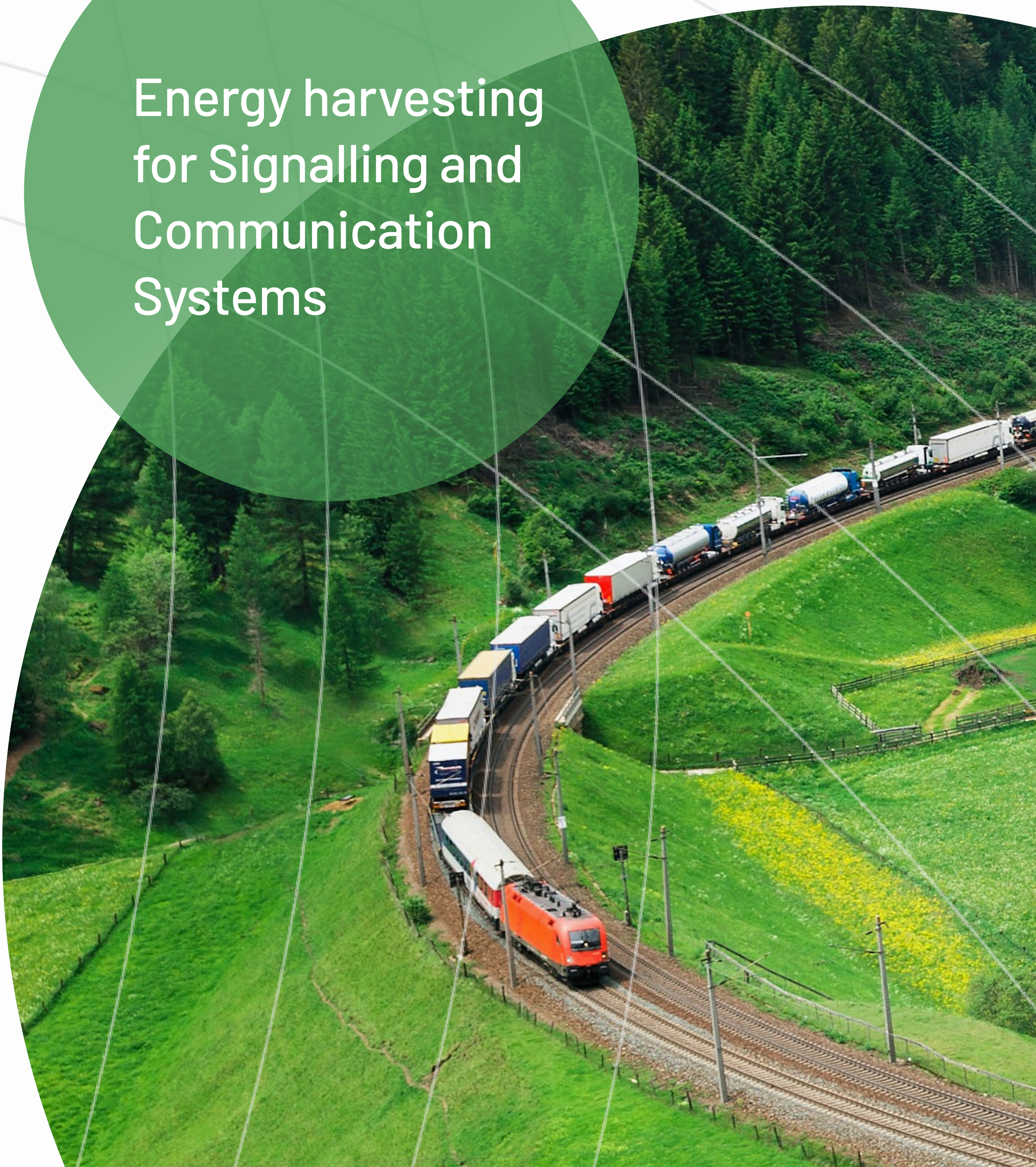
Etalon
Energy & communication

Energy harvesting for Signalling and Communication Systems



Foreword

The safe localisation of trains is an essential aspect of railway traffic supervision. It ensures appropriate separation of trains to avoid collisions and prevent them from passing a "danger point". Traditionally, safe train localisation has been performed by trackside systems like axle counters or track circuits. This solution requires extensive and costly trackside installations (including cables), and train location is assigned according to the "block sections" occupation. Additionally, this system does not always register the "identity" of the train.

Localisation based on information sent by the train itself creates significant advantages. This system increases a line's capacity by spacing trains based on positions of their rear ends (moving block) and generates significant cost reduction by reducing the amount of needed trackside infrastructure. To best exploit this configuration, the solution requires a safe, on-board system to detect the train integrity (completeness).

Although research and experimentation in this field has been done for many years, a standard solution that proves viable for all types of trains is not yet commercially available. The main problem for freight trains is that no power source is normally available on their wagon. Solutions are limited by the fact that many freight trains may require frequent changes in their composition, separating and re-assembling of wagons for different missions.

These considerations emphasise the importance of developing train integrity solutions based on radio communication between vehicles with locally generated power (energy harvesting on-board). Trackside train detection systems are expensive and potentially difficult to maintain. Often, they require trackside cabling to connect control centres and object controllers. Radio communication provides significant advantages, and locally generated power would eliminate the need for cables.

Mutually compatible radio communication systems and energy harvesting solutions are therefore enabling technologies with a wide range of applications and great capability of improving the railway system. This increases the capacity, performance of service and economic viability that supports the overall targets of Shift2Rail (S2R).

ETALON addressed these challenges with a vision to ensure as much as possible backward compatibility with existing systems. ETALON will take care of the appropriate integration of on-board train integrity (OTI) solutions, in line with ERTMS needs.

Project Structure

The ETALON project has explored the development and adaptation of both communication and energy harvesting technologies for infrastructure and rolling stock. These innovations will provide On-board Train Integrity functionality for unpowered wagons of freight trains and contribute to the reduction of trackside infrastructure, especially the cables, facilitating the deployment and maintenance of new trackside object controllers.

The project was developed through two main work Streams:

1. Creation of a prototype capable of carrying out On-board Train Integrity through a reliable communication system powered by an on-board energy harvester.

2. Development of competitive energy harvesting solutions for enhancing trackside object controller deployment, with the vision to minimizing trackside infrastructure like cabling.

In these two areas, the project has provided a coordinated set of technical key contributions including but not limited to:

- System Architecture based in a preliminary specification of Functional and System requirements.
- Low power consumption wireless communication prototype for sending information on board the train with the capacity to carry out OTI.
- On-board energy harvester, power storage and management prototype capable to support OTI function.
- Trackside Energy Harvesters capable to supply reliable energy for new Object Controllers.
- Economic models for the energy harvesting systems capable to provide suitable energy supply for trackside signaling equipment to minimise their infrastructure, essentially cables.

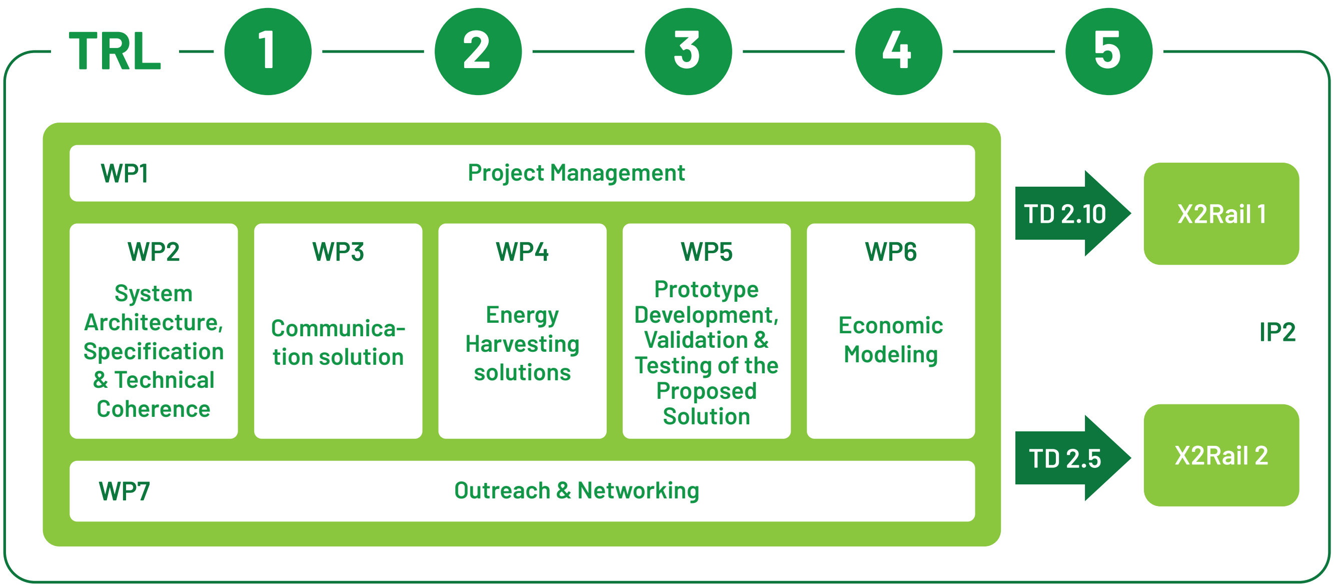


FIGURE 1
Project Structure

ETALON has contributed to these main objectives throughout the design, development, prototyping and testing of new innovative Communication and Energy Harvesting solutions that will help to achieve the goals defined by the Shift2Rail Joint Undertaking Multi-Annual Action Plan MAAP. ETALON in collaboration with the complementary Call for Members projects of the Innovation Programme 2 (IP2) will participate actively in the achievement of the goals of the technical demonstration TD 2.5 On-board Train Integrity solutions and TD 2.10 Smart Radio connected all-in-all Wayside Objects.

System Architectures, Specifications

The on-board train integrity is a special functionality to immediately detect one or more wagons disconnection from a railway convoy. This functionality will be essential as soon as the moving block concept will be implemented, and the railway track will be freed from electronic devices required to detect the train in a fixed block. The ETALON project aimed to develop and validate in controlled and real environment a prototype of On-Board Train Integrity (OTI) solution, powered by energy generated from the vibrations produced by the movement of the train. A second stream aimed to develop and validate in a controlled environment a prototype of trackside energy harvesting solutions to power the object controllers.

In this sense, ETALON WP2 was envisaged to define the system architectures, based on a preliminary consolidation of functional and system requirements for each of the two streams. The definition of the engineering rules and maintenance requirements for the overall system was planned to be also an important activity of this WP. Finally, the technical coherence activity and the alignment with the activities of the Shift2Rail JU should contribute to ensure the consistency not only of the technical solution proposed within ETALON but also with the wider activity of the complementary Call for Members projects.

The main objective of WP2 "Definition of a robust system architecture able to operate in the particularly hostile railway environment "relies on a good consolidation of functional and system requirements specification.

In this sense, WP2 identified a requirement development methodology based on a continuous process of requirements consolidation. This methodology ensures the technical coherence of the requirements but also permits to take advantage of the previous work done for the consolidation of the next group of requirements. WP2 started its activity with the consolidation of the functional requirements to continue afterwards with the development of the system requirements using the previous one as a basis. Therefore, the system requirements specification were consistent with the functional requirements and on top of that they benefit from the previous work done. Both functional and system requirements specifications have followed existing standards related to safety critical applications and have been written paying attention to the safety and security aspects based on the SIL4 analysis.

Two strands of work have been assessed during the requirement specification phase: the first one concerned the development of the on-board train integrity specifications and the driver cabin control module and the second one was related to the energy generated from the environment.

Using as a basis the outputs coming from the requirements specification phase and the inputs received from regular meetings with X2Rail1 and X2Rail2 (complementary projects), the process to consolidate the System Architecture was structured in 4 iterative steps: Concept Definition, Technical Solution and System Definition, System Development and Integration and finally Validation and Testing process. The output of each of the steps were used to consolidate the final System Architecture of the project.

In the first working period, WP2 analysed the potential working conditions and issues caused using an external OTI device inserted on the communication network and the transmission of wrong information. The output of this analysis constituted the input for the definition of the autoconfiguration procedure described in WP3. ETALON also verified in this working period requirements for the second work stream related to the Trackside Energy Harvesting (TEH) solution, in particular the capacity of energy production by the movement of the train passing through a limited track area, using as a basis the physical principles of variable reluctance displacement and vibration. This concept is especially appealing on freight wagons that are currently unequipped with any power supply.

In the final step the ETALON WP2 defined the engineering and maintenance rules for the whole system.

D2.1 Functional Requirements Specification
D2.2 System Requirements Specification
D2.3 Engineering Rules and Maintenance Requirements

Communication Solutions

WP3 aimed to investigate and develop methods of checking the integrity of a train, and design, simulate and prototype wireless communication platforms for sending information on-board and off-board the train capable to be powered by energy harvesting technologies.

In the early stage of the project a specification for OTI was developed, in order to understand the possible energy demands on the system. Several possible schemes for determining train integrity were considered, and some functions supporting train operation (such as determining the consist formation) were added to the requirements. These considerations led to the addition of a sensor in the Wireless Sensor Network (WSN) to detect and measure the distance to the next wagon, using Ultra-Wide Band (UWB) radio. This is a very low power system that has been developed for localisation indoors, but we chose to attempt an installation for trains, so that not only can the system check wagon-wagon distances, but also systematically determine the identity and order of wagons in a consist, delivering further value to the operator.

In order to demonstrate that the energy output of the on-board vibration energy harvester is enough to power the communication requirements of OTI, prototype communication systems were developed with the capacity to carry out OTI. These systems had the following features:

The low power communications system with a multi-hopping communication method capable of delivering messages from the end of the train every few seconds while the train is in service, implemented in a low power embedded system with the harvester, for demonstration on a running train.

A demonstrator platform with more sophisticated train integrity functions including, additionally, a wagon-wagon distance measurement sensor that could be used for both OTI and consist determination (discovery) of freight trains.

Due to the communication packet size and frequency, either of these systems could be implemented on a low power platform and achieve a similar power consumption.

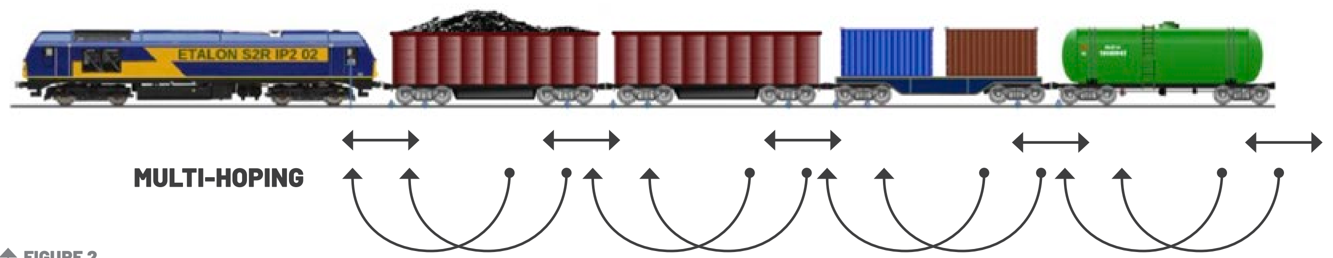


FIGURE 2
OTI Including Wagon-Wagon Distance Measurement and Multi-Hopping Radio Network

Below is a more detailed explanation of the design and development of a method for checking the integrity of a train and prototyping of a low power wireless communication system for sending this information to a Control Module (CM) located in the locomotive.

The designed solution, called the OTI system, is based on a Wireless Sensor Network (WSN) that employs a sub-GHz communication radio band. Since the solution aims to be deployed within the EU (European Union), the used sub-GHz ISM (Industrial Scientific and Medical radio bands) band is the 868 MHz.

The designed OTI system is composed of two main components:
The SN (Sensor Node) able to assess the integrity between adjacent wagons. This Train Integrity (TI) data is then propagated across the WSN network toward the locomotive.

The CM (Control Module) able to collect all the TI information and display the current status on a Graphical User Interface (GUI).
As shown in the deployment scheme in Figure 3, the OTI system foresees the installation of four SN modules for each wagon and a CM on the leading locomotive.

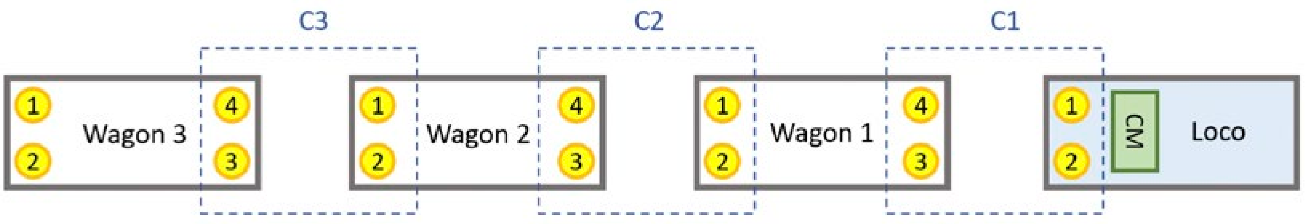


FIGURE 3
Deployment Scheme of the OTI System.

Communication Solutions

The OTI system performs a period collection of the TI data provided by the SNs mounted on the wagons. TI messages are forwarded from the various SNs towards the CM mounted on the leading locomotive. The TI is assessed by measuring the distance between two facing SNs across each coupling and comparing it with a predefined threshold. A measured distance above the admissible threshold is decoded as a "broken coupling" and signaled to the CM that will output a TI not confirmed or TI lost signal to the CM in case the distance is not available. The current status of the TI is continuously displayed in the GUI of the CM.
All SNs are identical to each other and based on the following components:

- Micro-controller module;
- Radio communication module;
- Distance Sensor (DS) module;
- Power supply.

Figure 4 shows a high-level architecture of the SN.

The OTI system foresees two main functionalities, namely Network Discovery and Train Integrity, described as follows.

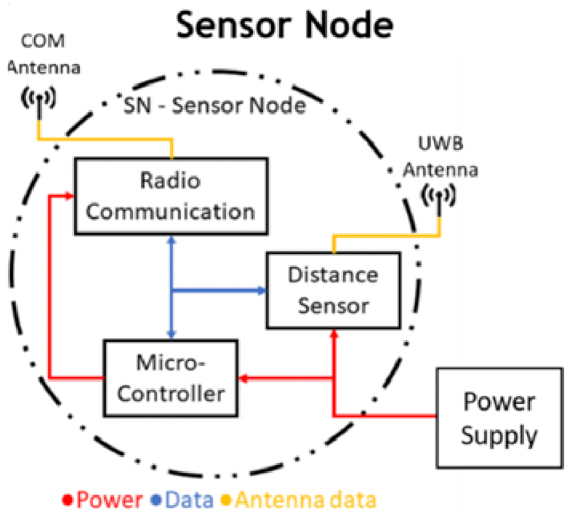


FIGURE 4
Sensor node architecture.

NETWORK DISCOVERY

The process of discovering all the SNs and the train couplings will be shortly denominated as Network Discovery (ND). This process is initiated by the CM installed on the leading locomotive, typically under explicit human request. Assuming a physical train composition as the one shown in Figure 3, the purpose of the ND is to collect all the SN Identifiers (IDs) that belong to the physical train. The ND procedure assumes that SNs on the same train element (wagon or locomotive) know the unique IDs of the other nodes on the same train element. The CM on the locomotive knows the IDs of all the SNs mounted on the locomotives itself. A full ND is achieved by sequentially discovering all the train's SNs by using the DS functionality to detect the closest SN mounted in the wagon in front of it.

TRAIN INTEGRITY

Train integrity (TI) is assessed by periodically measuring the distance between directly coupled wagons and checking that this measurement does not exceed a threshold. This threshold is equal to the distance between facing SNs measured during the ND phase plus one meter.

TI is considered confirmed when the distance between any of the directly coupled wagons (including the distance between the leading locomotive and the first wagon) is equal or below the above predefined threshold. Since there are multiple distance measurements for a coupling, if a single measurement respects the threshold, then TI is considered confirmed. If both measurements of the corresponding coupling are above the threshold or both measurements are invalid, then TI is considered compromised. This is an emergency case that should be notified to the CM on the leading locomotive as soon as possible. In addition, if the CM does not receive a periodic update from the SNs from a specific coupling, then the TI status of that coupling should be considered compromised.

Considering the train elements in Figure 3, the integrity of the train is checked sequentially, one coupling at a time. TI assessment is started periodically by the last wagon. In particular, the TI assessment procedure consists of the following two main operations:

1. Assessment and record of integrity of one coupling;
2. Backward propagation (from end of train to the locomotive) of the recorded coupling integrity to the SNs of the previous coupling. In turn, these SNs will update their status with their integrity data until the message reaches the CM.

Communication Solutions

The TI assessment starts with a request sent by the CM to all SNs till reaching the end of train. Once this request is received by the SNs assigned to the last coupling, they will start the "backward propagation". All SNs of every coupling will start a periodic TI assessment. The resulting coupling integrity messages are sent to the CM which will be updated by every coupling. For each coupling, the TI assessment procedure includes several operations and WSN communications explained as follows:

a) Use the DS to measure the distance between each pair of facing nodes twice, for redundancy:

- Distance between node 4 and 1;
- Distance between node 3 and 2.

b) Each measured distance is compared with the predefined integrity threshold to assess and encode the integrity of the coupling or possible error states;

c) Each node updates the integrity message with its information and sends it towards the CM which will interpret the data to assess the overall status.

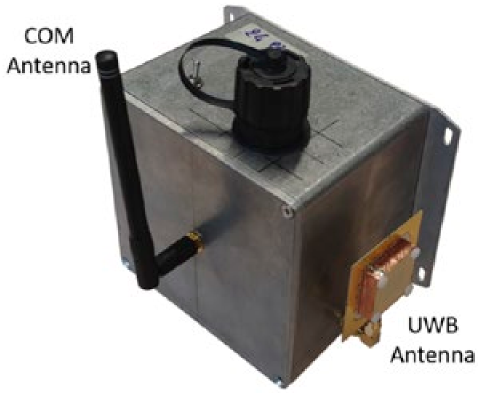


FIGURE 5
OTI casing with all interfaces mounted

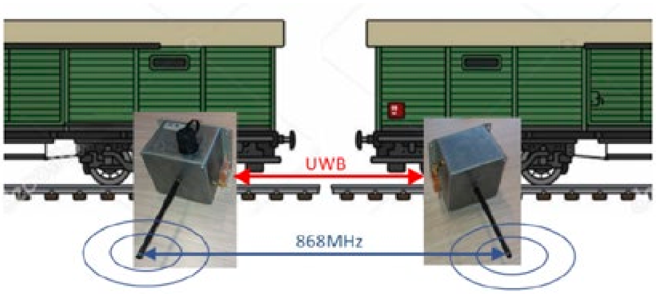


FIGURE 6
Example of a pair of OTI nodes installed in one side of the train

GRAPHICAL USER INTERFACE

The CM provides a GUI that reports the current network and TI status as well as historical data in logfile. For the current prototype, the user can manually insert the train speed and the TI frequency, whereas the final implementation could be directly interfaced with the on-board system to receive in a real time fashion these data.

The current GUI is displayed in Figure 5. As it can be observed, the GUI provides the status of all wagons that have been added to the network. The interface also provides the following interactions:

- A button, called NS (Network Setup), to start the ND generation procedure;
- A textbox to enter the TI period in seconds or the train speed;
- A button to stop the TI assessment procedure.

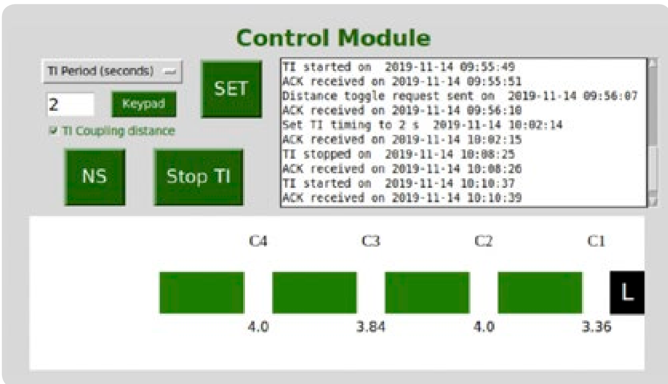


FIGURE 7
GUI of the CM

D3.1 Trade-off analysis for on-board and track-side communication systems
D3.2 On-Train Communication Systems and RF Components Report
D3.3 Prototype showcasing the On-Train Communication Systems and RF Components
D3.4 Train Integrity Methods Power Requirements and System Analysis
D3.5 Communication Systems and RF Components for Trackside and Power Requirements

Energy Harvesting Solutions

The ETALON project answered an open call from the Shift2Rail, related to projects X2Rail-1 (telecommunications) and X2Rail-2 (train integrity). Both X2Rail projects (-1 and -2) were focussed on start-up activities and specification of systems requiring reliable communication either around the infrastructure or around rolling stock. Trackside cabling for communication and power could become a significant impediment to improvements in reliable communication and safety for the next generation of signalling, and communicating train integrity on the unpowered wagons of freight trains by adding power and communication cables to low cost unpowered wagons were both seen as applications where energy harvesting could provide a solution to low cost local power sources.

ENERGY HARVESTING IN THE RAIL ENVIRONMENT

The costs and opportunities for trackside and on-board energy harvesting are very different, and at different stages of technology development, (depending on the amount of power required and the application). For this reason, trackside and on-board energy harvesting were dealt with in different development programmes, and at different technology readiness levels:

TRACKSIDE

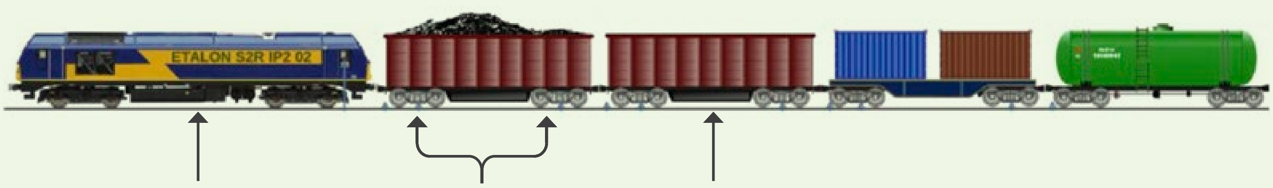
The aim of the trackside energy harvester development was to provide enough energy for new "ultra-low energy" object controllers, although this could be expanded to discrete communication devices. The actual power requirements of new object controllers are undefined (future developments within X2Rial-1), but this work has shown what could be achieved, and what an installation could look like. Powering control elements (motors, gates, heaters etc.) was not considered – there are no sources of ambient or "waste" energy that are feasible with the necessary reliability around the rail environment. Energy harvesting, based on harvesting energy derived from the passage of trains, could however be capable of powering reliable and distributed communications, with a data rate proportional to traffic density.

Current trackside controller technology, due to reliability and redundancy requirements, has significant power requirements and there has been no historical demand for associated energy harvesters, therefore energy harvesting technology is at a purely research and development stage. Some applications exist for monitoring control element status as part of a remote conditioning programme. There is a limit to the energy available from wheel-rail interaction due to the transient nature of a train passing and the momentary wheel-rail contact at any given location. Extraction of any significant energy from a single point risks placing significant loads on the wheel or track, adding the risk of localised wear points in the network.

Environmental energy harvesting (wind, solar) might have the capacity to supply much higher power, but at a rate that is not related to traffic density. This carries the risk that under some circumstances energy supply might not meet demand, causing systematic control failure inconsistent with a SIL-4 compliant system. Remote condition monitoring of local rail infrastructure could still be consistent with this approach, or it could be used under limited circumstances but would not be a solution applicable to all parts of Europe. Commercial solutions also exist for environmental energy harvesting, so practical investigation of these solutions was outside the scope of the project.

ON-BOARD

Two methods for on-board energy harvesting are already in commercial use; vibration from axle-boxes and solar PV on vehicle tracker devices. Requirements from X2Rail-2 include bogie condition monitoring (e.g. wheels and bearings) as an additional benefit expected from the system (to mitigate installation and implementation costs). As a result, the Perpetuum axle-box vibration monitoring system was selected as a starting point for the On-Board Train Integrity power supply. The harvester, power supply and energy storage were modified and improved to meet the increased power demands of enabling on-train integrity (OTI), taking into consideration additional constraints from operating in a SIL-4 environment.



Energy sources on a freight train. Greatest demand (train to ground communications, location services) is in the locomotive, wheel mounted energy harvesters provide ample power when the train is moving to achieve rapid communication along the length of the consist. Vehicle mounted devices (solar or battery power) cannot support high communication rates when the train is moving but can provide continued location services when the wagon is stationary (or detached), at a much lower message rate.

FIGURE 8
Energy Sources on a Freight Train

Energy Harvesting Solutions

TRACKSIDE ENERGY HARVESTERS

Three different approaches were taken to trackside energy harvesting, each using a different energy transduction method, only one of them requiring contact with the train wheel:

- Vibration energy (resting on the sleeper).
- Magnetic reluctance (using the train wheel to change a clearance of magnetic circuit).
- Displacement (using the wheel to push a linear displacement electromagnetic generator).

Comparing the three trackside energy harvesters, each one exploring an alternative energy transduction process, different to other approaches that have been taken, the methods requiring close or actual contact with a passing train wheel both generate more power (as might be expected). The non-contact, vibration energy harvester can be applied in a more discrete, sleeper-based installation but harvests less energy. If we consider the useful energy required from these devices, even the low power output from the vibration energy harvester would be enough to power an ultra-low power communication and control device using the latest available radio and microprocessor technology. None of the devices would be capable of powering existing models of object controller and would certainly not be capable of powering mechanical components in the rail system. Fundamental studies of the energy balance in the wheel-rail interface show that indirect "harvesting" of the power available is only capable of powering communications and (potentially) condition monitoring devices, adding reliability to the rail system, not signaling functionality.

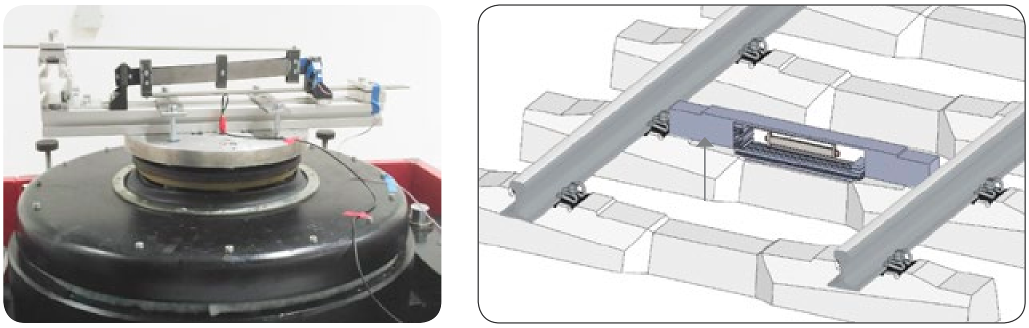


FIGURE 9
Trackside Vibration Energy Harvester – 5-50mW average during train passage

FIGURE 10
Variable Reluctance Energy Harvester (non-contact). 10W Theoretically output peaks during wheel passing, , around 250mW average power.

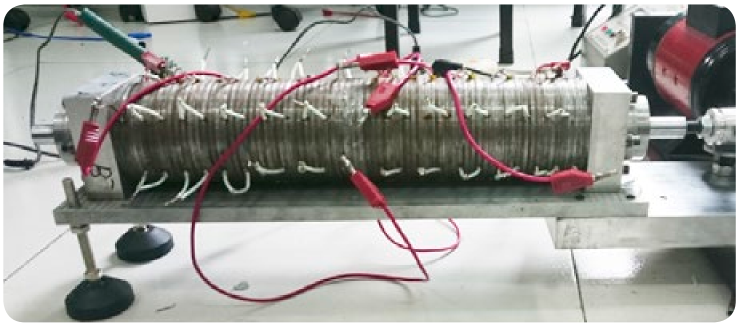


FIGURE 11
Linear Generator Components of a Prototype Displacement (contact) Energy Harvester - 5W output during actuation at 7Hz.

D4.1 Trackside Energy harvester solutions report
D4.2 On-board Energy Harvester, Power management and Energy Storage solution, design and predictedperformance report for adapted or developed solution
D4.3 Validated on-board energy harvester system solution
D4.4 Design report on TEH prototypes produced, proving capability of fulfilling signalling requirements. Laboratory technology demonstrator(s)

Prototype Development, Validation and Testing of the Proposed Solutions

Etalon WP5 is aiming to validate and demonstrate the performance of the On-board Train Integrity (OTI) and TEH prototypes and components developed within WP3 and WP4. In this sense, a specific test methodology was developed to validate both prototypes and demonstrate the compliance with the functional and system requirements produced in WP2. Different testing environments and test methodologies were defined for OTI and TEH prototype due to their different level of maturity.

D5.1 OTI Prototype
D5.2 Analysis of OTI Prototype test results
D5.3 Analysis of TEH Prototype tests results

OTI PROTOTYPE VALIDATION AND TESTING

A progressive test methodology was developed for the OTI prototypes to validate the performance of the system, detect potential failures and shortfalls at each stage and provide the opportunity to rectify them before moving towards the final testing in the Relevant Environment.

All the test scenarios were formalised in a matrix that specifies the main aspects of the system's functionality and performance to be tested and the conditions under which each test should be carried out. Each test was assigned with a priority using the MoSCoW prioritisation technique which is recorded in the Test Matrix. The following picture depicts the test methodology used for the validation of the OTI prototypes constituted by the communication and energy harvesting system. Three main phases were planned during the proposal of the project: Power Consumption, Controlled and Relevant Environment tests but due to development delays and mitigation of the detected risks three additional phases were added to the methodology Lab Corridor, Car Park and Power Consumption measurements.

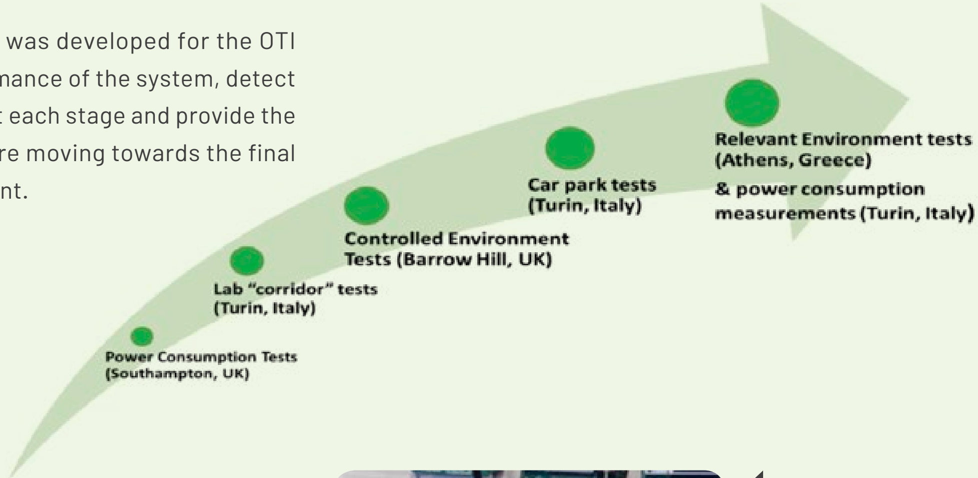


FIGURE 12
OTI Test Methodology

OTI POWER CONSUMPTION TESTS

This group of tests aimed to demonstrate the capability of the On-board Vibration Energy Harvester and Power Management System to power the Communication System, complying with power consumption identified in the requirements definition phase. The Power Consumption tests were at Perpetuum's premises where there was access to controllable electro-mechanical shakers.

FIGURE 13
OTI Corridor Tests

OTI CORRIDOR TESTS

The OTI system was initially firstly tested in laboratory conditions at LINKS premises. The purpose of this activity was to incrementally test and improve the main functionalities of the OTI system before carrying out long and cumbersome tests in the carpark, in "controlled" and then "relevant" environments. The laboratory tests were performed in a long corridor (about 120 m length) as depicted in Figure 13. 20 OTI nodes have been used; thus, emulating a train composed of a locomotive and 5 wagons, each wagon of length about 20 m and a coupling distance of about 2 m.

Prototype Development, Validation and Testing of the Proposed Solutions

OTI CONTROLLED ENVIRONMENT TESTS

The next step after the laboratory tests were the controlled environment tests carried out in Barrow Hill (Chesterfield, UK). Static vehicles and low speed train movements in a controlled environment were used to test the ETALON OTI system. The testing environment involved a train of railway vehicles (including a locomotive) dedicated to the tests and took place at the Barrow Hill Roundhouse Railway Centre site near Chesterfield, UK. This site is an active railway depot with a maximum line speed of 16km/h within the yard area and 32km/h outside the yard area. It has several different sections of line that were available to represent a range of conditions found in the railway environment.

FIGURE 14
OTI Controlled Environment Tests

OTI "CAR PARK" TESTS

Additional tests were performed in a car park in Turin close to the LINKS premises with the final goal to iteratively improve the performance of the OTI system before proceeding with the Relevant Environment tests in Greece.

The Figure bellow shows a top view picture of the car park in Turin. Yellow pointers represent the position of the OTI nodes deployed between cars in order to emulate the reflection and attenuation effect of a train. In total four tests were performed in Turin in these dates: 10th July; 25th July; 11th September and 4th October 2019.

FIGURE 15
OTI "Car Park" Tests

OTI RELEVANT ENVIROMENT TESTS

The Real Environment tests of the OTI were carried out over two days (13th and 14th November 2019) at the Thriasio Freight Centre in Athens, Greece.

FIGURE 16
OTI Relevant Environment Tests

Prototype Development, Validation and Testing of the Proposed Solutions

Installation and set-up of the OTI components occurred before proceeding with the tests. The brackets needed to hold the sensor nodes and the Energy Harvesters were previously installed on the locomotive and cars.

Multiple tests were performed during these two days to demonstrate the complete functionality of the OTI prototype and its components with very satisfactory results. All the details with regards the results and conclusions can be found in the public deliverable D5.2.

OTI POWER CONSUMPTION TESTS (2ND ROUND)

Since OTI devices were modified and upgraded for the Relevant Environment tests, new power consumption tests were made in LINKS premises in order to measure their actual power necessities.

OTI ROTATION AND PERMUTATION FUNCTIONALITY TESTS

Wagon permutation and rotation functionality has been considering one of the main priorities of the OTI workstream since the very beginning, due to its link with the operational requirement identified during the requirements specification phase of ETALON and its impact on the system operation.

This functionality is relevant due to the fact that the OTI workstream is aiming at providing a solution for cases where trains do not have any power supply available on the wagons, mainly freight wagons, where the composition of the wagon could frequently change. It means that wagons could be permutated and even rotated during the change of composition and in this sense, it needs to be taken into account during the network discovery phase.

The final tests of the Wagon rotation and permutation tests were performed in Turin on 28th January with the participation of main partners of X2Rail2 T.D2.5.

TEH PROTOTYPE VALIDATION AND TESTING

The aim of the tests related to the TEH prototypes was to demonstrate their capacity to generate the required amount of power to feed the communication system of the Trackside Object Controllers.

Three different technologies were used in the development of the prototypes Vibration, Variable Reluctance and Linear Generator that were mainly tested in lab environment and some cases in controlled environment.

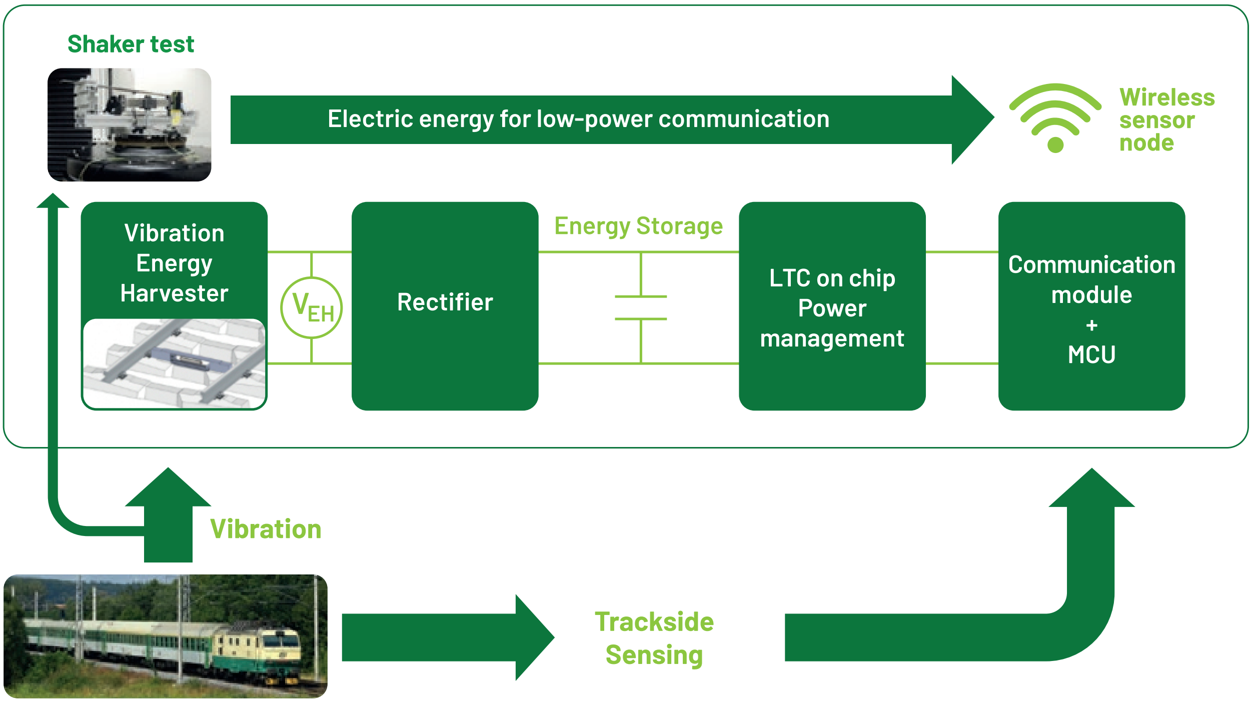
FIGURE 17
OTI components Installation in Relevant Environment

CONTROLLED ENVIRONMENT TESTS OF VIBRATION TEH

The vibration TEH is placed on a shaker device that can reproduce vibrations measured on the trackside with representative trains. A behavior of the vibration TEH in this type of the testing should be the same as in the real environment; the testing precision depends on shaker quality and the measured acceleration data from the real trackside. The controlled environment tests were realized with different connected electric device on output of the harvester for characterization of the harvester and demonstration of an operation as an autonomous source of energy for communication modules, see Figure 18.

Prototype Development, Validation and Testing of the Proposed Solutions

FIGURE 18
Controlled Environment shaker test of vibration TEH + communication module



The scenario test, depicted in Figure 18, of power management circuit and RF communication module shows continuous operating with communication module during passing the train. LTC on-chip module is used as power management circuit and RF module NRF24L01 as transmitter with the Microchip MCU for measuring and transmitting operation of trackside signals.

Figure 19 and Figure 20 below show the voltage on energy harvester and voltage and current on LTC chip. The current peaks on chip depict communications in frequency 8 messages per second. The transmitting of measured signal (600 samples per second) starts around 1 second after train coming and continue few seconds after train departs. Train with Loko380 vibration has higher vibrations, so the transmitting time after train departs is higher – about 15 seconds. The average power consumption of radio transmitting is 4.5 mW.

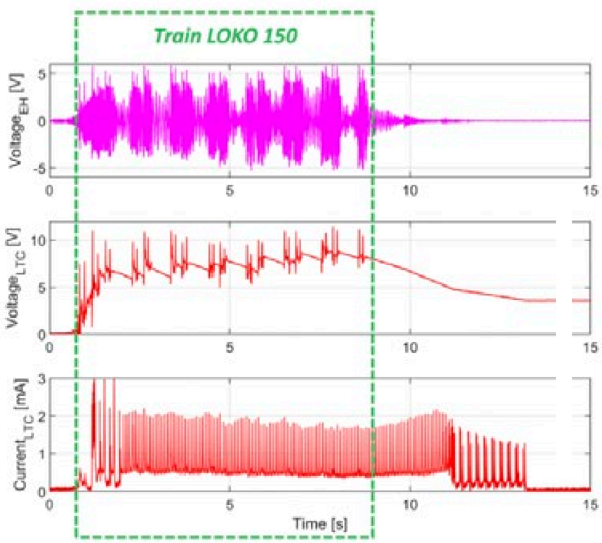


FIGURE 19
Voltages and current; vibration test Loko 150 (sleeper sag around 1.5 mm)

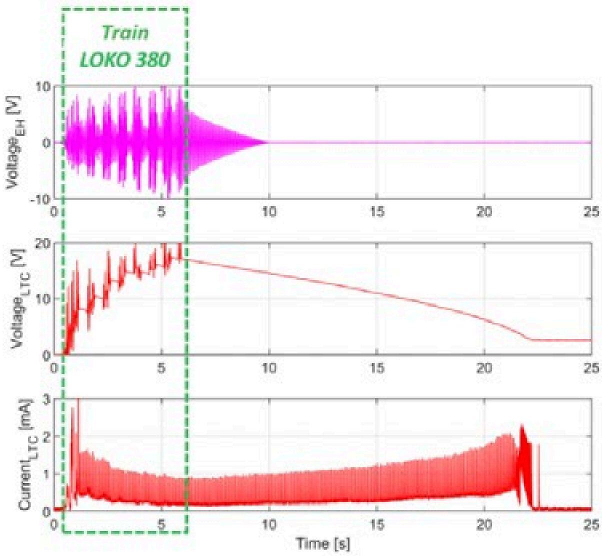


FIGURE 20
Voltages and current; vibration test Loko 380 (sleeper sag around 2 mm)

Prototype Development, Validation and Testing of the Proposed Solutions

Furthermore, LoRa communication module was tested with both vibration courses. A communication process of LoRa module was observed. It was possible to send one message using energy from passing train in course Loko 150 with the sleeper sag around 1.5 mm. The LoRa module has significantly higher energy consumption than module used in previous measurement, but it could be still used for trackside monitoring applications.

CONTROLLED ENVIRONMENT TESTS OF VARIABLE RELUCTANCE TEH

The variable reluctance TEH was tested in lab environment for different speed, wheel clearance and electrical load. A ferromagnetic element, which interprets a part of train wheel in magnetic circuit was fixed on carousel devices. The carousel testing device was developed under ETALON project for the testing scenario, see Figure 21. It can provide a wheel element velocity up to 90 km per hour.

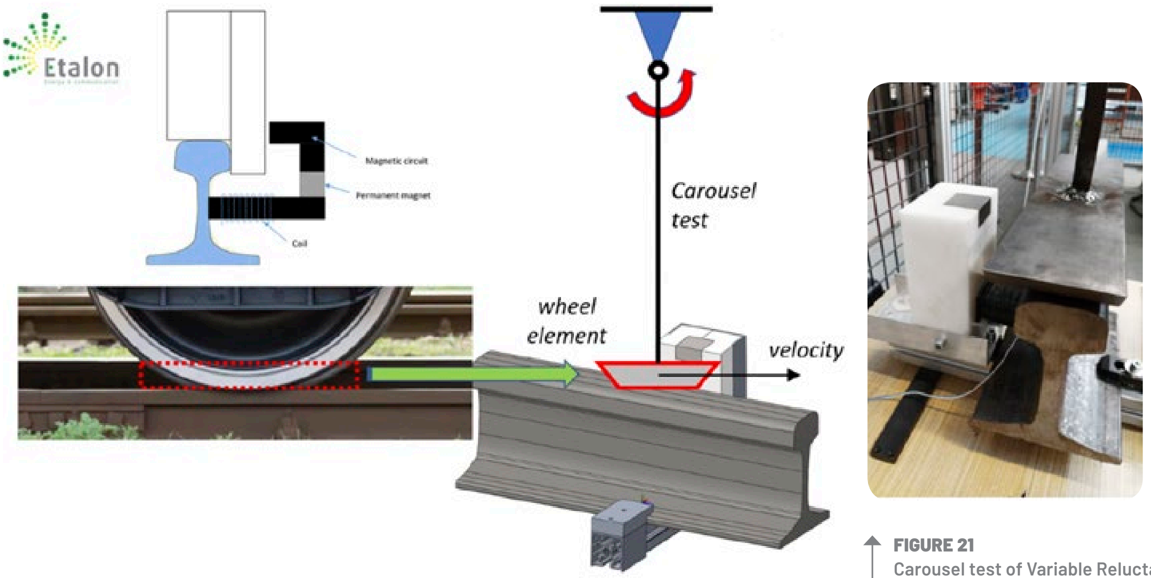


FIGURE 21
Carousel test of Variable Reluctance TEH with wheel element

The open voltage measurements for different train speed and wheel clearance 25 mm are shown in Figure 22. Measurements of open circuit voltage show that this system is not suitable for trackside application due to higher magnetic losses (i.e. eddy current and hysteresis losses) in speed operation. The magnetic losses are caused by a changing of magnetic flux density in ferromagnetic material (i.e. rail segment and wheel element). This undesirable effect is significant in typical range of train speed. The voltage is not proportional with the train speed and the harvester cannot provide enough power for traveling train speed. Furthermore, this system has very high sensitivity on a clearance in magnetic circuit, which is varied in time of passing train for individual bogies. For this reason, any power management electronics and communication operation were not tested under project. The average power outputs were on lower level as vibration TEH device.

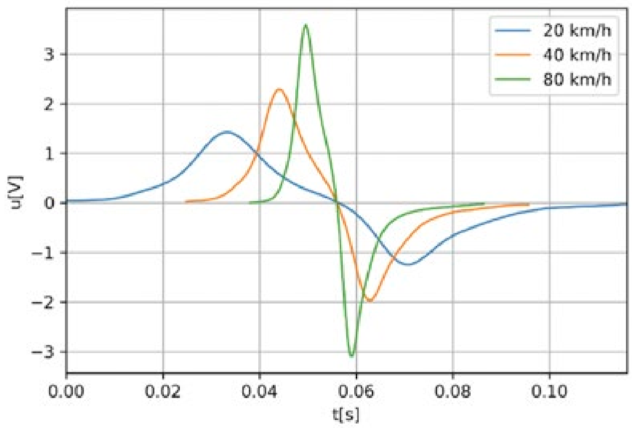


FIGURE 22
Open circuit measurement of Variable Reluctance TEH for high speed test

Prototype Development, Validation and Testing of the Proposed Solutions

CONTROLLED ENVIRONMENT TESTS OF DISPLACEMENT TEH

An outline design for the Linear Generator Trackside Energy Harvester (LG TEH) has been developed, and the linear generator component designed and constructed. The outline design of the LG TEH has been used to determine the actuation profile of the linear generator when actuated by a wheel. Testing of the linear generator energy harvester are proceeding in two stages. The first stage, which consisted of the linear generator shaft connected to a continuously rotating crank by a connecting rod, is complete and validated the linear generator construction, showing that the generator was able to harvest around 5W when actuated at around 6-7Hz. The final stage of testing, which is still in progress, is to test the linear generator on a specially constructed test rig to provide an actuation profile of the linear generator which represents that which would occur with the outline design LG TEH so that the energy output from this design can be accurately predicted.

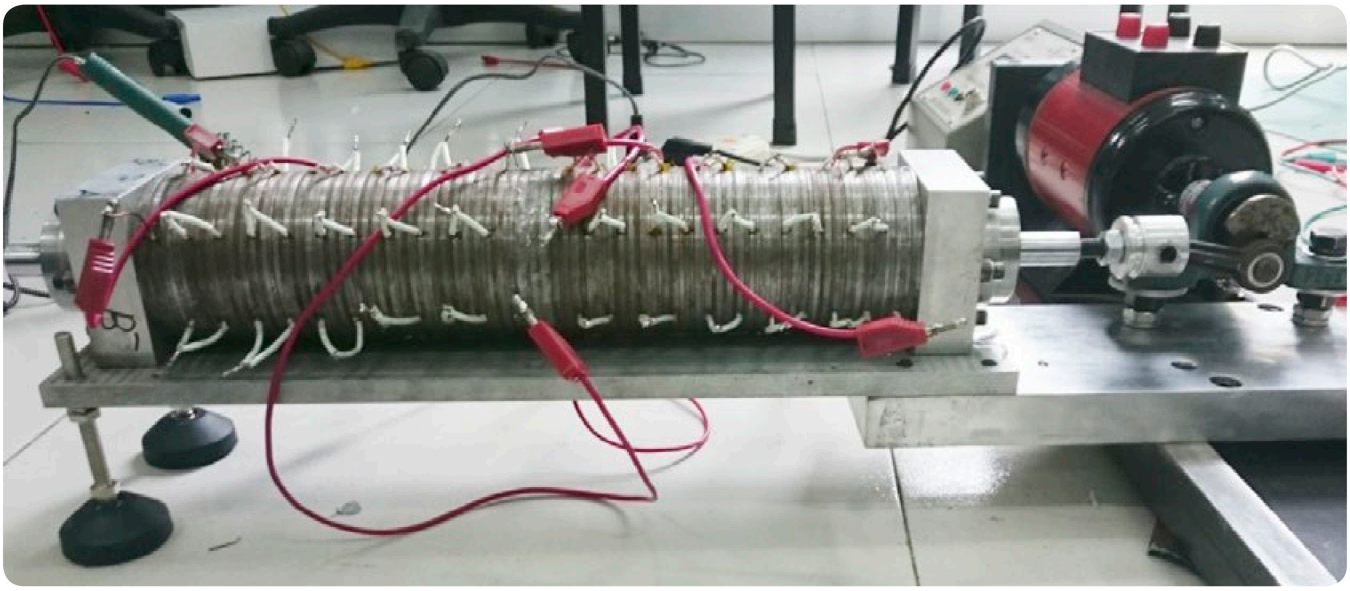


FIGURE 23
Initial linear generator validation test rig showing linear generator actuated by a rotating crank

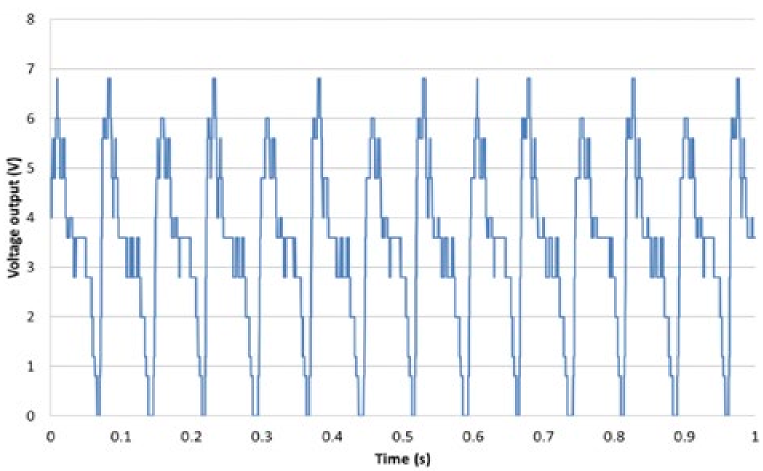


FIGURE 24
Linear generator voltage output on initial test linear generator construction validation test rig at 400rpm (6.67Hz) with 2 Ohm resistive load and 1.6A average current

Economic Modelling

Acknowledging that rail transportation systems (i.e., freight and passenger train, mainline, regional lines, subways, etc.) represent an important role in people's daily life and for the economic and labour environment, the trackside infrastructures are essential both for the current and the future railway systems in order to improve the quality of services and the safety systems. The electric infrastructures are the core of the overall system and reliable and low-maintenance power supplies are essential requirements for several services, fixed elements (FEs) and object controllers (OCs) sited on the trackside (e.g., warning and signal lights, track switches, grade crossing signals, track-health monitoring systems, wireless sensors for monitoring and communication access points, bridge monitoring, positive train control systems and train position, etc.). Mainly in remote or difficult to access areas where electrical infrastructures are poor there are lack of reliable power supply and low-maintenance battery. For this reason, the increasing of demand for electronic trackside devices is an important driver for designing a cost-effective and reliable power supply solution for trackside devices themselves where the energy harvesting (EH) systems will make the railroad more independent from national energy grid.

WP6 focused on the analysis of the economic impact whether, when and how the existing trackside energy system with its infrastructures – which are extremely costly in many EU countries – can be replaced by a more environmentally friendly and economically efficient technology by using renewable resources. Indeed, the current status of trackside systems in Europe provides for using cables and supplying energy through systems that have high costs for infrastructure managers (IMs) due to several factors as cables theft, high long run maintenance costs, high costs in some difficult to access area, etc. Because of these hurdles, railway enterprises that own the network infrastructure can be interested in the advent of new energy power solutions from renewable resources – trackside energy harvesting (TEH) systems – in order to obtain greater benefits, both in terms of cost reduction, savings, efficiency improving and reduction of pollution.

METHODOLOGICAL TECHNO-ECONOMIC APPROACH

WP6 started from M1 to M8 of the project, hence, before testing the candidate trackside energy harvesting (TEH) solutions investigated by Etalon project. For this reason, the main scope of WP6 was to provide a methodological approach to be used for building a decision support system (DSS) to be applied for a preliminary analysis of the possible future scenarios for TEH systems with respect to the counterfactual scenario currently implemented and widespread in all the European railway sector. In particular, the economic evaluation has been done taking into account the picture of the current deployment of power infrastructure for supplying energy to object controllers (i.e. AS-IS or status quo) to be compared with the possible options TEH system by capturing the market trends acting as backdrop for the specification of a sound TO-BE market proposition.

This work package had the ambition to design a theoretical quantitative model, called "Virtual Route Model" (VRM), simulating three main scenarios: the current scenario with cables for powering object controller (AS-IS scenario), the railway LTE network and the wireless sensor network (WSN) deployment through the use of smart wayside object controller (SWOC) powered by TEH systems (TO-BE scenarios). In doing this, we identified the values of several parameters and the main conditions for which the TEH scenarios can be more economically convenient with respect to the AS-IS.

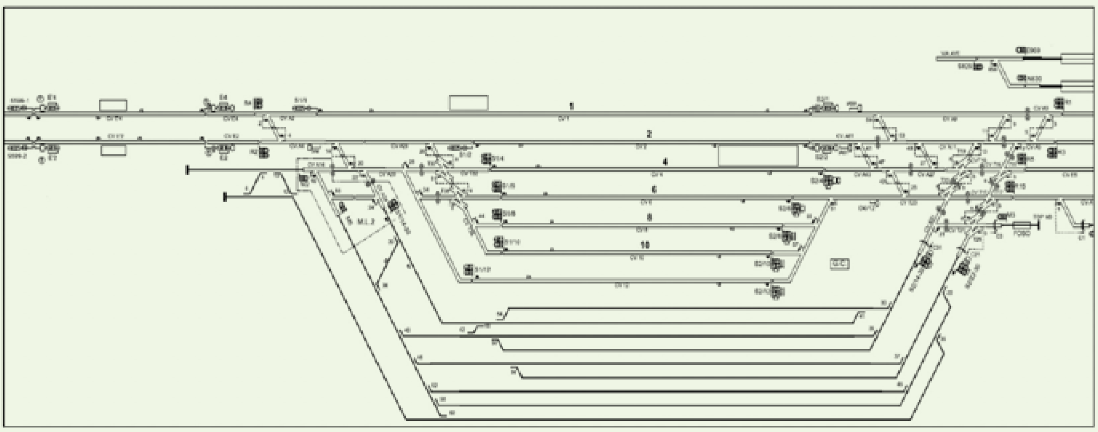


FIGURE 25
AS-IS scenario with real track layout of a main station on conventional line

Economic Modelling

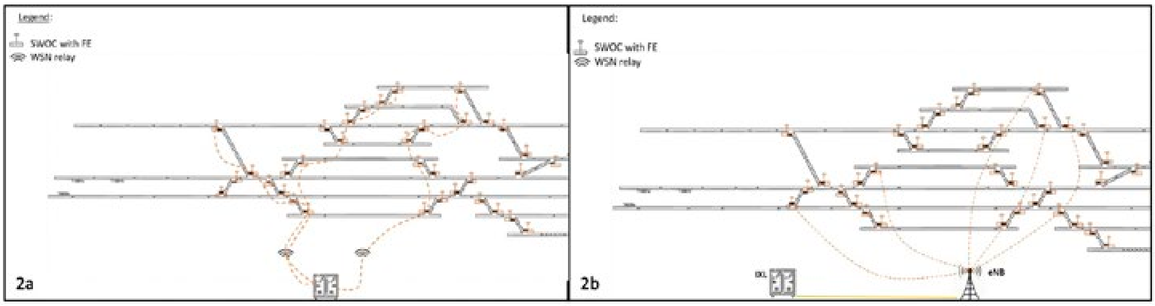


FIGURE 26
TO-BE scenario with SWOC integrated with fixed elements in LTE network (2a) and WSN architecture (2b), respectively

As a work package developed in the initial stage of the ETALON project, information from WP2 and WP4 concerning technical requirements and EH technologies for trackside train integrity and signaling, respectively, have been collected in order to build the three theoretical scenarios considering both the centralized cabling system and the decentralized EH systems deployed along the railway infrastructure. Indeed, the goal of the model was also to evaluate their economic impact taking into account if the infrastructure is sited in an urban or remote area. The economic evaluation has been done by developing an advanced capital budgeting analysis on a counterfactual basis by juxtaposing possible EH systems (TO-BE) with what would have occurred in absence of interventions (AS-IS). In doing this, we build a total cost of ownership (TCO) function with a parametric model that has been refined in order to facilitate a further sensitivity analysis.

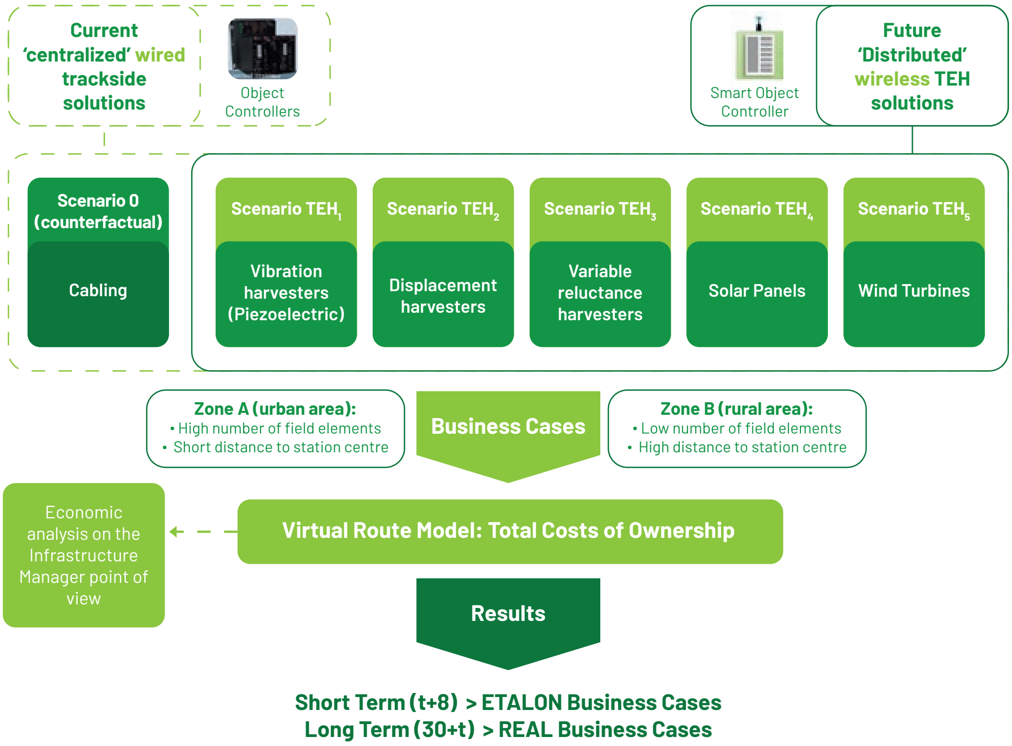


FIGURE 27
Description of the theoretical virtual route model (VRM) for the economic evaluation

The economic model has been called Virtual Route Model (VRM) since we build a 'theoretical' (virtual) railway route by using real inputs coming from the Partners of the ETALON Consortium and from the literature to compute and provide insights useful for the external stakeholders or decision makers in depicting the pros and cons in the migration from current AS-IS system towards TO-BE one. Useful and needed inputs (i.e., parameters and variables of the model) has been collected through a survey with all the technical Partners involved in the project and from suitable hypothesis and as realistic as possible assumptions. To achieve its goal, first ETALON WP6 performed an analysis of the state-of-the-art technologies for the most promising EH systems, based on mature and cutting-edge solutions that can provide the sufficient energy to power ultra-low power consumption smart

Economic Modelling

OCs and/or FEs as radio systems and energy storage solution for trackside smart objects (i.e., smart wayside objects control – SWOC). We exclude the more energy intensive FEs since they require a number of kW too much high to be powered by small EH solutions. After having collected a plethora of theoretical EH solutions from the literature and from the technological Partners, which can be transferred in the railway's field, WP6 identified the best five EH solutions, considering specific use cases: vibration harvester, displacement harvester, variable reluctance harvester, solar panel, wind turbine.

PARAMETERS	DESCRIPTION
Type of line	High Speed Line (HSL), mainline, regional line, freight line, length
Capacity of a route	Number of train in a route, traffic density, ridership (PPHPD)
Energy equipment and budget supply	Type, cost, metrics
Cables	Length (number of km in a route), cost of deployment, cost of dismantling in case of substituting with new EH systems
Cost of restore the line after cable theft	Additional cost for railway operators in case of theft of cables, damage of equipment, additional test on-site, deployment in the night, etc.
Operational (ordinary) maintenance	Costs and frequency of maintenance
Power consumption or energy efficiency	Metrics to measure energy efficiency of current cabling to be compared with the TEH systems
Geography	Urban, remote area (rural, regional area) and 'difficult to access' area (mountain, tunnels) where independent equipment could be needed
Suppliers of trackside technology for OCs	Names, size of enterprises
Labor Cost	Number of employee involved in the deployment and maintenance of current and future system
Theft of cables	Average economic value

FIGURE 28
Example of a subset of inputs and parameters collected for the techno-economic model (VRM)

Summarizing, the main high-level outcomes of the WP6 activities have been:

- Definition of a methodological approach for analysing different business scenarios differentiated by area (urban-centralized and remote-decentralized) and type of technology ('wired' cabling system, 'wireless' TEH solution for powering small radio communication systems);
- Collection and analysis of technological and economic data and parameters from the Partners of the ETALON Consortium and from the technical and economic literature;
- Definition of a functional form for a quantitative capital budgeting analysis and creation of a techno-economic model based on a Total Cost of Ownership (TCO) functional form (CapEx, OpEx, etc.) called virtual route model (VRM);
- Computation of a sensitivity analysis for providing some preliminary quantitative results of the deployment of future EH technologies;
- Elaboration of a SWOT (Strengthen-Weakness-Opportunity-Threat), Stakeholder, Market and Gap analysis of the introduction of EH solutions;
- Creation of a Decision Support System (DSS) tool through a spreadsheet and a guideline useful for future implementation of more realistic scenarios with new parameters' values.

The output of this techno-economic modelling approach requires further refinement with the collection of new inputs and parameters to figure out more precise results once more accurate real data could be collected thanks to the improvement and innovation of the EH solutions that can be supplied to the market.

D6.1 Analyses of the economic models for energy harvesting systems

FACTS & FIGURES

Total Project Value
1.7 million

9 Partners

Duration
30 Months

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