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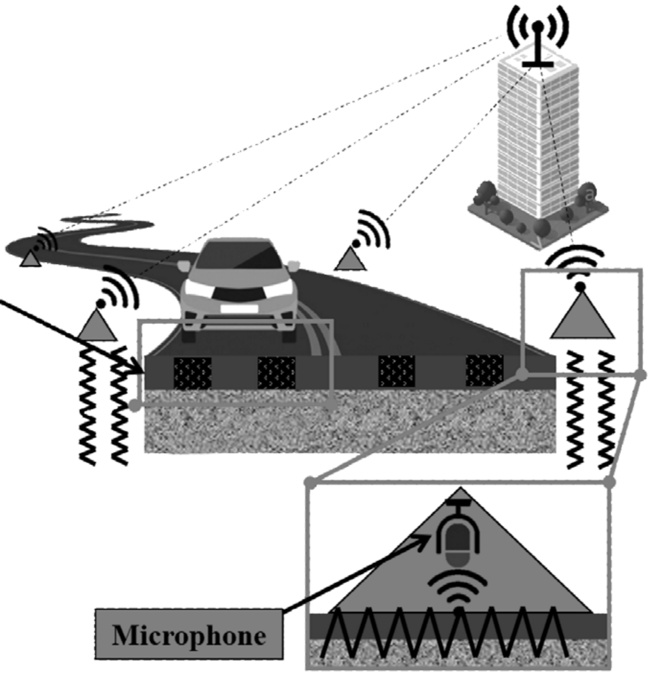

Materiali e tecnologie intelligenti per allerta, monitoraggio, e per aumentare la vita utile delle infrastrutture di trasporto

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Differenti approcci possono essere utilizzati per rendere le città e le infrastrutture di trasporto più intelligenti, sostenibili e durature. Queste tendenze influenzeranno positivamente il lavoro di molti portatori di interesse come ad esempio le autorità competenti, le società che si occupano di strade, i cittadini, gli utenti, ed i veicoli senza guidatore. Sfortunatamente, malgrado il fatto che i materiali intelligenti sono sempre più utilizzati, il livello di integrazione tra materiali intelligenti e tecnologie per l'allerta precoce ha ancora bisogno di un approccio olistico.
Alla luce di questo, l'obiettivo principale del lavoro presentato in questo documento è quello di fornire una panoramica su soluzioni basate su materiali e tecnologie che potrebbero essere utilizzate nel campo delle infrastrutture di trasporto per soddisfare alcuni degli obiettivi della risoluzione per lo sviluppo sostenibile (Sustainable Development Goals) *delle Nazioni Unite (A/RES/70/1/2015). Le soluzioni su citate includono un metodo innovativo, messo a punto dagli autori della memoria, il quale è basato sul concetto di firma vibro-acustica. Il metodo su citato è una soluzione basata su test non distruttivi (NDT) e sensori per l'identificazione di danni nelle pavimentazioni stradali. Il metodo proposto è stato validato attraverso simulazioni fatte con un modello agli elementi finiti (FEM), e indagini sperimentali seguite da un'analisi dati svolta usando un modello basato sull'apprendimento automatico (machine learning).*
I risultati mostrano che materiali e tecnologie intelligenti possono essere utilizzate per raggiungere gli obiettivi della risoluzione A/RES/70/1/2015 e migliorare la sostenibilità delle attuali e future pavimentazioni stradali.

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ArcHistoR EXTRA 6 (2019)
ISSN 2384-8898
Supplemento di ArcHistoR 12/2019
ISBN 978-88-85479-08-1
DOI: 10.14633/AHR197

Smart Materials and Technologies for Early Warning, Monitoring, and Increased Expected Life of Transportation Infrastructure

Filippo Giammaria Praticò, Rosario Fedele

This paper refers to two out of the seventeen Sustainable Development Goals defined by the General Assembly United Nations (Resolution A/RES/70/1, September 25th, 2015). The work reported in this paper is focused on Goal 9. *Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation* – and on Goal 11. – *Make cities and human settlements inclusive, safe, resilient and sustainable*. To be more precise, this paper refers to several sub-goals (i.e., 9.1, 9.4, 9.c, and 11.2) and reports possible solutions that can be classified into two main classes:

- those related to materials (i.e., 9.1.a, 9.4.a-b, and 11.2.a);
- those related to technologies (i.e., 9.1.b, 9.4.c, 9.c, and 11.2.b-c).

For this reason, aiming at providing crucial information on the two classes of solution mentioned above, the two corresponding sections were introduced. Finally, a solution (i.e., a monitoring method for road pavements) developed by the authors of this paper is presented.

Smart Materials to Increase the Expected Life of Transportation Infrastructure

This section of the paper focuses on different strategies to develop quality, reliable, sustainable, resilient, and safe infrastructure (cf. Goals 9 and 11). In particular, it includes possible solutions to obtain innovative and smart materials which act on Asphalt Concrete (AC) mix design.
Smart materials are «materials, which possess the ability to change their physical properties in a specific manner in response to specific stimulus input»[1]. With this in mind, several solutions were proposed in order to promote the self-healing of AC road pavements and change their life expectancy. Note that AC may be considered a self-healing material because it has the built-in ability to automatically repair damage to itself. This process can be fostered and strengthened as follows[2]:

- rejuvenators (i.e., substances of a high penetration value that are able to recover the viscoelasticity of the aged bitumen of the wearing course layer);
- healing agent encapsulation (i.e., microcapsules that contain recuperating substances, e.g. resins that are broken up by the energy produced by the micro-cracks occurring in the AC);
- nanoparticles, such as nanoclay (used as aggregate, which have the ability to repair small scale splits), or nanorubber (melted into the bitumen, which has the ability of enhancing the mending properties of the bitumen);
- randomly direct/oriented fibres. Electrically conductive filaments and fillers (such as carbon strands, graphite, steel filaments, steel wool and the conductive polymer polyaniline) are used to obtain the Fibre-Reinforced Asphalt-Concrete (FRAC). Induction heating is used and it takes advantage of electrical conductivity and of the thixotropic effect. An increase in the life expectancy of about 10%, energy savings of about 3%, and a decrease in CO_2 emissions of about 3% can be obtained (see note 2). Improvements are still needed in terms of technologies and modelling while several doubts still remain, because the technical levels have not yet been achieved, legal obstacles and the involvement of several stakeholders[3].

Note that the use of smart materials should be linked to the use of waste/alternative materials. Alternative materials for road construction have been proposed and analysed in terms of Lifecycle Cost Analysis (LCA)[4]:

1. Susmita 2013.
2. Mahajan, Joshi, Goliya 2017; Sun *et alii* 2018.
3. Poulikakos *et alii* 2017.
4. Balaguera *et alii* 2018.

- using Reclaimed Asphalt Pavement (RAP). An exhaustive analysis[5]showed that, although the use of RAP is a well-established and efficient way to save money and materials, a proper design is required to avoid a more expensive maintenance process, negative impacts on greenhouse gases, and higher energy consumption (which depends on moisture and RAP contents, blending efficiency, and performance levels);
- using other waste in the mixture. For instance, by-products, such as Crumb Rubber (CR), plastics, blast furnace slags, fly ashes, leachate, glass, concrete, wood ash, and fire extinguisher powders have been recently taken into account as alternative materials because of the restrictions on landfill disposal[6]. Bio-oil by-products (e.g., waste cooking oil) were taken into account as a substitute for bitumen (bio-binders)[7]. The first results show that bio-binders have a higher recovery ability and fatigue performance than conventional binders, but this success depends on their inner characteristics. Another possibility refers to the use of the Crumb Rubber (CR), as an additive in the asphalt binder (wet process) or as a substitute for aggregates (dry process)[8].

Smart materials, recycling, and reuse interact with mix types. Porous pavements include Porous Asphalts (PA), Porous Concretes (PC), Open-Graded Friction Courses (OGFC), and permeable friction courses (PFC). They are able to improve drainability and skid resistance, minimizing hydroplaning, reducing the flash flood risk, reducing splash and spray, improving visibility, and reducing noise levels between the tyre and the road surface[9]. Their main disadvantage is the occlusion of the surface and internal pores (clogging) that dramatically affects their advantages (i.e., quietness and drainability). They can be used to deal with the Urban Heat Island (UHI) effect, together with reflective pavements (which are light coloured, have increased albedo, and reflect primarily visible wavelengths)[10]. These latter are included in the set of “cool pavements”, and have been pointed out by the US EPA together with other possible strategies (i.e., the use of trees and vegetation, and of green and cool roofs). Cool pavements are able to:

5. Chen, Wang 2018.

6. Praticò, Moro, Ammendola 2010; Praticò *et alii* 2016; Jamshidi *et alii* 2017; Appiah, Berko-Boateng, Tagbor 2017; Wang *et alii* 2018.

7. Yang, Suciptan 2016; Wang *et alii* 2018.

8. Hassan *et alii* 2014; Praticò, Moro, D’Agostino 2015; Wulandari, Tjandra 2017.

9. Koshy, Sachdeva, Sreedevi 2015; Bichajlo, Kolodziej 2018.

10. US EPA 2008.

a) store less heat than the conventional materials;
b) reduce the risk of rutting (premature depressions) due to heavy vehicles;
c) slow the rate of aging, and, in turn, minimize the related road distresses.

Technologies for Early Warning and Monitoring to Increase the Life Expectancy of Transportation Infrastructure

The use of Information and Communication Technologies (ICT) in order to develop Intelligent Transportation Systems (ITS) is encouraged by the Directive of the European Union 2010/40/EU and aims at targeting goals 9 and 11 above.

Intelligent Transportation Systems (ITS) are needed for all the involved stakeholders (authorities and agencies that are responsible for the assets' management, users, service providers, etc.) in order to:

a) gather road (e.g., infrastructure characteristics), traffic and travel data (e.g., historic and real-time data on traffic characteristics);
b) optimize the use of the collected data through processing that aims at extracting important information from them;
c) use the information extracted to improve environmental performance, sustainability, and efficiency of road infrastructure.

Furthermore, the concept of the ITS is strictly related to the emerging request of smart cities and smart roads, which should be able to improve the daily life of their citizens/users[11] by means of the combination of ICT and Internet of Things (IoT). This approach has a good chance of succeeding, but the involvement of several sectors, stakeholders, authorities, and services make it really complex. Hence, real implementation must take into account:

a) innovative ways to share the information (e.g., mobile applications among vehicles, and/or among vehicles and infrastructure);
b) alternative transportation modes (e.g., bike or car sharing);
c) adopting innovative and efficient management strategies (e.g., P traffic management systems, and/or Pavement Management System, PMS).

11. Pop, Prostean 2018.

Real time traffic management systems have been proposed in order to intelligently pilot the vehicles, discourage the formation of traffic jams and optimize the power requirements of hybrid vehicles (e.g., fuel cell-based, or autonomous)[12].

The preservation of the infrastructure assets is commonly accomplished through the Pavement Management System (PMS) approach, which is likely the most widespread and cost-effective tool used by officials and practitioners[13]. PMSs are used to gather information from the asset, to identify any backlog work, to set goals and schedule maintenance and rehabilitation (e.g., for 3-5 years) in order to prioritize and limit the interventions, as well as saving time, energy, and money (as budget stretching and return on investment). The approach "worst-first" is usually considered the best way to fix a road pavement, but it is clear to see that by using a PMS it is less expensive to maintain pavements in a decent condition than completely reconstruct it, when it is in bad condition[14].

PMS can be improved using ICT-based monitoring systems (e.g., sensor-based, or machine learning-based) able to carry out real-time and continuous (in time and space) monitoring of the road infrastructure (from a security, structural, and environmental point of view), aiming at identifying the presence of damage and/or potential failure. Noteworthy and recent examples of monitoring systems refer to the use of fixed systems (based on several types of sensors, such as wireless, embedded, etc.)[15], and mobile scanning technologies[16]. The data collected using the systems mentioned above, are analysed using two main approaches[17]:

a) the traditional statistical approach (e.g., multivariate statistics);
b) the emerging computational intelligence-based approach (e.g., machine learning).

A statistic approach[18] aims at collecting, organizing and interpreting numerical data. This approach is particularly suited when the data characteristics are inferred from sampling, while it is not recommended for the analysis of complex and highly nonlinear data. Computational intelligence[19]

12. Zheng *et alii* 2015; Saikar *et alii* 2017.
13. Scarpati, Guerra 2013.
14. Fedele *et alii* 2018a.
15. Grace 2015; Hasni *et alii* 2017; Lenglet, Blanc, Dubroca 2017.
16. Schnebele *et alii* 2015; Cafiso *et alii* 2017.
17. Karlaftis, Vlahogianni 2011.
18. Zang *et alii* 2004.
19. Ceyla, Bayrak, Gopalakrishnan 2014; Gajewski, Sadowski 2014; Tong, Gao, Zhang 2017.

combines learning, adaptation, evolution and fuzzy logic to structured from unstructured data. Consequently, the more appropriate data process should be selected case by case.

Despite all the innovative methods and devices that have been presented in recent decades, it is still difficult to find them in real and widespread applications. This discrepancy can be mainly attributed to their costs and complexity, and sometimes, to poor efficiency, reliability, and sustainability.

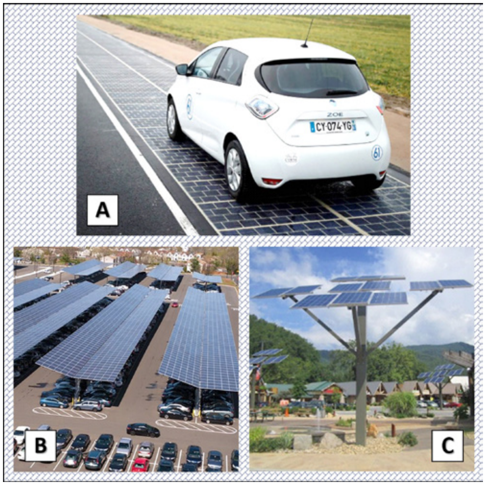
The Sub-Goal 9.4. c refers to sustainability and encourages the adoption of clean and environmentally sound technologies. For this reason, recent and relevant examples of Energy Harvesting Technologies (EHTs) are reported (figg. 1-4). The aforementioned can be used to obtain, from vehicles and roads, renewable energy[20]:

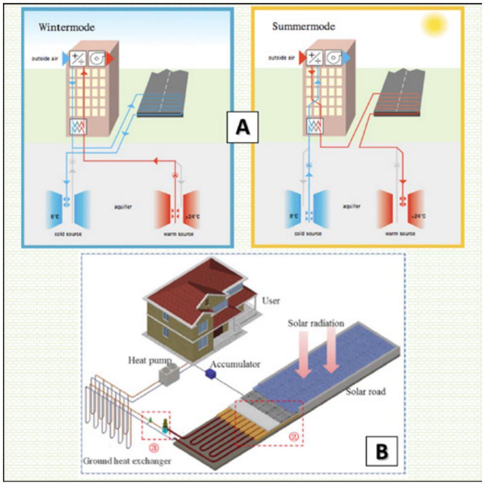
a) Offering electric energy to power mobile/laptop/electric vehicles, street lighting, and household/industrial supplies;
b) Using solar radiation for heating and cooling purposes (e.g., UHI effect reduction, snow melting/de-icing on road surfaces, or the air conditioning of buildings).
c) Optimising space/land management, reducing the land carbon footprint, and improving public perception.

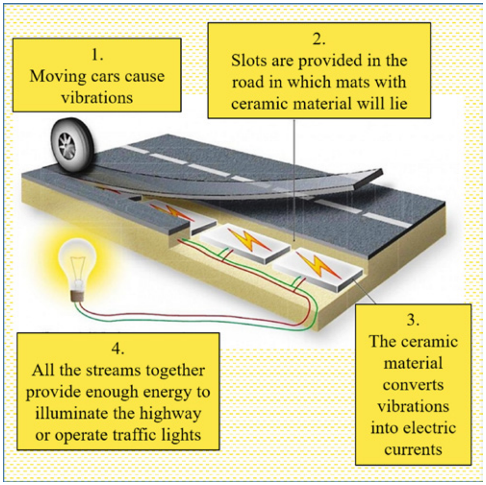
Their potential depends on power output, cost-effectiveness, the availability of the appropriate level of technology, their strengths and weaknesses, and support from government and industry[21]. The main challenges associated with the EHTs listed above involve high investment costs, medium/poor energy performances, construction optimization (e.g., Photovoltaic roads have to guarantee suitable roughness, resilience, stiffness, sustainability), the environmental impact (good for the renewable energy produced, poor if the material/-process needed are hardly recyclable/complex) and the need for carefully designed maintenance.

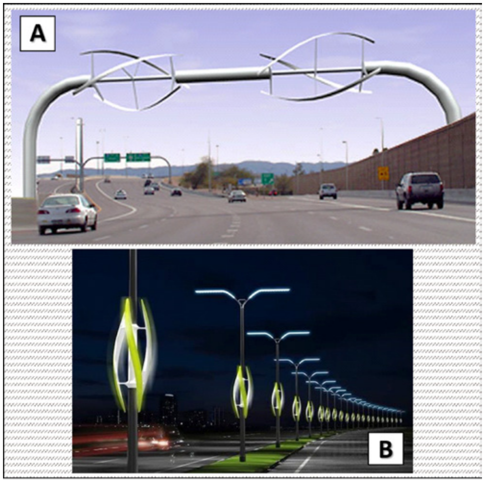
20. Fedele *et alii* 2018b.

21. Wang, Jasim, Chena 2018.









From top to left; figure 1. Example of (A) solar road (da SILVA 2016), (B) bus shelters, and (C) PV tree (da bucket.sunshineworks.com 2018); figure 2. Example of (A) Asphalt Solar Collectors (ASC) (da Ooms Avenhorn Holding Bv 2003), and (B) photovoltaic thermal hybrid solar collectors (da Xiang *et alii* 2018); figure 3. Example of Piezoelectric Energy Harvesters (PEHs) into the road pavement (da Engineersonline.nl 2012); figure 4. Examples of wind turbines on highways (A) (da Chapa 2007) and (B).

The Proposed Monitoring Method

An innovative monitoring method, designed by the authors of this paper, is presented in this section (fig. 5). It mainly refers to Goal number 9 above.

It is a Non-Destructive Test and sensor-based solution for the early identification of damage in road pavements. This method is based on the concept of vibro-acoustic signature. The proposed method was validated using Finite Element Modelling simulations[22], and experimental investigations followed by data analysis carried out using Machine Learning – and Wavelet – based algorithms[23]. Results show that the proposed approach can be used to improve the sustainability of the current and future road pavements and increase their life expectancy.

22. Fedele, Praticò, Pellicano 2019.

23. Fedele, Praticò 2019; Praticò *et alii* 2019.

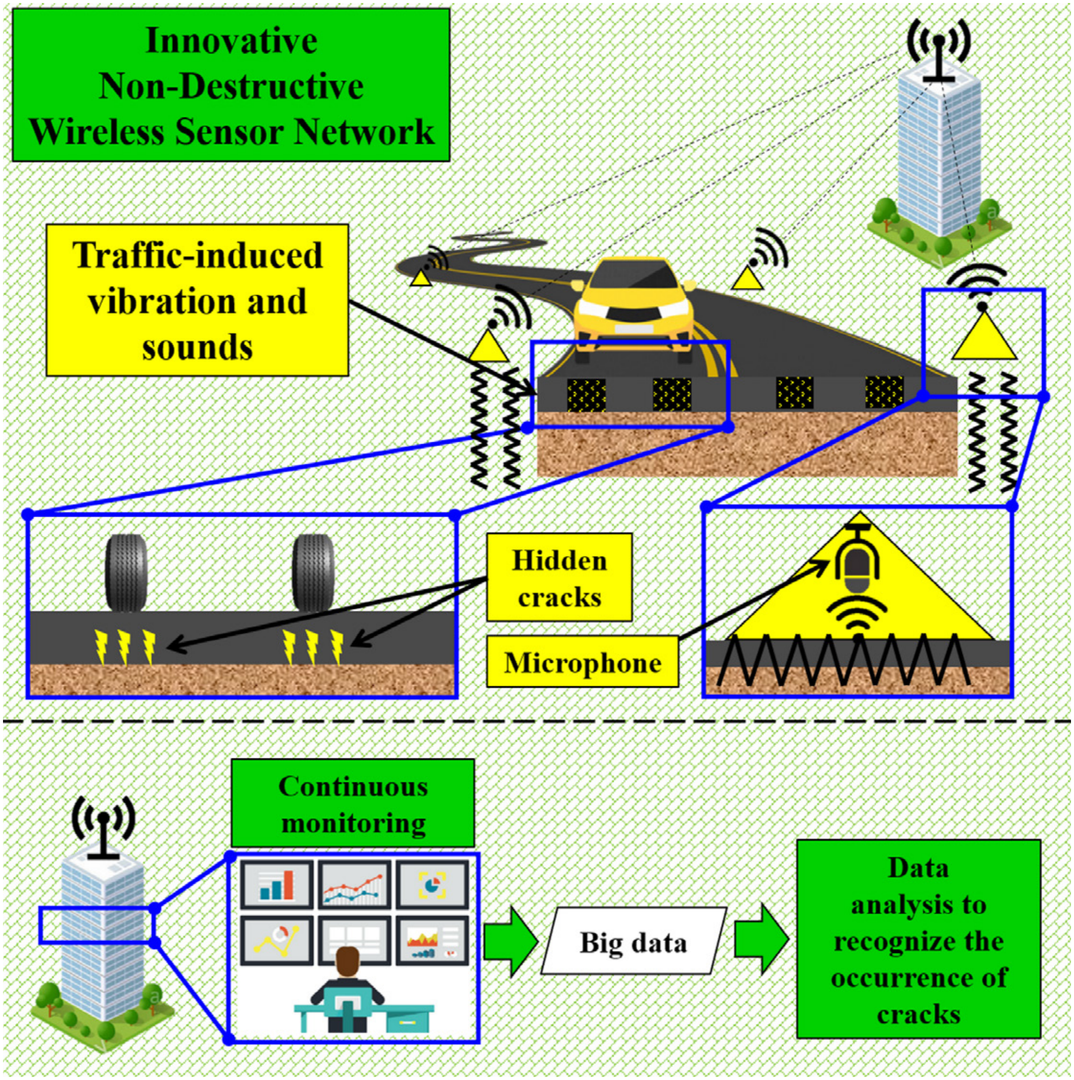


Figure 5. Schematic representation of the monitoring method proposed by the authors.

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