



Interoperable hydrogen refueling station interface for railway vehicles in the Rail4Earth project: design approach and new normative requirements

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The RAIL4EARTH project, carried out under the Europe's Rail Joint Undertaking (ERJU), focuses on the decarbonization and sustainable development of railway systems. One of its key areas is the development of interoperable and safe hydrogen refueling stations for rail applications. This paper presents the research and development activities conducted within Work Package WP9, including the analysis of technical interfaces (mechanical, electrical, communication, and safety) and ensuring compliance with SAE J2601, while being informed by the SAE J2601/5 Technical Information Report (TIR). The engineering challenges related to the design of hydrogen refueling connectors for trains are discussed, with particular attention to high mass flow rates, material requirements, and operational safety. The final outcome of the R&D work will be the demonstration of a universal refueling interface compliant with European and global standards, enabling the rapid deployment and commercialization of hydrogen technologies in the railway sector.

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1. Introduction

The flagship project 4: RAIL4EARTH – “Sustainable and Green Rail Systems” focuses on the development of sustainable and environmentally friendly railway systems, including rolling stock, infrastructure, stations, and their subsystems. The project started at the turn of 2022/2023 and will last four years. Its main objective is to decarbonize diesel-powered trains, reduce noise and vibration, improve energy efficiency, implement circular economy principles, minimize resource consumption, enhance climate resilience, and increase the attractiveness of passenger rail transport [2, 5].

The project involves 71 partners, including Polish entities such as Polskie Koleje Państwowe S.A. (PKP), the AGH University of Krakow, Centralny Port Komunikacyjny sp. z o.o., Infrabyte sp. z o.o., Łukasiewicz Research Network: Institute of Electrical Engineering, Warsaw Institute of Technology, Institute of Artificial Intelligence and Cybersecurity, Railway Institute (POLTRIN network), PKP Energetyka S.A., PKP Informatyka sp. z o.o., Poznan Uni-

versity of Technology, International Union of Railways (UIC), and the Military University of Technology in Warsaw.

The four-year scope of Rail4EARTH includes all essential actions to improve the sustainability performance of the rail sector and to contribute to the European goals of sustainable transport (a climate-neutral Europe by 2050, the European Green Deal, and the Sustainable and Smart Mobility Strategy) [3, 4].

It includes work on “Neutral Station with Smart Transit-Oriented Development elements”, “Extending the BIM standard with railway components and developing a digital twin of the station”, as well as “Hydrogen Refueling Stations for Rail” and “Holistic Traction Energy Management”.

The project aims to develop and demonstrate (up to TRL7) new scientific and technical solutions that enhance the environmental efficiency of the rail system, while verifying their economic feasibility for fast commercialization to benefit European citizens.

The project aligns with other activities under the Europe's Rail Joint Undertaking (ERJU) and related European research programs such as Clean Hydrogen

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JU and Batt4EU, maximizing the synergy of ongoing initiatives.

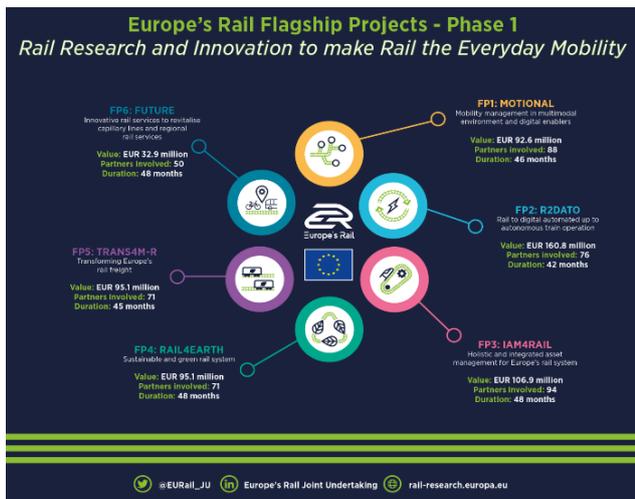


Fig. 1. Europe's Rail Flagship Projects (<https://rail-research.europa.eu>)

The Łukasiewicz Institute of Electrical Engineering (Ł-IEL) participates as an implementing partner of PKP S.A., responsible for selected tasks within Work Package 9 – Development of an Interoperable Hydrogen Refueling Station. Within WP9, the focus is on defining location selection mechanisms considering parameters such as the maximum expected refueling time. On one hand, faster refueling interfaces minimize train downtime; on the other, they require greater investment to prevent hydrogen overheating, which could create ignition risks. The task, implemented jointly by PKP, AGH University of Krakow, Railway Institute, and Ł-IEL, will culminate in the demonstration of a new hydrogen refuelling interface. Standardization of the interface will reduce future costs related to non-compatible refuelling technologies.

The purpose of this paper is to present the R&D assumptions for developing an interoperable hydrogen refuelling station interface for railways, compliant with SAE J2601 and SAE J2601/5 standards. The paper discusses the main technical challenges, safety requirements, and expected demonstration results within WP9 of the Rail4Earth project.

2. Hydrogen train technology and manufacturers

Hydrogen train technology is being developed as part of the green transformation of railway transport. It relies on fuel cells that generate electricity from hydrogen to power electric traction motors. Although the concept itself is not new, its commercial implementation is relatively recent and still evolving.

The most used systems include Proton Exchange Membrane Fuel Cells (PEMFC), composite hydrogen

storage tanks (350–700 bar), lithium-ion batteries for energy recovery and acceleration assistance, and energy management systems to control power flow between the cells, batteries, and regenerative braking [6]. Propulsion is provided by AC traction motors powered by the fuel cell system and/or batteries.

The leading manufacturers implementing hydrogen-based train propulsion are Alstom (France) [1], Siemens Mobility (Germany), Stadler Rail (Switzerland), CRRC (China), and Hitachi Rail/Eversholt Rail (UK). In Poland, PESA Bydgoszcz presented its first hydrogen train at the TRAKO 2023 trade fair [6].

3. Materials and methods in the area of hydrogen refuelling stations

The R&D work under WP9 includes the analysis of normative requirements, conceptual design of the refueling interface, and the development of a methodology for technological validation. The methodology is based on comparative analysis of SAE J2601 and SAE J2601/5 Technical Information Report (TIR), testing of flow parameters, and thermodynamic modeling of the refueling process.

The key objective for Ł-IEL is to develop and standardize a refueling interface for railway rolling stock that enables hydrogen refueling in the shortest possible time while maintaining full safety. The standards must account for various fuel inlet designs used in current locomotive models and provide design guidance for future manufacturers, ensuring interoperability and non-discrimination among suppliers.

Due to the properties of hydrogen, excessive refuelling rates pose risks of ignition or explosion [6]. Ensuring safety requires detailed experimental studies to establish safe operating frameworks, along with control algorithms capable of automatic response if parameters exceed allowable limits. The outcome will be the formulation of standardized regulations defining safety and performance requirements at European and global levels.

Innovative solutions will be verified through operational testing, assessing system reliability under various refuelling scenarios. The results will form the basis for future standardization and implementation work, accelerating commercialization of hydrogen technologies to the benefit of European citizens.

Hydrogen-powered trains require precisely defined interfaces between the vehicle and support infrastructure to ensure safe and reliable operation. The main types of interfaces include:

- Hydrogen refueling interface – provides a tight, fast, and safe connection between the refueling station and onboard hydrogen tanks, preventing leaks

- and ensuring compliance with pressure and temperature standards
- Power interface – supplies onboard auxiliary systems such as lighting, HVAC, and controls
- Communication interface – enables data exchange between the vehicle and ground infrastructure for monitoring, diagnostics, and fault reporting
- Mechanical interface – ensures safe physical coupling and docking between train and infrastructure components during maintenance or station stops
- Safety and emergency interfaces – include automatic leak detection, emergency shutdowns, and alarms to protect passengers and personnel.

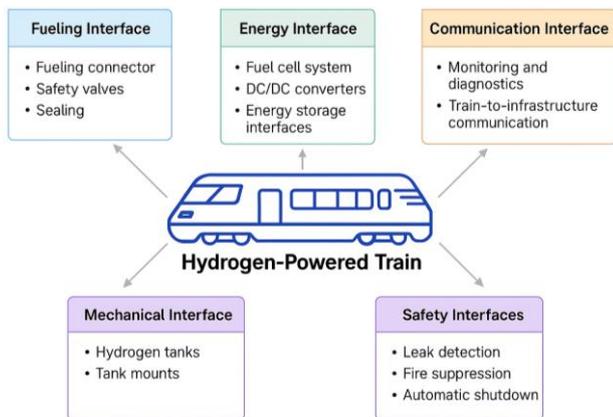


Fig. 2. Main interfaces between the train and support infrastructure

Hydrogen refueling interfaces must comply with SAE J2601 [10] and should consider the SAE J2601/5 Technical Information Report (TIR) [11], defining the principles of safe, rapid, and standardized hydrogen refueling. The earlier SAE J2601 covers refueling procedures for light-duty vehicles, while SAE J2601/5 TIR extends these rules to heavy-duty and off-road vehicles such as trains and buses, considering larger storage capacities, longer refueling times, and higher gas flows [8, 9, 11].

To improve clarity, a simplified graphical representation of the universal hydrogen refuelling interface is shown in Fig. 3, illustrating the gas, control, and safety subsystems.

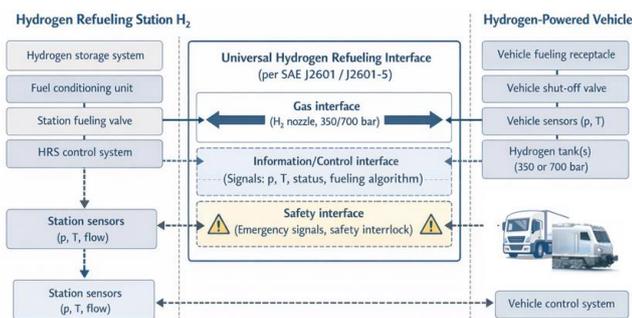


Fig. 3. Simplified block diagram of a universal hydrogen refuelling interface for railway applications

The applied methodology included the analysis of flow, temperature, and pressure parameters, modelling of refueling connectors, and defining Vehicle-to-Station (V2S) communication requirements in accordance with ISO 15118-20 and ISO 19885. Functional safety standards such as ISO 26262 and IEC 61508 were also considered.

4. Development of an interoperable hydrogen refueling station – results and discussion

The refueling interface must comply with the technical requirements of the referenced standards, including ISO 17268-compatible connectors, high-pressure fittings, temperature and pressure sensors, and integrated safety systems. Bidirectional communication between the vehicle and the refueling station is required to exchange real-time data such as tank parameters, refueling status, and fault messages. This communication is typically implemented using industrial communication technologies such as CAN, Ethernet, or wireless interfaces, selected to meet the functional requirements rather than being explicitly mandated by the standards.

Safety interlocks are fully integrated with the refueling control system and operate in accordance with the operational limits specified in SAE J2601, enabling automatic shutdown in the event of excessive temperature, pressure, or communication failure. These mechanisms ensure a high level of operational safety for both maintenance personnel and vehicle occupants.

In practice, the hydrogen mass flow rate is not a fixed parameter but is dynamically regulated based on real-time temperature and pressure feedback from the vehicle tank. The maximum allowable tank temperature, specified to be approximately 85°C, constitutes the primary safety constraint. As this limit is approached, the control system automatically reduces the hydrogen mass flow rate to prevent excessive thermal loading of the tank structure and liner materials.

4.1. SAE J2601 – automotive hydrogen fuelling standard

The SAE J2601 standard, developed by the Society of Automotive Engineers (SAE), regulates hydrogen refueling for light-duty vehicles. It defines process limits for 35 MPa and 70 MPa systems and specifies refueling profiles with hydrogen inlet temperatures typically ranging from -40°C to -20°C, depending on ambient and initial conditions.

It uses lookup tables or dynamic models to define pressure ramp rates and allows refueling with or without communication.

Key principles include:

- safety through controlled temperature and pressure
- fast refueling (3–5 minutes)
- temperature compensation
- interoperability between stations and vehicles
- defined refueling profiles (T40, T30, T20, T10).

During fast hydrogen refueling, the temperature evolution inside the onboard storage system is governed by gas compression, heat transfer to the tank walls, and the initial temperature of the dispensed hydrogen.

For instance, in the T40 refueling protocol, defined in SAE J2601, the hydrogen temperature at the dispenser outlet may be as low as -40°C . This pre-cooling is required to limit the temperature rise of the tank walls during rapid filling. Although the hydrogen is supplied at cryogenic temperatures, the tank wall temperature increases monotonically during refueling due to adiabatic compression of the gas and viscous dissipation. As a result, the temperature of the composite pressure vessel approaches its maximum allowable value near the end of the filling process, when the pressure and gas density are highest. According to SAE J2601, a maximum permissible tank temperature is defined to prevent thermal degradation of the storage system, particularly polymer liners and composite overwrap materials used in Type IV pressure vessels.

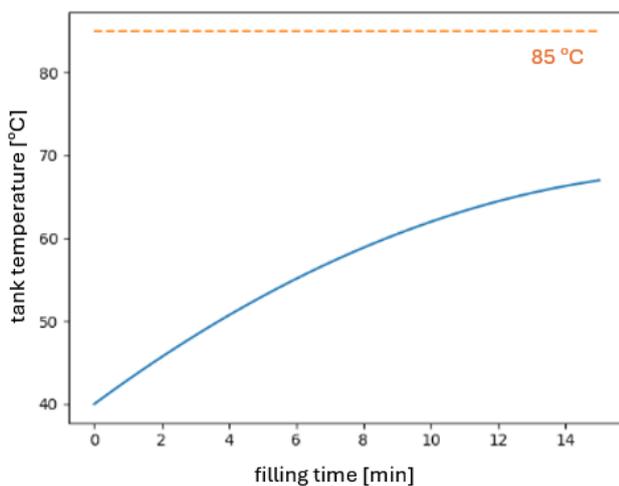


Fig.4 Indicative temperature profile during hydrogen refueling using the T40 protocol

The solid curve (Fig. 4) represents a schematic evolution of the tank wall temperature as a function of normalized filling time (or state of charge). The dashed horizontal line indicates the maximum allowable tank temperature specified in SAE J2601. Despite the low inlet hydrogen temperature (-40°C), the tank temperature increases during refueling due to gas

compression and heat transfer, approaching but not exceeding the normative limit.

The T40 protocol is therefore designed such that, under worst-case ambient and initial conditions, the tank wall temperature remains below this threshold throughout the entire refueling process. It is important to note that the temperature of the dispensed hydrogen and the temperature of the tank walls are not equal; rather, the refueling algorithm controls pressure ramp rates and gas temperature to ensure compliance with the tank temperature limit.

4.2. SAE J2601/5 – fuelling protocol for heavy-duty vehicles

While SAE J2601 primarily addresses refueling of light-duty vehicles with relatively small onboard storage volumes, SAE J2601/5 extends the methodology to heavy-duty applications characterized by significantly larger tanks and higher thermal inertia. Importantly, SAE J2601/5 does not modify the maximum allowable tank temperature; instead, it introduces adapted refueling strategies and enhanced thermal models to ensure compliance with the same temperature limits under markedly different operational conditions.

SAE J2601/5 was published in 2024 as a Technical Information Report (TIR) rather than a full standard, reflecting the limited availability of large-scale field validation data. The document extends the J2601 framework to heavy-duty vehicles, including emerging applications such as rail transport. It addresses refueling scenarios involving large onboard hydrogen storage volumes (typically from several hundred up to several thousand liters) and high hydrogen mass flow rates (on the order of tens to a few hundred grams per second).

The protocol allows for the use of hydrogen pre-cooling, potentially down to -40°C if required, depending on the specific thermal response of the storage system, while relying on real-time process control, bidirectional communication between the vehicle and the refueling station, and compatibility with ISO and European standards.

In practice, the achievable mass flow rate is continuously limited by the thermal response of the tank, making temperature evolution within the storage system the dominant factor governing the refueling process, as discussed in Section 4.

4.3. Comparison: SAE J2601 vs SAE J2601/5

The main differences between SAE J2601 and SAE J2601/5 are related to the typical tank capacity, hydrogen mass flow rate, and thermal behavior of the storage system. SAE J2601 is primarily applied to light-duty vehicles with relatively small onboard tanks

(typically on the order of 100–150 L) and moderate mass flow rates, whereas SAE J2601/5 addresses heavy-duty applications with large-capacity tanks exceeding 600 L and hydrogen mass flow rates in the range of approximately 60–200 g/s.

SAE J2601 relies on predefined refueling profiles, including the T40 protocol, which may require hydrogen inlet temperatures as low as -40°C to ensure that the tank wall temperature does not exceed the maximum allowable limit. In contrast, in typical operating scenarios, SAE J2601/5 allows higher hydrogen inlet temperatures (e.g., up to approximately -20°C), enabled by longer refueling times, increased thermal inertia of large tanks, and more detailed thermal modeling.

Both standards employ temperature–pressure lookup tables to control the refueling process; however, SAE J2601/5 incorporates expanded datasets that account for larger hydrogen masses, diverse tank geometries, and material-specific thermal responses. Consequently, SAE J2601/5 represents a more complex refueling framework, requiring enhanced process control and infrastructure while maintaining the same fundamental safety limits for internal tank temperature.

5. Design of hydrogen refueling couplings for railway applications

According to the SAE J2601/5 TIR, railway vehicles require refueling connectors capable of supporting very high hydrogen mass flow rates in the range of 60–200 g/s, and withstanding high operating pressures up to 875 bar (87.5 MPa). The operating temperature range is -40°C to $+85^{\circ}\text{C}$, while all components must maintain a leakage rate below 10^{-5} Ncm³/s for hydrogen under test conditions [8, 9, 11]. The connector design must comply with strength requirements corresponding to at least 125% of the nominal pressure and demonstrate durability for 10,000 connection/disconnection cycles without loss of sealing integrity.

Connectors designed for railway applications must provide a large flow cross-section, high pressure resistance, and thermal stability. Materials must be suitable for low-temperature operation (down to -50°C), such as stainless steels, composites, or advanced elastomers that retain their mechanical properties under cryogenic conditions. Large hydrogen storage tanks used in railway applications exhibit significant thermal inertia, which extends refueling times and requires precise control of process parameters. To ensure stability and safety, temperature and pressure sensors are often integrated directly into the connector, enabling real-time monitoring during refueling.

The SAE J2601/5 TIR also defines the Vehicle-to-Station (V2S) communication interface, based on ISO 15118-20 and ISO 19885 standards, which allows data exchange – such as temperature, pressure, state of fill, and vehicle ID – at a frequency below 100 ms. Gas flow control is governed by the Thermodynamic Demand Gas (TDG) model, which dynamically adjusts refueling parameters according to tank pressure and temperature. This approach can reduce refueling time by 20–30% while maintaining thermal safety. The connector acts as a feedback element, transmitting sensor data to the station’s control system, enabling adaptive process regulation. Redundant sensors, data integrity verification, and functional safety mechanisms compliant with ISO 26262 or IEC 61508 are also implemented.

Given the large hydrogen quantities and high operating pressures, even minor leakage in the connector can pose a serious hazard. Therefore, the design of connectors compliant with SAE J2601/5 places strong emphasis on safety and reliability. Mandatory protective elements include:

- check and emergency shut-off valves
- hydrogen leak detectors
- mechanical interlocks preventing disconnection under pressure
- automatic flow cut-off systems activated upon communication loss or parameter exceedance.

Connector designs must also allow pressure burst tests (up to 125% of nominal pressure), dynamic leak tests after 10^4 cycles, and cryogenic testing at -50°C . This comprehensive validation ensures compliance with safety and interoperability requirements for hydrogen infrastructure.

Ultimately, the design of railway refueling connectors in accordance with SAE J2601/5 requires integration of mechanical, material, electronic, and safety aspects, enabling full interoperability of hydrogen refueling infrastructure across railway, road, and industrial applications.

6. Summary

Hydrogen technology represents a key pillar of the energy transition in railway transport. The development of interoperable hydrogen refueling stations and their integration with rolling stock systems provides both a technological challenge and an opportunity to establish a new European rail infrastructure standard [10–12].

The RAIL4EARTH project, through its work on a universal refueling interface developed in accordance with SAE J2601/5 (TIR), contributes to the standardisation and advancement of safe, efficient, and high-performance hydrogen refueling systems for

heavy-duty vehicles. Implementation of project outcomes will foster competitive industrial solutions, supporting sustainable railway development and the European Green Deal objectives of climate neutrality by 2050 [4, 45].

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