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Review

Smart roads: A state of the art of highways innovations in the Smart Age

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A B S T R A C T

The years we are experiencing are often identified as those of the Age of Smart Technologies. Smart is now a very popular term, with the meaning of clever, intelligent, sharp, quick on the uptake. Its extensive meaning can be grasped if we consider it as an acronym for Self-Monitoring Analysis and Reporting Technology to indicate the essential features of the innovative technologies that characterize today's society in its daily life. Thus, the advent of the Smart Age, which is therefore the era of smart technologies, has heavily characterized and modified many aspects of today's society compared to the past. In this panorama, some arising questions regard transport infrastructure systems and, first of all, road transport. This research proposes a focus on one main issue: how roads fit into this smart revolution? Actually, the paper aims to offer an overview of the smart approach in road engineering by proposing a broad discussion about the current state of innovation in the smart roads field, i.e. the roads of the Smart Age. After defining the key functions of a smart road, the paper reviews some innovative technologies that make these items effective. These are studied in depth both with regard to motorway-type infrastructures and urban roads and intersections, with attention to the various technological aspects and to the benefits perceivable by management, users and the community. The paper, therefore, offers a bird's eye view of this extremely dynamic sector with innovative technologies for a new intelligent and connected mobility, and discusses some of their criticalities and strengths allowing for optimization and development of new transport functions and services, improving energy efficiency and promoting social, economic and environmental sustainability.

Contents

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1. Introduction

During the 1980s, the advancement from analog electronic and mechanical devices to digital technology led Humanity to a revolution, the so-called Digital Revolution. Also known as the Third Industrial Revolution, from a boost of innovation begun in the 60 s [1] it marked the beginning of the Information Era, which continued in the following years that are often referred to as Computer Age, Digital Age, or New Media Age.

Starting from the definition given by Klaus Schwab, founder of the World Economic Forum, in the last few years some have recognized a Fourth Industrial Revolution building on the Third one [1–3], characterized by the fusion of modern intelligent technologies. This new revolution is also often identified with the term Industry 4.0, which will bring computerization and inter-connection into the traditional industry, connecting the physical to the virtual world, achieving a higher level of automation and improving operational productivity and efficiency [4]. What we are now experiencing is often identified as the Age of Smart Technologies, describing a world where individuals move between digital domains with the use of connected technology to enable and manage their lives [2].

Nowadays smart is a very buzz term used with its meaning of "intelligent", "clever", "sharp", "quick on the uptake" to describe any kind of available technology with an high innovative contribution. Actually, the term "smart" can be viewed as the acronym for "Self-Monitoring Analysis and Reporting Technology" [5], although this acronym was created in Computer Science to indicate systems for controlling the reliability of hard drives [6]. Thus, "smart technologies", including both physical and logical applications, identify solutions that are capable of automatically adapting to the context, to improve the management of several aspects of human life.

The advent of the Smart Age has heavily characterized and modified many aspects of today's society compared to the past. Significant innovations in this direction are progressively characterizing multiple aspects of the current reality, from science, economy, education, health, governance, modifying peoples' lifestyles and proposing a new focus on the sustainability of the planet's ecosystems. Smart technologies are undergoing profound changes in business models, institutions and the whole society, making collaborative resources available and accessible. These include a number of Information and Communications Technologies (ICTs), such as end-user Internet service system, Internet of Things (IoT), Cloud Services, Big Data, Artificial Intelligence (AI) and Edge Computing (EC).

From the concept of smart technology, a natural extension leads us towards the concept of "smart city". Modern cities collect many aspects of life of modern societies, and mobility appears in a widespread and recurrent way as a critical issue. Key enabling technologies for smart cities mostly find their concretization in the ICTs field [7]. Industry 4.0 and its concrete expression in the Internet of Things (IoT) allows to create a massive network of interconnected physical objects embedded with electronics, software, sensors, and network connectivity becoming the building block for next-generation smart cities [8]. The smart city, therefore, integrates information from sensors, communication technologies and various physical devices to optimize the efficiency of city operations and services to deliver a sustainable, prosperous, and inclusive future for its citizens [9]. Thus, smart technologies can be organized in a productive and effective way to promote intelligent and connected mobility schemes, to allow for an optimization of urban functions and services, improving energy efficiency and promoting social, economic and environmental sustainability.

Information and communication technologies have enabled the design and implementation of intelligent transportation systems (ITSs) [10,11]. ITSs combine various technologies and services to optimize mobility, making the transportation sector safer and more sustainable and efficient [12]. In this panorama, some arising questions regard transport infrastructure systems and, first of all, road transport. From this point of view, some questions arise: How roads fit into this smart revolution? If there is a need to make some revolutionary changes in concepts of roads and highways, how can they become smart? What do "smart road" and "smart highway" mean, and what can they be?

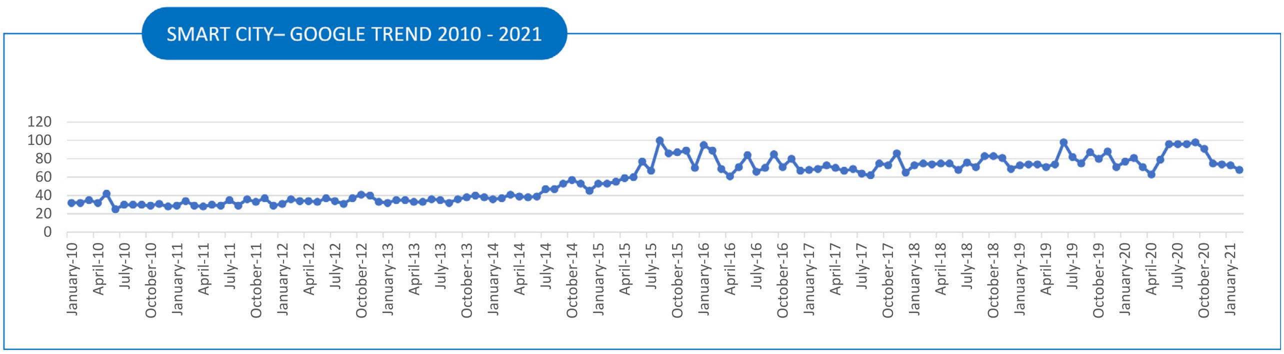
We can find many definitions for the term "smart highway" [13], but the most general is that smart highways and smart roads are terms for a number of different technologies incorporated into roads [14]. In a deeper way, it is an extensive concept for roads of tomorrow, looking at innovative ideas that apply the opportunities offered by new technologies in smart ways. Thus, we can say that a smart highway combines physical infrastructures with software and data. In these terms, the road itself can be a platform for innovations. A smart highway will allow for technological integration into current transportation roadways, including connected devices and IoT, to increase transport efficiency, drivers' and pedestrians' safety, clean energy consumption, and to promote sustainability.

In the wake of the general fascination for the concept of "smart", "smart city", "smart mobility" and "smart highway" have become topics of growing interest in recent years, as evidenced by the trends in searches by Google users shown in Fig. 1. Time series by Google Trends [15] starting from January 2010 to February 2021 show an evident growth for all the four terms analyzed. In particular, considering the overall annual values for 2010 and 2020, a growth of about 94% was recorded for "smart", 165% for "smart city", 82% for "smart mobility" and 64% for "smart highway". More specifically, the growth has been much more consistent if we look at the research field in the last two decades. Fig. 2 shows the exponential growth trends from 2000 to 2020 of the annual number of documents indexed by Scopus [16] with the presence of the terms "smart", "smart city", "smart mobility" and "smart highway" +"smart road" in the reference fields.

In the last decade, several experimentation projects using innovative technologies applied to road transport have been launched in the world, such as intelligent systems and devices supporting management projects of motorway corridors, especially by infrastructure managers and local governments [17]. Recently the interest in smart roads has taken on a systemic dimension. In the last few years, many governments and transport authorities have interpreted the value of smart technologies not as an isolated and circumscribed experiment at the level of a single infrastructural corridor, but as an integrated system design for the efficient and innovative management of the whole road network. Smart, or intelligent, highways could turn from serving a singular purpose in being the backbone of various countries' transportation systems to provide additional value for both drivers and transportation administrators. Therefore, it appears that smart roads are the near future of road networks, and intelligence is becoming a promising direction of research and development in the field of road engineering, both in construction and management [13] with different integrated applications of Building Information Modeling (BIM) [18,19] and Intelligent Transport System (ITS) [10,20] promoting innovation, automation, connectivity, cooperation, proactivity, safety and cost savings.

Smart roads are the key piece of the EU plan "Cooperative Intelligent Transport Systems" (C-ITS), which will allow road users and traffic managers to share information and use it to coordinate their actions. Innovation, cooperation, connectivity, and automation will make Europe's roads smarter. On 30th November 2016 the European Commission adopted a European Strategy for C-ITS in

(A)



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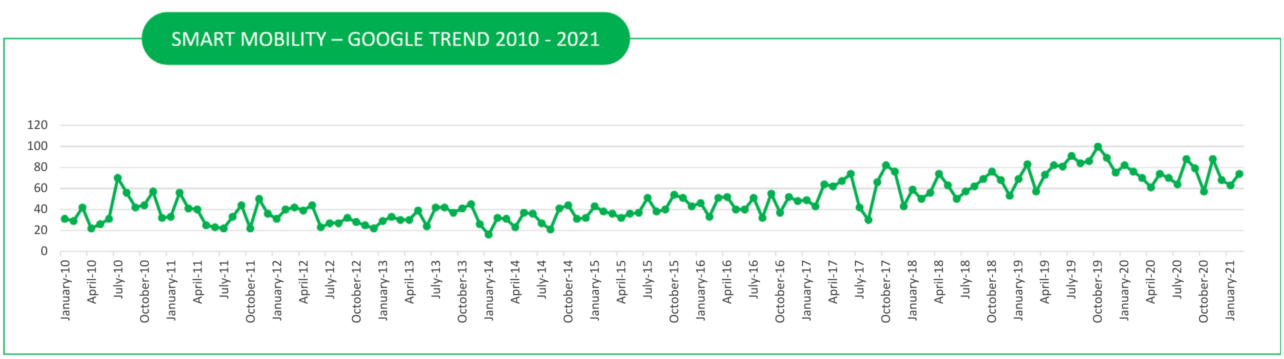

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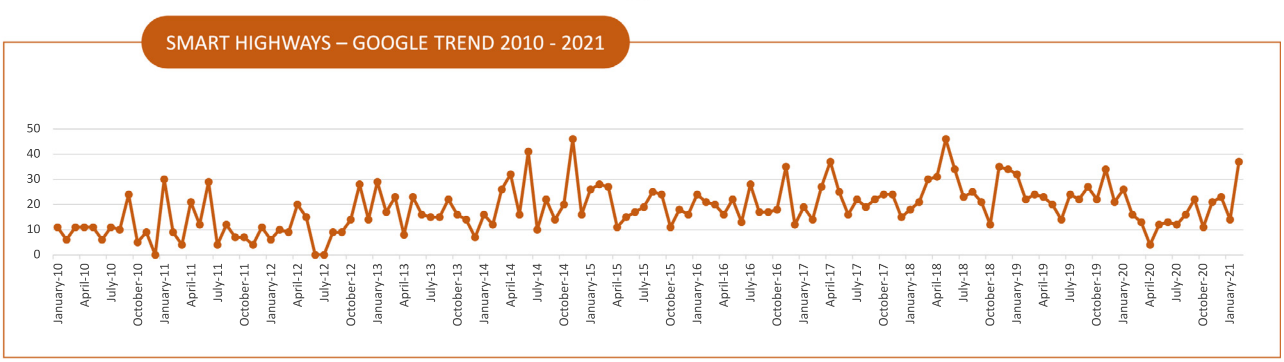

(D)

Fig. 1. Time series of Google Trends [15] searching interests – Monthly values from January 2010 to February 2021 for: (A) "smart"; (B) "smart city"; (C) "smart mobility"; (D)" "smart highway".

order to facilitate the convergence of investments and regulatory frameworks across European countries [21]. In this context, European countries (and some market operators) have organized themselves in a common framework for sharing projects and experiences in the innovation of smart roads, which is the C-ROADS platform [22].

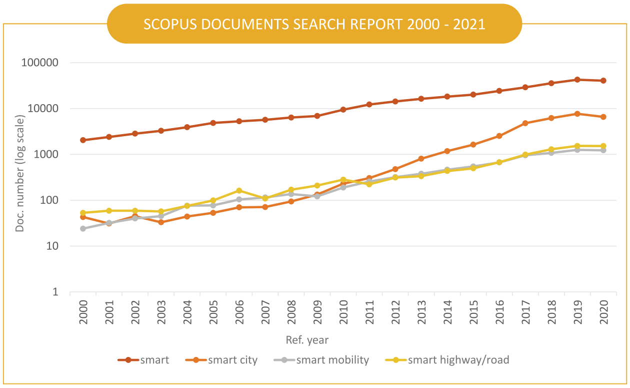

Fig. 2. Annual number of documents (log scale) indexed by Scopus [16] from 2000 to 2020: searching results for: "smart"; "smart city"; "smart mobility"; "smart highway" + "smart road".

These significant stances expressed at a European level are kicking off the policies of member states, followed by the initiatives and the first actions by the entities and operators involved. An example that can be indicated in this regard is represented by the Italian case. In April 2018, the Italian Ministry of Infrastructure and Transport (MIT) issued a specific law, the so-called Smart Road Decree (DM 28/02/2018) [23], with which the smart road's advent officially started in Italy. It should also be noted that important references to smart roads at a national level have been approved by the Italian Parliament at the end of 2017 for the 2018 Budget Law. The Smart Road Decree identifies the functional standards to create more connected and safer roads which can communicate with users onboard the vehicles, to provide real-time information on traffic, accidents, weather conditions, and other information thanks to new technologies, for better travel comfort and better infrastructure management. MIT has also identified the first interventions in this innovative direction, which will concern the motorway network, considering sections of new construction or subject to extraordinary maintenance. In the first phase, by 2025, action will be taken on the Italian infrastructures belonging to the TEN-T network, Trans European Network-Transport, and on the entire national motorway network; progressively, the services will be extended to the entire network of the integrated national transport system. Into this groove outlined by European and national institutions, Anas S.p.A., a joint-stock company that has been part of the FS Italiane group since 2018 and which manages roads and motorways owned by the Italian State, has prepared its Smart Road Plan to provide the country with an efficient road network, open to the new challenges of the future, for a total investment of approximately one billion euro in the next 10 years [24].

Returning to the international context, as reported by INDRA in the ITS Industry Report 2019 [25], smart road technologies belong to an expanding sector, with enormous market prospects and opportunities. The report estimates that the growth of this market in the coming years will be 7% per year, with an annual forecast for 2022 that in Europe would exceed 2 billion euro.

In this context, which is innovative and dynamic by vocation, this paper aims to offer an overview of the smart approach in road engineering by proposing a broad, although not exhaustive, discussion about the current state of the art in smart road developments. Starting from the definition of the functions of the smart road and more generally of mobility in a smart city context, this work reviews the most recent lines of innovation in this sector. The paper, therefore, proposes a discussion on the actual ability of these innovations to achieve the objectives underlying the vision of the smart road, in a perspective of environmental and social sustainability. This discussion, in fact, aims to highlight some strengths and criticalities of these current innovations in the market for infrastructures and services for road mobility, in light of the focal points of the Smart Age mobility.

The paper is structured as follows. In Section 2 smart road themes are discussed in the broader context of the design and management of road infrastructures. Thus, Section 3 presents some of the advances in transportation technologies for road transport and their integration policies, which define the path undertaken towards the highways of the future. Finally, section 4 discusses the environmental and social sustainability aspects of the innovations reviewed and Section 5 defines some conclusions.

2. For a smart road concept in highway engineering

Several decades ago, Ferrari [26] outlined the future of motorways. At the dawn of traffic control technologies, he identified the direction of infrastructural development towards greater specialization, with the use of control systems for traffic management to ensure more efficiency, reliability and safety for highway infrastructures, with effective interventions and with a limited commitment of capital and land use.

Ferrari [26] linked the greater safety and reliability of transport infrastructures to the less freedom of use granted to vehicles. In this way, reliability and safety are minimal on urban roads and maximal on railway infrastructures; they also decrease as the number of vehicles increases. In this sense, he identified the motorway as the result of the attempt, undertaken in the 30 s and 40 s of the twentieth century, to create a road transport system with stricter rules and controls than urban roads, to bring its performances closer to those of railways.

The link between control, reliability and safety clearly emerges from these considerations and moves into the Smart Age, which is the future Ferrari [26] wrote about. In the Smart Age, control strategies go hand in hand with sensor networks, connection and cooperation, IoT and AI, and this happens in an exemplary way in the world of transport systems. As already mentioned in the introduction, the Cooperative Intelligent Transportation System (C-ITS, according to the European nomenclature) is an emerging technology based on the communication and cooperation between vehicles, as well as between vehicles and physical infrastructures. This is so true that the so-called Connected Vehicles (CVs) and smart road concept are often considered synonyms. Even though this is certainly a simplification, as seen in the introduction and as clarified by the previous items, CVs represent a central element of the smart road.

In a very synthetic way, we can say that CVs are equipped with advanced communication technologies that allow an exchange of information between the various elements of the transport system, configuring what is generically identified as Vehicle to Everything, or V2X [27]. A V2X network connection is actually specified with respect to the nature of the relationship between the vehicle and the outside world, including Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), Vehicle-to-People (V2P), Vehicle-to-Network (V2N).

The new V2X technologies, even mixed with non-CVs, are arousing a growing interest as usher in new operation models, change in traffic flow fundamentals and management, and redesign in safety and mobility management [28,29]. As highlighted by Guerrieri et al. [30], recent innovations in vehicle automation make it necessary to investigate new design criteria in highway engineering. These authors point out that future road evolution will produce a transition from the current transport system based on the interaction among human-vehicle–road components to a

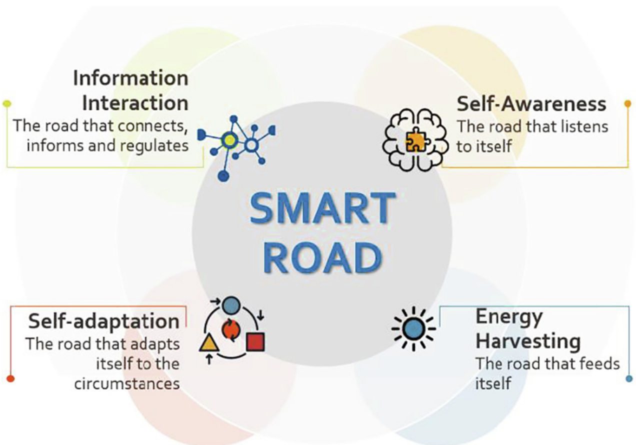

Fig. 3. Key features for Smart Road.

smart system with the only vehicle–road and vehicle-vehicle interactions. Thus, design criteria are to be modified since the human factors are going to be less significant in driving processes [31]. From these assumptions, Guerrieri et al. [30] propose design criteria for automated highways, regarding stopping sight distance, straights design, horizontal circular curve design, transition curve design, crest vertical curve design, sag vertical curve design, capacity estimation and safety condition assessment.

If connection and cooperation emerge as fundamental topics for a smart road configuration in a V2X context, the point of view must necessarily be broadened to have a full representation of the smart road concept. In this regard, the approach followed by Zhao & Wu [13] and based on the enumerative definition is very useful for an adequate classification of terms and functions. For these authors, therefore, smart road deals with four basic items (see Fig. 3):

- self-awareness, i.e. the ability to monitor the road conditions (even traffic status) automatically and in real-time;
- information interaction, i.e. the ability to link intelligent devices for road and vehicles monitoring and to connect sensor-network and databases within an intelligent communication system;
- self-adaptation, i.e. the ability to automatically adjust to the various circumstances of the road;
- energy harvesting, i.e. the ability to collect green energy from pavements, sub-grade and other infrastructures, and supply energy for the whole smart road system or some other objects.

Following the enumerative definition [13], each item manifests itself through a certain number of functions (e.g. structural health monitoring or traffic detection for self-aware service items) which in turn are implemented through technologies (e.g. non-destructive testing technologies or distributed sensors detection).

It is clear that for correct classification, the smart road cannot be considered as a collection of single and independent service items, functions or technologies. By its very nature, a smart road is a system in which the items are integrated, as well as the functions and technological or design solutions that allow their implementation. This integration must follow two levels [13]: a logical level that defines the connections between the subject items (e.g. a logical link between self-awareness and self-adaptation, i.e. adaptation based on what is monitored; a logical link between self-awareness and information, i.e. informing about existing conditions; logical link between self-adaptation and information, i.e. informing about changes taking place; and so on); a physical frame that is the concrete realization of the logical frame through the use of technologies to realize the smart road's functions.

In this perspective and looking back over the list of items, the attention to the design criteria and construction techniques of the smart highways of the future must include in a wider context other aspects related to the capability of the infrastructure to "learn", "interact", "adapt" and "feed". The following section is dedicated to the in-depth study of each of these aspects, identifying key functions and innovative technologies for the smart road, i.e. the highway concept for the Smart Age.

3. Key functions and innovative technologies for the smart road

3.1. The road that listens to itself

Within a smart road system, all the components are sources of a large amount of useful data that is generated in a short time. This happens because a smart road utilizes sensors and devices to monitor the infrastructures' condition or traffic status. These data are Big Data resources [32], containing detailed information about the infrastructures' condition and drivers' behavior.

In a smart road system, data can be obtained from various sources [33,34], such as a large number of sensors, smart cards, satellite systems, cameras, social networks, etc. These Big Data resources are logically and physically decentralized, but they need to be centralized, processed and interconnected in an acceptable time, in order to be available for use by each component of the system. Lopes et al. [33] identify three major methods for traffic data collection, that are roadside data, wide-area data and floating car data. Roadside data referred to vehicular traffic regard microscopic and macroscopic traffic variables, vehicle type and weight, which are measured by sensors and devices located along the roadside. These sensors and devices can be: inductive magnetic loops, pneumatic road tubes, piezoelectric loops arrays; microwave radars, ultrasonic and acoustic sensor systems, magnetometer detectors, infrared systems, light detection and ranging (LIDAR) and video image detectors. Wide-area data monitor highway traffic conditions within a defined area using: photogrammetric acquisition and processing, video and audio analysis, satellite acquisitions from space. With the recent technology developments, vehicle-based detection represents a data collection method of increasing use. Floating Car Data (FCD) refer to mobility data collection using vehicles as sensors and providing a point-to-point path, with detailed information about the trip. Examples of FCD technologies are: Wireless Communication and Global Navigation Satellite System (GNSS) such as Global Positioning System (GPS) devices for V2V and V2X cooperation, License Plate Recognition (LPR) systems, On-Board Transponder Units (OBTU). Vehicles equipped with various kinds of floating sensors have the potential to be the perfect tools for transportation infrastructure monitoring using crowd-sourcing sensors in moving traffic units [35].

An extended monitoring system suitable for a smart road uses capacitive sensors, vibratory sensors, accelerometric sensors, infrared sensors and optical fiber sensors to acquire information on the state of the infrastructure (vibrations, stress, wear, failures, etc.) and the surrounding environment (temperature, weather humidity, pressure, wind, lighting, visibility, etc.). Considering the infrastructure and the environmental situation, we can distinguish pavement and sub-grade/soil monitoring [13]. Pavement condition sensors regard, for example, temperature, moisture detection, icy condition, structure damage detection; sub-grade/soil slope sensors regard sub-grade freeze and thawing monitoring, sub-grade settlement monitoring, slope stability monitoring.

The smart road is therefore capable of listening to itself thanks to the installation of a plethora of connected sensors. The evolution in the field of sensors has been enormous in recent years, and the consequent applications in the road sector have increased incredibly, allowing the development of systems in which things and people can connect anywhere, activate processes and exchange data in a productive way. This is the IoT frontier that is identified as the Internet of Everything and Everywhere (IoEE), a pervasive network of connections in the perspective of the smart city and smart mobility [36]. Miniaturization is a driving element of the research and production of technological devices operating in an IoEE context, and this is also beginning to emerge in the field of mobility, making its way into the realm of microelectronics and entering that of nanotechnologies. These microdevices networks form the so-called "smart dust", a dense mesh of tiny electromechanical sensors (MEMS) [36].

In the field of acquiring updated and detailed information, growing opportunities are also offered by Unmanned Aerial Vehicles (UAVs). UAVs, or most commonly known as drones, present powerful dynamic integration capability with their high time–space resolution and flexibility. They can serve different purposes related to road safety (accident investigation, risk assessment), traffic monitoring and management (vehicle detection and extraction of traffic parameters, traffic flow and traffic behavior analysis), and highway infrastructure management (structures inspection, pavement condition, road distresses monitoring) [37].

This wide range of sensors of different nature and the consequent production of enormous quantities of data relating to the infrastructure and environmental and traffic conditions performs that key function that has been identified as self-awareness of the smart road.

3.2. The road that connects, informs and regulates

As mentioned above, sharing information, connection and cooperation emerge as fundamental topics for a smart road. Thus, information-exchanging systems are key elements that need to be equipped in smart roads, providing uploading and related feedback of condition (both infrastructure and environment) data and vehicle data [12].

IT networks for smart roads are substantially based on Wireless communication technologies, and in particular on in-motion technologies, which ensure fast roaming and continuous communication service. These communication systems play a fundamental role to ensure connectivity between people and digital instruments, vehicle connectivity, infrastructure connectivity and their mutual connection. Smart road users share the information that are collected by the sensors and processed by technological systems and applications to be usable and useful for a more comfortable, reliable and safe driving experience. Thus, users are provided with real-time services by means of on-board vehicle devices and/or personal devices, such as smartphones and tablets.

Each technological device that is fitted with sensors, both on-road structures and vehicles, is part of an IT network. All these connected devices, which collect huge amounts of data each minute of the day, together form what is called the Internet of Things (IoT). Actually, IoT is the evolution of Machine-to-Machine communication (M2M). If M2M links one device to another, IoT connects different M2M technologies together in order to transfer the data between multiple devices of the same kind, without the intervention of humans [38]. Thus, the Big Data collected and exchanged between devices and sensors regarding vehicles, infrastructure and the surrounding environment are the lifeblood of the smart road. In the near future, Big Data analytics is anticipated to significantly increase its role in road management, safety and maintenance, allowing us to superimpose a digital layer over the existing physical infrastructure of the road network, to gather better data about our highways [39].

To ensure active perception (i.e. listen to itself) and to transform this into automatic discrimination (learn and inform), which are the capabilities required for a smart road [40], this enormous amount of data concerning various aspects of the infrastructure and its daily operations? (or, even better, its instantaneous functioning) must be properly collected, filtered, processed and classified.

If, on the one hand, IoT generates massive amounts of information, on the other hand, data-driven technologies grouped into what is referred to as Artificial Intelligence (AI) offer algorithms to make sense of all this data. Machine Learning and Deep Learning provide a variety of advanced analytical tools for predictive analytics, which in turn can inform preventive actions [41]. Beyond these algorithms for Big Data analytics, AI cognitive computing tools allow watching the data over time, underlining the role of learning, memory creation, experience retrieval and adaptability for the smart road [42].

On smart roads, vehicles exchange information with each other, with infrastructures and also with other interested and authorized subjects. In a very general way, we talk about Vehicle-to-X connections, in a word V2X (see Fig. 4), where X can be represented by [27]: V, to indicate another generic vehicle, for example to provide and receive alerts on traffic conditions; I, to indicate infrastructure, for example, to allow vehicles to be warned about rules (speed limits, traffic restrictions, etc.) or temporary occurrences (accidents, maintenance operations, work zones, etc.) and, eventually, to adapt driving to the current or future environment; P, to indicate people, for data exchange with devices in the nearby to receive information; N, to indicate network, for data exchange with an Operational Control Center (OCC). V2X connectivity could allow the full and profitable application of modern solutions for highway traffic management, by means of variable speed limits, ramp metering, hard shoulder running, platooning, and other cooperative adaptive cruise control systems [43] (see section 3.3).

In the smart highway of the near future, connected vehicles will also be autonomous, and for this reason they are called CAVs (Connected and Autonomous Vehicles), i.e. vehicles equipped with non-human driving systems. Vehicle automation is a concrete application of Artificial Intelligence (AI) in the field of transport. By using a huge amount of data (those that we have already identified as Big Data and which are incessantly produced by the smart road), AI algorithms make calculators capable to perform activities for humans, such as driving. From a simple Driver Assistance to the Full Automation (according to the 5 degrees of automation defined in standards by the International Society of Automotive Engineers [44], as in Fig. 5), Autonomous Vehicles (AVs) are configured with different types of sensors, allowing them to adapt to the existing road context thanks to on-board technologies. Actually, this circumstance is implementable, effectively and safely, in the real-life world if an AV can establish a continuous dialogue with the other X elements of the system. That is, in an environment of

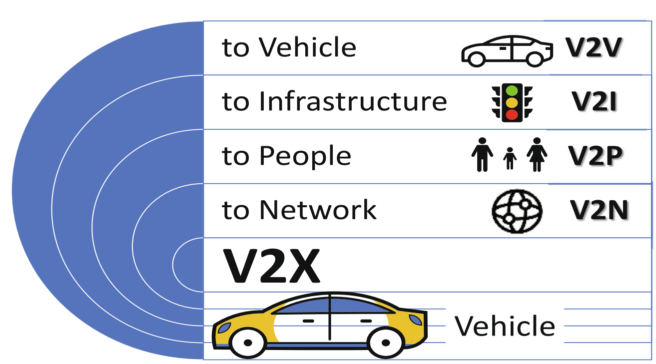

Fig. 4. V2X technologies.

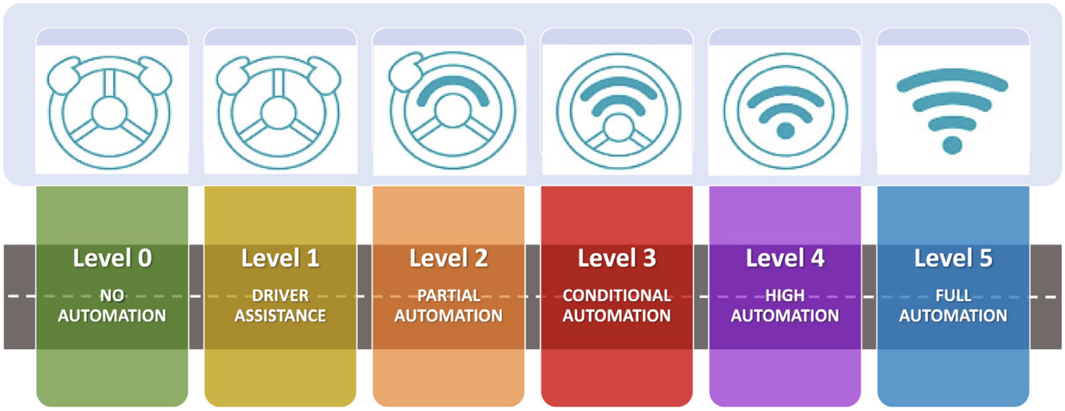

Fig. 5. SAE Level of vehicles automation.

autonomous and connected vehicles that we have identified as CAVs.

Vehicular Ad-hoc Network (VANET), Dedicated Short Range Communication (DSRC) and Wireless Local Area Networks (WLANs) such as Wi-Fi offer the potential to effectively support safe V2X communications [45]. VANET allows vehicles that are close to each other within a small distance to connect and exchange information, and enables the roadside equipment to communicate with vehicles by making a wide network. A VANET is implemented through a DSRC technology to create wireless V2X communications. Technologies in this field evolve rapidly, with new protocols that increase the efficiency and security of communications [46] (e.g. satellite, cellular, Wi-Fi wireless local area network (WLAN) and its wireless access in vehicular environments (WAVE) evolutions, Bluetooth wireless personal area network (WPAN), mm-Wave, infrared and radio frequency identification (RFID)). As the integrity of communication within a VANET is extremely important and high-risk situations for the security of the infrastructure and the privacy/safety of its users depend on it, new solutions are continuously proposed to improve resistance to possible attacks [47]. In this sense, the latest innovations concern the use of a computing paradigm borrowed from the Bitcoin crypto-currency, the so-called Blockchain technology [48] based on a distributed ledger, which can be read and modified by multiple nodes on a network. The ledger entries are grouped into "blocks", concatenated in chronological order, and whose integrity is guaranteed by the use of cryptography. The addition of a new block is globally governed by a shared protocol. Once the addition of the new block has been authorized, each node updates its private copy and this guarantees the absence of possible manipulations. Though Blockchain technology is still in an early stage, it appears extremely promising also in the field of transportation systems as showed by Astarita et al. [49] in their up-to-date literature review.

In a recent work, Guerrieri et al. [50] recognize positive environmental effects of smart motorways compared to conventional ones. They use a Life Cycle Assessment LCA analysis, taking into account the impacts due to the construction and maintenance of the infrastructure, the environmental effects produced by the traffic emissions and safety effects related to innovative barriers and ITS solutions such as platooning (see Section 3.3). The results show a significant reduction in energy consumption, pollutant emissions and accident events for new smart highways compared to traditional ones.

Several researches – for example, see [29] or [50] – highlight considerable benefits involving the infrastructure's functionality of a smart road emerging from V2X and CAVs: lane capacity increasing due to the reduction in the drivers' perception and reaction times (human factor); reduction in the frequency of flow-breakdown phenomena (flow instability); safety improvement resulting from the potential reduction of accident numbers. Actually, these are the results that Ferrari [26] already glimpsed a few decades ago (see Section 2) as a consequence of an increasing presence of control systems for highway traffic management.

As well as for the infrastructure operation, data collected from smart roads would be useful in urban planning and infrastructure design and management. Traffic Big Data storage and analysis could be used by engineers to analyze the traffic flow in a specific area, detecting the space–time fluctuations of macroscopic and microscopic variables and looking for the best solutions to prevent congestion and manage mobility, with high standards of efficiency and safety. This happens also with the use of various levels of simulation techniques (i.e. macro-, meso- and microscopic) that typically characterize the analysis approaches of Traffic Engineering. Similar considerations can be made for infrastructure and environmental data, which can flow into the Building Information Modeling (BIM) platforms for the representation of the infrastructure and its components, highlighting the relationships with the surrounding environment. BIM, therefore, organizes data from sensor networks not only for design purposes, but also to support construction, maintenance and management of the operation of the infrastructure.

Traffic, infrastructure and environmental data are the power source of the Structural Health Monitoring (SHM) systems. SHM refers to the process of implementing changes detection of the material and/or geometric properties of a structural system to determine the current state of system health. In the field of highway design, management and maintenance this especially concerns critical structures such as bridges, viaducts and tunnels [51] for rapid condition screening to provide, in near real-time, reliable information regarding the integrity of the structure. This is a new perspective that transforms the current reactive approach into a new proactive one [50]. Section 3.3 explores some solutions that use the information on the state of the surrounding environment and infrastructure to allow the latter to better respond to the occurrences of the moment.

In addition to the above, it should be noted that one of the very important components for smart roads is to provide accurate information regarding the current conditions to road users. Information can be made available inside the vehicle thanks to on-board or personal devices, in ways that inform and do not distract and confuse drivers and users. Augmented reality (AR) possesses great potential as a human–computer interface, which enhances the driver's perception by superimposing a useful real-world context in minimal detail in a driver's line of sight [52]. From the point of view of the infrastructure, the smart solution is to show the information contents on dedicated adaptive road signs and markings equipped with a variety of sensors and led displays [53]. Since these are also adaptive components, they are detailed in section 3.3.

All of these applications will receive a significant boost with the advent of 5G communication, due to the limitations of 4G technologies [54]. 5G and Edge Computing will allow to process large quantities of locally produced data and to send the same data in a much more compact form to remote systems. Thanks to the possibilities of network availability anywhere overcoming the current boundaries of time and data size [54], these two key technologies will allow applying an intelligence layer in devices and sensors with greater resilience and greater effectiveness in real-time, to generate an advanced communications system that makes collaborative, connected and autonomous driving feasible and effective [25]. The most efficient management of this huge data traffic will be the task of 6G. This sixth- generation mobile technology will be called upon to address this engineering and computational challenge, with higher bandwidth and lower latency that will ensure faster response times and even more devices connected to a single antenna. 6G will ensure a dense AI presence that will create context-sensitive intelligent services and applications for human and non-human users, and ubiquitous services, which will follow users seamlessly [55].

3.3. The road that adapts itself to the circumstances

As already discussed, CAVs and V2X connectivity open up the possibility of implementing ITS solutions for highway traffic management more effectively, such as: Variable Speed Limits, Ramp Metering, Dynamic Lane Management and Hard Shoulder Running, Platooning and other Cooperative Adaptive Cruise Control Systems strategies [43]. These are a kind of solution that can be seen as self-adapting smart road applications.

Variable Speed Limits (VSL) and Speed Harmonization (SH) strategies [56–58] enable speed limits to be changed dynamically in response to traffic conditions. VSL and SH can involve gradually lowering speeds before a congested area or a work zone, in order to reduce congestion and to improve safety. Traffic sensors monitor real-time conditions and send information to the OCC to calculate optimal speeds. This information is shared with the vehicles. It can be made available to drivers of human-driven vehicles on on-board devices for connected vehicles and on adaptive overhead signs for non-connected vehicles, or directly used by CAVs to adjust their speed to the recommended level.

Ramp Metering (RM) and Coordinated Ramp Control (CRC) strategies [58,59] are used to regulate the volume of vehicles entering a motorway to ensure optimal traffic operations. Access ramps are controlled by adaptive traffic signals. Red/green times are powered by AI algorithms that use real-time traffic data to determine the optimal entry rate. Thus, the platoons of entry vehicles are broken in compliance with the estimated optimal entry rate. Surplus vehicles form a queue on the ramp in attempting to merge onto the mainline. The RM/CRC algorithms ensure that mainline vehicles will not need to reduce their speed as much, thanks to the optimal time spacing of the entering vehicles.

Dynamic Lane Management (DLM) and Hard Shoulder Running (HSR) [60,61] are reconfiguration strategies for the cross-section of an existing motorway. If the shoulder lane is converted into an additional lane for vehicles, that is Hard Shoulder Running. HSR generally assumes a dynamic character, which allows increasing the motorway capacity during rush periods. Overhead signs on the carriageway indicate whether the hard shoulder is open to traffic and the mandatory speed limit which varies depending on the traffic conditions and HSR opening/closure. In some cases the possibility of traveling the shoulder lane is permanent, i.e. the shoulder lane is closed only for emergencies. This operating scheme goes under the name of All Lane Running (ALR) [62]. A particular type of DLM is the Contra-Flow Lane (CFL) [63–65], i.e. the reversal of some lanes in order to temporarily increase the directional capacity of a road. As the basic requirements to support dynamic lane reversal are the speed and safety with which the inversion operation must take place, this has greatly limited its application in real cases.

The concept of Platooning refers to a group of vehicles traveling in convoy, with a short distance from each other. Thanks to communication technologies (VANET DSCR), the management of the platoons can be done automatically and safely. The vehicles can communicate with each other in order to travel in a synchronized manner with the head of the convoy which plays the leading role. Platooning is a traffic control and optimization strategy that is experiencing various experiments and first applications in the field of goods transport, with the so-called truck platooning. The first applications begin to be available for vehicles of the same brand, awaiting inter-brand extensions [66] on transnational networks, such as the European network [67]. In addition to advantages from the point of view of increasing the capacity and safety of the infrastructure, truck platooning allows further benefits by increasing efficiency and sustainability: reducing the friction of air resistance, it reduces fuel consumption and emissions, thus reducing business and social costs [68].

These strategies, which are briefly reviewed here, will determine interesting enhanced applications in the future of the smart road, thanks to the connectivity and automation of vehicles, the availability of real-time data, the application of IA-based decision systems and the self-adaptation of highway elements. As already highlighted, an important aspect of infrastructure adaptability concerns road signs and markings. The fundamental elements of the latest generation road signs are their adaptive information LED panels showing the data monitored in real time by local sensors or processed by OCC, as a further evolution of the Variable Message Panels (VMP), which have long been present on road infrastructures. Adaptive traffic signs and streetlights equipped with sensors can take the form of Multifunctional Poles or Multifunctional Stations [24], realized with the most appropriate technological and communication solutions to ensure the best usability of the information.

Smart highway innovations relating to adaptive lighting and marking include Dynamic Lines Markings (DLM), Interactive Lighting (IL) and Dynamic Paint (DP). DLM and IL systems are perhaps the most popular at the moment. Among these, in fact, are the optimal adjustments of light intensity in variable traffic and environmental situations. An example of DLM is constituted by the optical light guides with LED lamps connected to sensors for fog and brightness detection. In case of poor visibility, the system automatically activates the corresponding section with the switching-on of the lamps which vary in intensity according to visibility. In case of danger, it is possible to activate the mode with a synchronized flashing of all the lamps in the section affected by the event. IL programs use sensors in streetlights for traffic and environmental conditions, to regulate lamps optimizing the visibility in compliance with the current situation (e.g. only when vehicles are present, etc.).

DP solutions explore the possibility to paint road pavements with innovative materials, i.e. the so-called Intelligent Materials, that are sensitive to light and temperature. This could create on the carriageway some dynamic markings that become visible in the dark. In the Netherlands a prototype highway installation works with a glow-in-the-dark pavement [69], made up of solar-powered photo-luminescent powder. Marking lines are charged by the sun during the day and emit their own light for up to

10 h at night. Solutions of this type can come into operation even in moments with low visibility during the day (e.g. fog). Extensive solutions on the pavement and not limited to lines can be useful when road conditions are slick, such as rain or ice conditions. Thus, pictograms and icons synthetic of a situation (e.g. rain, ice, etc.) emit shines on the carriageway pavement to guide drivers safely along the road, and then become transparent when road conditions become safe again. Further intelligent and innovative solutions concern the management of interactions between vehicles, pedestrians and cyclists, especially in the case of pedestrian crossings. Also in this case, adaptive solutions can bring considerable benefits. For this aspect, refer to section 3.5 where solutions for urban roads and intersections are discussed in more detail.

Beyond adaptive markings solutions, some references must also be made with respect to Intelligent Materials in a broad sense [40] considering self-healing or self-restoring materials, a promising type of smart materials for road construction. Self-healing technology is a new field within material technology that can find interesting applications in the road design process [70]. The most explored solutions concern self-healing asphalt concrete, which can reduce the premature ageing of highway pavements, with significant environmental and business cost savings for road maintenance.

Referring to recent updated reviews on these innovative smart materials for further details and insights [70,71], however, we can cite here what these authors identify as the three main self-healing technologies available for asphalt pavement design: nano-particles (nano-clays and nano-rubbers), induction heating (electrically conductive asphalt pavements) and rejuvenation (engineered cationic emulsions). Research and innovation directions in this field concern healing-on-demand, speeding up and overlapping of multiple processes and autonomous self-healing assessment mechanisms [70].

Heating cables and conductive grids or the innovative solutions of conductive asphalt concrete (induction heating) represent active research fields for the definition of efficient and safe design solutions for highway pavements [13,72] with cost-saving and sustainable technologies for electric melting of ice and snow. It is known, in fact, that timely and efficient prevention and treatment of ice and snow are of great importance for highway safety and capacity, but on the other hand traditional methods (i.e. manual cleaning, mechanical cleaning and spraying de-icing salt) cause problems for road pavements and structures. Treatment with defrosting salts also has significant effects on environmental ecosystems. Alongside the solutions identified above, we can also add [13]: self-temperature-control (heat-reflective and self-cool pavements); self-drainage pavement and subgrade; self-reducing noise and exhaust gas pollutants.

3.4. The road that feeds itself

In addition to the aforementioned positive impacts on the environment, linked to the possibility of operating with lower emissions and consumption in construction, management and maintenance operations [50], the smart road represents an ideal platform for the installation of innovative systems for energy production. Actually, smart highways can be seen as a great opportunity for sustainable energy growth, enabling power generation. Thus, a smart road should be a self-sustaining system that maintains all its functions and technologies using self-generated energy power [40].

We can identify three directions that are most practicable by smart highways in order to harvest energy [13]: solar energy, thermal energy and mechanical energy. Taking these forms of energy into consideration, Wang et al. [73] offer a comprehensive and up-to-date review about energy harvesting technologies in roadways for different applications, as promising techniques that can produce renewable and clean energy and improve the sustainability of infrastructures. For an in-depth study on the various energy harvesting technologies, which have emerged as promising ways to generate clean and regenerative energy, and above all for an extended discussion on the relative costs, opportunities and technology readiness level, reference can be made to the aforementioned study [73]. Below we offer a brief review of the solutions presented by these researches.

Solar energy harvesting can be obtained by Photo-Voltaic (PV) cell technology, which converts solar radiation into electric power. PV installations can take place with solar cells on road pavements and noise barriers. Solar energy can also be captured and transformed by using the so-called Solar Collector Systems (SCS). These allow capturing solar energy, which is absorbed by the pavement and can be transformed into thermal energy stored by a hot fluid flowing in a network of pipes embedded in the carriageway. The heat captured by the pipes of the SCS can be used to generate electric energy by thermoelectric generators. Another form of thermal type is the so-called Thermo-Electric Generator (TEG), based on thermo-electrical principles, which harvests energy from the thermal change of the surrounding environment, such as pavements and subgrade layers. Extending the energetic system to the deep inside of the Earth, forms of Geo-Thermal (GT) energy exploitation can also be implemented in the highway sector, with heat pumps harvesting underground thermal energy storages. From a mechanical point of view, energy harvesting regards Piezo-Electric (PE) materials and Wind Turbines (WT). PE materials generate electric charges as a result of mechanical stresses. Thus, the deformation of road pavements can represent a strategy for energy harvesting using conductive asphalt layers and piezoelectric material layers to collect dissipated vehicle kinetic energy, i.e. Energy Harvesting Pavement System (EHPS) [74,75].

Turning to another form of clean and renewable energy, namely wind, we can easily imagine that the air flow generated by the passage of a vehicle at a certain speed can be used to move WT. It is clear that, when the transit volume and speed allow us to deal with generated winds of a certain constancy and speed, highway windmills can represent a noteworthy clean energy collection system. Liew et al. [76] propose an up-to-date review of feasibility WT technologies for highway energy harvesting, regarding vertical and horizontal axis WT. However, the study of the shape and optimal positioning of these turbines, of the wind characteristics of the area and of the wind power of a certain highway are crucial aspects to deepen, in assessing its real feasibility.

Alongside the production of energy harvested from clean and renewable sources, smart highways must also make this energy available for direct use. If a distribution network, even of a traditional type, can make it possible to supply infrastructures and technologies for road management (i.e. sensors, systems, lighting, etc.), it is necessary to make a substantial leap in innovation when we move towards vehicle powering. Electric vehicles (EVs) have recently increased their market penetration significantly. Moreover, in the near future, we can imagine that all CAVs will be electric. Thus, the highway of the future must allow these vehicles to be powered, or rather to be recharged, and this must inevitably happen without any plug-in charging system. Wireless electric vehicle charging systems (WEVCS) can take place as a static wireless charging system (S-WEVCS) and a dynamic wireless charging system (D-WEVCS) [77]. S-WEVCS implies that the vehicle is stationary on an area specially set up for charging, without however needing a plug-in connection, and for these reasons it is suitable for parking areas. D-WEVCS is also known as in-motion charging or charging while driving [78], and for this reason it is the eligible solution in an evolved EVs environment (i.e. V2G connection) [77].

The Inductive Power Transfer (IPT) is a first-order D-WEVCS technology for wireless charging of EVs based on several primary

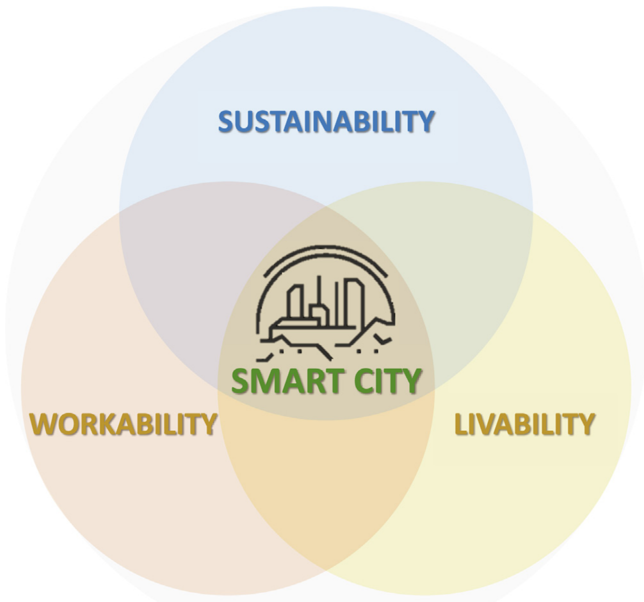

Fig. 6. The three focus areas of smart cities.

coils embedded in the road lane, which transfer induced power to the secondary coils of the EV while it is moving [79]. For more in-depth information on electric vehicle wireless charging technologies, a helpful and comprehensive review is offered by Panchal et al. [77] and Ahmad et al. [80].

3.5. Smart city, smart road and smart intersections

Even though in the previous sections the discussion on the smart road has been almost oriented towards infrastructures with motorway characteristics, this in no way excludes the extension of this innovative concept to urban road networks.

As mentioned in the introduction of this paper, modern cities represent the ideal context in which new technologies for intelligent and connected mobility can be organized in a productive and effective way to allow for optimization of urban functions and services, improving energy efficiency and promoting social, economic and environmental sustainability. In this perspective, as in Fig. 6, the new inspiration for Smart Age cities, the so-called smart cities, regards [81]:

- livability: cities that provide clean, healthy living conditions without pollution and congestion with a digital infrastructure that makes services instantly and conveniently available anytime, anywhere;
- workability: cities that provide the enabling infrastructure — services, energy, connectivity, computing — to compete globally for high-quality jobs;
- sustainability: cities that provide services without stealing from future generations.

Extending the smart road concept, in the future smart cities' road networks will be managed by intelligent systems that will be able to consider each individual vehicle and to communicate with it. These future networks, composed of intelligent and cooperative elements, will be able to guarantee self-awareness in operation, information interaction and connection, self-adaptability to circumstance and energetic efficiency, reducing congestion and promoting safety and sustainability.

It goes without saying that smart road networks for smart cities need smart intersections. Actually, intelligent and connected intersections are a foundational piece for a smart city.

Taking into consideration the case of signalized intersections, for some time cities have been organized with road intersections equipped with adaptive traffic signals based on in situ traffic measurements with actuated control schemes and coordinate control. Traffic-responsive and coordinate signals are now quite widespread in our cities, and Ni [82] proposes a complete discussion of such systems with the most innovative solutions. Recently Astarita et al. [83] published an interesting and detailed literature review about FCD adaptive traffic signals, which represent the starting point for innovative control systems. Referring to the study cited above for the detailed literature reference, a quick review of solutions sees in particular mobile phones and wireless communications combined with GNSS technologies, such as GPS. The same authors also report some studies investigating the potential of V2X connectivity. Actually, connected vehicles and V2X could make it possible to regulate adaptive traffic signals on the basis of more detailed traffic measures. This expands enormously the possibility of implementing AI solutions for better real-time management of the single intersection, some consecutive intersections along a road, or even large portions of the city.

As well as the management of the signaling system installed on the road junction, V2X communication would allow real-time on-board information on the vehicles. Currently, the second of these two aspects has been experimented with on-board systems that allow the use of information coming from the traffic signal to adjust driving patterns (e.g. [84–86]). As for the first aspect, which affects the traffic signal control system, the first experiments are beginning to show their results (e.g. [87,88]).

It goes without saying that these systems must be designed to take into account the coexistence of autonomous and connected vehicles and human-driven vehicles. The control systems of adaptive traffic signals in a V2X context will be able to handle this coexistence in safety, keeping adequate constraints in the management of conflicting maneuvers. This will make it possible to manage an increasing penetration rate of CAVs in the mobility market, ensuring safe operations for the various shares of traditionally-driven vehicles, which will initially predominate and will gradually decrease.

In the future scenario that sees the total presence of self-driving vehicles in an extensively interconnected environment (i.e. V2X), even the problems relating to the management of non-signalized intersections can be adequately resolved. Once again, in fact, the Big Data collected by the sensors and the AI algorithms can ensure the implementation of real-time traffic management and control systems for scheduling the transits of each single CAV and the elimination of the risk of conflict.

Vehicular platooning systems, speed harmonization and trajectory optimization systems allow eliminating the uncertainty in the management of the maneuvers at a non-signalized intersection of the smart road network. This intersection, in fact, can be managed by the central traffic control system (which we have referred to as OCC) according to a performance optimization plan. In this sense, therefore, in a V2X environment with only CAVs, the intersection is found to operate in a deterministic manner (as all the vehicle paths are known and shared) according to a plan defined in real time by the OCC and considering traffic, infrastructure and environment context under some pre-ordered criteria (e.g. of transport efficiency, safety of maneuvers, passenger comfort, energy consumption, environmental impact, etc.).

More generally, automated approaches for non-signalized intersections can be classified as being either centralized or decentralized [89]. Centralized solutions include V2I communication which shares the best crossing sequence, identified by the OCC through a decision algorithm to achieve a safe and optimal crossing sequence. Decentralized solutions are based only on communication between vehicles arriving at the intersection and without centralized coordination (i.e. V2V), to perform cooperative maneuvers. Centralized and decentralized solutions can operate optimizing the crossing sequence and dynamical behavior of the vehicles using cooperative driving techniques, such as Cooperative Adaptive Cruise Control (CACC) [90].

Although CACC is properly identified when it is managed at a higher level in centralized systems, Medina et al. [89] introduced a Virtual CACC for decentralized solutions by means of virtual platoons of cooperative autonomous vehicles, based on V2V communications only. Azim et al. [91] introduced a space-temporal technique called BRIP, Ballroom Intersection Protocol, to manage autonomous vehicles at intersections. BRIP enforces synchronized arrival patterns for CAVs at intersections known or broadcast to all approaching vehicles.

These aspects also concern roundabouts, both in conventional and innovative forms such as the so-called turbo-roundabouts, with their different layouts. Thus, a number of technologies and standards can be implemented to optimize traffic flow in roundabouts through V2X, but these are not applicable without major complications in the case of the concomitant presence of both CAVs and conventional human-driven vehicles.

To overcome this limitation, some studies have begun to address the problem. Among these, Masi et al. [92] proposed a virtual platoons approach roundabout traffic considering also human-driven connected vehicles and non-connected vehicles, knowing their position on the geometry of the intersection by means of adequate sensors. This approach allows to apply a platooning strategy to manage complex scenarios of non-signalized intersections (including roundabouts) with partial automation and/or connection for vehicles. In the intention of preserving compatibility with human-driven vehicles, Ibanez et al. [93] have recently proposed their synchronized model called Synchronous Roundabouts with Rotating Priority Sectors, SYRPO. SYRPO, which incorporates smart technologies such as sensors, CAVs, V2X, IoT, and AI, is based on vehicle platoons arriving at the roundabout at a uniform speed and within an assigned time slot for their entry. Its signaling system is visual for human drivers and wireless for CAVs, and the control strategy prevents conflicts and stops.

In urban areas, but not only, road intersections are places of the confluence of different classes of users, first of all motorized and non-motorized ones. From this point of view, pedestrian and cycle crossings cannot be neglected by smart innovations. Pedestrian crossings are one of the most dangerous places in the transport field, as most of the traffic accidents happen there. Thus, ITS and smart mobility solutions can support in developing infrastructure that can best manage these crossings. Pau et al. [94] reviewed a series of ICT solutions to improve crossing safety with high-performance recognition systems and adaptive logic for controlling the traffic light phases. Reference should be made to this study for an in-depth bibliography on the subject. These solutions, however, are generally characterized by extensions and particularizations of the solutions already discussed for traffic management in the mixed case (i.e. with the presence of CAVs and human-driven vehicles), in order to take into account the presence of non-motorized users. Actually, these are clearly solutions that fulfill the key functions of the smart road: self-awareness, connection and communication, self-adaptation and even self-supply when technological solutions include renewable energy (mainly solar) for their operations.

A new category of innovative pedestrian and cycle crossings, which conform to the key function referred to above, is represented by the so-called smart zebra crossing. Some prototypes have recently been developed, to activate laboratory experiments and to launch subsequent real-world installations. Among these, we can mention the Starling Crossing system, that is a self-adaptable road marking system. The Starling (STigmergic Adaptive Responsive LearnING Crossing) prototype by Umbrellium for Direct Line with Saatchi & Saatchi [95] consists of a responsive road surface with ultra-bright LEDs that can tell the difference between vehicles, pedestrians and cyclists and a network of cameras. The crossing space appears as a digitized version of a traditional zebra crossing but it is activated when there is a crossing request (i.e. pedestrian or cyclist) and the control system considers that the crossing can take place safely. A crossing symbol, which is first red and then green, appears on the floor at the edge of the road. The digitized crossing markings will widen if a crowd tries to cross at once, and these disappear when no longer required or the crossing can no longer take place safely. The system uses the principles of stigmergy [96] – i.e. the pheromone traces that ants leave, attracting other ants to the best paths toward food sources – and ant-based algorithms of AI to monitor and adapt to the pedestrian's will and to ensure the possibility of a safe crossing in the current environmental/road/traffic conditions.

A final observation for a smart intersection regards the capability of feeding itself. For urban roads and intersections it is more difficult to hypothesize a multiplicity of sources for the generation of renewable energy as it has been done for motorways, with the exception of quantities of solar energy; but, anyway, their intelligent management can still produce significant energy savings, as well as lower environmental impacts. Also in this case, research is continuously being developed and new energy harvesting hypotheses are being studied. A recent one by Ibrahim et al. [97] attempts to take advantage of the pressure of moving vehicles and pedestrians over a traffic road junction and, in turn, to convert it into electrical energy using mechanical arrangements and Piezoelectric materials.

Smart mobility concept relates to multimodal and intermodal characteristics of passenger transport, especially for shifting people from private car usage to more sustainable alternatives. Following the definitions by Willing et al. [98], multimodality is the availability of multiple and alternative transportation modes for the same trip, while intermodality is the opportunity for a passenger to have access, in a single trip, to a combination of distinct modes of transportation. These authors reviewed a number of existing solutions for multimodality and intermodality in passenger transport systems, highlighting their role as activators of more sustainable mobility behavior and as solutions for relieving strained urban mobility systems. On information systems perspective, the smart city enhances multimodal and intermodal transport policies providing web platforms for travel planning and transport systems integrations. A growing demand for more personalized transport services has pushed towards new digital services enabling users to plan, book, and pay for multiple types of mobility services. This is the so-called Mobility-as-a-Service (MaaS) [99], a service concept that integrates different types of mobility services, such as traditional public transport, car parking locations, taxis and ride-sharing with a set of core attributes, such as: demand orientation; multiple public and private actors; tariff integration and payment harmonization; ICT and ITS solutions; digitalized planning channels and tools for user's trip choices customization. Actually, these types of applications are intended to propose the most appropriate combination of transport modes/solutions for a specific trip route, based on the underlying scenario of the available transport modes and the preferences according to a few important criteria that are relevant to users and to smart city policies. As accurate high-quality travel behavior knowledge is a prerequisite for an efficient service, to provide an effective and useful choice support, it is important to have an accurate high-quality travel behavior knowledge, both as automated transportation mode detection and relevant criteria characterization for users. From this point of view, Feilhauer et al. [100] propose an advanced automatized travel behavior detection and analysis platform for multimodal and intermodal trip optimization.

4. The smart road as a socially and environmentally sustainable vision of modern road transport

In light of the definition of smart road that we have tried to summarize, starting from the key functions and reviewing the innovative technologies and strategies which are the current interpretation of the Smart Age in the road field, it makes sense to ask ourselves: what kind of general vision can we consider for the roads of the future? Actually, we can add another not obvious question, that is: how do the options identified as currently available fit into this vision?

Smart Transport Alliance (STA) [101], a not-for-profit global collaborative platform for transport infrastructure innovation across modes and the smart city, offers an effective criticism for road transport [102]. Road infrastructures, which are certainly the oldest and most widespread ways for the movement of people and goods, have undergone a growing degenerative process in social perception. Infrastructure and road traffic are increasingly and directly linked to exclusively negative concepts, due to their social and environmental negative impacts. At the social, media and political level there are different aspects which substantiate this bad perception, which mainly relate to: air and noise pollution impact, both locally and globally with the contribution to global warming and both on different components of the biosphere and on human health; hazard rates induced by certain types of transport and general accident rates still not sufficiently reduced. At the same time, the quality of the service that the road system is able to provide in developed countries is constantly decreasing. The increase in congestion, in addition to amplifying the environmental and health effects mentioned above, reduces the comfort of travel and increases the time taken away from other main activities. These aspects represent a typical source of frustration and reduction of psycho-physical well-being in modern society, both for the individual and for the entire community.

It should also be noted, in the experience of recent decades, that the effort in technological innovation weighs against road transport, in comparison with other modes of transport. Rail, air and naval transport have undergone substantial changes, offering an ever-expanding range of new and competitive solutions. The same thing has not happened for road infrastructures: for a long time innovation mainly concerned vehicles. The growth in the number of moving vehicles, and the consequent increase in congestion and environmental and health impacts, have exasperated the negative social connotation of road transport.

It seems that the time has come to re-discuss this declining role, bringing back the positives aspects of using highways as effective and efficient components of a modern integrated transport and communication system. Investing in innovative road infrastructures, in fact, can represent a profit opportunity for the entire community, an opportunity to increase the well-being of the same as an increase in accessibility to other transport infrastructures, production plants, markets, services, structures. health, cultural and recreational opportunities and participation in all aspects of social and productive life.

STA proposes a comprehensive vision for smart road, as a moment of rebirth for the role and significance of highway infrastructures in social and territorial relations: it "must address people's highest expectations in relation to road transport and, so doing, define a model for highway of tomorrow that adapts to societal demands" [102]. Taking into consideration this vision, a panel of criteria can be identified, which represent the multiple dimensions according to which this face-change in road infrastructures can be substantiated, through solutions that can make them more reliable, more comfortable, more sustainable and safer. In other words, this panel of criteria interprets the multiple requirements that the roads of the future must meet in order to be considered in line with the expectations of the community. These can be defined as below:

- A: Mobility efficiency improvement;
- B: Environmental performance improvement;
- C: Advanced traffic control strategies implementation;
- D: Life-cycle analysis of construction and maintenance costs and energy inputs examination;
- E: User-oriented designs;
- F: Safety and security performance improvements;
- G: Long term validity.

At this point, it seems interesting to propose a compliance assessment for the key solutions reviewed in the previous sections, based on the panel of criteria identified according to the vision of STA. The evaluation consists in assigning a score to each solution in consideration of each criterion according to a three-level scale: very significant; significant; not significant. Therefore, Table 1 shows the key solutions and relative score by criterion, together with an overall score as the average of all seven criteria (score level/color/weight: very significant/red/2; significant/orange/1; not significant/yellow/0).

According to the scores we have decided to assign, Table 1 shows that the solutions proposed for the different features and functions are oriented towards what we can consider a good degree of significance in achieving the objectives of the referred vision, with respect to each of the criteria and their overall satisfaction.

It is clear, however, that the solutions reviewed are not to be considered as pieces of a puzzle, in which the lack of an element prejudices the entire work. These are rather elements of a rich toolbox, which we can draw on to create, from time to time, a complex smart road project, compliant with a socially and environmentally sustainable vision and adequate for the actual needs of the transport system and society.

In any case, in our opinion, attention must be drawn to the potential risks deriving from optimism, which could be lurking when it comes to new technologies. Technologies are not to be considered in themselves capable of making roads safer, cleaner, more efficient and more comfortable just because they are innovative, in the wake of a self-referenced modernist attitude. They must be carefully and responsibly studied, implemented and calibrated on the specificity of the situations to be effective and sustainable for society and the environment. From this point of view, it must be kept in evidence that innovations can add levels of complexity to the road transport framework. In a non-exhaustive but illustrative way, and keeping in mind the solutions reviewed as technological aspects of the smart road vision, we can think of topics such as: security of the data flow and information storage; privacy and responsibility of individuals; safety and protection of all road users, with particular attention to the weaker ones; new forms of pollution, to the detriment of human health and the environment.

Numerous solutions proposed have a high need for information, namely Big Data at various levels of aggregation, which feed AI applications for the control of highly interconnected systems and with high degrees of automation. The aspects of security and prevention of attacks on these systems, as we have already had the opportunity to specify (see Section 3.2), are highly critical for the smart road, and the search for safe and unassailable protocols is

Table 1
Key solutions assessment according to the STA vision criteria.

Key feature	Key function	Key solution	Criteria (*)(**)							
			A	B	C	D	E	F	G	AV
Learn	Traffic monitoring and traffic modeling	Road-side vehicle and traffic data detectors	red	yellow	red	orange	orange	orange	red	orange
		Wide-area traffic data detectors	red	yellow	red	orange	orange	orange	red	orange
		Floating Car Data	red	orange	red	orange	red	red	red	red
	BIM and SHM	Pavement monitoring systems	red	red	red	red	red	red	red	red
		Sub-grade/soil slope monitoring systems	red	red	red	red	red	red	red	red
		Buildings monitoring systems	red	red	red	red	red	red	red	red
		Environment monitoring systems	red	red	red	red	red	red	red	red
Interact	IoT, IoEE	Big Data and AI applications	red	orange	red	red	red	red	red	red
		V2X framework	red	orange	red	red	red	red	red	red
		Augmented Reality applications	red	yellow	red	orange	red	red	red	red
		MaaS	red	red	red	orange	red	orange	red	red
Adapt	Traffic Management	ITS solutions for traffic	red	red	red	orange	red	red	red	red
	Road signs, markings and signals	ITS solutions for adaptive signs/lights	red	orange	red	orange	red	red	red	red
	Construction materials	Intelligent Materials	red	red	red	red	red	red	red	red
Feed	Energy Production	Solar energy	orange	red	orange	red	orange	yellow	red	orange
		Thermal energy	orange	red	orange	red	orange	yellow	red	orange
		Mechanical energy	orange	red	orange	red	orange	yellow	red	orange
	Energy Supply	Vehicle charging systems	orange	orange	red	red	red	yellow	red	orange

* Criteria: A = Mobility efficiency; B = Environmental performance; C = Advanced traffic control strategy; D = Life-cycle analysis of construction and maintenance cost and energy inputs; E = User-oriented designs; F = Safety and security performances; G = Long term validity.
** Levels: red = very significant; orange = significant; yellow = not significant. This is the format for table footnotes.

and will continue to be the subject of great research and experimentation in IoEE context.

Big data also means a lot of personal information and these must be constantly protected from external permeability and inappropriate uses, always guaranteeing privacy to the individual users. CAVs and extended ITS solutions are a challenge also from the point of view of responsibility for the actions taken by AVs and OCC, and the accidental consequences that these can have. This topic opens up to complex problems of legal and insurance nature, for which substantial reflections and insights will be necessary.

Concrete actions for the benefit of safety and comfort, which are deep-rooted for vehicles in the planning and control of ITS, must be maximally expressed also and above all, for weak users. Increased safety levels must be ensured for pedestrians and cyclists, providing for an integration of control systems to take into account the needs of these mobility components. In-depth analysis and developments are therefore expected in the field of smart intersections to ensure shared and safe use of infrastructures, especially in the urban environment.

Finally, in the review we have presented different solutions that, according to the criteria and scores of Table 1, have been evaluated as capable of bringing environmental and health benefits, taking into account their ability to lower emissions of known pollutants and pressure factors. However, for these solutions and for those to come in the future, the possibilities of new pressure factors on the environment and human health must be kept in mind. In this regard, just think of the innovative construction materials, the new technologies for wireless connection, transfer of information and energy distribution, the dense network of sensors of an increasingly miniaturized nature (MEMS), and whose effects on human health and the environment must be properly investigated.

5. Conclusion

The smart road concept, namely the highway of the Smart Age, extends road infrastructures improving their operational capability to respond to the modern needs of road users with intelligent mobility solutions.

The paper aim was to offer an overview of the smart approach in road engineering by proposing a broad discussion about the current state of the art in smart road developments. Actually, the paper presented a general discussion on what "smart road" and "smart highway" really mean and what they can be. The use of functional definitions in the literature has allowed us to highlight the key functions of the smart road: self-awareness; information and connection; self-adaptability; energy harvesting. By examining each of these key functions, the paper offered a bird's eye view of the most modern technologies based on Information and Communications Technologies, such as end-user Internet service system, Internet of Things, Connection and Cooperation Services, Big Data, Augmented Reality, Artificial Intelligence, Edge Computing. Alongside these, other innovative technologies were reviewed, which concern the use of Intelligent Materials or the exploitation of clean and renewable energy sources.

Starting from the definition of the functions of the smart road and more generally of mobility in a smart city context, the paper proposed a discussion on the actual ability of these innovations to achieve the objectives underlying a vision of the smart road, in a perspective of environmental and social sustainability. The solutions reviewed showed an excellent degree of compliance with the criteria that were identified starting from this vision. Some points of attention emerged from the discussion, highlighting some strengths and criticalities of current innovations in the market for infrastructures and services for the road mobility in the Smart Age and especially of their future developments. These may concern, with greater attention, issues such as: security of data flow and storage; privacy and personal responsibility; traffic safety and protection of weaker users; any new forms of pollution, to the detriment of human health and the environment.

Actually, it is a rapidly expanding sector with very broad market prospects in the coming years, oriented to win the major challenge to connect users, vehicles and infrastructures in an intelligent, efficient, safe and sustainable manner. Even though these innovations still represent a small slice of the present, they are destined to enrich themselves and constitute a large slice of the future in the panorama of mobility, both for people and goods.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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