4. DAC to adapter mounting screws setup from front

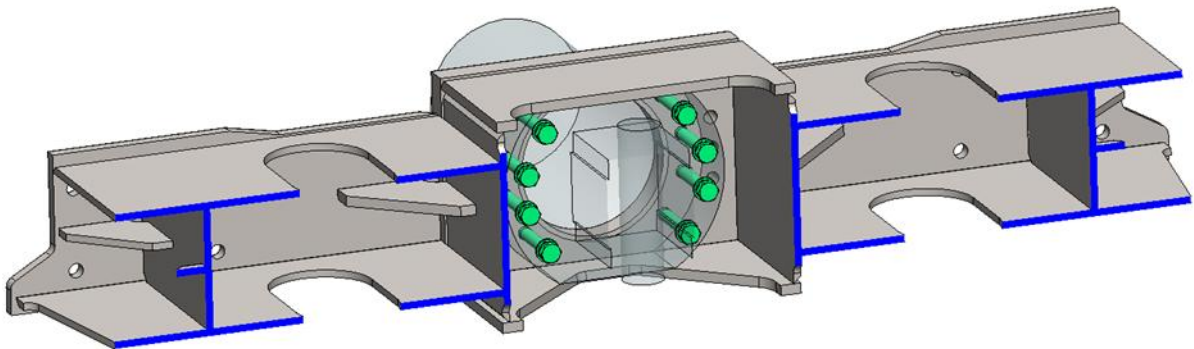


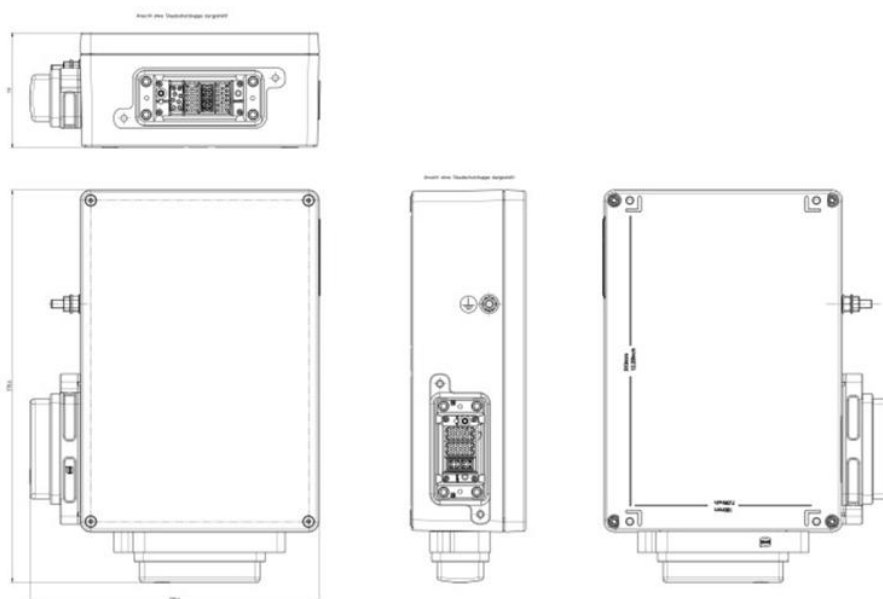
Fig. 6.5. DAC to adapter mounting screws setup from back

6.2.2 Electrical interface

A junction box is used for the electrical connection of the locomotive to the respective coupler (one box per coupler). This allows sensor values to be read in and corresponding communication as well as supply voltages to be provided. The locomotive will use a hybrid coupler, which requires an extended interface (Connector X1). Additional sensors for position detection and the associated power supply (24 V DC) are required at interface X1 (see also Figure 6.6).

As the locomotive must still retain the side buffers, installation as on the wagons is not possible. For this reason, the locomotive manufacturer is required to find an individually suitable position and mechanical interface on his vehicle. This must be agreed with the relevant coupler supplier so that cable lengths and other factors can be adhered to.

The box will look like this:



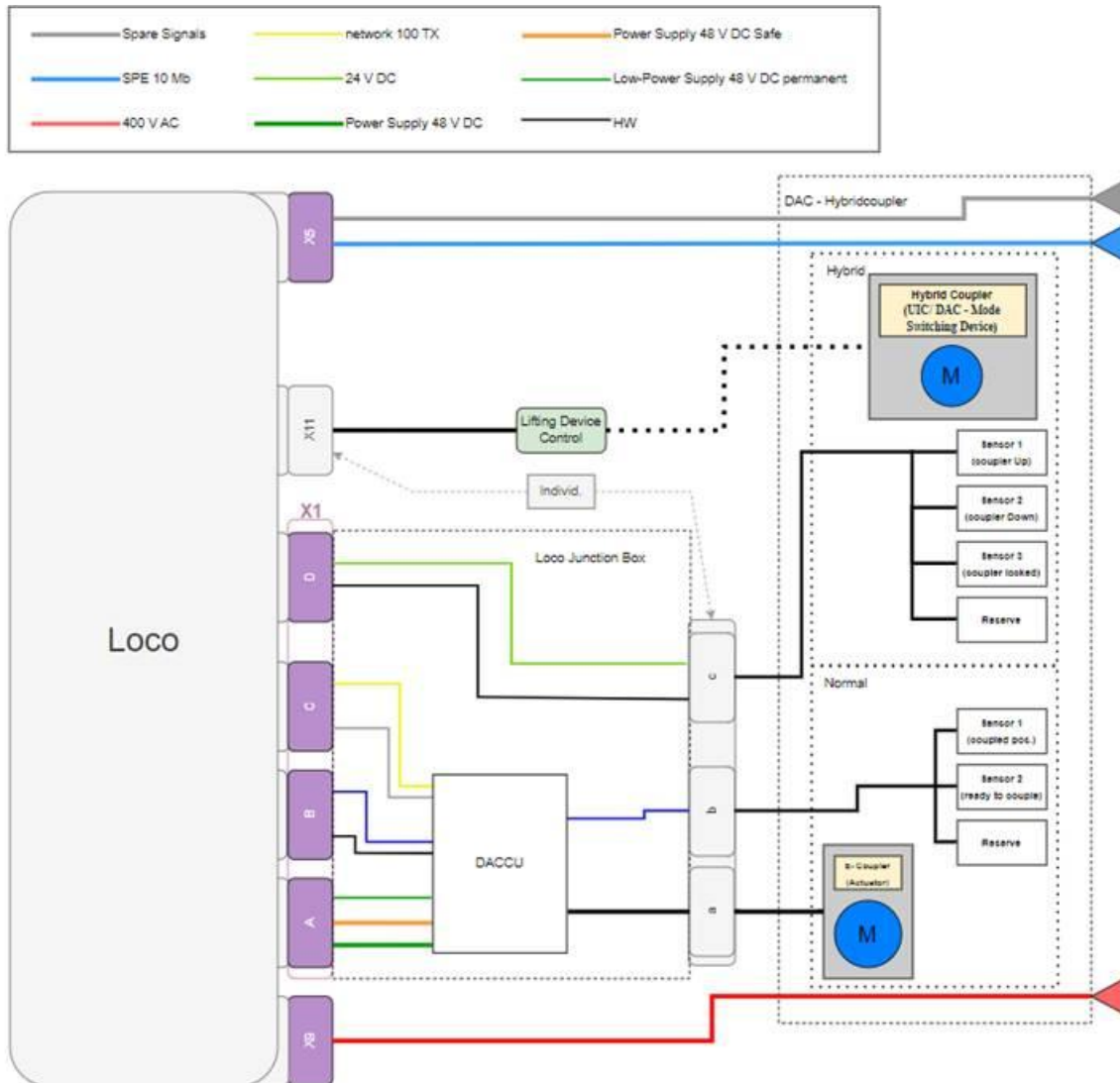


Fig. 6.6. Interface between Locomotive and Junction Box (X1 and X11)

The junction box / DACCU connector X1 (HAN6 or compatible) is defined as follows:

Table 1. Junction box pin data

Pin	Signal Name	Max. Current Draw	Cross Section	Contact Material
A1	Power Supply 48 VDC Safe	Max. 10 A	0.14...4.0mm ²	QMM
A2	Power Supply GND Safe	Max. 10 A	0.14...4.0mm ²	QMM
A3	Power Supply 48 VDC	Max. 10 A	0.14...4.0mm ²	QMM
A4	Power Supply GND	Max. 10 A	0.14...4.0mm ²	QMM

A5	Low-Power Supply 48 VDC Permanent*	Max. 1 A	0.14...4.0mm ²	QMM
A6	Low-Power Supply GND Permanent*	Max. 1 A	0.14...4.0mm ²	QMM
A7	n.c.		0.14...4.0mm ²	QMM
A8	n.c.		0.14...4.0mm ²	QMM
B1	n.c.		0.14...2.5mm ²	AU
B2	n.c.		0.14...2.5mm ²	AU
B3	n.c.		0.14...2.5mm ²	AU
B4	n.c.		0.14...2.5mm ²	AU
B5	n.c.		0.14...2.5mm ²	AU
B6	n.c.		0.14...2.5mm ²	AU
B7	n.c.		0.14...2.5mm ²	AU
B8	n.c.		0.14...2.5mm ²	AU
B9	n.c.		0.14...2.5mm ²	AU
B10	n.c.		0.14...2.5mm ²	AU
B11	n.c.		0.14...2.5mm ²	AU
B12	n.c.		0.14...2.5mm ²	AU
B13	n.c.		0.14...2.5mm ²	AU
B14	n.c.		0.14...2.5mm ²	AU
B15	n.c.		0.14...2.5mm ²	AU
B16	n.c.		0.14...2.5mm ²	AU
B17	n.c.		0.14...2.5mm ²	AU
C1A	ECN (TX+)		0.14...2.5mm ²	AU
C2A	ECN (RX+)		0.14...2.5mm ²	AU

C3A	ECN (TX-)		0.14...2.5mm ²	AU
C4A	ECN (RX-)		0.14...2.5mm ²	AU
C1B	Wagon End Monitoring Common		0.14...2.5mm ²	AU
C2B	Wagon End Monitoring 1		0.14...2.5mm ²	AU
C3B	Wagon End Monitoring 2		0.14...2.5mm ²	AU
C4B	Reserve pin		0.14...2.5mm ²	AU
D1	Hybrid Coupler Sensor coupler-up NO		0.14...2.5mm ²	AU
D2	Hybrid Coupler Sensor coupler-up NC		0.14...2.5mm ²	AU
D3	Hybrid Coupler Sensor coupler-up GND		0.14...2.5mm ²	AU
D4	Hybrid Coupler Sensor coupler-down NO		0.14...2.5mm ²	AU
D5	Hybrid Coupler Sensor coupler-down NC		0.14...2.5mm ²	AU
D6	Hybrid Coupler Sensor coupler-down GND		0.14...2.5mm ²	AU
D7	Hybrid Coupler Sensor coupler-locked NO		0.14...2.5mm ²	AU
D8	Hybrid Coupler Sensor coupler-locked NC		0.14...2.5mm ²	AU
D9	Hybrid Coupler Sensor coupler-locked GND		0.14...2.5mm ²	AU
D10	Hybrid Coupler Sensor reserve pin		0.14...2.5mm ²	AU
D11	Hybrid Coupler Sensor reserve pin		0.14...2.5mm ²	AU

D12	Hybrid Coupler Sensor reserve pin		0.14...2.5mm ²	AU
D13	N.C.		0.14...2.5mm ²	AU
D14	N.C.		0.14...2.5mm ²	AU
D15	N.C.		0.14...2.5mm ²	AU
D16	Hybrid Coupler Low-Power Supply 24 VDC		0.14...2.5mm ²	
D17	Hybrid Coupler Low-Power Supply GND		0.14...2.5mm ²	
Housing	PE + Shield		6.0mm ²	

Additionally, the actuator and sensor in the DAC will need to be connected to the junction box, details must be coordinated between loco and coupler manufacturer.

The hybrid coupler further uses two HAN6 or compatible plugs to connect a) the 400V (X9) and b) the SPE (X5) to the loco

Details see below (Fig. 6.7):

Pin	Signal Name	Max. Current Draw	Cross Section	Contact material	Connector
A1	Power Distribution Line 400 VAC L1_1	Max. 16 A	1.5...6.0mm ²	QMM (silver plated)	X5
A2	Power Distribution Line 400 VAC L2_1	Max. 16 A	1.5...6.0mm ²	QMM (silver plated)	X5
A3	Power Distribution Line 400 VAC L1_2	Max. 16 A	1.5...6.0mm ²	QMM (silver plated)	X5
A4	Power Distribution Line 400 VAC L2_2	Max. 16 A	1.5...6.0mm ²	QMM (silver plated)	X5
B	Dummy module				X5

Pin	Signal Name	Max. Current Draw	Cross Section	Contact material	Connector
A1A	DA+ Bus 1		0.14...2.5mm ²	AU (gold plated)	X5
A2A	DA- Bus 1		0.14...2.5mm ²	AU (gold plated)	X5
A3A	n.c.		0.14...2.5mm ²	AU (gold plated)	X5
A4A	n.c.		0.14...2.5mm ²	AU (gold plated)	X5
A1B	DA+ Bus 2		0.14...2.5mm ²	AU (gold plated)	X5
A2B	DA- Bus 2		0.14...2.5mm ²	AU (gold plated)	X5
A3B	n.c.		0.14...2.5mm ²	AU (gold plated)	X5
A4B	n.c.		0.14...2.5mm ²	AU (gold plated)	X5
B1	Spare-pin		0.14...2.5mm ²	AU (gold plated)	X5
B2	Spare-pin		0.14...2.5mm ²	AU (gold plated)	X5
B3	Spare-pin		0.14...2.5mm ²	AU (gold plated)	X5
B4	Spare-pin		0.14...2.5mm ²	AU (gold plated)	X5
B5 - B17	n.c.		0.14...2.5mm ²	AU (gold plated)	X5

Fig. 6.7. Pin and signal setup of the junction box

6.2.3 Data interface

1. The Train Bus (Communication Line)

The DAC creates a physical and logical data link throughout the entire train. The industry has converged on Single Pair Ethernet (SPE) as the standard for the physical layer.

Automatic Train Inauguration: The interface allows the locomotive to automatically detect the number of wagons, their sequence, and their orientation within the consist.

High Bandwidth: It supports high-speed data transmission, which is essential for managing long trains (up to 740m or more) without signal lag.

In industrial settings, the HMI is typically a touch panel or software dashboard used to manage how digital values are converted into analogue signals (e.g., 4-20mA or 0-10V) to control hardware like valves or motors.

Set-point Entry: The operator inputs a desired value on the screen, which the system sends to the DAC to produce the corresponding voltage/current.

Visual Feedback: The HMI displays real-time graphs and numerical data representing the DAC's output.

Calibration & Scaling: It allows users to define the relationship between digital bits and physical units.

2. Power Supply Integration

The data interface is typically paired with a power line. This provides a continuous power supply to every wagon, eliminating the need for individual batteries or axle generators. This power is used to run the sensors, telematics, and actuators required for modern freight operations.

3. Critical Functions Enabled by the Interface

Automated Brake Testing: The driver can perform a full brake test from the cab via the data interface, reducing a process that used to take 45 minutes to just a few minutes.

Condition-Based Monitoring (CBM): Real-time data regarding wheelset temperature, load stability, and door status is transmitted directly to the locomotive and the operator's cloud.

Safety Integrity (SIL4): The interface is designed to meet strict safety standards, paving the way for future Autonomous Train Operations (ATO).

4. "Mix and Match" Challenges in Data

In the "Mix and Match" testing phase, the data interface is the most complex component to standardize. The goal is to ensure:

Physical Interoperability: That the digital pins/connectors from different vendors (Voith, Dellner, Wabtec) align perfectly.

Protocol Compatibility: That the software "language" (the communication protocol) remains consistent so that a Dellner-equipped wagon can talk to a Voith-equipped locomotive without errors.

6.3 Operational Modes

6.3.1 DAC ↔ DAC

Coupling and Uncoupling Functions

The vehicles are coupling automatically when they move towards each other (Fig. 6.9). They also couple automatically even if there is a lateral or vertical misalignment of the couplings within the gathering range. When the vehicles couple, the air pipes connect simultaneously (Fig. 6.8). When the uncoupled vehicles move apart, the air pipes disconnect simultaneously. The operating pressure of the main air reservoir line (HBL) is maintained. The operating pressure of the main air line (HL) is not maintained (the vehicle-side shut-off valves must have been closed before!). The electric coupler couple automatically as soon as the vehicles couple mechanically and uncouple automatically as soon as the vehicles uncouple mechanically. The electric coupler can be locked so that they do not couple if required for operational reasons. In an emergency, the coupled vehicles can be uncoupled manually. The coupler locking mechanism is immediately ready for re-coupling as soon as the uncoupled vehicles move apart.

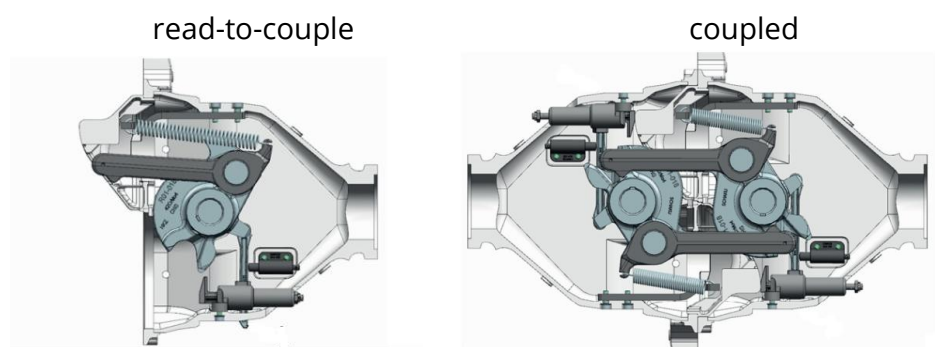


Fig. 6.8. Hybrid DAC coupling mechanism

DAC Mode

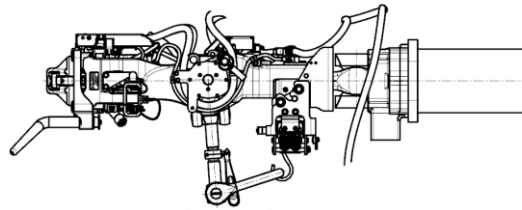


Fig. 6.9. Hybrid coupler in DAC coupling mode

6.3.2 Screw Coupler ↔ Screw Coupler

The hybrid DAC joint system allows for the DAC head to be lifted up to enable screw coupling as well (Fig. 6.10). This involves a locking mechanism to keep the DAC face at an angle, as well as a system for reducing the torque needed to lift the DAC head, so that it can be safely lifted by a single person. When lifted the DAC draft gear no longer receives the force of impact between the locomotive and wagons during coupling. This is why the adapter retains space for the buffers to be brought forward and ensure the energy of collisions is absorbed.

UIC Mode

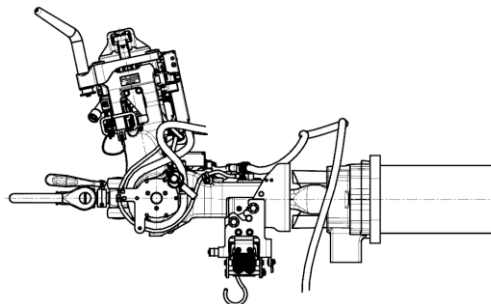


Fig. 6.10. Hybrid DAC in UIC mode (lifted for screw coupling)

7 Mechanical Interface Feasibility Analysis

7.1 Load Transfer and Structural Considerations

Both the DAC adapter, as well as the locomotive frame with the adapter attached. Distribution of von Mises stresses arising in the structure when under extraordinary loads was analysed along with an analysis of local stress concentration. Conducted tests were used to confirm the physical integrity of the DAC adapter and its stability when mounted to the locomotive frame. The proper transfer of both compressive and tensile forces through the adapter and the locomotive frame was ensured. The test report is available at the manufacturer, and the results are to be published. The accessories used for this modification included a hybrid DAC and standard buffers (Fig. 7.1.) and the location was on the front and back of the locomotive SM42 (Fig. 7.2.). The load-bearing elements have been rendered as 3D models and tested (Fig. 7.3. and 7.4.) using a mesh method for the calculations (Fig. 7.5. and 7.6.).

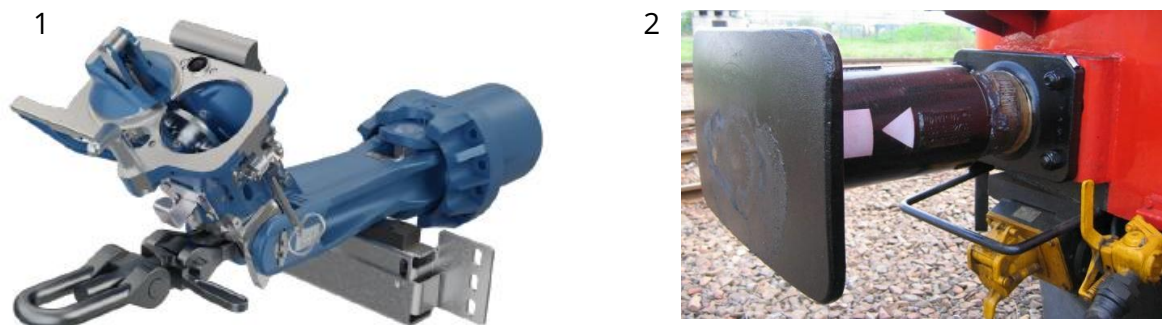


Fig. 7.1. Accessories attached to the adapter: 1 - DAC coupler; 2 - bumper



Fig. 7.2. DAC adapter mounting location on the SM42 (6D series) locomotive

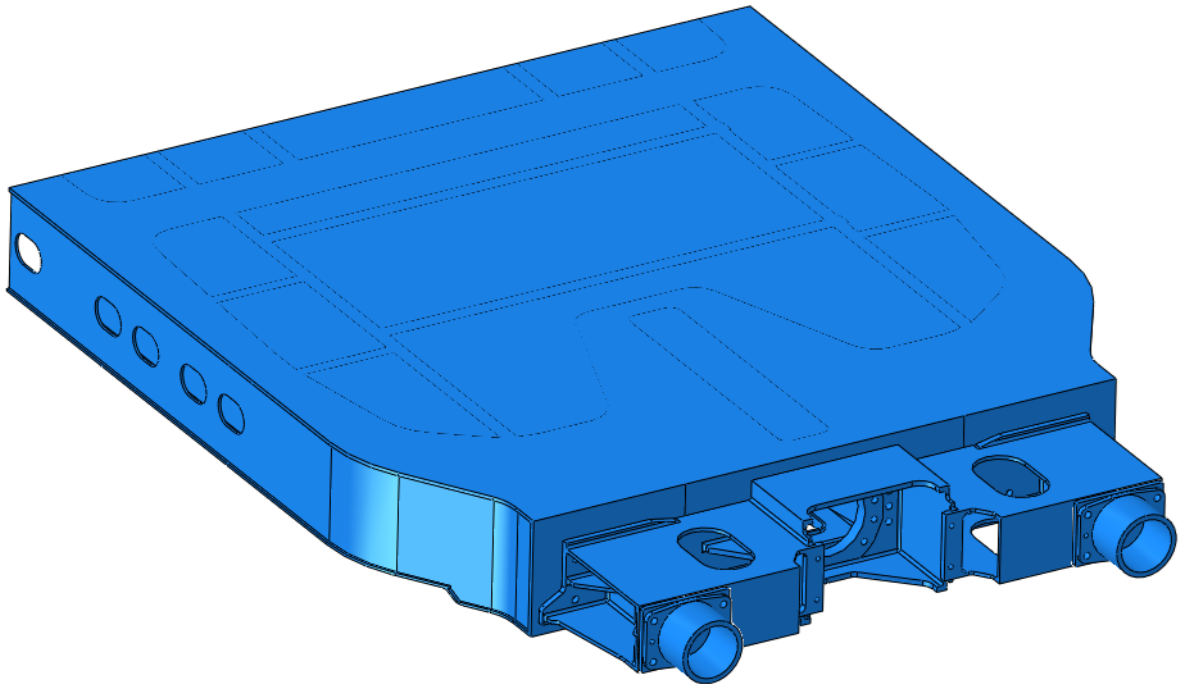


Fig. 7.3. The considered solid load-bearing elements of the DAC calculation model – general top view

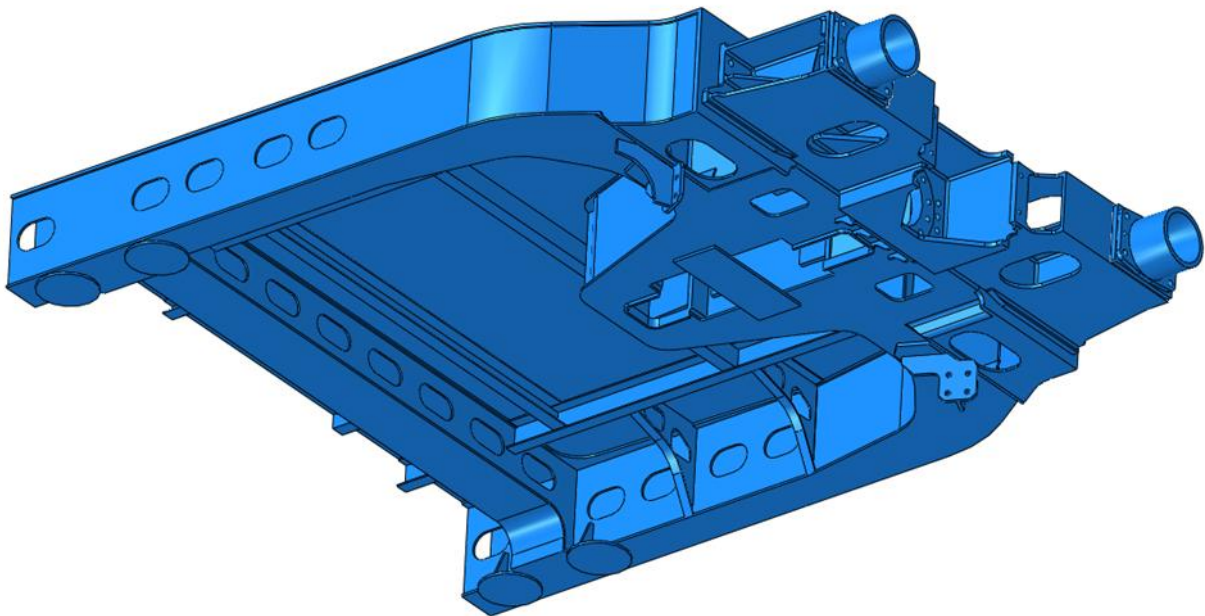


Fig. 7.4. The considered solid load-bearing elements of the DAC calculation model – general bottom view



Fig. 7.5. DAC adapter computational model used – top side

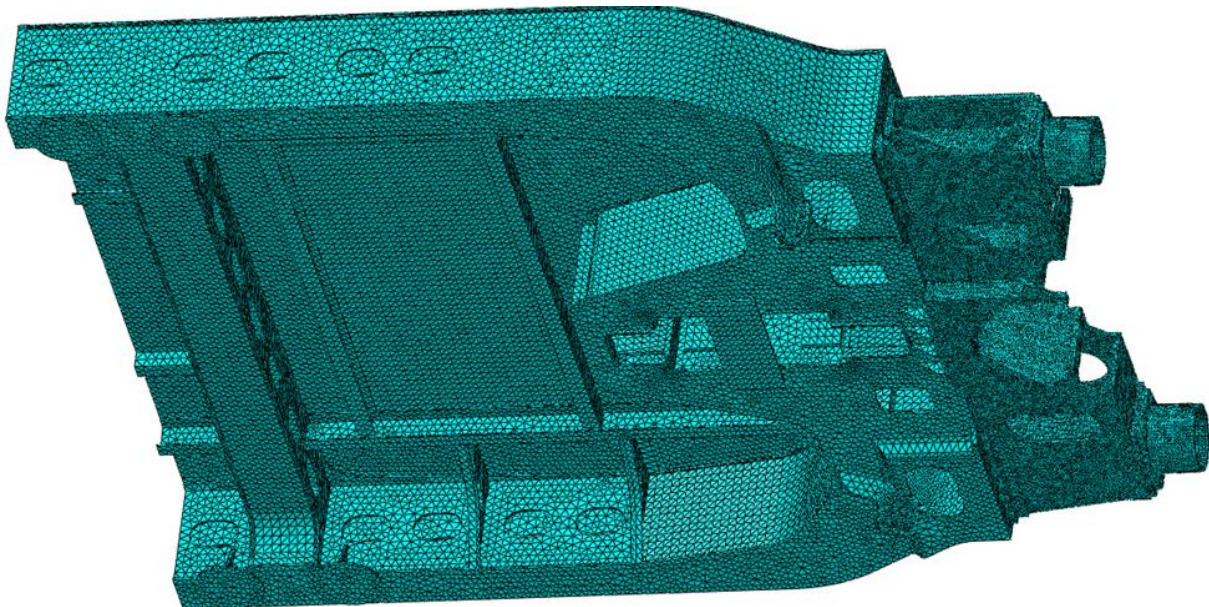


Fig. 7.6. DAC adapter computational model used – bottom side

The results of calculations carried out to assess the strength of the DAC coupler adapter frame show that the applied design solution meets the strength criteria specified in the Report in accordance with PN-EN 12663-1^v.

7.2 Geometrical and Installation Constraints

The SM42 locomotive was tested to ensure the modified vehicle keeps within the gauge and clearance on turns. The vehicle gauge outline was determined in accordance with the requirements of the PN-EN 15273-2^{vi} standard for the G1 kinematic profile. A model of the DAC was fitted with the adapter in a digital environment. It was concluded that the actual outline of the digital coupler installation on the SM42 series locomotive frame does not exceed the restricted outlines (see Appendix B). This was tested as part of the standard testing procedures, ensuring sufficient clearance between the locomotive

elements and the maximum gauge outline (Fig. 7.7.) Due to the vehicle proportions and locomotive would require extensive locomotive frame modifications, leaving the use of space in the locomotive head it was concluded that installing a DAC onto an unmodified an adapter as the only viable solution.

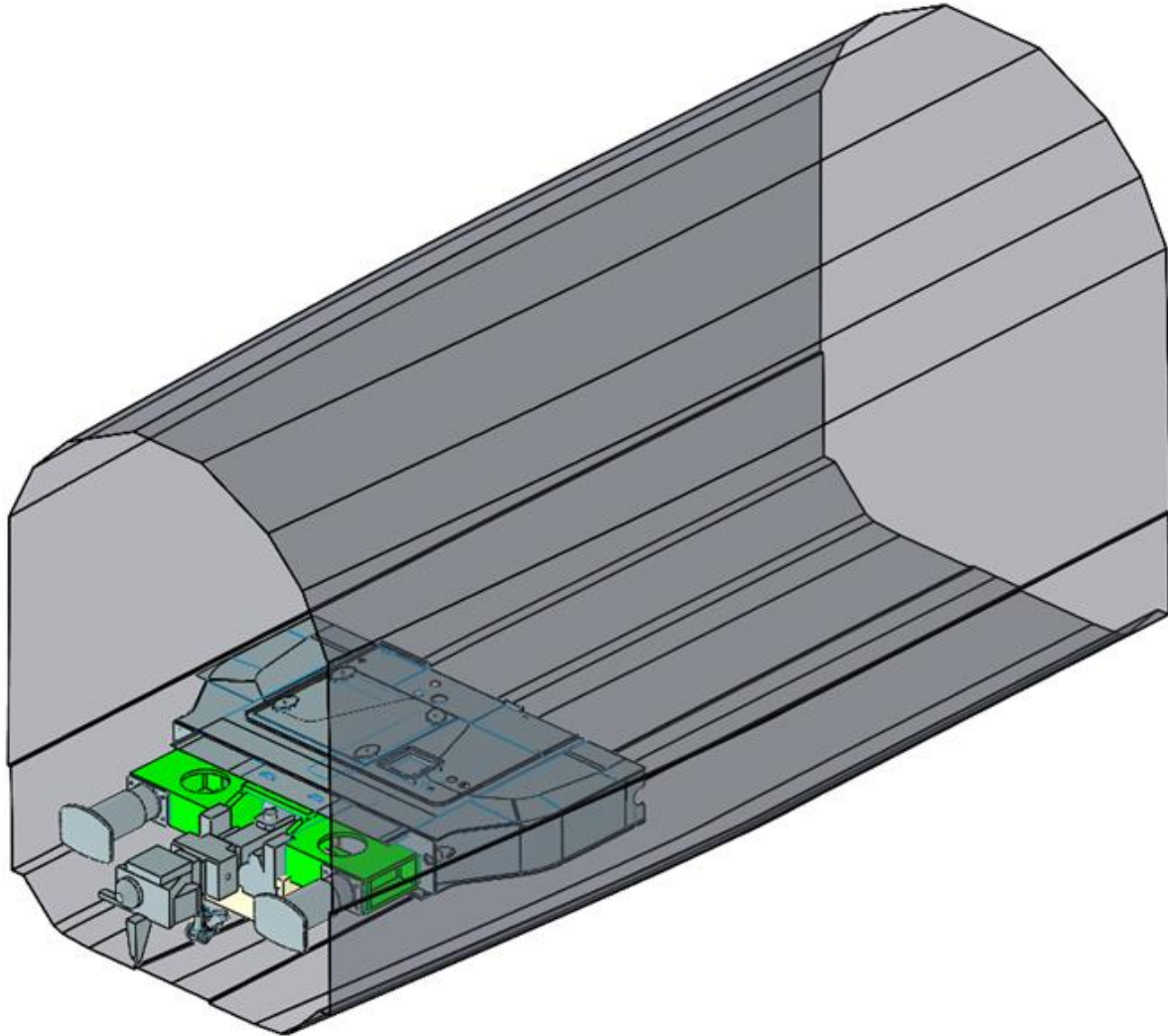


Fig. 7.7. Example of the extended locomotive length due to DAC and adapter fit within the gauge constraints

7.3 Shunting vs Mainline Operation Aspects

The solution of locomotive adapter to enable a DAC installation was deemed viable for both mainline and shunting operations of the SM42 locomotive. The modified locomotive was deemed applicable for both types of operation. Whether the vehicle can be cleared to operate as a mainline locomotive will depend on a further assessment of the extent of necessary certification requirements.

8 Electrical Power Interface Feasibility Analysis

8.1 Power Supply Requirements

The DAC systems require a power supply of 48V with a sustained 10-20W power. However, this system also needs to be able to supply up to 500W for about 3 seconds to power the decoupling actuators during automatic decoupling process. In order to enable the transfer of electric power to other vehicles in the trainset also requires a single phase 400V connection with 3kW of power. This power supply is only needed for either the front or back coupler at any given time.

Input Voith:

Since the freight wagons do not have a power source of their own, the locomotive shall provide power to the wagons through the coupler. To this means, some parameters have been defined in the Trans4m-r project which shall be fulfilled here as well.

The locomotive shall provide 400VAC (+10-0%, single phase), 50Hz-60Hz (IPTRANS-8206, IPTRANS-8852). The voltage shall be sinusoidal with a THD $\leq 10\%$ and a power of 3kW/3.2kVA (fundamental) / 3.75kVA (total power incl. Harmonics). (IPTRANS-8208, 7733).

The system shall be protected against overvoltage ($>460V$) and overcurrent (11.3Arms) (IPTRANS-8224, 8192, 9893 and 8855).

Only the coupler at the rear end on the loco (in direction of travel) shall be energized (IPTRANS-9895).

The loco shall use an insulation monitoring system to detect failures in the isolation system (IPTRANS-804).

For more details, please refer to Trans4m-r D5.4, chapter 7.2.

8.2 Integration with Legacy Electrical Systems

The SM42 locomotive provides a native power supply of 3 phase 400V AC. The DAC requires a 400V AC source which is then provided to the wagons on either side of the locomotive. This will be achieved by adding a transformer to convert the 3 phase 400V AC current available in the locomotive into two 1 phase 400V AC lines (one for the DAC at locomotive head, the other for the back). Such a solution ensures that any wagons connected to the modified locomotive are provided with power. The DAC itself also requires power. In this case, a 48V DC power supply is necessary with a constant 10W of power. This power supply also needs to be able to provide up to 500W for up to 3 seconds in order to ensure proper operation of the uncoupling mechanism. This problem will be resolved by adding a converter, also supplied from the locomotive's native source, and connecting that to the DAC on each locomotive end. After analyzing the possible solutions an approach was chosen, a simplified schematic of the proposed setup was provided

(Figure 8.1). The cables and electronic elements need to be safely affixed to the locomotive, to ensure safe operation during DAC operational tests.

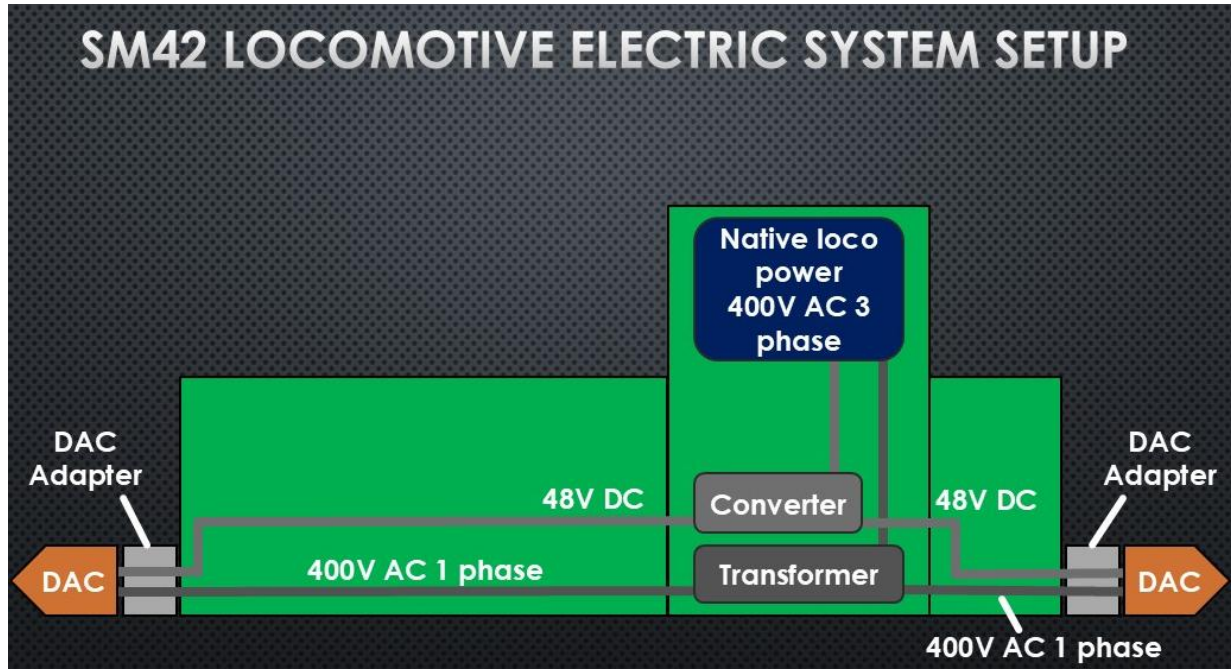


Fig. 8.1. Simplified schematic of the power setup for the modified SM42 locomotive equipped with DACs

In addition to the transformer and converter, boxes with electric components for the DAC Control Unit, the HMI, and any other necessary components provided by the manufacturers will need to be mounted on the locomotive. An assessment of the space available on the locomotive for this additional equipment is being conducted along with the selection of specific electric components to be purchased.

8.3 Limitations and Boundary Conditions

The primary limitations in the modification of the SM42 locomotive to power DAC systems relate to the additional electrical systems necessary to convert the native electric supply to work with the needs of the DACs. The main aspects faced so far were finding the space on the locomotive that can fit the extra devices (transformer and converter), as well as finding fitting electric elements that will also meet the standards for use in rail vehicles. The power output needed may also be a limiting factor for some of the additional DAC functions.

9 Interoperability and Operational Use Cases

9.1 Use Cases for Shunting Operations (SM42)

The integration of the Digital Automatic Coupler (DAC) into the SM42-6Dg would revolutionize shunting operations by enabling fully automated coupling and uncoupling directly from the driver's cab. For a dedicated manoeuvre locomotive, the primary operational benefit is the drastic reduction in time required to form train compositions at marshalling yards, as the DAC automates mechanical, pneumatic, and data connections in a single step. The digital layer of the system allows the SM42-6Dg to perform automated brake testing and real-time monitoring of wagon status, eliminating the need for manual inspections between tracks. Furthermore, the combination of the locomotive's modern microprocessor control system with the DAC's data transmission capabilities enables precise control over longitudinal forces during humping operations. This transition enhances safety by removing ground personnel from the danger zone between wagons and optimizes the "last mile" logistics, making the SM42-6Dg an efficient, digitally connected hub for freight terminal operations.

9.2 Use Cases for Mainline Operations (ET22)

Production of the ET22 locomotives ended in 1989. PKP purchased a total of 1,183 units. Several vehicles were also produced for export to Morocco. Several have returned to Poland in recent years, three of which are already operating freight trains for private carriers.

The locomotive is designed for operation with the following types of trains:

- Freight trains weighing 2500–3150 t on flat lines at a maximum speed of 70 km/h. On these lines, the locomotive can move through traction-relevant gradients of up to 7% with the above-mentioned trainsets.
- Express freight trains weighing up to 1200 t at a maximum speed of 100 km/h.
- Passenger trains up to 650 t at a maximum speed of 125 km/h.
- Detailed Technical Parameters

The ET22 (type 201E) is a six-axle electric locomotive with a powerful construction, characterized by the following data:

- **Axle arrangement:** Co'Co' (two three-axle bogies)
- **Continuous power:** 3,000 kW (approx. 4,080 hp)
- **Starting tractive effort:** 412 kN
- **Design speed:** 125 km/h
- **Service weight:** 120 tonnes (axle load on rails is 20 t)
- **Total length:** 19,240 mm (including buffers)
- **Power system:** 3,000 V DC (direct current)
- **Traction motors:** 6 motors, type EE841

- **Gear ratio:** 79:18
- **Braking system:** Pneumatic brake (Oerlikon), along with auxiliary and hand brakes

9.3 Interoperability with DAC and Conventional Rolling Stock

Use of hybrid couplers enables the train to function for shunting operations with both DAC wagons as well as conventional screw coupler wagons, but not with a mixed group (unless used with an adapter wagon). This requires DACs to be adopted for at least whole trainsets at a time to enable their function, assuming no wagons are planned to be exchanged between adapted and non-adapted locomotives. This fact informed the choice of vehicles for this Work Package, prioritizing the shunting/line locomotive SM42, which is widely in use throughout Poland, with over a thousand of locomotives in operation on the railways. Adaptation of other old locomotives may pose greater challenges, such as the adaptation of an ET22 line locomotive. The structures of most old locomotives are not easily convertible for DAC installation. For many locomotive types, a significant modification of the locomotive structure may be necessary to enable DAC installation, often to the point of invalidating the existing approval and certification documents that enable the locomotive operation. This poses additional challenges, since re-certifying a new modified locomotive variant adapted for the use of DACs can be costly, difficult, and in some cases no longer possible due to changes in laws and regulations concerning rail operations.

A hybrid coupler enables operation with wagons that have been DAC adapted as well as conventional and older ones. To use a hybrid DAC safely, the adapted locomotive needs to retain its buffers (for operations with the DAC head lifted), and their proper function needs to be verified. Tests conducted within the scope of this project are aimed to test and verify that this proper function is maintained.

10 Technical Risks, Assumptions and Open Issues

10.1 Key Technical Risks

The main technical risks include:

- inability to create an adapter/locomotive modification that will comply with the existing regulatory limits,
- DAC adapter not becoming a proper interface for DAC mounting,
- The necessary additional electrical systems being too large to fit in the locomotive,
- The locomotive native power supply being insufficient to provide the power necessary for all the new DAC functions,
- The DAC with adapter mechanical tests not reaching satisfactory results in tests.

10.2 Assumptions and Design Constraints

The main assumptions regarding feasibility of the project include the assumption that the SM42 native locomotive power supply can be converted to match the needs of DAC systems and subsystems. It was presumed that the vehicle's mass and length will not hinder DAC adaptation, which has since been confirmed true. The vehicle frame was also able to manage forces transferred through a centrally placed DAC as well as the buffers on the sides. The electrical components used for testing within the scope of the project may not always meet the rail industry standard requirements (in terms of durability and safety) due to the cost and time related to procurement of more technically advanced components. Therefore, the final form of locomotive adaptation for DAC operation will need to consider the additional costs of using more advanced equipment.

10.3 Open Issues for Further Analysis and Validation

Issues of the electric system adjustments for SM42 locomotive DAC integration are still to be resolved as manufacturers complete the prototypes of their electrical control units. Further analysis is necessary for the adaptation of the ET22 locomotive for DAC integrations, as the necessary structural changes were found to be greater than initially predicted. The degree of change in ET22 structure may require initiating a whole new certification and approval procedure, which may greatly reduce the feasibility of DAC adaptation of legacy locomotives for actual freight operations.

11 Conclusions

The main objective of the task was to verify the feasibility of implementing Digital Automatic Coupler (DAC) technology based on tests conducted on mainline and shunting locomotives used in Poland. The work aimed to confirm whether these units can be adapted for hybrid coupling—integrating mechanical, pneumatic, and digital connections—while maintaining full backward compatibility with traditional screw-coupling rolling stock. Such modernization is set to revolutionize rail operations by enabling automated coupling directly from the driver's cab, which drastically reduces train formation times and allows for automated brake testing.

However, the analyses conducted revealed significant technical and formal challenges. While modern shunting units are well-suited for such modernization, older mainline locomotives require extensive structural modifications to enable the transmission of forces through a centrally placed coupler. These changes carry the risk of invalidating existing operational approvals, which could necessitate costly and complex re-certification processes. Additionally, adapting the power systems of older vehicles to meet the needs of new digital subsystems remains a challenge. Specifically, the reduction in the scope of work for the ET22 locomotive results primarily from the conclusions of the physical inspection and the inability to install the coupler without significant interference with the vehicle's frame. In conclusion, while the implementation of hybrid couplers is vital for the competitiveness of rail transport, the adaptation of legacy mainline locomotives requires further analysis regarding structural integrity and economic feasibility.

12 References

Standards:

- ⁱ EN 16019:2023 *Railway applications – Automatic coupler – Performance requirements, specific interface geometry and test method*. Brussels: European Committee for Standardization; 2023.
- ⁱⁱ PN-EN ISO 4014 *Bolts* – specifies the requirements for hexagon head bolts with shafts (partially threaded), ranging from M1.6 to M64, in product grades A and B.
- ⁱⁱⁱ PN-EN ISO 10512 *Hexagonal nuts* – This norm specifies the requirements for prevailing torque type hexagon regular nuts with non-metallic (nylon) inserts and metric fine pitch threads, ranging from M8 to M39.
- ^{iv} PN-EN ISO 7089 *Washers* – defines standard flat washers (normal series, product grade A) with no chamfer, commonly used with bolts and nuts ranging from M1.6 to M64.
- ^v PN-EN 12663-1 *Railway Vehicle Bodies* – This European Standard specifies minimum structural requirements for railway vehicle bodies.
- ^{vi} PN-EN 15273-2 *Rolling Stock Infrastructure Gauge* – The aim of this series EN 15273 is to define the rules for the calculation and verification of the dimensions of rolling stock and infrastructure from a gauging perspective.

13 Appendices

Appendix A: Locomotive frame with adapter gauge test report

ⁱ EN 16019:2023 *Railway applications – Automatic coupler – Performance requirements, specific interface geometry and test method*. Brussels: European Committee for Standardization; 2023.

ⁱⁱ PN-EN ISO 4014 *Bolts* – specifies the requirements for hexagon head bolts with shafts (partially threaded), ranging from M1.6 to M64, in product grades A and B.

ⁱⁱⁱ PN-EN ISO 10512 *Hexagonal nuts* – This norm specifies the requirements for prevailing torque type hexagon regular nuts with non-metallic (nylon) inserts and metric fine pitch threads, ranging from M8 to M39.

^{iv} PN-EN ISO 7089 *Washers* – defines standard flat washers (normal series, product grade A) with no chamfer, commonly used with bolts and nuts ranging from M1.6 to M64.

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