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Decarbonization and climate change analysis of tunnels in an Asset Management framework through MIRET

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Abstract

The planning and the management of existing infrastructures (and tunnels) is already a central challenge for industrialized countries to manage heritage and strategic infrastructures ensuring a resilient asset against extreme events such as climate change. The functions and tools for assessing and mitigating the risks of climate change are fundamental for identifying and managing the elements of the territory, among which infrastructures play a key role due to their role and the numerous strategic interferences with the environment.

To meet this challenge in infrastructures and major civil works like tunnels, an approach for decision-making is being developed in a digital and multidisciplinary environment, which takes the name of MIRET (Management and Identification of the Risk for Existing Tunnels). ETS has established itself in recent years with numerous research and innovations in the field of sustainability and modelling the risk analysis of infrastructures. The risk process is built through a Stakeholders Engagement process involving Owners, Contractors, Designers, Government, Communities and Suppliers, and guided by the team of specialists of the Center for Climate Change (C3) of Rovira I Virgili University.

The paper focuses on the MIRET technologies and innovations to reach a more sustainable Asset Management of tunnels. The decarbonization is analyzed for the survey and inspections phase, comparing consolidated multi-dimensional mobile mapping systems and digitalized processes to the relevant baseline. In this framework, a focus is dedicated to two topics developed by ETS: the effort in implementing Artificial Intelligence algorithms for the transition towards Smart Data, and the quantitive approach to assess the climate impacts. The implementations are contextualised on actual case studies involving strategic tunnels in Italy.

Keywords: Sustainability, Tunnel, Digitalization, Climate Change.

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1. Introduction

The scientific community does not doubt that in order to prevent the worst impacts of climate change, global temperature increase needs to be limited to 1.5°C above pre-industrial levels, as called for in the Paris Agreement, through the cutting of emissions by 45% by 2030 until net zero will be reached by 2050 (Emissions gap report 2022). Currently, the Earth is already about 1.1°C warmer than it was in the late 1800s and global emissions continue to rise, so we're not on track: current national climate plans – for 193 Parties to the Paris Agreement taken together – would lead to a sizable increase of almost 11% in global greenhouse gas emissions by 2030, compared to 2010 levels. So decarbonization is the path we need to go through now to reach net zero emissions by 2050.

In these complex conditions, infrastructures have a crucial role, in fact, they represent a lifeline for sustainable economic and agricultural livelihood, as well as several indirect benefits including access to healthcare, education, credit, political participation, and more, enabling more efficient transportation of goods and people (Schweikert et al 2014; Kaluarachchi 2021). Particularly tunnels offer rapid connections maintaining insulation from the surrounding environment without spoiling the superficial environmental landscape.

The management of existing infrastructures (and tunnels) is already a central challenge for industrialized countries to manage heritage and strategic infrastructures ensuring a resilient asset against extreme events related to climate change (R B Jackson et al 2018). Nowadays, surveys and inspections of tunnels are usually performed by operators walking on the line and with the help of lifting platforms. The operator takes notes and photos of defects and fills the technical sheet (Foria 2022). This workflow is slow, so it needs partial to total disruption of the line and leads to subjective evaluations. The long time of the operations in situ generates a lot of emissions, caused mostly by transports, logistics and hotels where operators have to stay until they collect all data.

ETS has carried out the diagnostic and maintenance of existing tunnels through a multi-dimensional survey system (ARCHITA) and a new methodology for the Management and Identification of the Risk for Existing Tunnels (MIRET) (Foria 2020; Foria 2021). ARCHITA surveys the geometrical and structural conditions of the tunnel without influencing the traffic. MIRET is a methodology, a process and a technology made for the integration of such data and the digital management of the tunnels. The main challenge driving this process is the coexistence and collaboration of environmental sustainability and exponential technology growth.

To evaluate the decarbonization of the entire process, MIRET emissions of carbon dioxide were computed, analyzed quantitatively and compared with two baselines which represent the most common way to inspect tunnels nowadays, one for rail tunnels and one for highways tunnels, both studied regarding carbon dioxide emissions.

2. Asset management of tunnels

Asset management is defined as a systematic approach to governance through a cycle of actions in an iterative way (ISO 55000), and, applied to tunnel surveillance, it is the systematic process of inspecting, operating, maintaining, improving, upgrading, and disposing of assets in the most cost-effective manner (including all costs, risks, and performance attributes) for the realization of value from the tunnels over their whole life cycle.

Every country has its standards for surveillance activities. In this paper, two categories of inspections are considered: ordinary and principal inspections. Data and information collected during the inspections about the conditions of the tunnel are entered into a management system (REF).

Ordinary inspection is the most frequent, it takes place every three to six months depending on the status of the opera. if the tunnel shows any hazard, the inspection is quarterly, otherwise, if the tunnel has good conditions, it's inspected every six months. During this kind of inspection operators walk on the line and inspect visually the tunnel, when they see a possible defect, a lifting platform is stabilized to lift them close to the possible anomaly, and an operator traces the defect with chess or spray paint, and registers it on the technical sheet. Eventual non-destructive tests (NDT) can be integrated punctually depending on the organization and personnel experience.

A principal inspection takes place every one to three years also depending on the conditions of the tunnel. The frequency improves if there are hazards to the survey. This inspection's more thorough than the ordinary one. The visual inspection is integrated with specific destructive tests such as coring and endoscopy, and NDT such as ultrasound tomography, thermography and Ground Penetrating Radar (GPR). There are specialized operators to complete the principal inspection, as the tunnel has to be studied deeply. After collecting and elaborating all data, the defects and all the observations are computed on the technical sheet or specific prospect attached to the final inspection report.

Both ordinary and principal inspections are performed by operators on the line during a partial o total disruption of the line. The operator fills technical sheet following the owner's standards, national code and practice; Generally, these forms contain general information about the tunnel (e.g., name, line, length, excavation type, lining material) and the outcome of the inspection in terms of defects detection of the tunnel structures and collateral elements. A set of photos is taken to be attached to the final inspection report showing and analyzing the main compliances with the final assessment of the tunnel (Foria et al. 2021, Foria 2022).

2.1. Carbon footprint

The carbon footprint is the measurement of the total greenhouse gas (GHG) emissions released in the atmosphere by an individual, event, organization, service, place or product, expressed as carbon dioxide equivalent (CO_2e). It's essential to calculate how many greenhouse gases a process release. To assess a process's carbon footprint, it's important to consider all the activities that produce emissions: not only the CO_2 that an instrument or transport releases during usage, but also the emissions generated during its construction with respect to its Life Cycle Assessment (LCA).

This paper aims to calculate the carbon footprint of the MIRET process and to compare it with the carbon footprint of traditional tunnel inspection methods, in order to understand the effective benefits of MIRET in the field of GHG emissions and climate change mitigation.

With data about GHG emissions of the MIRET process, it was possible to perform a DNSH (Do No Significant Harm) analysis concerning objective 1 Climate change mitigation. DNSH is the fundamental principle of the European Taxonomy, which is a classification system, that establishes the requirements to evaluate if an economic activity is environmentally sustainable. DNSH principle says that every objective can't have, at least, any negative impact from every activity; the objectives can be sustained or have a significant contribution.

2.2. Baselines

The MIRET process has been confronted with two baselines that use traditional methods of inspecting, as described before, respectively for highway and railway tunnels. The general organization of these inspections is well-known thanks to the authors' experience, and it does not represent data or procedures officially released from any authority.

Regarding the highway tunnels, the ordinary inspection is usually performed by one specialized operator and four technicians for a total of five people on the line. As mentioned, before it's a visual inspection with the help of a lifting platform so the on-site operations proceed with an average pace of 0.25 km/h. The transports used for the process are a lifting platform during the inspection and cars for the logistics. Usually, the ordinary inspection doesn't require destructive tests, but operators can prescribe them if there's a hazard to be studied immediately, otherwise, the only instruments used are a reflex camera to photograph the defects and a PC or tablet to register them. The tests that can be performed during an ordinary inspection in a tunnel could be video endoscopy, ultrasound tomography or hammering.

The principal inspection of highway tunnels is similar to the ordinary one but it requires more specialized operators. The main inspector must be an engineer with a consolidated experience in the field. The total number of people on the line increases to seven: one engineer, four technicians and three operators for assistance. The transports are the same as the ordinary inspection: a lifting platform and cars for logistics. The principal inspection requires a deep study of the tunnel so it's necessary to implement tests beyond the visual inspection, the instruments necessary for the examination could be a hammer, drilling equipment, endoscope, caliper with measuring rod, emery stone, plaster, binoculars, reflex camera to take photos of the defects and PC or tablet to register them. The principal inspection is slower because of the tests required and the general deeper focus on the conditions of the tunnel, so its pace is approximately 0.11 km/h.

For the railway tunnel, the ordinary inspection needs one qualified operator and two technicians so there are usually three people on the line. The transports are the same as the ones used during the inspections of highway tunnels: lifting platforms for inspection and vehicles for logistics. This kind of inspection it's mostly visual but it can comprehend some tests. The instruments used to complete observations and tests could be: laser distance meter, crack meters, measuring tape, plumb bob, binoculars, magnifying glass, telescopic scale, hammer, reflex camera to photograph the defects and PC or tablet to register them. The operator, during the inspection, has to prescribe the right tests to study the specific hazards observed in the tunnel, nonetheless, if there isn't any evident defect, the ordinary inspection can be just visual. The pace of the ordinary inspection of railway tunnels is about 0.25 km/h.

The principal inspection of the railway is carried out by a team similar to the ordinary one: one qualified operator and two technicians, with altogether three people on the line. Also, the transports and the instruments needed are generally the same as the ordinary inspection, the main difference is that the principal inspection aims to study deeply the conditions of the tunnel, so more tests are required. The specialized operator needs to analyze and register the conditions of every possible hazard, so principal inspections are slower, with an approximate pace of 0.06 km/h.

The examination of defects during principal inspections for both the cases produces various kinds of data, so this kind of inspection requires a technician to process data in the back-office operations with a more elaborated final report.

2.3. MIRET: Management and Identification of the Risk for Existing Tunnels

The MIRET process allows for performing both ordinary and principal inspections, following a precise workflow. The tunnel survey made with MIRET methodology is based on the mobile mapping system ARCHITA which collects different kinds of data simultaneously without operators walking on the line. As mentioned before, new management approaches and technological methods applied to tunnels are necessary to reach the need to join costs and resources. This direction is followed by ETS and with this purpose, the MIRET process is developed. MIRET has a smart new unifying approach to the existing tunnels based on Figure 1, which represents the puzzle chart of the workflow, based on logical and coordinated decisions in a digital and multidisciplinary framework. This approach can be defined through the following milestones: Survey and inspection (SI); Digitization (DI); Defect Analysis (DA); Planning and design (PD); Work and Maintenance (WM); Monitoring (MO).

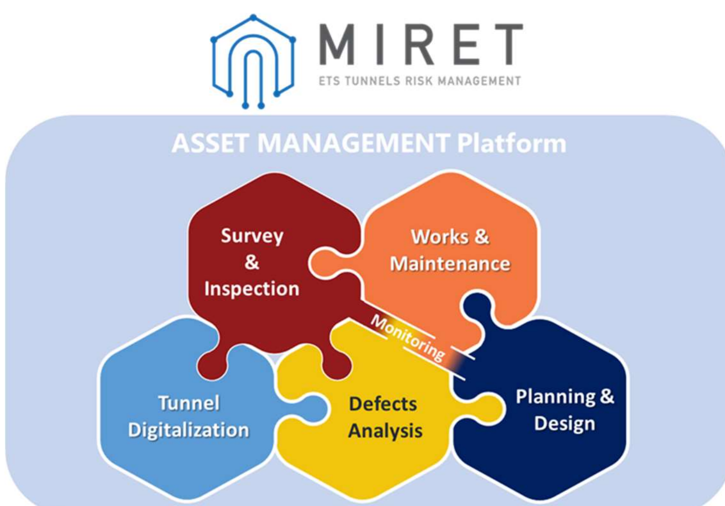

Figure 1: Puzzle chart of the MIRET workflow

More recent technologies allow the survey and inspection of tunnels and infrastructures with mobile mapping, ETS developed the mobile mapping system ARCHITA to collect all data with one system, and its usage results in multiple advantages such as:

- Eliminating intrusive structural surveys;
- Minimizing the time of traffic disruption;
- Increasing safety by reducing the time and number of operators working from within the tunnel, on the line;

- Increasing back-office activity: the data are acquired on-site, but the elaboration, the interpretation and the analysis are moved from onsite to the office, leaving only specific tests to be undertaken on-site;
- Integration with traditional methods and on-site measurements/inspections is possible.

ARCHITA, as mentioned before, is the multi-dimensional mobile mapping system developed by ETS consisting of linked and integrated equipment (Foria, 2019) of survey and positioning sensors. The system operates at an average speed of 5- 30 km/h and consists of (Figure 2):

- Laser scanner to acquire 3D point cloud;
- Linear cameras take high-resolution photos of the tunnel lining, detecting the components and the conservation state;
- GPRs to survey the ballast thickness, status and humidity, the lining thickness, and the cavities that lie behind;
- Thermal cameras to detect and double-check defects on the lining
- The different tools are integrated and linked to each other, allowing to the acquisition of multiple information for every single point simplifying the acquisition.

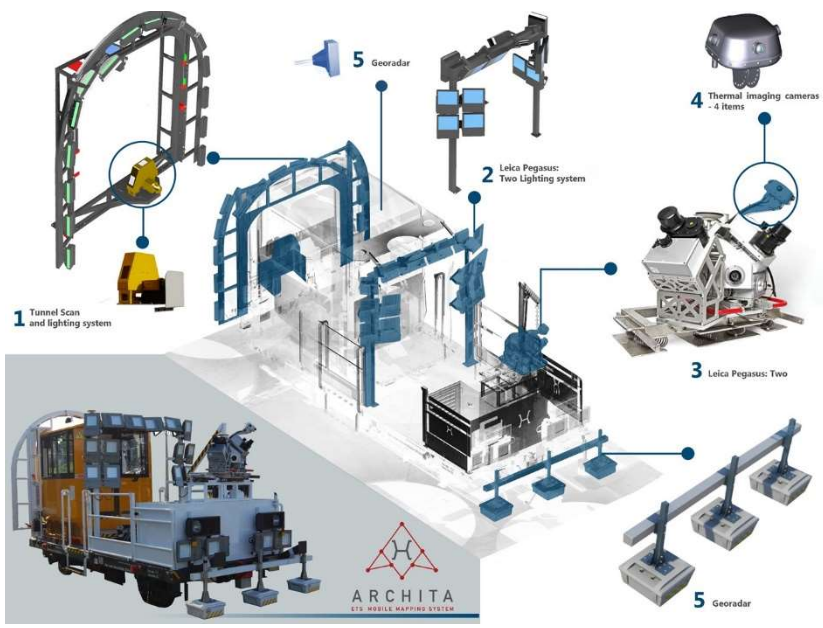

Figure 2: Representation of the multidimensional system ARCHITA and the single instruments (ETS). Configuration RAIL (2019).

To achieve an innovative multi-dimensional mobile mapping and integration by non-destructive diagnosis techniques, ETS developed both hardware integration and an IT environment for data digitalization and engineering. The mapping of the defects can be carried out by combining linear HD cameras and the laser scanner. The two technologies allow for positioning, measuring and quantifying the defects identified on the tunnel lining.

3. Analysis and results

After studying the general organization and characteristics of the ordinary and principal inspections made by the baselines and MIRET, all information about vehicles, instruments and workers was organized following an incremental approach and divided into six categories:

Transports: how many kg of CO_2 was necessary to make every vehicle and, based on its general duration, how many kilograms of CO_2 are released every kilometre;

Transport movements: the kilograms of CO_2 emitted for every kilometre during operations and logistics;

Materials/instruments: the kilograms of CO_2 used for their construction;

Operators and activities: emissions linked to every activity, for example, a significant source of emission is represented by personnel logistics necessary for operators when inspections last days or weeks;

Survey energy: CO_2 emissions required for the loading of the battery of the instruments;

Back-office: CO_2 was released for using the computers and software during the elaboration of data.

The emissions of CO_2 of every category are added to understand how much CO_2 is needed in total for every kilometer of tunnel studied whether during ordinary or principal surveys.

The following Table (1) shows the summary of the environmental accountability carried out concerning the average value resulting from all the aforementioned inspection and analysis procedures. The results are in terms of kilograms of CO_2 emitted per kilometer for the whole process of the ordinary and principal inspection for MIRET (M-), highway (H-) and railway (R-).

Table 1: kilograms of carbon dioxide emitted every kilometre of tunnel complete inspection. The results are in terms of kilograms of CO_2 emitted per kilometre for the whole process of the ordinary and principal inspection for MIRET (M-), highway (H-) and railway (R-).

Inspection	$KgCO_2$/km
M-ORIDINARY	60.1
M-PRINCIPAL	94.4
H-ORDINARY	147.2
H-PRINCIPAL	704.5
R-ORDINARY	132.2
R-PRINCIPAL	502.3

MIRET and the baseline emissions can be analyzed through pair comparison matrix to see the percentage ratio between every kind of inspection (ordinary and principal) accomplished. In Table 2, there is a comparison between total CO_2 emissions generated for ordinary and principal inspections carried out by MIRET (M-), railway (R-) and highway (H-) tunnel inspections.

Table 2: Percentage difference between CO_2 emissions generated during ordinary and principal inspections of M- MIRET, R-railway and H-highway.

CO_2 EMISSIONS MATRIX						
	M-ORDINARY	M-PRINCIPAL	R- ORDINARY	R- PRINCIPAL	H- ORDINARY	H- PRINCIPAL
M-ORDINARY	100.0%	63.7%	45.5%	12.0%	40.8%	7.1%
M-PRINCIPAL	157.1%	100.0%	71.4%	18.8%	64.1%	11.1%
R-ORDINARY	220.0%	140.1%	100.0%	26.3%	89.8%	15.5%
R-PRINCIPAL	835.5%	532.0%	379.8%	100.0%	341.2%	59%
H-ORDINARY	511.0%	325.4%	232.3%	61.2%	100.0%	17.3%
H-PRINCIPAL	1682.9%	1071.6%	765.0%	201.4%	578.6%	100.0%

It's evident from Table 1 and Table 2 that MIRET process needs significantly less amount of CO_2 emissions compared to traditional state-of-the-art procedures for highways tunnels and railway tunnels following the DNSH principle.

4. Conclusions and future prospectives

Researchers made clear there is an advantage in terms of climate change mitigation: MIRET process allows to cut emissions of up to 45.5% compared to nowadays highways tunnels ordinary inspections and up to 40.8% compared to railway tunnels ones. In case of principal procedure, the inspection phase on-sites includes destructive and invasive test for the operations that significantly increase the duration of the inspection and the impact in terms of emissions, instead of a gradual approach screening with non-destructive test. This result highlights that MIRET workflow can bring a significant contribution to the decarbonization of tunnel management and optimization of resources.

The less amount of CO_2 emissions generated by MIRET is possible thanks to many factors; one of the main contributors is represented by the pace of the mobile mapping system ARCHITA running at 5-30 km/h. Reduced time of in-line inspection weights a lot on CO_2 emissions for multiple reasons, for example, it's possible to have fewer logistics, such as a lower number of operators' car or wagon trips needed to arrive at the tunnel from dwelling or hotel during the period required to surveys the tunnel.

The workflow and technologies adopted by MIRET allow not only to cut CO_2 emissions and improve safety for workers on the site, but also to increase the reliability and objective of the outcome through time, moving the activity mostly to back-office operations. MIRET data are rather different from the visual observations performed during traditional tunnel inspections since they enable the generation of a digital twin of the tunnel allowing the comprehensive integrated analysis for risk assessment and maintenance through time.

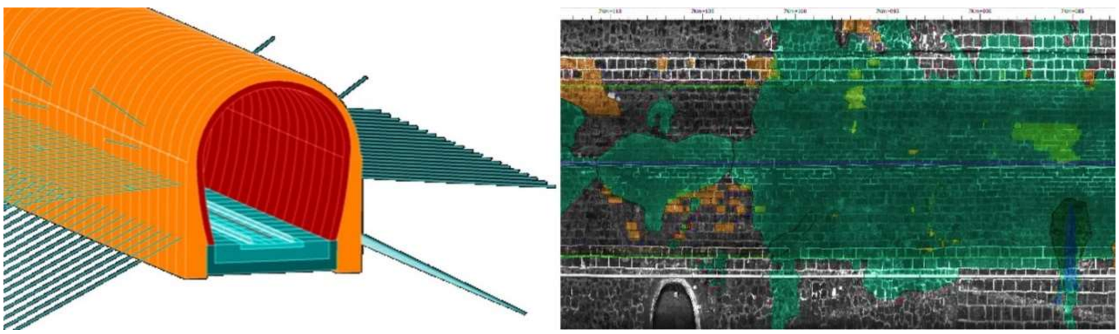

Figure 3: Digital twin of the masonry tunnel (Railway Viterbo-Attigliano): Rehabilitation (on the left) and Inspection (on the right).

Other than mitigation, also adaptation to climate change is a key challenge today. Two protocols (Breeam and Envision) allow the evaluation of the sustainability of infrastructures, also considering the resilience as a parameter. Tunnels are peculiar infrastructures, because their lifetime is usually very long and the sustainability evaluation become more important for maintenance and operation phases. Today protocols, instead, give more focus on planning and construction, and this topic should be taken in consideration while building sustainability protocols for tunnels.

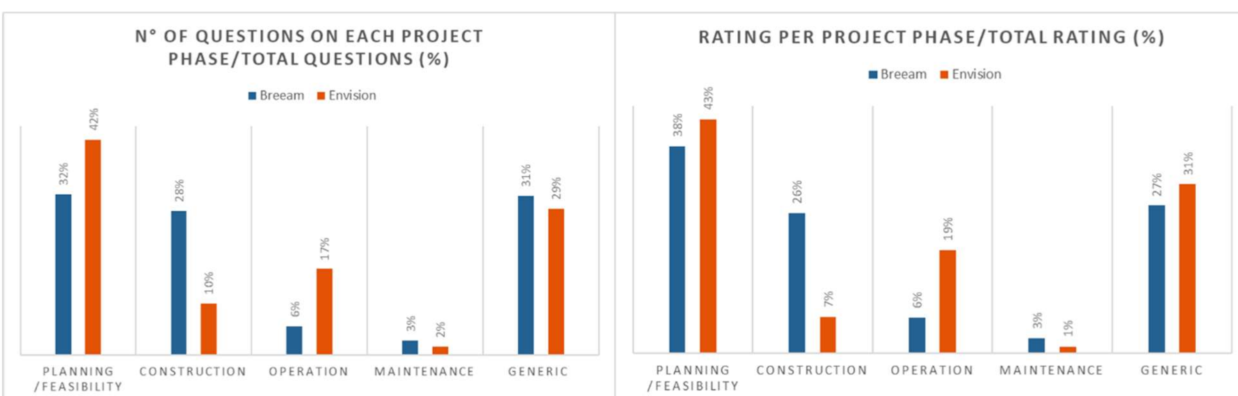

Figure 4: Comparison between Breeam and Envision protocols in terms of number of questions (a) and rating (b) for each project phase.

Long lifetime of tunnels, in some cases up to two hundred years (compared to the usually 50 years of lifetime for other infrastructures), is linked also to their resilience towards climate change effects. For this reason, a tool able to measure the vulnerability to climate change of tunnels will be of a crucial importance.

Following the method proposed by a research team of Universitat Rovira i Virgili (Font Barnet et al, 2021 and Boqué et al 2023) and tailored by ETS for infrastructures. it is possible to assess the vulnerability of tunnels against climate change. This method consists of a stakeholder engagement stage and co-creation process for definition of critical parameters, downscaling of past climate data and forecasting of possible future climate scenarios.

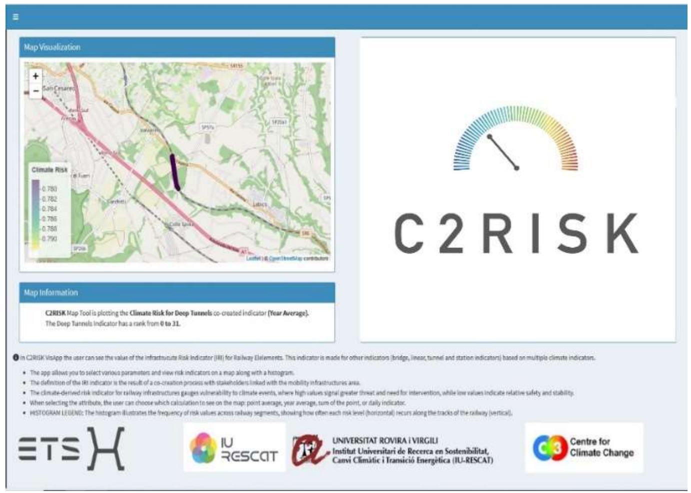

Figure 5: Example of a tool for the quantification of a vulnerability of a tunnel along a railway (C2RISK).

5. Acknowledgements

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