Available online at www.sciencedirect.com

ScienceDirect

Transportation Research Procedia 71 (2023) 395–402

Transportation Research Procedia

www.elsevier.com/locate/procedia

XV Conference on Transport Engineering, CIT2023

Smart on-Road Technologies and Road Safety: A short overview

Francesco Angioi[a*], Alberto Portera[b], Marco Bassani[b], Juan de Oña[c], Leandro L. Di Stasi[a]

[a]*Mind, Brain, and Behavior Research Center, University of Granada, Campus de Cartuja s/n, 18071 Granada, Spain*
[b]*Department of Environment, Land, and Infrastructure Engineering, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy*
[c] *Department of Civil Engineering, University of Granada, Campus Universitario de Fuentenueva (Edificio Politécnico), 18071 Granada, Spain*

Abstract

Smart on-Road Technologies (SRT) are installations on the road, with which drivers interact passively, designed to reduce road accidents by increasing driving performance and/or road network sustainability. Although SRT are a core element of the future Smart Road Infrastructures, as they might significantly improve the road system, they are usually presented just as conceptual models instead of actual solutions. Consequently, evidence on the effectiveness of SRT in increasing driving performance and/or safety are scarce and not conclusive. Here, we present an overview of SRT systems (theoretical or existing) to try to identify their goals and objectives in terms of impact on road safety and driving behavior. More than 100 peer-reviewed articles on SRT, published in the last five years, were screened. Based on their impact on the road transportation system, we classified SRT into two main categories: (i) those that encourage appropriate road users' behaviors and awareness, including active and adaptive road delineator systems such as luminescent horizontal road markings, temperature-sensitive paints, or musical roads, and (ii) those able to reduce the environmental impact of the road transportation system, including technologies such as electrified priority lanes, and smart road lightning. Preliminary empirical evidence has shown the effectiveness of SRT in improving drivers' performance (e.g., vehicle lane positioning) and perceived safety. This result is based on just eight works, however. Overall, our results pointed out that SRT lack dedicated research aimed at evaluating the effects on driving performance and safety (traffic crash/injury prevention). To discourage the misuse of any new SRT, future research investigating the impact of these advanced innovations, using both simulated and real settings, is needed.

Keywords: intelligent road technology; smart mobility; smart tehcnology effectiveness; human factor.

* Corresponding author. Tel.: +34-604238798.
E-mail address: frangioi@ugr.es

2352-1465
10.1016/j.trpro.2023.11.100

1. Introduction

In line with the European "Vision Zero" policy (European Commission, 2021), the installation of (Smart) technology on road infrastructure is a promising technique for reducing road accidents. In this context, the term Smart usually refers to technologies that self-adapt to the traffic and environmental context, aim to increase sustainability of the road network, reduce road accidents, and eliminate the negative impact of human factors on road safety (e.g., Pompigna & Mauro, 2022). In this overview, we defined on-road Smart Road Technologies (hereafter SRT) as fixed installations on the road surface with which the drivers passively interact. To date, SRT have been mostly classified into two categories based on their main functions: (i) reducing the environmental impact of the road transport system, and (ii) promoting appropriate road user behavior and awareness. For instance, while the first category includes technologies such as electrified priority lanes, and smart road lighting (Toh et al, 2020), the second one comprises active road delineator systems (e.g., luminescent markings, active road studs), and traffic sensitive markings (Zhu et al. 2021; Llewellyn et al., 2020). Even though SRT are reshaping road and city concepts (Savithramma et al., 2020), in most of cases, they are only a concept without scientific evidence supporting their effectiveness. Besides, evidence suggest new technological innovation may have a negative impact on safety due to changes in risk perception and acceptance by drivers (Wilde, 1998; 1982), and general technophobia may influence users' intention to use new technologies (Koul and Eydgahi, 2020). Thus, it is utterly relevant to understand the effects of these new technologies on drivers' behavior and attitude toward SRT.

Our overview aims to explore the existing research on SRT (theoretical and currently used) to map the current state of evidence and identify knowledge gaps for further studies. The key objectives of this work are twofold: (i) identifying the SRT and their purpose, and (ii) assessing the impact of SRTs on road safety and driving behavior.

2. Search methodology

In this overview, we summarize the state of the art of on-road SRT reporting technologies and their evolution, their goal, impact on the road transportation system, driving behavior, performance, and acceptance. We conducted a comprehensive search including peer-reviewed articles, technical reports, and news (from websites/newspapers) in any context that included, at least, one on-road SRT. We used four electronic bibliographic databases: Scopus, ProQuest One Academic, MedLine, and Web of Science. Moreover, Google Scholar online tool was used to broaden the search. We included English and non-English (Spanish and Italian) scientific literature published before January 2023. The keywords included terms such as smart and intelligent, which are often used in the literature when referring to innovations within road technologies. Moreover, the terms active and dynamic are usually associated with technologies capable to self-adapt to different traffic situations (e.g., variability in traffic flow and/or road visibility). As we focused on technologies applied on the road surface, we included road, pavement, and horizontal terms in the search strategy. Finally, we used truncation, and phrase searching to search in a broad range of databases (e.g., smart AND (road OR pavement OR horizontal) AND (technolog* OR marking*), (active OR dynamic) AND (road OR pavement OR horizontal) AND (marking*).

3. Smart Road Technology

We extracted 267 studies from the databases. After removing duplicates (n = 55), two reviewers (authors: FA and AP) independently screened 212 studies. To assess the eligibility of documents, the reviewers independently performed first a title and abstract screening, and then a full-text screening of the included records. We found 31 studies that met the eligibility criteria and were used to identify the SRT. Afterward, we assigned each SRT to the respective category according to their main goal (for a schematic representation see Fig. 1). Finally, we analyzed whether the studies included any results on drivers' behavior, performance, and acceptance using objective (e.g., speed, lateral position) and/or subjective (e.g., self-reported measures, questionnaires) indicators.

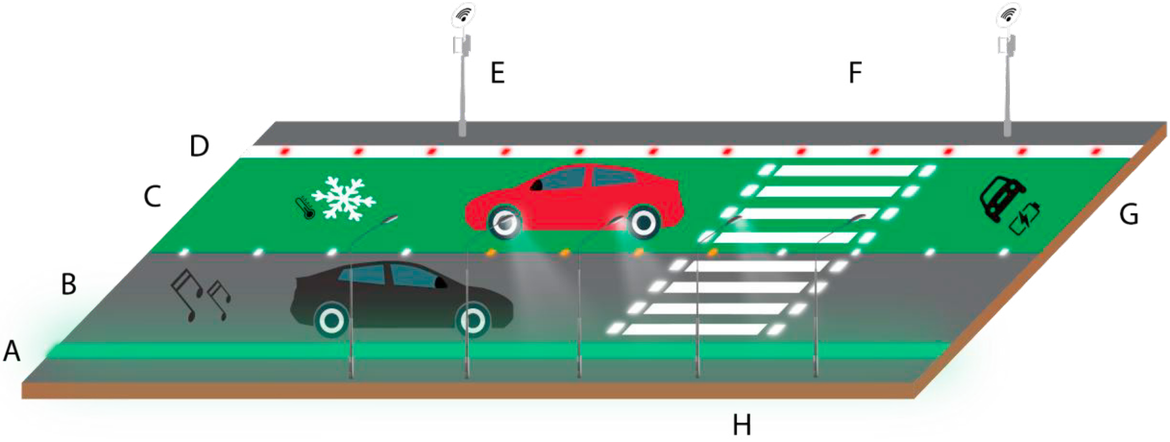

Fig. 1. Schematic representations of SRT on the road surface. In this figure we represent photoluminescent road markings (A), musical roads (B), temperature-sensitive paint (C), dynamic road markings (D), multifunctional posts (E), smart crosswalk (F), electric vehicles charging lane (G), smart street lightning (H).

3.1. SRT improving sustainability of the road network

We identified four types of SRT aimed to enhance the sustainability of the road network: (i) the solar road, (ii) piezoelectric road, (iii) smart road lighting, and (iv) electric priority lanes. Most of these SRT are just proof-of-concept designs which are in development and testing phases (i.e., not currently installed on road) or employed in a few road stretches.

The solar road concept combines road infrastructure with photovoltaic technology that converts sunlight into electricity to provide clean energy (Solar Impulse Foundation, 2019). This SRT can be installed on shoulders, cycle paths, car parks and urban areas, and can also empower the street lighting. Piezoelectric roads consist of piezoelectric devices and a stainless-steel substrate installed underneath the road pavement which collect the kinetic energy coming from the movement of road users (Giudici & Pèrez-Fortes, 2022). This smart energy-harvesting system is expected to reduce or eliminate the black ice problem by measuring the temperature of the road surface (Do Hong et al., 2022). Smart road lighting technology may exploit those energy sources. It can sense the environment and react accordingly by providing different lighting conditions, focusing on specific users, or illuminating specific sections of the road when a car is approaching (Mao et al., 2021; Todorović & Samardžija, 2017; Samardžija et al., 2010). This strategy saves a significant amount of electricity and is expected to improve driver visibility and reduce the number of accidents. However, while the payback in terms of energy consumption has been demonstrated for all three SRT, their influence on drivers' performance is still unclear. Finally, the increasing uptake of electric vehicles (EVs) requires the development of a charging network to support the transition to the new generation of low-emission vehicles (for a recent review, see Hemavathi & Shinisha, 2022). Therefore, SRT such as electric priority lanes will soon be introduced in the European road network, allowing cars and trucks to charge using magnetic field or contact with rail technologies (Toh et al., 2020). Nevertheless, it is worth noting that the introduction of these lanes will probably lead to an increased number of lane-changing maneuvers, but the effect on longitudinal and lateral driving behavior has not been investigated yet.

3.2. SRT encouraging safe driving behavior

We identified four types of SRT aimed to enhance driving behavior and promote road safety: (i) active road markings, (ii) musical roads, (iii) multifunctional posts, and (iv) temperature-sensitive paints.

Firstly, active road markings aim to support driver's vision in low-visibility traffic scenarios by making the horizontal markings visible beyond the vehicles' headlamps beams during the night, which represents the main improvement with respect to conventional passive (retroreflective) markings. These SRT can be divided into two categories: photoluminescent road markings, and electric luminous road markings (for a recent review see, Lin et al., 2023). Photoluminescent technology allows to produce the "glow-in-the-dark" markings by employing materials which accumulate energy during the day to release it as light at night (Bhujbal et al., 2022; Zhu et al., 2021). The results obtained with different materials are promising and this solution does not require any changes in the road structure (Villa et al., 2021; Yanqiu et al., 2020). However, factors such as daily color variations, painting formula, and temperature make it complicated to define material service life and a standard characterization methodology (Lin et al., 2023; Villa et al., 2021). On the other hand, electric luminous markings employ light emitter devices which are empowered by an electric energy supply or solar energy (Llewellyn et al., 2021; Grabinsky, 2019). Electric energy supply is mainly used by dynamic road markings, active road studs, and smart crosswalks. Dynamic road markings consist of a series of LED sensors (without painted markings) integrated with intelligent transport system devices aiming to improve traffic management and safety (Wiafe et al., 2020; Nguyen, 2018; Le Roux, 2013). Then, active road studs consist of self-illuminating LED devices applied in combination with existing painted lanes, which aim to control drivers' over-speeding behavior, improve lateral vehicle control, and provide light-based traffic guidance (Tao et al., 2022; Llewellyn et al., 2020; Shahar et al., 2018; Shahar & Bremond, 2014; Samardzija et al., 2012; Birk & Osipov, 2008). Finally, smart crosswalks aim to improve driver behavior (e.g., longitudinal speed) and the interaction with pedestrian at night. They are mainly composed of detection system (optical or integrated), and an alerting unit which mainly consists of a set of high-brightness LED (Lozano Domínguez et al., 2021; Patella et al., 2020; Lozano Domínguez & Sanguino, 2018). Although electric luminous markings are a remarkable leap forward in road safety, lightening intensity management, system reliability, and high cost of implementation and maintenance require further research (Ram et al., 2021; Villa et al., 2015a; 2015b).

We identified also SRT exploiting auditory stimulus, such as musical road, to induce appropriate speed behavior and warn drivers of hazardous situations (Toh et al., 2020). Musical road technology has been mostly adopted in Japan and consists of a series of grooves and rumble strips applied to the road pavement that produce different tones as vehicle pass, depending on their speed (Zhou et al., 2018). Finally, we found other two proof-of-concept SRT, which are multifunctional posts, and temperature-sensitive paints. Multifunctional posts will wirelessly detect incoming environmental conditions and dangerous situations (e.g., passing vehicles, wildlife, and pedestrians in poor visibility conditions) and alert drivers by displaying the information on an external screen with a simple visual interface installed on the post (National Highway Authority [ANAS], 2021; Agafonovs et al., 2013). The temperature-sensitive paint is transparent under normal conditions, but becomes visible under adverse meteorological conditions (e.g., icy conditions) and reveal warning symbols on the road (Studio Roosergaarde, 2013; Dumé, 2008).

4. Effectiveness of SRT on driving behavior and road safety

In this section we present studies reporting results on the effects of existing SRT on driving behavior, performance, and acceptance, and/or road safety. We found that only 26% of the included studies (i.e., 8 out of 31) showed specific outcomes on SRT effectiveness (see Table 1). To assess the impact of the SRT studies on road safety and driving behavior, we extracted information on the population, the investigated conditions (comparison, if applicable), and the research outcomes. Four of the included studies do not report any information on population characteristics (Patella et al., 2020; Hakkert et al. 2002; Llewellyn, 2015; Llewelyn et al., 2021). When reported, the mean age of the drivers recruited was about 37 years old (SD from ±10.2 to ±11 years), with the number of participants ranging from twelve to thirty-one (Zhu et al., 2021; Shahar et al., 2018; Shahar & Bremond, 2014). Finally, Llewellyn and colleagues (2020) considered respondents to a survey older than 18 years old (Llewellyn et al., 2020).

Regarding the study settings, we found three driving simulation studies, four naturalistic (on-road) studies, and one survey. Three driving simulation studies explored the effectiveness of active road markings (i.e., LED studs or continuous markings) on driving behavior showing mixed results, however. Factors such as illumination, road section, and light color were investigated (Zhu et al., 2021; Shahar et al., 2018; Shahar & Bremond, 2014). Active road studs seem to induce a similar speed along curved sections as the passive conventional markings condition, but a higher speed was detected along straight sections on rural roads (Shahar et al., 2018; Shahar & Bremond, 2014). Moreover, active LED markings induced lower speed variance than conventional markings, suggesting a positive effect on drivers' vehicle speed control (Shahar et al., 2018). However, Zhu and colleagues (2021) observed higher vehicle speeds with active road markings when compared to passive road markings along highways. Thus, results on the effect on drivers' longitudinal behavior are inconclusive. Regarding lateral behavior, active road studs were effective in improving lateral control (Zhu et al., 2021; Shahar et al., 2018; Shahar & Bremond, 2014). In addition, a comprehensive driving performance indicator combining physiological (i.e., pupil area change rate) and driving performance variables (i.e., steering wheel speed, brake pedal force, gas pedal, lane departure, speed), showed that yellow LED active road markings were more effective than white and continuous active markings along highways (Zhu et al., 2021). Finally, roads including active road studs were perceived to be safer, more comfortable, and allow better vehicle control (Shahar et al., 2018; Shahar & Bremond, 2014).

Concerning the naturalistic (on-road) studies, we identified four observational studies that investigated the effects of smart crosswalks (Patella et al., 2020; Hakkert et al., 2002), and active road stud (Llewellyn et al., 2021; Llewellyn, 2015) which reported results on driving behavior and/or road safety. Smart crosswalks showed beneficial effects on driving behavior, performance, and pedestrian safety as the mean speed of vehicles was significantly decreased at the smart crosswalk with and/or without pedestrian (Patella et al., 2020; Hakkert et al., 2002). Although outcomes are promising for road safety, findings must be interpreted with caution as some results appeared to be site dependent (Hakkert et al., 2002). On the other hand, the application of active road studs on rural road and spiral-marked roundabout showed beneficial effects on driving behavior. Llewellyn and colleagues (2021; 2020) observed a positive influence on driver confidence and a significant decrease in mean speeds immediately after installation of the road studs and in low-light condition (speed limit 70 mph). However, long term beneficial effects of SRT were not demonstrated and change in mean speed by road sites and light condition were mixed both in direction and magnitude (Llewellyn et al., 2021). The implementation of active road studs on spiral-marked roundabout induced a better drivers' lane discipline (i.e., reduction in lane transgression) which means lower probability of vehicle conflicts and more predictable drivers' behavior (Llewellyn, 2015). Nevertheless, it is not clear whether this SRT can effectively reduce collisions and if the beneficial effects will be durable and sustainable.

Table 1. Review of previous studies reporting outcomes on impact of SRT on driving behavior, performance, and acceptance and/or road safety.

SRT	Participants	Study setting	Observed indicators	Results	Reference
Active road markings (yellow/white and stud/continuous)	N = 31 Age (M, SD) = 37.5, 10.2 years 45.2% female	Driving simulation, highway	Pupil area change rate (%) Steering wheel speed (°/s) Brake pedal force (N) Gas pedal (%) Lane departure (m) Speed (km/h)	A comprehensive indicator showed that yellow active road stud with a moderate blinking (40 times per min) was the best SRT in promoting safer driving behavior.	Zhu et al., 2021
Active road stud	N = 20 Age (M, SD) = 37.0, 11.0 years 25.0% female	Driving simulation, rural	Speed (km/h) Lane positioning (m) Crossover (s) Questionnaire (3 items)	On straights, participants drove faster with SRT, and closer to the lane centerline. Drivers also had better vehicle lateral control along curve with SRT.	Shahar et al., 2018
Active road stud	N = 12 Age (M, SD) = 37.9, 10.2 years 33.3% female	Driving simulation, rural	Speed (km/h) Lane positioning (m) Questionnaire (3 items)	Participants drove faster on straights with SRT. Drivers had better vehicle lateral control along curves with SRT, and considered this scenario safer, more comfortable and allowing better control.	Shahar & Bremond, 2014
Active road stud	ND	On road, rural	Vehicle speed (mph)	SRT was effective in reducing speed immediately after installation and in dark condition (limit = 70 mph).	Llewellyn et al., 2021
Active road stud	ND	On road, roundabout	Lane transgressions (-)	SRT reduced lane transgression rate for almost all vehicle types and maneuvers during daytime.	Llewellyn, 2015
Active road stud	N = 698 ≥18 years 35.8% female (N = 589)	Survey, rural	Survey (16 items, and open-ended questions)	Drivers reported a positive level of confidence both during hours of daylight (87%) and nighttime (52%).	Llewellyn et al., 2020
Smart crosswalk	ND	On road, urban	Speed (km/h) Deceleration (m/s^2)	SRT was effective in reducing speed both with pedestrian absence, while decelerations were higher.	Patella et al., 2020
Smart crosswalk	ND	On road, urban	Speed (km/h) Yield to pedestrian (%)	Reduction in vehicle speeds near the crosswalk zone of 2–5 km/h in mean	Hakkert et al., 2002

	User conflicts (-) Pedestrian crossing (%)	speeds, and in the conflict rates to less than 1%. Increased rate of giving way to pedestrians.

5. Conclusions

We aimed to map the existing and theoretical SRT solutions and investigate their influence on road safety and driving behavior, performance, and acceptance. The overview highlighted that most of the literature dealt with technical issues, while few studies have investigated the fallouts of these technologies on traffic operation and safety, as well as on drivers' behavior and acceptance. SRT effectiveness on driving behavior and road safety have been rarely targeted by previous research, while others are only futuristic concepts that are not yet ready to be implemented and tested. Although technological innovations such as active road markings and smart crosswalks have shown promising positive effects on driving behavior and road safety, there are few studies reporting research results, and those outcomes are not always consistent. Finally, as SRT are being slowly introduced on European public roads, it is essential to fill these gaps and avoid any costly mistakes before their widespread implementation.

Acknowledgements

The Neuroergonomics & Operator Performance Laboratory is funded by the HADRIAN (Holistic Approach for Driver Role Integration and Automation Allocation for European Mobility Needs) project. HADRIAN has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 875597. This document reflects only the authors' view. The European Climate, Infrastructure and Environment Executive Agency (CINEA) is not responsible for any use that may be made of the information it contains. We thank Dr. Giuseppe Marinelli (NORD University, Norway), Dr. Carolina Díaz-Piedra, Dr. Rocio De Oña (both University of Granada, Spain), and Leila Maboudi (Politecnico di Torino, Italy) for the comments and assistance.

References

Agafonovs, N., Skageris, A., Strazdins, G., Mednis, A., 2013. IMilePost: Embedded solution for dangerous road situation warnings, in: Proceedings - 1st International Conference on Artificial Intelligence, Modelling and Simulation, AIMS 2013. https://doi.org/10.1109/AIMS.2013.88.

Bhujbal, S.A., Bhosure, A.G., Sonawane, G.S., Patel, P.R., Jadhav, V.R., Dhivare, J., 2022. Study Smart Road with Glowing Lines. Int. J. Appl. Sci. Eng., 10(4). https://doi.org/10.22214/ijraset.2022.41965.

Bi, Y., Pei, J., Chen, Z., Zhang, L., Li, R., Hu, D., 2021. Preparation and characterization of luminescent road-marking paint. Int. J. Pavement Res. Technol., 14(2), 252-258. https://doi.org/10.1007/s42947-020-0229-3.

Birk, W., Osipov, E., 2008. On the design of cooperative road infrastructure systems, in: Proceedings of Reglermöte 2008.

Dumé, B., 2008. Intelligent paint turns roads pink in icy conditions. https://www.newscientist.com/article/dn13592-intelligent-paint-turns-roads-pink-in-icy-conditions/ (accessed 10 February 2023).

European Commission, 2021. Report on the EU road safety policy framework 2021-2030 – Recommendations on next steps towards 'Vision Zero'. https://www.europarl.europa.eu/doceo/document/A-9-2021-0211_EN.html#_section2. (accessed 23 February 2023).

Giudici, H., Pérez-Fortes, A.P., 2022. How recent developments in smart road technologies and construction materials can contribute to the sustainability of road infrastructure. J. Infrastruct. Syst., 28(4), 02522002. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000711.

Grabinski, S., 2019. Improved visibility - Solar powered road markers on polish roads. IOP Conf. Ser.: Mater. Sci. Eng., 661(1). https://doi.org/10.1088/1757-899x/661/1/012150.

Hakkert, A.S., Gitelman, V., Ben-Shabat, E., 2002. An evaluation of crosswalk warning systems: Effects on pedestrian and vehicle behaviour. Transp. Res. F: Traffic Psychol. Behav., 5(4), 275–292. https://doi.org/10.1016/S1369-8478(02)00033-5.

Hemavathi, S., Shinisha, A., 2022. A study on trends and developments in electric vehicle charging technologies. J. Energy Storage, 52, 105013. https://doi.org/10.1016/j.est.2022.105013.

Hong, S.D., Ahn, J. H., Kim, K.B., Kim, J. H., Cho, J.Y., Woo, M. S., Song, Y., Hwang, W., Jeon, D. H., Kim, J., 2022. Uniform stress distribution road piezoelectric generator with free-fixed-end type central strike mechanism. Energy, 239(4), 121812. https://doi.org/10.1016/j.energy.2021.121812.

Koul, S., Eydgahi, A., 2020. The impact of social influence, technophobia, and perceived safety on autonomous vehicle technology adoption. Period. Polytech. Transp. Eng., 48(2), 133–142. https://doi.org/10.3311/PPtr.11332.

Le Roux, J.H., Barnard, A., Booysen, M.J., 2013. Remotely controllable wireless road stud network, in: 16th International IEEE Conference on Intelligent Transportation Systems, Proceedings, ITSC. https://doi.org/10.1109/ITSC.2013.6728323.

Lin, H., Chen, F., Zhang, H., 2023. Active luminous road markings: A comprehensive review of technologies, materials, and challenges. Constr. Build. Mater., 363, 129811. https://doi.org/10.1016/j.conbuildmat.2022.129811.

Llewellyn, R., 2015. Lighting the way: the use of intelligent road studs at spiral-marked roundabouts, in: Proceedings of the 43rd European Transport Conference, AET 2015.

Llewellyn, R., Cowie, J., Maher, M., 2020. Active road studs as an alternative to lighting on rural roads: Driver safety perception. Sustainability, 12(22), 9648. https://doi.org/10.3390/su12229648.

Llewellyn, R., Cowie, J., Fountas, G., 2021. Solar-powered active road studs and highway infrastructure: effect on vehicle speeds. Energies, 14(21), 7209. https://doi.org/10.3390/en14217209.

Lozano Domínguez, J. M., Sanguino, M., 2018. Design, modelling, and implementation of a fuzzy controller for an intelligent road signaling system. Complexity, e1849527. https://doi.org/10.1155/2018/1849527.

Lozano Domínguez, J. M., Al-Tam, F., Sanguino, M., Correia, N., 2021. Vehicle detection system for smart crosswalks using sensors and machine learning, in: 18th International Multi-Conference on Systems, Signals and Devices, SSD 2021.

Mao, G., Hui, Y., Ren, X., Li, C., Shao, Y., 2021. The internet of things for smart roads: A road map from present to future road infrastructure. IEEE Intell. Transp. Syst. Mag., 14(6), 66–76. https://doi.org/10.1109/MITS.2021.3115126.

National Highway Company (ANAS), 2021. Smart road book. https://www.stradeanas.it/sites/default/files/pdf/Smart_Book_%28eng%29.pdf. (accessed 18 February 2023).

Nguyen, T., 2018. Ahead of the curb: Smart roads, in: 2018 IEEE International Smart Cities Conference, ISC2 2018, 1–2. https://doi.org/10.1109/ISC2.2018.8656667.

Patella, S. M., Sportiello, S., Carrese, S., Bella, F., Asdrubali, F., 2020. The effect of a LED lighting crosswalk on pedestrian safety: Some experimental results. Saf., 6(2), 20. https://doi.org/10.3390/safety6020020.

Pompigna, A., Mauro, R., 2021. Smart roads: A state of the art of highways innovations in the smart age. Eng. Sci. Technol. an Int. J., 25 (2). https://doi.org/10.1016/j.jestch.2021.04.005.

Ram, M., Bhandari, A. S., Kumar, A., 2022. Reliability evaluation and cost optimization of solar road studs. Int. J. Reliab. Qual., 29(1). https://doi.org/10.1142/S0218539321500418.

Samardzija, D., Kovac, E., Isailovic, D., Miladinovic, B., Teslic, N., Katona, M., 2010. Road nail: Intelligent road marking system testbed, in: 2010 IEEE Vehicular Networking Conference, VVNC 2010. https://doi.org/10.1109/VNC.2010.5698254.

Samardzija, D., Teslic, N., Todorovic, B., Kovac, E., Isailovic, D., Miladinovic, B., 2012. Road nail: Experimental solar powered intelligent road marking system. J. Electr. Eng., 63(2), 65. https://doi.org/10.2478/v10187-012-0010-1.

Savithramma, R. M., Ashwini, B. P., Sumathi, R., 2022. Smart mobility implementation in smart cities: A comprehensive review on state-of-art technologies, in: 2022 4th International Conference on Smart Systems and Inventive Technology, ICSSIT 2022. https://doi.org/10.1109/ICSSIT53264.2022.9716288.

Shahar, A., Brémond, R., 2014. Toward smart active road studs for lane delineation, in: Transport Research Arena: Transport Solutions: From Research to Deployment-Innovate Mobility, Mobilise Innovation!.

Shahar, A., Brémond, R., Villa, C., 2018. Can light emitting diode-based road studs improve vehicle control in curves at night? A driving simulator study. Light. Res. Technol., 50(2), 266–281. https://doi.org/10.1177/1477153516660146.

Solar Impulse Foundation, 2019. Solar road: Wattway, on the road to renewable energy. https://solarimpulse.com/news/wattway-on-the-road-to-renewable-energy. (accessed 10 February 2023).

Studio Roosegaarde, 2013. Smart Highway. https://www.studioroosegaarde.net/project/smart-highway. (accessed 10 February 2023).

Tao, Z., Quan, W., Wang, H., 2022. Innovative smart road stud sensor network development for real-time traffic monitoring. J. Adv. Transp, 8830276. https://doi.org/10.1155/2022/8830276.

Todorovic, B. M., Samardzija, D., 2017. Road lighting energy-saving system based on wireless sensor network. Energy Effic., 10(1), 239–247. https://doi.org/10.1007/s12053-016-9447-6.

Toh, C. K., Sanguesa, J. A., Cano, J. C., Martinez, F. J., 2020. Advances in smart roads for future smart cities. Proc. R. Soc. A., 476(2233), 20190439. http://doi.org/10.1098/rspa.2019.0439.

Villa, C., Brémond, R., & Saint-Jaques, E., 2015a. Smart intensity management of LED road studs, in: Proceedings of 28th CIE Session, 883–891.

Villa, C., Bremond, R., Saint Jacques, E., 2015b. Visibility and discomfort glare of LED road studs. Light. Res. Technol., 47(8), 945–963. https://doi.org/10.1177/1477153514563637.

Villa, C., Bremond, R., Eymond, F., Saint-Jacques, E., 2021. Characterization of luminescent road markings. Light. Res. Technol., 1-15. https://doi.org/10.1177/14771535221111052.

Wiafe, I., Abdulai, J.-D., Katsriku, F., Kumi, J. A., Koranteng, F. N., Boakye-Sekyerehene, P., 2020. Controlling driver over-speeding with a persuasive and intelligent road marking system. Adv. Transp. St., 50, 19–30. https://doi.org/10.4399/97888255317322.

Wilde, G. J. S., 1982. The theory of risk homeostasis: implications for safety and health. Risk Anal., 2(4), 209-225. https://doi.org/10.1111/j.1539-6924.1982.tb01384.

Wilde, G. J. S., 1998. Risk homeostasis theory: an overview. Inj. Prev., 4(2), 89-91. https://doi.org/10.1136/ip.4.2.89.

Zhou, M., Huang, D., Hu, Y., Zhou, L., An, L., 2018. Musical road: design, construction and potential economic and safety benefits. Transp., 75(1), 34-42. https://doi.org/10.1680/jtran.18.00136.

Zhu, B., Song, C., Guo, Z., Zhang, Y., & Zhou, Z., 2021. Effectiveness of active luminous lane markings on highway at night: a driving simulation study. Sustainability, 13(3), 1043. https://doi.org/10.3390/su13031043.