SAFE RAIL
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PROJECT N° :   FP6-PLT-506218

ACRONYM :   SAFE-RAIL

TITLE :   Development of an Innovative Ground Penetrating Radar System for Fast and Efficient Monitoring of Rail Track Substructure Conditions

INSTRUMENT :   SPECIFIC TARGETED RESEARCH OR INNOVATION PROJECT

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PROJECT CO-ORDINATOR :   D'APPOLONIA S.p.A.
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1   ABSTRACT

The SAFE-RAIL project is a Research & Development activity, funded by the European Commission in the frame of FP VI Sustainable Development, Global Change and Ecosystems Programme (Contract Number FP6-PLT-506218). Its purpose is the development of an innovative Ground Penetrating Radar (GPR) system for efficient, cost-effective, fast and safe rail track substructure conditions monitoring. The project was started in February 2004 and ended in 2008 with the successful completion of the demonstration phase: the SAFE-RAIL System prototype is now operational, and fully validated.

2   THE SAFE-RAIL PROJECT

2.1   Introduction

According to the EC White Paper "European Transport Policy for 2010: time to decide" (2001), the statement of improving capability and exploitability opportunities of European Transport Network represents the key strategic action for the Sustainable Development. In particular, the improvement of the capacity and safety of the railway infrastructure represents the main objective to be achieved in the midterm at both national and trans-national level. The accurate, fast and continuous assessment of rail-track conditions is today widely recognised as the primary need of railways owners and users towards the minimisation of the traffic slow-down and the optimisation of the network capacity and safety: as a matter of fact, extensive human resources are currently applied to the problem of evaluating railroad health, and important factors, such as the condition of the ballast, sub-ballast and sub-grade, critical in the maintenance and integrity of rail track systems, require subsurface measurements to be made. An innovative approach is required for optimising rail-track monitoring actions in order to minimise their impact and slowdown effects on the railway traffic. This can potentially bring to optimisation of the network capacity and safety. The SAFERAIL project was designed and proposed for developing efficient technological tools for achieving continuous assessment of the hidden and hard-to-monitor substructure conditions in fast and accurate way. The identification of the dielectric and geometric properties of the ballast layer is the main objective on which SAFE-RAIL project is focused; availability of such information concretely allows qualitative and quantitative evaluation of the conditions of the rail-track substructure. The SAFE-RAIL processing tools are designed to allow increasing risk management and accident prevention capabilities while optimizing planning of construction, reconstruction and maintenance operations along the rail network with the minimum possible degradation of rail network capacity.

2.2   Radar technology

The hidden and hard-to-monitor substructure conditions are extremely important to railway track performance. **Ground Penetrating Radar (GPR)** is today the most promising technology for non-destructive subsurface investigation and buried object detection, localisation and classification. A wide set of dedicated studies and relevant scientific literature is currently contributing to promoting GPR based solutions and technologies in several fields of application. Several railway companies have started to use GPR data for monitoring the condition of ballast and sub-ballast layers; GPR systems have been mounted on trains, lightweight inspection carts and also hand carried to measure ballast and substructure condition and to identify fouled ballast and trapped water on railroad. GPR technology based sensors are used to detect the geologic structure under the railway and to map the subsurface conditions giving the GPR images a good indication of the subsurface layer configuration.

Although the use of a GPR as railroad track's inspection equipment is becoming increasingly popular especially in Europe, it is usually performed with systems not particularly designed for such a purpose, and hence largely suffering from limitations arising from the specificity of the railroad application such as the high speed platform operation and the critical disturbances environment. The effectiveness of the Radar method is today strongly limited by the following main drawbacks:

- the actual ground and sub-ground dielectric properties cannot be accurately estimated and have a major impact on the achieved penetration depth and vertical resolution with currently used GPR antennas;
- the collected data positioning and referencing is difficult and often very inaccurate due to the fast moving platform and time triggered transmission;
- the on-board data interpretation and fault detection capabilities are very poor, and still primarily based on the visual inspection of collected radargrams by expert geophysicists;
- an integrated approach based on appropriate information technology tools is required in the long term monitoring of large (trans-national) railways infrastructures, in order to optimise planning and scheduling of maintenance policies.

Based on an evolutionary approach specifically intended to overcome the identified limitation of conventional radar instrumentation, the SAFE-RAIL project seeks to develop an innovative rail-track substructure conditions monitoring system. The successful completion of the SAFE-RAIL Project, thanks to this evolutionary approach, led to the following **major achievements**:

- To demonstrate the capabilities of quickly and accurately referenced detection, localisation and classification of rail track condition deterioration in the rail-track ballast, sub ballast and sub-grade;
- To provide a prototypic processor for user-friendly on-board diagnostic data interpretation and early warning against the probability of critical failures of the line.

2.3 SAFE-RAIL Team

The SAFE RAIL Consortium is composed by eight European partners, industrial and research centres, with substantial know-how in the design, development and use of GPR technologies and technological experience in diagnostic systems design and development and railroads monitoring services provision, as follows:

- a leading engineering design and consulting company specialised in the design and integration of radar-based systems as well as in the coordination and performance of RTD projects at International level (**D'Appolonia SpA**, Italy);
- the European leading Manufacturer of Impulse Radar Instruments for GPR applications (**Malaa Geoscience** Ab, Sweden);
- the Italian leading Manufacturer of Rail Diagnostic Systems and Provider of Rail track Monitoring Services (**Mer Mec SpA**, Italy);
- a Centre of Excellence in the field of antennas and equipment for non-destructive testing applications (**Federal Institute for Materials Research and Testing**, Germany);
- a Centre of Excellence in the field of Construction and Materials Assessment, specialised in the application of Information Technologies and Advanced Software Design (**Building Research Establishment Ltd**, United Kingdom);
- an Academic Research Centre in the field of neural electromagnetic computational techniques and algorithms design (**Dept of Electronics Engineering** – University of Pavia, Italy);
- two Subsurface Survey Service Providers Companies, specialised in site investigations (roads, railways, concrete, etc.) by means of GPR as well as other instrumentation (**Structural Testing Services Ltd**, United Kingdom; **G Impuls Praha spol. S.r.o.**, Czech Republic).

2.4 SAFE-RAIL Methodology

In the four-year project the SAFE-RAIL Consortium followed a coherent, engineering approach for the achievement of the stated objectives. The key implemented steps are the following:

- Identification of User main needs via engagement of End Users (Rail Track owners, Rail Track Maintenance Engineers);
- System Requirements specification and System Design, including the identified HW and SW sub-systems;
- Sub-Systems Development and Testing (prototyping, assembling, coding, etc.);
- Sub-system validation, including the collection of validation sources (e.g. commercial GPR data);
- System integration;

- System Testing via data acquisition campaigns in real scenarios with the collaboration of End Users;
- Assessment of system performances on the basis of the collected datasets.


3   THE SAFE-RAIL SYSTEM

3.1   System Architecture

The SAFE RAIL System is composed by the following major components:

- the **Fast Substructure Array Radar (FSAR)**, based on:
    - o **Innovative Antennas Array (ANTS)**, allowing precise estimation of subsurface layers while maximising penetration depth under any terrain conditions in real track scenarios and optimising high speed platform operations;
    - o **High Performances Radar Control Unit (HPRCU)**, allowing real time control of position channels and recording of raw collected data supporting train speeds higher than 300 Km/h;
- an innovative **Rail-Track Positioning Unit (RTPU)**, allowing fast and accurate measurement of the platform position and radar triggering;
- an innovative **On-Board Processor (OBP)** based on Expert Systems and Neural Networks Algorithms for real-time GPR data interpretation, acquisition strategy supervision and control, and user-friendly presentation;
- a **Networked Data Interpretation and Processing Software (NDIPS)**, supporting long-term monitoring of rail substructure conditions through the networking of different sensors operating along multiple segments of the railway infrastructure.

Figure 3-1 shows the SAFE RAIL System Architecture, in which the mentioned components are reported together with their Developers. The ANTS unit is suitably designed to be mounted under railway diagnostic vehicles (Figure 3-1) and is directly connected to the HPRCU. The OBP is located in the cabin on the diagnostic vehicle; it provides a user interface for System on-line results reporting and System control. The OBP is connected with the HPRCU to control the Antennas and to the RTPU, which gives the positioning information based on GPS technology and wheel odometer. Both the RTPU and the HPRCU are also located in the cabin close to the OBP unit (see Figure 3-3). The NDIPS unit is connected to the OBP with Software connection based on shared database. In Figure 3-4 we present the diagnostic vehicle used for live demonstrations.
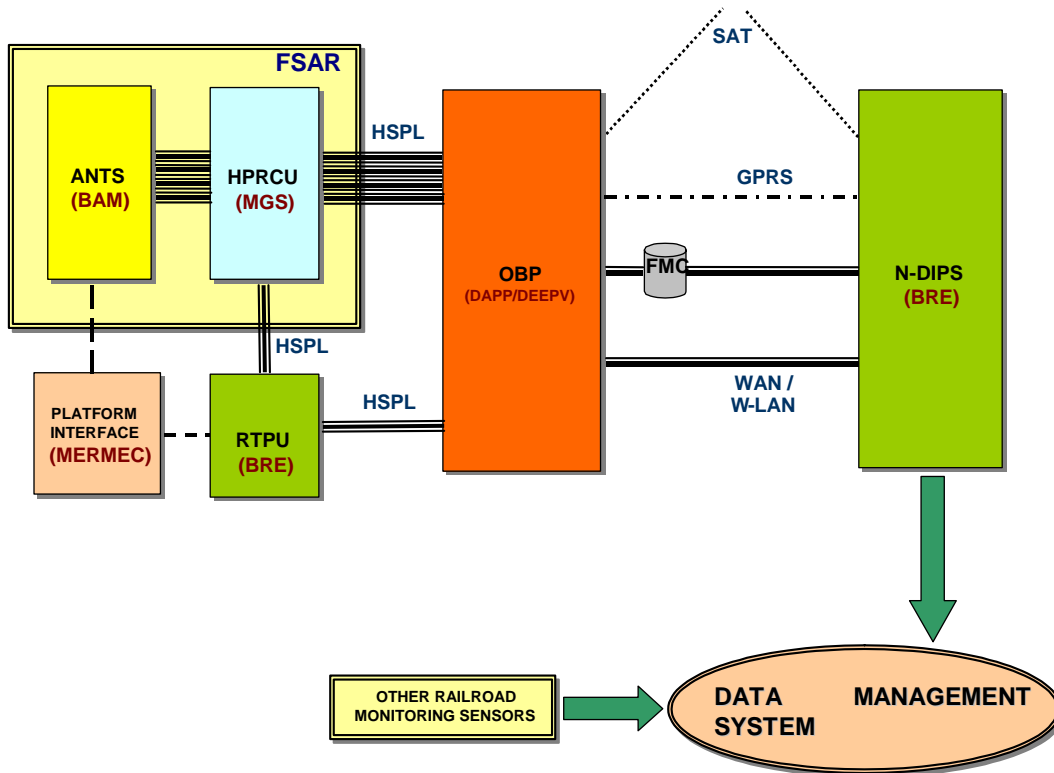
ANTS	Antennas System
HPRCU	High Performance Radar Control Unit
RTPU	Railtrack Positioning Unit
HSPL	High Speed Parallel Link
OBP	On-Board Processor
FMC	Flash Memory Card
N-DIPS	Networked Data Interpretation and Processing Software

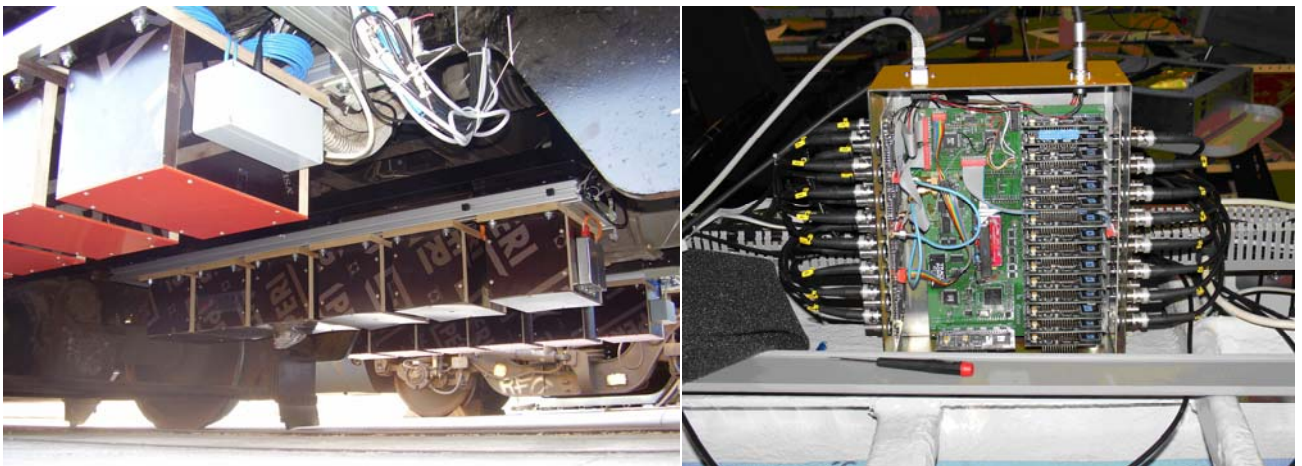**Figure 3-1 SAFE RAIL System Architecture.**

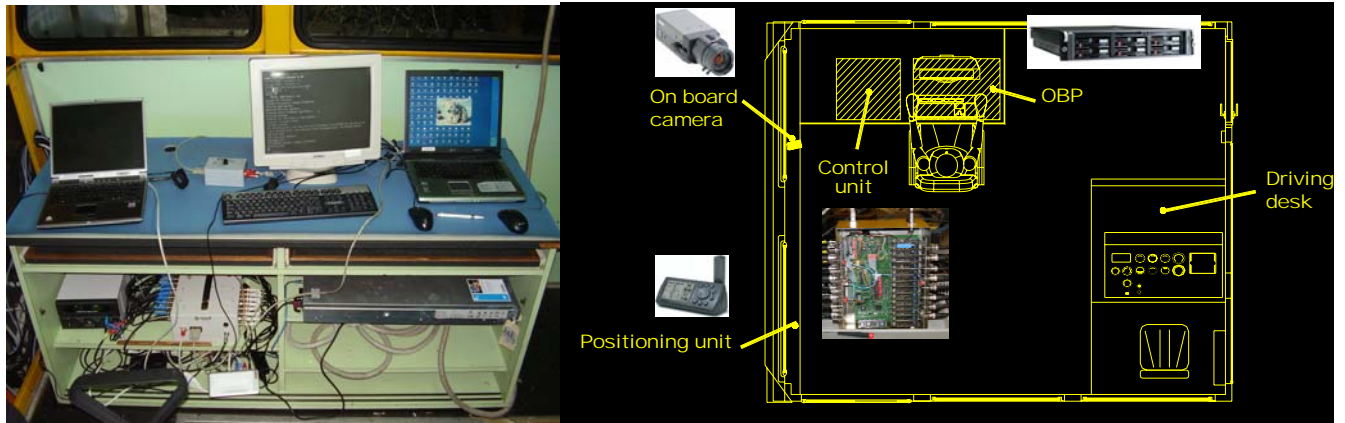**Figure 3-2 ANTS and HPRCU prototypes.**

Figure 3-3 OBP, HPRCU and RTPU in the diagnostic vehicle cabin.

Figure 3-4 Diagnostic vehicle.

3.2   Sample RESULTS from live tests

The main result of SAFE RAIL Project is represented by the operational, fully validated **system prototype** (see Figure 3-2, Figure 3-3 and Figure 3-4). The successful integration of the components and their subsequent validation represents an important goal due to the innovative technologies involved and to the development of components via a distributed strategy. The SAFE-RAIL system in final configuration completed its first run on real rail track scenarios in December 2007.

The following key results followed from the demonstration phase.

- **SAFE-RAIL Data Acquisition**. The acquisition campaigns by means of the integrated system prototype have been performed on different diagnostic vehicles involving up to three Antenna Arrays with a maximum of 15 simultaneous receiving channels. During data

acquisition different along track resolutions have been used as a function of train speed. The resolution has been varied between 2 cm to 1 metre while the vehicle speed has been raised up to 200 Km/h. The Prototype has shown the capability of transmitting the radar signal at the commanded repetition rates with continuity and to correctly acquire and store the collected data from the subsurface. Test campaigns have been performed on different railways tracks with acquisition distances up to 30 km;

- **SAFE-RAIL Data Interpretation**. The extraction of the information regarding the subsurface layers (ballast, sub-ballast, sub-grade) from raw collected data has been performed by the OBP during data acquisition tests in both on-line mode – showing the real time instrument processing capability – and in off-line mode for algorithms parameters tuning. Figure 3-5 shows the radargrams collected by the SAFE RAIL instrument, while Figure 3-6 reports the graphical user interface (GUI) on which the interpreted information is presented to the User in on-line mode;

- **SAFERAIL Data Inversion**. The **dielectric constant estimation** of the ballast layer by means of the Neural Network processing applied to the data acquired during test campaigns has been tested in on-line and off-line mode to ensure real time requirements and algorithms best tuning. Figure 3-7 presents sample results from Neural Network algorithms run, which are usually depicted on the GUI in Figure 3-6.
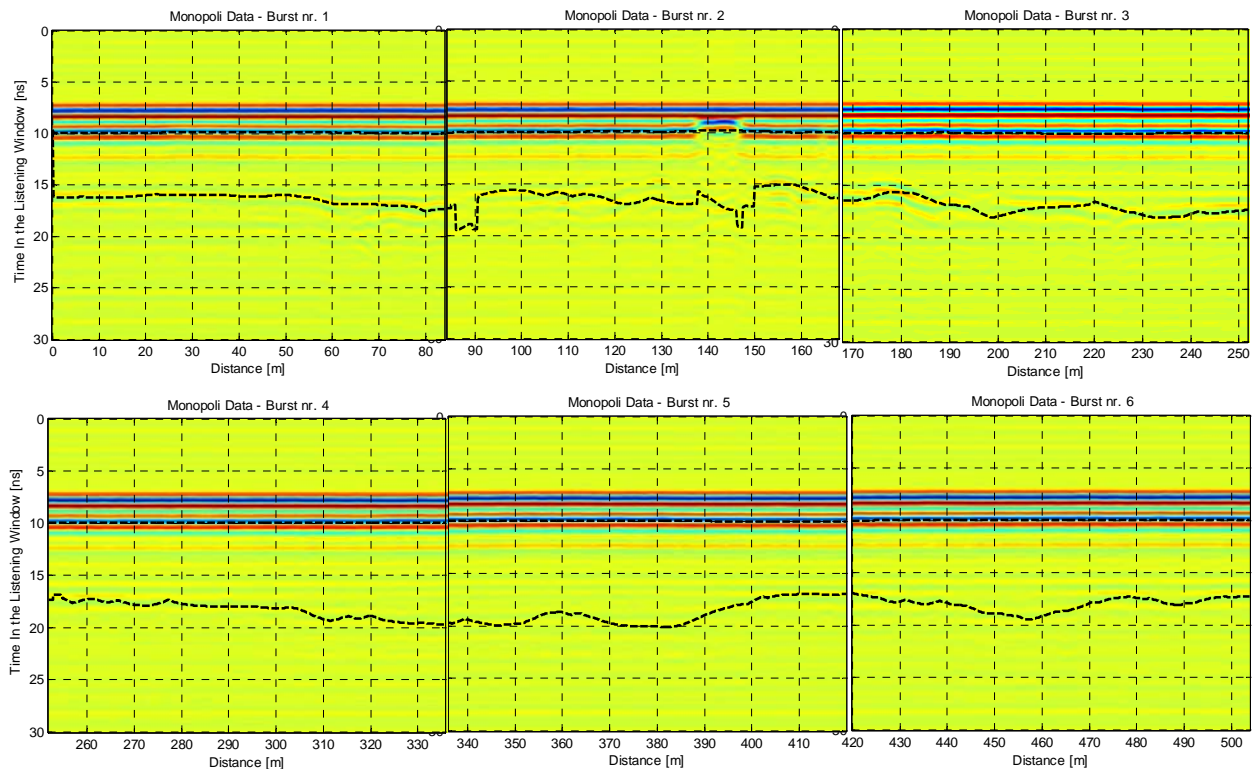
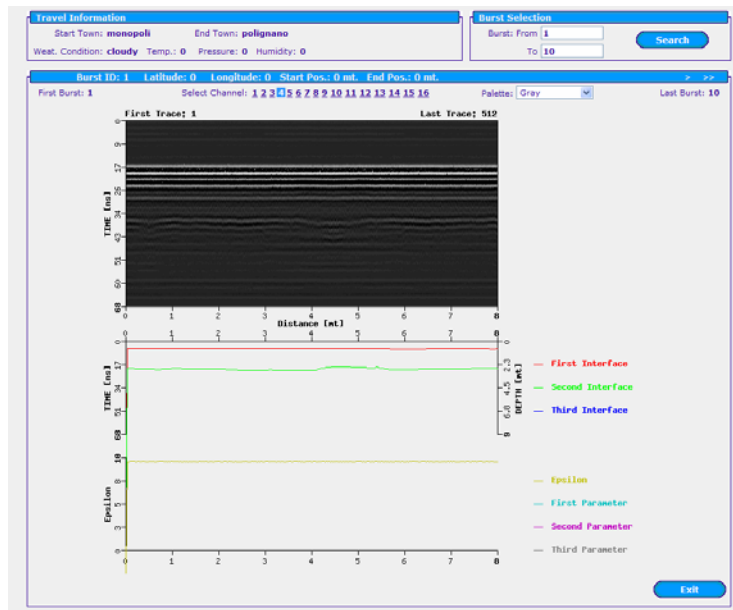**Figure 3-5 Interface extraction on GPR radargrams.**

Figure 3-6 User Interface for radargrams and interfaces extraction information
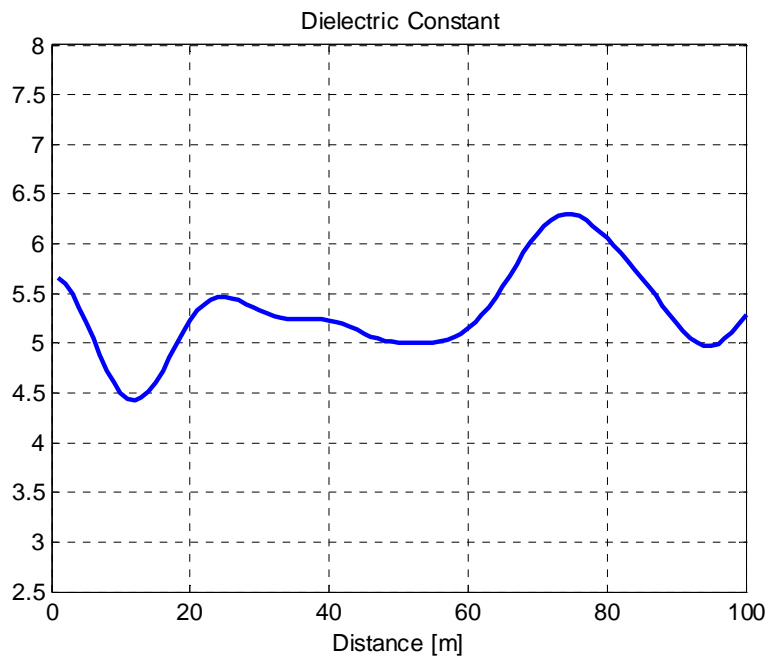

Figure 3-7 Dielectric Constant of ballast layer estimated by Neural Network processing.

4   THE WAY AHEAD

Two key issues depict the way ahead for the SAFE-RAIL System:

- The SAFE-RAIL system clearly demonstrated potential added value for applications based on fast monitoring of the subsurface. It yielded full complementary with the whole set of system/products used for the diagnosis of the rail track conditions, against which it has been analysed and compared. This is true from both technological and inspection/monitoring capabilities points of view.

- Though every single item of SAFE RAIL System can be exploited separately and located on addressable commercial sectors within its potentialities, it is fundamental to underline how the SAFE-RAIL system itself represents the main "vehicle" for addressing market's "exploration".

The full exploitation of the SAFE-RAIL scientific and technological results in the mid-term, will lead to the provision of improved performance diagnostic systems and platforms including powerful radar-based subsurface assessment capabilities, which will allow much more efficient, cost-effective, faster and safer construction and re-construction of railroads, as well as optimised planning of railways network maintenance strategies.

With more detail we can focus on the following main issues:

- SAFE RAIL System guarantees real-time data acquisition/processing/delivering directly on board enabling immediately integration of results on more complex diagnostic platform comprehensive of other diagnostics systems;

- SAFE RAIL high speed potentialities assure minimised impact on regular railways traffic. Actually the railway inspection typically requires the traffic interruption on inspected rails for the entire duration of the works with the subsequent traffic slow down; fast diagnostic platforms - for which the SAFE RAIL System is conceived – can monitor the railways without such constraints giving real time information about track conditions;

- SAFE RAIL System gives information on the conditions of the under-rails structures mainly represented by ballast, sub-ballast and sub-grade layers. State-of-the-art diagnostic Systems monitor the railways surface shape but can not give any insight of underground structures steadiness;

- SAFE RAIL System is thought to guarantee long-term monitoring and historical analysis of rail-track "health" trends by means of dedicated database and tools to collect and process data coming from different track/inspection time instants.

The abovementioned features of the System well match the requirements of the market and the user needs for continuous, efficient monitoring of the railways conditions in traffic management applications and maintenance operations.

With such assumptions, the results exploitation and market exploration routes of the SAFE-RAIL project will be directed towards:

- The industrialisation of a new Diagnostic System, able to perform surface and subsurface measurements from fast (>300 Km/h) train platforms, and featuring on-board user-friendly railroad condition estimation, as well as overall rail infrastructure monitoring through networked data interpretation and processing;
- The launch of an innovative portfolio of services for long term rail-track condition monitoring, featuring lower costs in spite of increased safety, speed and environmental care.

5   CONCLUSIONS

The SAFE-RAIL project fully succeeded in the development of an "Innovative Ground Penetrating Radar System for efficient, cost-effective, fast and safe rail-track substructure conditions monitoring". The main innovation issues in radar and ICT technology were addressed by the SAFE-RAIL Consortium through the effective design, implementation, testing and overall engineering of a rail-track monitoring system based on three antenna arrays in multi-channel configuration and on an innovative data interpretation and analysis tool based on expert systems and neural networks. The outstanding result of the Project, consisting in an operational, fully validated system prototype, paved the way to the integration of the SAFE-RAIL subsurface monitoring system on high-speed diagnostic trains for (i) the real-time subsurface assessment and the delivery of "diagnostic" information to the on-board operator, and (ii) the storage of the collected information for off-line multi-temporal multi-instrument analyses.

6   CONTACTS

For any inquiry please contact the SAFE-RAIL team at   **saferail@dappolonia.it**   or visit the Project web site http://**www.saferail-project.eu/**