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ABSTRACT

Maintenance and protection of road infrastructures (RIs) are increasingly exposed to natural hazards. This requires an effective risk assessment and mitigation methodologies considering a suitable resilience approach. Accordingly, several research projects focusing on RIs have developed resilience frameworks built on anticipatory, absorptive, restorative, and adaptive capacities. Among these, PANOPTIS conceptual resilience framework deals with scenarios linked to disastrous events based on actual data-driven from sensors (terrestrial and airborne). The main aim of PANOPTIS is minimizing service interruptions and quickly recovering with a holistic approach through an integrated platform with structural and geotechnical simulation tools. This paper presents the use of sensors-based monitoring systems: skid resistance measurements through novel mobile and passive road sensors for road surface; and in-situ measurements by a remote-real-time-automated monitoring of corrosion velocity in steel rebars of reinforced concrete bridge structures. Data collected from sensors are processed using automated algorithms to assess the monitored RI states depending on various alert thresholds of control parameters for each application (e.g., corrosion rate and velocity, ice percentage, road surface friction, etc.). These parameters are integrated in a specific platform provided to support decisions-making owners, in this case RI operators. These RI operational monitoring systems contribute in the assessment of RI resilience, in particular for resilience indicators related to the anticipatory capacity of the system. Monitoring data plays a key role in risk reduction and control strategies against negative impacts of disruptive scenario, and to build resilience improving the continuity of RI service. Besides that, broadened idea of the monitoring on-site data reliability is presented.

Keywords: critical infrastructure, sensor-based monitoring, resilience assessment, performance indicators, corrosion, road surface friction

INTRODUCTION

Maintenance and protection of Road Infrastructure (RI) as part of country's Critical Infrastructure (CI), is essential to contribute the developments of a community assuring citizens' daily mobility and transport of goods. CIs are defined as "asset, system or part thereof in member states which is essential for the maintenance of vital societal functions, health, safety, security, economic or social well-being of people, and the disruption or destruction of which would have significant impact in a member state as a result of the failure to maintain those functions"(Mansfield, 2018). Moreover, RIs are often lifeline systems for rescuing people and for repairing and restoring other transportation systems. On this purpose, risk assessment methodologies should

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be integrated with a resilience approach in order to develop a methodological framework as adopted by recent EU policy trends (Theocharidou et al., 2020) to analyze and improve CI performance facing disruptive events. Resilience for CIs is defined as the "ability to anticipate, absorb, adapt to, and rapidly recover from a potentially disruptive event, whether naturally occurring or human caused" by National Infrastructure Advisory Council (NIAC, 2009). The concept of resilience and its assessment are defined according to its main characteristics through the evaluation of global resilience index or combining indices attributed to resilience capacities. In (Petit et al., 2013), components or procedures of the infrastructure system are identified to be associated with the different resilience capacities, then the assessment methodology is based on the related rankings or weighted values attributed. Several methodological frameworks (Francis & Bekera, 2014; Jovanovic. A.; Klimek, 2019; Nan & Sansavini, 2017; Rehak et al., 2019) are based on this approach, providing a general methodology for assessing resilience that was considered in this study in relation to its application to a RI system. Thus, by investigating different research projects addressing road infrastructure resilience, a list of resilience performance indicators (Prior, 2015) is referred to that can be attributed to the main resilience capacities. Within the PANOPTIS project (PANOPTIS, 2018), which aims to improve RI resilience, the resilience conceptual framework is based on a holistic approach to the main capabilities of a resilient infrastructure through the use of assessment tools that integrate data from a multiplicity of novel sensors monitoring the different RI components.

This paper shows how sensor-based monitoring system, in particular sensors for the corrosion detection of steel bars in reinforced concrete structures and for the skid-resistance of road pavements, can contribute to the anticipatory capacity of a resilient infrastructure. The presence of such monitoring systems is taken into account by performance indicators that are used for a qualitative assessment of the overall resilience of the road infrastructure. In addition, a reliable data driven on-site for the RI monitoring system is crucial for the road management authorities in order to provide a safe transport infrastructure considering best reliability engineering practices.

RESILIENCE AND PERFORMANCE INDICATORS FOR CRITICAL INFRASTRUCTURES

The definition of resilient infrastructure is a system capable of dealing with scenarios linked to disastrous events with the aim of minimizing service interruptions and quickly recovering, harmonized the different definitions of resilience associated with critical infrastructures. Then, a resilient CI is characterized by the anticipatory (predicting and resisting the impact), absorptive and coping (withstanding the damage), restorative (recovering after damage) and adaptive (modifying and adapting) capacities which are based on the 4R fundamental properties (Robustness, Redundancy, Resourcefulness and Rapidity) combined with Technical, Organizational, Social and Economic (TOSE) dimensions (Bruneau et al., 2003). Based on the above-mentioned capacities, several research projects dealing with CIs resilience have developed frameworks in order to evaluate and improve the resilience of the system against extreme and climate change-related hazard events. The main distinction between the different approaches is the type of assessment, i.e. qualitative or quantitative focusing on one or more of the resilience capacities. RESOLUTE project (Ferreira & Simões, 2016), focused on transportation systems, relies the methodology on qualitative estimation of the adaptive capacity according to operational pressures related to disruptive events. FORESEE project (Adey et al., 2019), on the other hand, considers a resilience quantitative assessment through specific indicators in terms of degrees of fixed service levels for passenger and freight transport. Other research projects, such as SAFE-10-T (de Paor et al., 2017), RESILENS (RESILIENS consortium, 2016), and EU-CIRCLE (Menaha et al., 2016) combine both qualitative and quantitative approach to take into account the contribution of anticipatory, absorptive and restorative capacities to the overall CI resilience.

The concept of CI resilience refers to a process contributing to system's ability to respond and recovery after a disruption; the identification and the measure of CI components' resilience degree is fundamental to manage disruption events and its consequences. Establishing a resilience measure allows to adopt suitable procedures for CI protection and risk management (Prior & Hagmann, 2012). Potential indicator for four main CI resilence capacities are setted for further assessment purposes including anticipatory, absorptive and coping, restorative and adaptive based on the research study conducted in Swiss National Strategy for Critical Infrastructure Protection (CIP) (Prior, 2015). In the resilience framework such as RESILENS and EU-CIRCLE take into account the indicators of resilience associated to each capacity, as reported in Table 1. CIP's study highlights how CI resilience is made up of the contribution of several factors that reflect the complexity of the system.

For this reason, it is important to underline that the indicators provide an estimate of one aspect/capacity of CI resilience. The overall evaluation should be a combination of these indicators, depending on the typology of infrastructure, the physical and organisational CI characteristics and the risk context.

Table 1 *Resilience capacities and related indicators.*

	Resilience capacities			
	ANTICIPATORY	**ABSORPTIVE&COPING**	**RESTORATIVE**	**ADAPTIVE**
Resilience Indicators	Probability of failure	Systems failure (unavailability of assets)	Post-event damage assessment	Substitutability (replacement of service)
	Quality of infrastructure	Severity of failure	Recovery time post-event	Adaptability / flexibility
	Pre-event functionality of the infrastructure	Just in time delivery - Reliability	Recovery/loss ratio	Impact reducing availability
	Quality/extent of mitigating features	Post-event functionality	Cost of reinstating functionality post-event	Consequences reducing availability
	Quality of disturbance planning/response	Resistance	Post-event damage assessment	
	Quality of crisis communication/information sharing	Robustness	Recovery time post-event	
	Learnability	Withstanding	Recovery/loss ratio	
		Redundancy		
		Resourcefulness		
		Response		
		Economic sustainability		
		Interoperability		

SENSOR-BASED MONITORING FOR RI RESILIENCE ASSESSMENT

The monitoring of road infrastructures in a pre-event scenario is necessary in order to increase their resilience, as the information it provides is fundamental for vulnerability assessment of the infrastructure to the various risks to which it is subjected. Moreover, the use of monitoring systems integrated into the various CI components or structures makes it possible to follow the evolution of eventual damage processes in real time in a post-event scenario. This constitutes a fundamental element to feed the CI anticipatory capacity as it is considered in PANOPTIS resilience framework for road infrastructure.

PANOPTIS resilience framework for road infrastructures

PANOPTIS resilience framework proposes to assess and improve the main resilience capacities through a holistic risk and impact assessment approach with an integrated system based on Holistic Risk Assessment Platform (HRAP). The conceptual approach, as shown in Fig.1, provides an integration of the different tools and components of the platform that contributes to each resilience capacity (PANOPTIS Consortium, 2019). The integrated management of components and processes provides: (i)prevention: options to minimize exposure of RI to hazards, through the more efficient and effective understanding and prioritizing of potential risk and threats ; (ii)reduction of potential impacts: enhance contingency planning and business continuity to ensure alternative supplies, reserve capacity, and/or rapid restoration of services ; (iii)adaptation to mitigating risk: investing in protection and defenses.

PANOPTIS resilience assessment combines qualitative and quantitative methods through several indicators referring to before and after events status of the RI system (Prior, 2015). Sensor-based monitoring of RI contributes mainly to the anticipatory capacity, that is the RI operational monitoring framework (corrosion sensors, passive and mobile road sensors, accelerometers, Satellites Mobile mappers/UAVs, fixed optical sensors, weather stations, Traffic control centre, ITS Systems, etc.). RI operational monitoring assess RI resilience before, and independent from, a shock or disturbance in terms of the following indicators: (i)Quality of infrastructure,(ii)Pre-event functionality of the infrastructure, (iii)Quality/extent of mitigating features, (vi)Quality of crisis communication/information sharing.

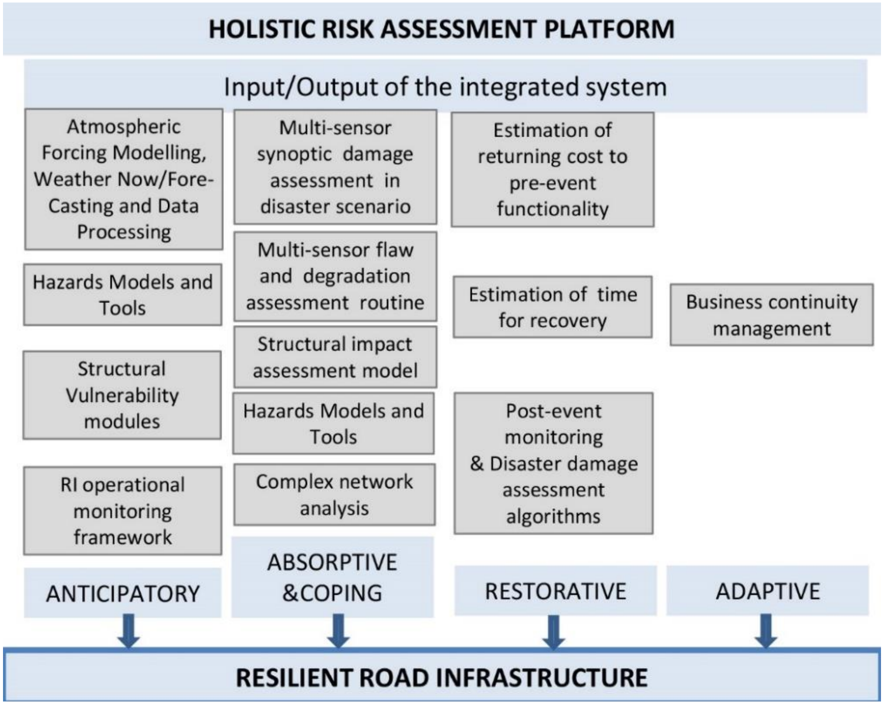


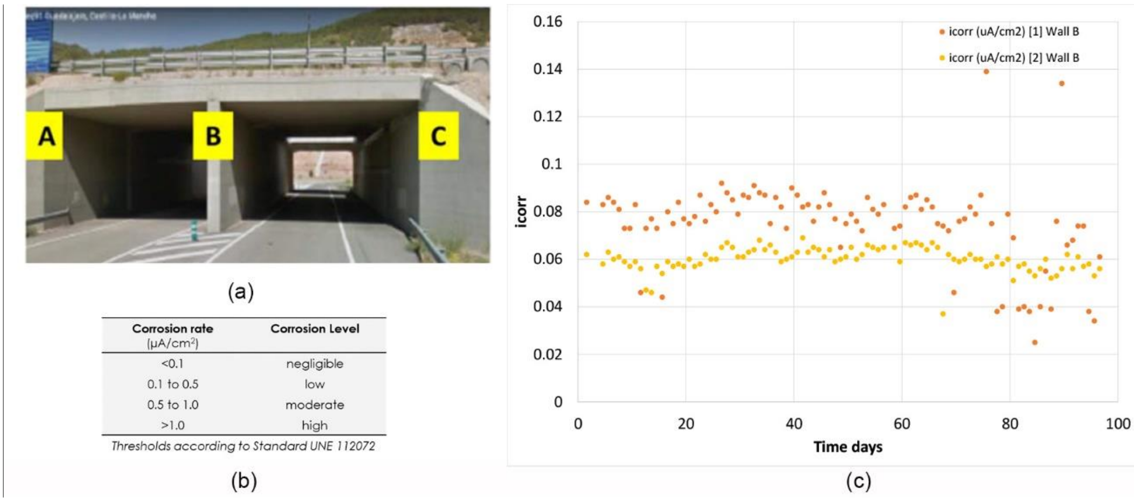
Figure 1 *PANOPTIS Conceptual Resilience framework ((*PANOPTIS Consortium, 2019)*).*

Sensor-based monitoring for road infrastructure

Corrosion sensors

Reinforced concrete structures such as bridges are strongly affected by corrosion phenomenon due to the depassivation of the passive layer of steel rebars embedded in concrete elements. The corrosion process is activated by the presence of chloride ions or CO_2 as aggressive agents in the environment. The corrosive attack due to the penetration of chloride ions can take place only when the concentration of chlorides reaches a (critical) threshold value in the concrete in contact with the reinforcement (Angst et al., 2009). Then, the corrosion rate depends by concrete physical-chemical properties such as resistivity. Indeed, concrete electrical resistivity (ρ) is a main qualitative parameter for inspection and monitoring system as four level of corrosion risk are detected according to (ρ) or the related current density (i_{corr}) (Rob B. Polder, 2001). The most widely used resistivity measurement technique for existing concrete structures is the four-points Wenner methods. The technique is a non-destructive method using a four-points probe applied to the concrete surface to measure the electrical resistance converted in apparent resistivity. Embedded monitoring methods are being used with greater frequency as they allow for real-time monitoring of concrete resistivity with associated parameters. The advantage is therefore better control of the parameters and the continuous real-time monitoring of the corrosion process of an existing RC structure.

For the corrosion measurements in the PANOPTIS project, a monitoring system through embedded sensors is installed on the surface of the steel rebars in two real scale RC bridges cases in Spain. These sensors are monitoring the corrosion intensity on real time (Fig.2). The INESSCOM (Integrated Network Sensors for Smart Corrosion Monitoring) system developed by Universitat Politècnica de València (Ramón et al., 2021) is a continuous semi-destructive monitoring embedded system allowing the continuous measurement of several corrosion parameters, particularly the corrosion intensity and velocity. The use of accumulated charge curve allows detecting the beginning of passive layer destruction and the progression of corrosion process. Therefore, embedded monitoring systems are beneficial compared to the classical method of on-site resistivity measurements as they assure: (i)multi-parameter monitoring, (ii)accessible remotely results, (iii)totally autonomous system, (vi)low maintenance.



Corrosion rate (μA/cm²)	Corrosion Level
<0.1	negligible
0.1 to 0.5	low
0.5 to 1.0	moderate
>1.0	high

Thresholds according to Standard UNE 112072

(b)

Figure 2 *RC Underpass of Spanish Highway section monitored through INESSCOM system, two sensors are applied to each underpass's walls B and C, related recorded i_{corr} data (c).*

Passive Road-based sensors

In last decades the measurement of skid resistance and friction coefficient of the road surface was based on various manual techniques, details can be found in previous literature studies (Acikgoz, 2016; Fwa & Chu, 2021; Rasol et al., 2021). In the framework of the PANOPTIS project, two main novel road-based sensors are used for the data collection on the road surface pavement of Spanish demo site highways section. These two sensors are defined as followings.

Mobile Advanced Road Weather Information Sensor (MARWIS) is a mounted sensor on vehicles on the road highway. The distance between the sensor and the road surface must be in a range 0.5-2 meters. The working principles of this sensor is based on the infrared measuring; four transmitter and two receiver diodes are capturing the reflected behaviour of the road pavement surface at a different wavelength. Various spectral properties of different substances can be measured via this sensor (e.g., ice percentage, water film thickness, snow thickness, ambient temperature, pavement temperature, dew point temperature, humidity and relative humidity, road condition and friction of the road pavement surface) (Lufft, 2021). The analysis and relation between such parameters and friction coefficient, or/and skid resistance is crucial to advance the knowledge about the functionality of the road surface in respect to the traffic management procedures. This could be significant for enhancing the RI resilience and particularly in the extreme weather condition. In addition, during the installation of MARWIS sensor, it has to be considered that vehicles will not disrupt the sensor face to avoid any inaccuracy in the data collection task. Sensor is protected from turbulences and dirt by a strong housing system 8900.G01 and 8900.G02.

Intelligent passive road-based sensor is considered one of the most efficient innovative technologies to monitor the meteorological factors that could have an impact on the traffic management procedures on the road highways. This sensor is commonly installed on the road surface in front of the vehicle acceleration direction (Fig.3). Besides, the intelligent passive sensor is connected to 4-pin cables with a length of 50 meters or 100 meters relying on the cable type and distance interval between sensor and control device. Similar to the

MARWIS sensor, several parameters could be measured by this passive road sensor such as temperature of the pavement, ambient temperature, ice percentage, road condition, water film height, friction and freezing point or freezing temperature (Rasol et al., 2021). The main purpose of the use of above-mentioned sensors are a real-time automatic monitoring weather condition related data, and the road surface friction of the roadways. Based on the above-mentioned information, an appropriate thresholding of the traffic management procedures could be standardized for a specific region. This can support the decision-making owners/end-users and operators to provide the most possible adequate required action for the traffic management system.

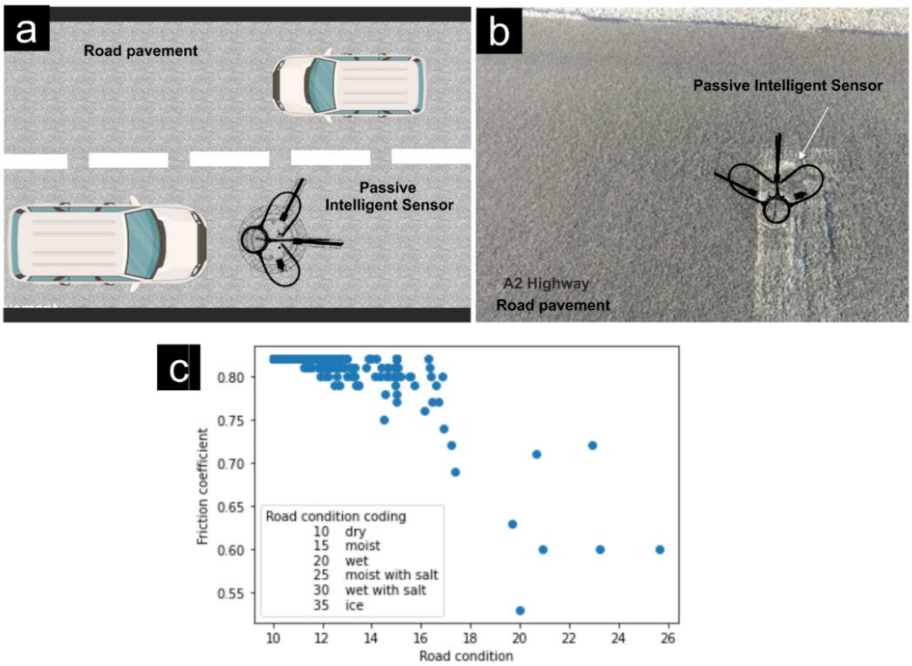


Figure 3 *Road surface friction monitoring on Spanish highway section: a) scheme of the road pavement while sensors are installed, b) On-site installed passive sensor, c) Results of road surface friction influenced by road conditions (adapted from* (Rasol et al., 2021)*).*

CONCEPT OF DATA RELIABILITY FOR RI MONITORING

An increase demand of a stable road networks has become a priority of road management authorities. The reliability analysis of the transportation system and monitoring techniques is crucial in order to provide a better and reliable services for transport infrastructures. Incorporation of the reliability analysis as an integration process involved in different construction process stages including planning, design, construction operation, monitoring and maintenance cycles of the critical infrastructures. In previous research studies, the importance of the reliability has been illustrated as a lifeline for transportation system (Chen et al., 1999; Iida, 1999). Reliability should not be limited only in the case of the extreme conditions, but also the daily operation disturbances (i.e., accidents, traffic congestion, unfavorable condition, road surface diagnostics, and advance understanding of the traffic management plan). The main aspects of the reliability are focused on the followings. Connectivity reliability is related to the probability of the network nodes remaining connected. Commonly the terminal reliability is the existence of a known path between two main road paths, which is origin-destination pair (OD) (Iida, 1999). Travel time reliability of the network is one of the main measurement indicators of the reliability analysis of the transportation system. This is considered as a success probability of the trip given between origin-destination pair (OD) within a specific internal time under normal daily flow variations (Chen et al., 2002). The concept of reliability is expanded due to the best reliability engineering practices to improve the reliable road infrastructures. An appropriate reliability analysis of the data driven in the real case studies could significantly improve several aspects of the functionality of road infrastructures. In this sense, several aspects are presented as follows (Kurtz et al., 2019): (i)Decrease the cost of the maintenance,(ii) Increase the lifeline time, despite the maintenance demands, (iii)Increase the operation efficiency for the road infrastructures, (vi)Accelerate an innovative system to mitigate failures and new design criteria.

Future trends of the reliable data collection and analysis is essential to increase the probability of an efficient monitoring approach for road infrastructures. On the other hand, in PANOPTIS project different non-destructive techniques and sensor-based analysis are proposed in various aspects such as corrosion monitoring in prestressed concrete bridges, influence of the weather condition on the road surface skid resistance measurements. In order to provide a useful tool for decision-making owners and operators, an advance knowledge of the reliable data is a key to understand a comprehensive knowledge of the road management systems.

CONCLUSIONS

RI maintenance and protection is a crucial issue for safeguarding the economic and social life of a country, in particular, related to the continuous and increasing exposure of critical infrastructure to extreme events linked to climate change or aging events. To this end, the resilience assessment of a road infrastructure is considered as an essential task in order to improve RI performance. The complexity of RI systems requires an appropriate assessment methodology based on the needs and actual condition of RI. PANOPTIS project, presented in this paper, relies the resilience assessment of RI system through performance indicators associated to the main resilience capacities. Among this, anticipatory capacity benefits from the presence of RI monitoring systems in order to enhance the related anticipatory performance indicators. Indeed, a sensor-based monitoring system integrated in RI component such as embedded sensors for steel rebars corrosion in RC bridges, or for skid resistance in road pavement allows real-time monitoring and provide valuable data correspond to the vulnerability of such infrastructures prior and post a disruptive event but also in operation conditions. Moreover, the use of a monitoring system increases the reliability of an infrastructure in terms of lifetime and maintenance demands. Besides, the importunacy of the developed models for a reliable operation and mitigations procedures of resilience RI system against disruptive events is discussed. Sensor-based monitoring systems allow a valid resilience assessment including a big data driven from real scale infrastructures and availability of the historical changes of different events. This could support better understanding of the future events and reinforce of the RI systems, as it is supported by data quality and availability.

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