



Contents lists available at ScienceDirect

Engineering Science and Technology, an International Journal

journal homepage: www.elsevier.com/locate/jestch

Improving road safety through a novel crosswalk: Comprehensive material study with photoluminescent resin

J.M. Lozano Domínguez, T.J. Mateo Sanguino^{*}, M. Redondo González, J.M. Davila Martin

University of Huelva, Higher Technical School of Engineering, Av. de las Fuerzas Armadas, s/n, Huelva 21007, Spain

ARTICLE INFO

Keywords:

Crosswalk
Road safety
Photoluminescent additive
Polyol-isocyanate resins
Characterisation
Speed reduction

ABSTRACT

It is well known that road safety is a major problem in cities, resulting in a large number of accidents with significant injuries and loss of life. Much of this problem occurs when vehicles interact with pedestrians. To try to minimize this problem to a large extent, a combined system using resins and a photoluminescent additive was proposed. To confirm the goodness of this material, a characterisation was carried out covering luminance, vibroacoustic and mechanical properties and a study of its photogrammetry under real conditions of use. A luminance of 68 mcd/m² at 20 min was confirmed, which would allow, by a wide margin, a pedestrian crossing to be observed in a vehicle more than 100 m away. The acoustic vibration test confirmed that the proposed system would provide a very efficient audible warning to pedestrians and would reduce the average vehicle speed by about 37 % overall, while in cases where vehicles have to stop for pedestrians, this reduction would be about 28 %. With the mechanical characterisation, it was possible to determine a vertical displacement of always less than 2 mm in vehicles with a wheel load of 12.5 kN, reaching a compressive and tensile strength of more than 56 MPa. The results obtained confirm a potential reduction in mortality of close to 110 %, and injuries by approximately 55 %, as a consequence of the reduction in vehicle speed. In addition, improved night-time visibility of pedestrian crossings would reduce deaths by 35 % and injuries by 26 %, while in the most favourable situations, these values would be 14 % and 10 % for deaths and injuries respectively. All this confirms the great advantage of the system for improving road safety in urban environments.

1. Introduction

Pedestrian-vehicle collisions, particularly at crosswalks, represent a significant safety concern on roadways. Only in 2022, there were 7,508 pedestrian fatalities in the United States, marking the highest number of such deaths in over four decades [1]. Many of these accidents stem from drivers failing to notice pedestrians, a factor that is often aggravated by poor visibility and high vehicle speeds. On other occasions, the reasons are due to uncivil attitudes and lack of compliance with traffic rules. For instance, one study found that a large proportion of drivers (36 %) typically do not yield to pedestrians at crosswalks. The probability of conflict increases when cars move at higher speeds and there is greater traffic density, among other causes [2]. The findings are consistent with other studies who highlight that vehicle speed and distance to pedestrians are the most important factors affecting the occurrence of accidents in vehicle–pedestrian interaction [3].

The perception that car drivers have towards vulnerable road users has been studied in cyclists, one of the main categories of users

particularly exposed to the risk of accidents [4]. Such study revealed that crossings are crucial points in the infrastructure where a notable level of distraction and workload is noted due to the interactions with different road users (e.g., pedestrians, vehicles or electric scooters). Another study highlighted the crucial role of visibility in road safety and demonstrated that higher reflectivity of pavement markings leads to longer visibility distances. The study concluded that drivers adjust their visual behaviour to brighter markings, resulting in higher preview times and longer distances. This improved visibility helps in the acquisition and processing of information, contributing to improved road safety [5]. Studies have also shown that drastic measures to reduce vehicle speeds in areas with high pedestrian traffic can significantly decrease the likelihood and severity of collisions [6]. These works collectively show that enhancing driver awareness, enhancing visibility and decreasing vehicle velocity at critical road points can lower the chances of accidents, which can be accomplished with the integration of innovative solutions [7].

Pedestrian crossings are critical points on the road that play a crucial

^{*} Corresponding author.

E-mail address: tomas.mateo@diesia.uhu.es (T.J. Mateo Sanguino).

<https://doi.org/10.1016/j.jestch.2024.101793>

Received 16 May 2024; Received in revised form 29 July 2024; Accepted 2 August 2024

Available online 9 August 2024

2215-0986/© 2024 THE AUTHORS. Published by Elsevier BV on behalf of Karabuk University. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

role in ensuring pedestrian safety. Data from the United States in 2021 revealed that of 957 pedestrian-related traffic collisions, 335 incidents involved pedestrians using crosswalks at intersections [8]. These findings account for approximately 35 % and align with studies conducted in other countries like Ghana and Poland [9,10]. In this regard, effective crosswalks have been shown to significantly reduce pedestrian deaths and injuries. As per the World Health Organization (WHO), well-designed and marked crosswalks help reduce accidents by improving visibility and predictability for both drivers and pedestrians [11].

Modern accident reduction measures can be divided into three primary areas of focus: active safety, passive safety, and integrated safety. The first category includes advanced driver assistance systems (ADAS) that use in-vehicle sensors and cameras to prevent collisions. Most manufacturers are integrating these systems into their high- or mid-range vehicles [12,13]. However, ADAS adoption remains limited due to its high cost and does not reach all users. Even though ADAS are being implemented in high-end or mid-range vehicles, these advances are not being installed in low-end vehicles. These vehicles are mainly used by commercial enterprises (e.g., service sector, electricians, delivery agencies, etc.). In addition, ADAS are also not included in trucks, buses, motorcycles, and emergency vehicles (e.g., police, fire-fighters, etc.). Another limitation is that ADAS are semi-autonomous and not fool proof. Vehicles currently reach a maximum autonomy level of 4 out of 5, which has led to injury and fatality accidents around the world. Another constraint is the mean age of cars [14]. ADAS typically include a motherboard, 12 ultrasound sensors, a front RADAR, 8 video cameras, a navigation map and a WiFi or 5G connection, which makes them unfeasible to include in older vehicles due to high software and hardware requirements [15]. For all these reasons, only car owners can utilize these solutions, which are not permanently deployed on public roads.

The second category includes structural designs to mitigate injuries, where a variety of concepts ranging from personal protection to road systems have been found. For instance, a novel sandwich-type hood with a straw structure has been created to prevent severe head injuries in kids from vehicle hoods [16]. Other solutions include basic road markers with illuminated canopies at pedestrian crossings, speed humps with passive lighting and traffic lights that can be operated manually or by sensors, among others. A detailed analysis of these road systems is provided in [17,18]. Their main drawbacks are: *i*) the lack of an established relationship between accident reduction and the visibility of road markings, attributed to the scarcity of studies, except those carried out by national authorities (e.g., DGT) or research actions such as COST 331, IMPROVER, and RAINVISION [19–21]; *ii*) many of these solutions are not available on the market as they are patented; *iii*) the procurement of infrastructure by public authorities mostly relies on economic criteria, which do not always prioritize security; *iv*) the solutions implemented normally require prior civil works for installation and the use of the electrical network for their operation, which makes them dependent, vulnerable to voltage variations, and costly. Therefore, traditional solutions such as speed humps, raised concrete pedestrian crossings, and pedestrian crossing markings with passive reflectors or illuminated canopies remain the most common and visible in cities today. For more details on these approaches, see [22].

The third category includes integrated safety solutions, that combine active and passive technologies with considerable benefits in pedestrian protection. A study analysed that –in 74 % of cases– the stopping distance of vehicles to pedestrians was less than the distance required to manoeuvre safely. The authors evaluated a controlled braking system, confirming it as an alternative to reduce pedestrian injuries caused by ground contact with vehicles [23]. Additionally, research shows that integrated systems are more effective in reducing severe head injuries of pedestrians compared to individual active or passive systems, with up to 42 % higher effectiveness [24]. Integrated passive and active systems are therefore recommended to improve pedestrian safety. However, the effectiveness of these measures depends on the type of vehicle, height and age of pedestrians, so specific vehicle designs and age profiles of the

population must be considered [25].

This highlights that traffic safety is a comprehensive system involving humans, vehicles, and roadways. Such an integral approach justifies the value of road safety research, as understanding and optimizing these interactions is essential for developing effective safety solutions. In line with this comprehensive approach, photoluminescence has recently been used as an additive pigment in various materials, such as plastics, metals, ceramics, or binders, to enhance urban infrastructures. For example, the creation of architectural and decorative concrete incorporating photoluminescent pigment has been investigated to improve safety and signage at night while preserving architectural expressiveness [26]. In this context, Ambient Glow Technology (Minnesota, USA) has registered the trademark AGT™ Glow Stone for concrete-based decoration in areas such as bathrooms, recreational areas and gardens.

Photoluminescence has not been widely used in road safety, more specifically in horizontal road marking. Its uses include reducing the costs of road lighting and implementing urban services with enhanced safety and efficiency for specific user groups, such as cyclists. For example, a 150 m² pedestrian path called Startpath has been developed, which consists of three layers of polyurethane to which a polyaspartic coating and a photoluminescent spray coating have been applied by Pro-Teq Surfacing (Cambridge, UK). The University of Texas (Texas, USA) and Tectas Transportation Institute designed and presented a cycle track with photoluminescent paint to improve safety, mobility and connectivity. Likewise, Studio Roosegaarde (Oss, The Netherlands) contributed by transforming a motorway using a combination of photoluminescent pigment and road coating to delineate continuous longitudinal markings. However, the use of photoluminescent substances in road marking remains largely unexplored. To the authors' knowledge, there is no previous research specifically addressing the application of photoluminescence at pedestrian crossings.

In a related study, the performance of photoluminescent paints on pavements was assessed using photometry techniques. The research considered different surfaces and paint treatments, modelling the photoluminescent phenomenon's charge and discharge time. Results proved that performance varies depending on pavement characteristics and paint treatments, offering insights for optimizing painting treatments for various bituminous mixtures. Nonetheless, the study's applicability may be limited to specific surface types (i.e., asphalt mixtures), potentially restricting broader applicability [27,28]. Additional limitations include performance dependent on lighting levels and specificity of results for certain pavement types, which limits generalization [29]. Another work explored the development of photoluminescent materials for highway markings, introducing a new paste formulation comprising polymeric components and photoluminescent colourants. This material exhibits wear resistance, resistance to atmospheric effects, and photoluminescence suitable for various coloured lines on highways. However, the study primarily focused on material development and lacked comprehensive performance evaluations [30]. Another research investigated the feasibility of photoluminescent asphalt coatings made from recycled expanded polystyrene and strontium aluminate particles. The characterization revealed the potential for improving road safety and aesthetics through artificial lighting without electricity consumption. Yet, further evaluations are needed to assess the coating's long-term performance under real-world conditions [31]. Finally, another study explored composite materials containing luminophores for highway markings and signs, emphasizing their potential for enhanced brightness compared to conventional materials. However, the research lacks discussion on compliance with visibility requirements and ways for further enhancing visibility, suggesting a need for comprehensive evaluations and considerations [32].

Based on the findings of these studies, this manuscript suggests a solution related to road safety, focusing on transportation systems and infrastructures, with a key emphasis on inorganic compounds. According to the United Nations Educational, Scientific and Cultural

Organization (UNESCO) nomenclature, the work is classified according to the codes corresponding to Transport Systems Technology (3327), Urban Planning (3329), and Chemical Engineering and Technologies (3303). The main objective of this work is to change the collective behavior of road users in order to reach “zero victims”, an objective in line with the policies of Sweden, Finland and the European Union itself. This is also a goal pursued by national initiatives such as the Spanish Traffic General Directorate (DGT) aimed at improving urban mobility, implementing new technologies for public benefit and promoting the development of intelligent and safe cities [33].

The objectives and hypotheses of this research focus on determining whether improving users’ perception of crosswalks could positively influence driver behaviour, which in turn would reduce speed and accidents (i.e., recognizing the importance of both seeing and being seen). This work seeks to expand previous research [34–36] by introducing an innovative approach to signalling pedestrian crossings, as well as carrying out new experimentation in mechanical, structural and vibroacoustic analyses. Accordingly, the contributions that differentiate this present study are the following: *i*) to use cold-injected resin-aggregate mixtures on silicone moulds for the fabrication of road tiles as a method not previously explored in the literature; *ii*) to carry out detailed experimentation to validate the mechanical, structural and vibroacoustic properties of the crosswalk; *iii*) to evaluate the feasibility of said approach to influence user behaviour and, as a consequence improve pedestrian road safety. Table 1 discusses the contributions of other academics in this field, contrasting their objectives and methodologies to understand the value and novelty of the present work.

To achieve these objectives, this manuscript follows the following structure: Section 2 describes the proposed crosswalk design. Section 3 details the materials and methods employed in its fabrication. Section 4 presents the mechanical, optical and functional properties of the system. Section 5 discusses the results of the experimentation conducted with the system. And, at the end, conclusions and future work are presented.

2. System description

This study focuses on road marking systems designed to reduce pedestrian-vehicle accidents through the use of photoluminescence. Electroluminescence occurs when an electric current passes through a material that requires an active source, while photoluminescence involves natural or artificial light illuminating a substance that emits its own light even after the activation source has been switched off.

Based on this idea, this work introduces an inventive crosswalk concept that incorporates new materials and shapes organized in diverse topologies, lengths, and quantities to establish road markings with a distinctive character. Specifically, the tiles have the purpose of replacing classical crosswalks through long-lasting elements and taking advantage of photoluminescence to emit more sustainable and safer light in situations of low or no illumination (Fig. 1). Photoluminescent materials offer the potential to bolster road safety by enhancing night-time visibility for drivers. Evaluations conducted on these materials involved laboratory tests and visibility computations, including luminance decay measurements under various night-time lighting conditions. Results indicate that photoluminescent road markings could extend the visibility distance beyond headlamp beams during the early hours of the night and in unlit areas. However, their effectiveness is contingent upon night-time illumination levels.

Benefits for road safety have been successfully proven in a relevant study for this proposal [37]. The solution is also applicable to other types of horizontal signage. This may include discontinuous transverse markings (e.g., stop line or pass line), arrows (e.g., direction, lane selection or exit), inscriptions (e.g., reserved zone or speed limit), curb/island markings, or other roadway signs (e.g., parking zones, railroad crossings, no-entry lines). The proposed approach offers numerous technical benefits compared to traditional signage methods such as acrylic, two-part paint and approaches based on cobblestone materials:

Table 1
Contributions of other scholars in research related to pedestrian crossings.

Ref.	Objectives	Methodology	Value and novelty
[23]	Assess controlled braking’s impact on pedestrian injuries	Simulations with software on various vehicle shapes and braking approaches	Significant injury reduction with controlled braking, enhancing pedestrian safety
[24]	Evaluate head injury reduction with protection systems	Database analysis, impact tests, and system comparison	Combining passive and active systems reduces severe head injuries more effectively
[25]	Review technologies and designs for pedestrian safety	Literature review and analysis of injury data and vehicle designs	Effective technologies for pedestrian safety, focusing on energy-absorbing materials and protection systems
[26]	Test photoluminescent materials in concrete	Study of physical properties and durability of concrete with photoluminescent pigments.	Improved nighttime visibility and durability, with potential road safety applications
[27]	Analyze photoluminescent paints on pavements	Laboratory measurements of photoluminescent paint properties and pavement characteristics	Performance depends on pavement characteristics; enhances nighttime visibility
[28]	Model photoluminescent phenomenon in pavements	Laboratory measurements and modeling of luminance and photoluminescence effects	Insight into how pavement features and seasons affect photoluminescence
[29]	Evaluate photoluminescent road markings’ effectiveness	Luminance and visibility tests under various lighting conditions	Improved driver guidance with enhanced nighttime visibility; effectiveness depends on lighting levels
[30]	Develop a durable photoluminescent material for road markings	Formulation and testing of a photoluminescent paste with high wear resistance	New material with high durability and effectiveness for various colored road markings
[31]	Assess a photoluminescent coating with recycled EPS	Characterization of coating with recycled EPS using microscopy and mechanical tests	Coating improves safety, reduces energy use, and enhances road aesthetics
[32]	Explore composite materials with luminophores for road markings	Development and testing of polyepoxy composites with luminophores	Enhanced brightness and visibility for road markings and signs
Authors	Develop and evaluate a photoluminescent resin system for crosswalks	Characterization of luminance, vibroacoustic, and mechanical properties; real-world photogrammetry study	Significant improvement in crosswalk visibility and vehicle speed reduction, enhancing urban safety

1) the maintenance costs for the municipality are reduced by eliminating the need for regular repainting of white road markings; 2) it requires no construction work and installation merely entails adherent fixtures or mechanical anchors, facilitating reuse; 3) improved perception is facilitated by enhanced visibility in low-light situations; and 4) it does not require any connection to an electrical lighting source, thus avoiding the energy dependence unlike active road marking systems.

2.1. Photoluminescence

A key aspect of the system is that it comprises a photoluminescent



Fig. 1. Crosswalk overview.

component that appears whitish during the day and emits passive self-light in conditions of partial or total darkness. As a result, it eliminates the need for connection to an electrical source, ensuring sustainability while attaining energy self-sufficiency unlike illuminated road marking crossings. This study primarily advocates for the use of photoluminescent blue, though other hues like white, green, purple, or orange offer diverse lighting effects. The photoluminescent material boasts waterproof properties, and luminosity may vary between 20 % and 50 % of the proportion of the base material. Quality of light intensity, measured on a six-level rating (A, B, C, D, E, S), aligns with level 2 as per DIN 67510 specification, facilitating clear identification of photoluminescent indicators in regions illuminated continuously.

2.2. Reflectivity

The proposed material integrates glass microspheres since they return part of the light coming from the vehicle headlights, thus making road markings more visible at night and safer for road users. Because light reflection is greater when the luminance of the base material is greater, the reflective effects are enhanced by combining glass microspheres on the photoluminescent substrate. This feature increases the visibility on pavements with low contrast or at greater distances, which differentiates it significantly from classic solutions. This improvement is even more important when the surface is wet, as *retro*-reflection typically decreases between 15–40 % in relation to its dry state. To this end, we used glass microspheres formed by $\text{Na}_2\text{Ca}_3\text{Si}_6\text{O}_{18}$ crystal with a circularity exceeding 70 %, density ranging from 1.55 to 1.65, refractive index between 1.5–1.55 and diameter between 60–850 μm in a proportion of 500 gr/m^2 .

2.3. Anti-slip

This characteristic is accomplished through the integration of two components. On the one hand, the substrate includes Al_2O_3 granules, meeting FEPA 20–36 standards designed to enhance traction and free from carcinogens and toxins. On the other hand, the components are engineered with a dual-purpose anti-sliding pattern. It features a macro pattern in the form of drainage ducts to facilitate liquid elimination, enhancing the system's effectiveness in damp situations. Moreover, the pieces incorporate small sub-patterns that enhance responsiveness, mitigating the likelihood of slipping by pedestrians and other users such as cyclists or scooter riders.

2.4. Sonority and vibrational capacity

The components of the crosswalk incorporate a surface pattern intended to generate physical and auditory effects when vehicles pass over them. The aim is to warn drivers to the necessity of adhering to the road's speed limit, as studies have demonstrated that auditory cues and vibrations play a role in reducing accident rates [38]. Consequently, the texture serves as an advisory mechanism for drivers, with its shape, height, and spacing engineered to increase sound when vehicle speed exceeds specific limits according to the road (e.g., between 20–50 km/h). A pattern resembling dots is proposed to transmit tremors through vehicle tires and increase sound levels. This mechanism not only proves beneficial in alerting pedestrians to the presence of silent vehicles (e.g., EVs) but also aids in guiding visually impaired individuals. This presents an advantage over other existing solutions, such as road lateral markings, which require maintaining the pattern with new layers of material during road sign repainting.

2.5. Durability

The goal is for the desired effects to emerge gradually over time as the road system materials wear down. This solution uses poly-iso resins protected against sunlight and high temperature hydrowashing up to 100 Celsius degrees. The white pieces are tinted with RAL 9016 colour (i.e., reference B-118 according to UNE 48103 standard). In parallel, there are the black pieces tinted in RAL 9017 to make it easier for users to walk on. Both the top and bottom sides feature identical construction features, allowing components to be rotated if worn, effectively doubling their lifespan without requiring replacement.

2.6. Removable

The parts are fixed on the asphalt by means of screws, although chemical adherent fixing can also be considered. Adherent elements include bituminous binders that harden with temperature. Nevertheless, it is preferable to use mechanical fixation means since the system parts can be quickly removed and replaced by road workers without requiring specific training (e.g., in eventual works when the resurfacing of a road section is required). Anti-vandalism fasteners with insertion in steel bolts were used to avoid unauthorized screw subtraction or unpinning caused by the traffic vibration. Finally, the height of the system pieces has been set to guarantee vehicle integrity and the occupants according to current traffic regulations.

2.7. Sustainability

Classical crosswalks made of white acrylic water-based paint requires a typical consumption of 0.2–0.25 kg/m^2 per layer. This results in a cost of 60–150€ per crosswalk with 5–12 bands (i.e., 1–4 lanes). In the case of white polyurethane paint, the construction of pedestrian crossings requires a typical wastage of 2–3 kg/m^2 , which has a cost of 135–200€. When constructed with granite pavers of 8 x 8 x 10 cm, the cost increases to 950–2200€. We estimate that the construction of a photoluminescent crosswalk costs about 767–1841€, thus being an intermediate feasible solution among classical crosswalks. Furthermore, streetlamps have an average power consumption of 200 W. This is equivalent to 2920 KWh of energy consumption considering a crosswalk illuminated by two conventional streetlamps for 2 years with an average of 10 h a day. If LED lighting is utilized, the energy consumption amounts to 1094.96 kWh. This translates to a reduction in carbon dioxide emissions ranging from 1080.40 kg to 405.14 kg released to air. Based on the annual mean price of CO_2 emission allowances as per the European Trading Scheme (ETS), the benefits represent a saving of €6.29 to €16.77 due to the lighting itself provided by the proposed system.

3. Materials and methods

This section provides detailed information on the design, materials and methods employed in the creation of the pedestrian crosswalk. Subsection 3.1 gives insights into the crosswalk structure and safety features. Subsection 3.2 describes precisely the composition of each component, including the pigments and surface treatments applied. Subsection 3.3 explains the manufacturing process involving, vacuum casting and surface treatment. Finally, the composition of the black and white parts is provided, specifying the percentages of polyurethane resin, photoluminescent powder and pigment in each one.

3.1. Design

It consists of two types of components differentiated by their location, either on the inside or on the edges of the pedestrian crossing. The inner pieces are square, 500 x 500 mm, and have the same shape on both sides, which allows them to be used on both sides. On the other hand, the peripheral pieces or ramps, measuring 500 x 250 mm, have a flat bottom surface and an edge height of less than 5 mm, which is according to current traffic regulations [38]. The different components are joined together using a ‘dovetail’ type assembly system, which ensures a uniform behaviour of the assembly. These elements are manufactured in alternating black and white stripes according to conventional road marking design. The illustration in Fig. 2 shows an inner slab on the left and the specific shape of the ramp on the right. It can be seen in the picture that the inner slabs have a wave design parallel to each other that is crossed at 90 degrees with respect to the movement of the vehicles, together with small 1 mm high cylinders, 8 mm in diameter and a separation between centres of 15 mm, which, together with the incorporation of glass microspheres, guarantees adherence. In the case of the ramp pieces, they have only the cylindrical projections with the same geometry as described for the slabs. The intention in designing the geometry of parallel waves in the inner parts is to ensure that the vibrations are transmitted to the vehicle through its wheels, raising the noise level by at least 3 dB. These waves would be 5 mm high and 100 mm apart, with an amplitude and width of 15 mm in both cases.

3.2. Materials

The basic material for the manufacture of the two parts of the photoluminescent pedestrian crossing is a thermosetting resin polymer obtained from polyol G0181RPC P-SL 120 000 and isocyanate G0181RPC I-SL000 221, both components being transparent and colourless and with the same viscosity value of 450 mPa.s determined by Brookfield LVT equipment according to MO-051 standard; and with very similar density values (1.08 and 1.10 g/cm³ respectively for polyol and isocyanate) according to MO-032. The resin obtained from this mixture is specifically indicated for use in vacuum moulds and is a mercury-free material that complies with the most important European directives in the environmental and safety field, such as 2002/96/EC, 2000/53/EC, 2000/11/EC, 2011/65/EU and 2017/2012/EU (RoHS), among others. This material is easy to work with and handle, can be easily dyed and polished, and is also UV stable, making it ideal for use in outdoor environments. In addition to the properties already indicated, Table 2 shows the most important mechanical and thermal properties of the

Table 2
Average mechanical and temperature traits of the polyurethane resin.

Feature	Testing procedure	Measurement
Temperature at which glass undergoes transition (°C)	ISO 6721–10: 2015	91
Temperature at which heat causes deflection (°C)	ISO 75–2: 2013	84
Hazen coloration at a thickness of 50 mm	ISO2211: 1973	< 30
Refractive index measured at a temperature of 20 (°C)	ISO 489: 1999	1.51
QUV-B accelerated degradation (ΔE after 1000 h)		< 3
Elasticity modulus under stress (MPa)	ISO 178: 2011	2200
Maximum elasticity modulus under stress (MPa)	ISO 178: 2011	88
Elasticity modulus under tensile stress (MPa)	ISO 527–1: 2012	2350
Deformation at maximum tensile strength (%)	ISO 527–1: 2012	6.5
Highest tensile strength (MPa)	ISO 527–1: 2012	65
Charpy impact resistance (kJ.m ²)	ISO 179–1/1eUb: 2010	84
Hardness / Shore D1	ISO 868	85

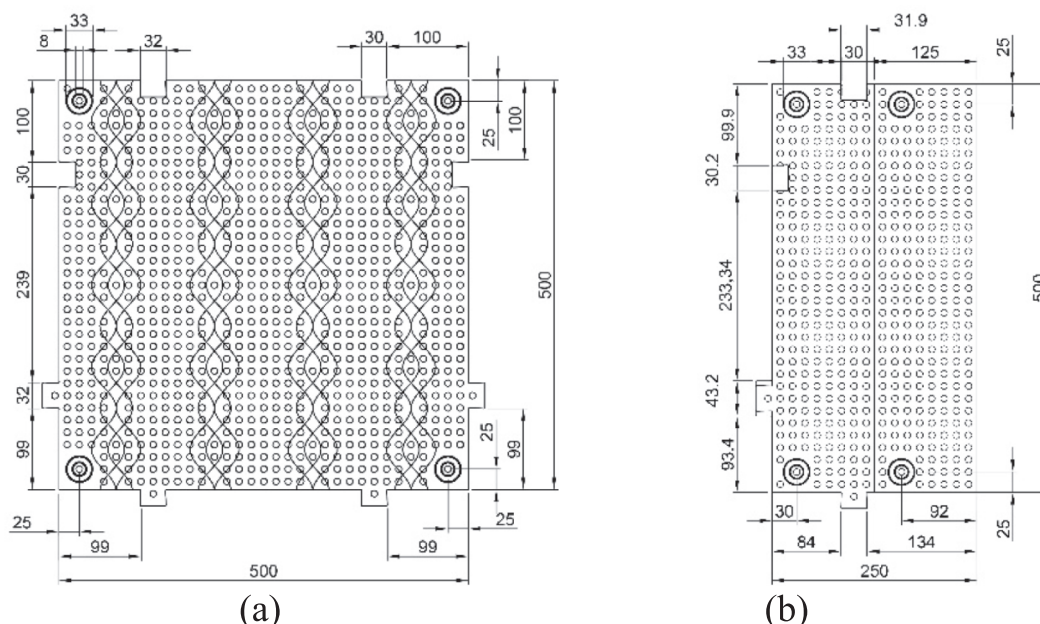


Fig. 2. Graphical representation of the pedestrian crossing components, where: a) corresponds to the central slab and b) to the perimeter ramp.

resin, whose average values have been determined on parts cured following a specific protocol indicated by the manufacturer: 2 h at 70 °C, then 16 h at 100 °C and, finally, 24 h at room temperature.

Although the black parts have not received any additional treatment than mentioned above, the white parts have been treated with photoluminescent powder. This additive gives them outstanding luminous properties: during the day they are white, but when night falls and the photoluminescent substance is activated, they take on a bluish hue. After being exposed to sunlight for only 10 to 30 min, they can glow for more than twelve hours. The photoluminescent powder, purchased from Zhejiang Minhui L&T Co. LTD under reference MHB-5B, consists of Sr4Al14O25: Eu⁺², Dy⁺³, a rare earth-activated strontium aluminate. This compound is safe, non-toxic and non-radioactive, chemically stable, in addition to being resistant to weather conditions, which allows it to reach a useful life of 15 years. Its characteristics, described in Table 3, include properties related to vibrations and luminosity, among others. The material complies with various European and US regulations, including the EU REACH Regulation (EC) No 1907/2006, and US toy safety regulations (ASTM F963-16), as well as total lead testing (CPSC-CH-E1003-09.1) and soluble heavy metals regulations (ASTM F963-16, Clause 8.3).

To achieve the final colour of the different pieces, two types of pigment were added. The black slabs and ramps were dyed using CAS-TRO Composite's black pigment, reference DTH9002D-0.03, which has a density of 1.05 gr/cm³ (±0.001), being a 30 % (±8%) non-volatile material. This dye is specially designed for outdoor use and works well with both water and solvent based paints. According to the information obtained through the GIMP application, the black tiles and ramps show RGB values of 38, 37 and 45, corresponding to the final colour RAL 5008 (specified on the website <https://hextoral.com/rgb-to-ral/>). In comparison with the so-called traffic black (RAL 9017), this colour presents a difference of 6.85, which implies a difference of 7.72 %.

Castro Composites' white pigment 501, reference WCP0501-0.1, was added to the white tiles and ramps. This colour concentrate in form of a medium viscosity paste (12.5 dPa.s at 25 °C) is specifically designed to dye different types of resins such as those used here and has an acidity index of 25 mg KOH/gr. All the white pieces were manufactured by the RGB values obtained using the GIMP application, with values 231, 235, 238, which coincides with a RAL 9003, according to the reference found at <https://hextoral.com/rgb-to-ral/>. Compared to the white defined for RAL 9016 traffic, a difference of 4.55 is observed, which represents a variation of 5.13 %. To evaluate the percentage difference between the colours used in the traffic paint, the total variation between RAL 9016 (white) and RAL 9017 (black) was considered to reach a value of 88.74.

To achieve a better finished product, two other components were used. Montana Colors thermoplastic acrylic resin-based varnish was added, which has the most important properties of excellent adhesion, durability, good hardness, drying in a few minutes, good elasticity, high water resistance, no yellowing, high gloss, simple application and repainting, and strong UV resistance. The specific properties of this material are detailed in Table 4. Finally, silica-sodium-calcareous glass

Table 4
Varnish coating's physical properties.

Feature	Measurement
Binder type	Thermoplastic acrylic
Colour	Transparent
Brightness 60° (ASTM D-523 ISO 2813)	>80 % bright; 15–35 % satin; <10 % matt
Touch-drying (ASTM D-1640 ISO 1517)	10 min
Total drying (ASTM D-1640 ISO 1517)	12 h
Dry layer thickness (ASTM D-823 ISO 2808)	15 µ/layer
Adherence (ASTM D-3359 ISO 2409)	4B
Theoretical yield (continuous painting)	5 m ² /l
Diluent	Butyl acetate
Product life	>5 years
Repainting	After 10 min
Heat endurance of paint	150 °C
Application requirements	Conditions for application include a minimum ambient temperature of 8 °C, surface temperature ranging from 5 °C to 50 °C, and a maximum humidity of 85 % R.H.P.

beads were used as a material to enhance the reflective effect, the characteristics of which are shown in Table 5.

3.3. Methods

To find an adequate balance between durability and the photoluminescent characteristics sought in the parts and given the lack of awareness concerning akin applications such as the one proposed, it was necessary to develop several samples varying the percentages of components such as photoluminescent powder, glass beads and various pigments. Initially, it was observed that the polyurethane-based formulations did not meet the requirements, which led to the decision to use a polyol-isocyanate-based mixture.

For the production of the slabs and ramps, the moulding method was chosen, using a vacuum casting machine. This required the creation of two different silicone moulds, one for each type of part. Once the moulds were prepared, the resin was cast according to the manufacturer's specifications. The ratio of polyol to isocyanate established for the mixture is 56 to 100 by weight. The procedure consists of nine points as follows: 1) the moulds are preheated to 70 °C, 2) the isocyanate is weighed into the upper cup, 3) the polyol, the second component of the resin, is weighed into the mixing vessel, 4) the mixture is exposed to vacuum for 10 min, 5) the previously weighed isocyanate is added to the mixing vessel, 6) the mixture is stirred until the mixture is completely clear and kept at 25 °C for at least 120 sec, 7) the mixture is poured into the silicone mould, 8) the oven is heated to 70 °C and kept for approximately 120 min, following the method described in MO-116 (the exact duration of this process depends on the thickness of the part), and 9) the part is cooled with compressed air so that it can finally remove from the mould. Following this procedure, a service life for the 160 g material at 25 °C of 9 min is achieved, following the indications in MO-062. Following this procedure, a shelf life for the 160 g material at 25 °C of 9 min is achieved.

Table 5
Attributes of glass beads.

Feature	Measurement
Circularity	Higher than 70 %
Density by volume (gr/cm ³)	1.55 – 1.65
Refraction coefficient	1.5 – 1.55
Width (µm)	37—45
Tolerant to	Water, solvents, mild acids, and bases

Table 3
Photoluminescent pigment properties and characteristics.

Feature	Measurement
Stimulus wavelength (nm)	240—440
Emission wavelength (nm)	490
Density (g/cm ³)	3.4
pH	10—12
Particle size (µm)	65—85
Luminosity (mcd/m ²) at 10 min (1)	700
Luminosity (mcd/m ²) at 1 h	120
Luminosity span (hours)	> 12*

(*) Testing luminance under standard D65 lighting conditions, using a light intensity of 1000 LX for an excitation period of 10 min.

On the resin base, three layers of varnish and glass microspheres were applied to all parts (both black and white), as detailed in Fig. 3. On top of the first layer of varnish (layer 1) and before it dried, glass beads (layer 2) with an approximate density of 500 gr/m² were uniformly applied. After the drying of this layer of varnish, two other layers of varnish were applied sequentially (layers 3 and 4 in Fig. 3), allowing each one to dry according to the manufacturer's instructions before applying the next one.

As for the final composition of the pieces, the white pieces consisted of 87.48 % resin, 9.84 % photoluminescent pigment and 2.68 % white dye. On the other hand, the black pieces, contained 97.03 % resin and 2.97 % black dye.

Comprehensive testing procedures were conducted on all prepared samples to ascertain Shore D hardness, tensile and compression properties. Tensile and compression tests were executed using the Servosis ME 403/200kN equipment, adhering to specifications outlined in standards UNE-EN ISO 527-1:2019, UNE-EN ISO 527-2:2012, and UNE-EN ISO 604:2003-2021. For hardness tests, a Sauter HDD 100-1 durometer was employed, following UNE-EN ISO 868:2003. Tensile tests were performed at a constant speed of 0.2 kN/s, while compression tests were conducted at a speed of 0.08 kN/s. Tensile samples, produced in a controlled laboratory environment at 20 °C and 50 % humidity, measured 170 mm in total length and 75 mm in initial length, featuring an average central section of 10 x 10 mm. Compression test samples, crafted under conditions of 58 % humidity and 22 °C temperature, possessed a length of 50 mm and a middle section of 10 x 10 mm. To determine the elastic modulus in resistance tests, predefined limits were established to accurately delineate the regression line. These limits comprised values proximate to 15 % and 35 % for tensile tests and 15 %, 40 %, and 20 % to 80 %, respectively, for compression tests involving polyurethane and polyol-isocyanate mixtures. The Shore D hardness test, contingent upon the elastic reaction generated when a pointed instrument is vertically introduced to the sample, was conducted on samples prepared with flat, clean surfaces. To minimize potential effects of sample hardening, four tests were conducted on each sample at different points, with 12 values determined per sample, with the exclusion of the highest and lowest values.

4. Mechanical analysis

4.1. Mechanical characterization

A total of 40 tensile tests, 40 compression tests, and 48 Shore D hardness tests were conducted to ascertain the optimal solution. The results obtained are shown in Fig. 4. The average values of the finally selected solution are a tensile strength of 58.6 MPa, a modulus of elasticity for tensile strength of 1119.1 MPa, and a strain at break of 9.5 %. Additionally, it offers a compressive strength of 56.3 MPa, a modulus of elasticity for compressive strength of 1618.0 MPa, and a strain at break of 4.2 %. Lastly, the modulus of elasticity E (MPa) for Shore D is 80.8.

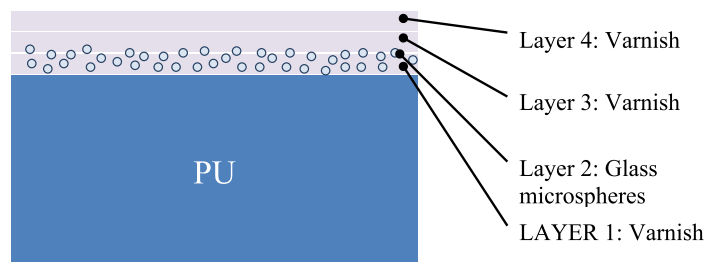
4.2. Structural assessment

The SolidWorks 2021 software was used to construct a system model, considering a vehicle with a weight of 50 kN. Each wheel supports a weight of 12.5 kN, applied on a 20x20 cm surface located at the most critical point of each piece. The parameters used to create the model include polyol-isocyanate as the material, Mohr-Coulomb as the error criteria, a specific weight of 11.2 kN/m³ at 20 °C, a tensile strength of 58.6 MPa, a compressive strength of 52.1 MPa, a tensile modulus of elasticity of 1119 MPa, and a Poisson's ratio of 0.4. The loads applied to both components are illustrated in Fig. 5. The contact planes with the ground are treated as mobile supports in the model of both components, allowing sliding along the supporting plane. Simultaneously, the anchor points to the road are modelled as fixed supports, preventing longitudinal movements but allowing free rotation. The type of mesh used is curvature adaptation with tetrahedral elements, with a minimum mesh size of 5 mm, 8 elements in cylindrical geometry, and 6 degrees of freedom per node (Fig. 6).

The stresses observed in both models, as depicted in Fig. 7, follow the Von Mises criterion. These stress values consistently remain below the strength threshold, with a safety coefficient exceeding 1.46 and stress levels below 40 MPa. Notably, in the case of the ramp, where continuous support spans its entire surface, this coefficient achieves a notably higher minimum, while experiencing significantly smaller deformations (Fig. 8). Regarding the central components, the maximum vertical displacements reach approximately 2 mm. Furthermore, a dynamic analysis incorporating six vibration modes was conducted, revealing that both maximum stresses and displacements were registered approximately 13 % higher in this scenario.

4.3. Photoluminescent characterization

A luminance meter has been used to evaluate the performance of the intensity of the photoluminescence generated by the pieces used to create the white stripes of the pedestrian crossing [39]. The device used complies with the JIS Z 9096:2012 standard, which includes the luminous intensity that the different types of horizontal road signs located on the ground must have [40]. The model of the instrument used is BM-100 from the company Topcon Technohouse Corporation. In addition, the UNE 23035-1 standard has been followed to measure photoluminescence in signs, which can be applied to fire safety signs, as well as to road signs in cycle paths in night-time conditions. According to the methodology outlined in the standard, brightness quantification is performed on the finished product. To achieve this, the pieces with photoluminescent material were irradiated with an artificial source for 5 min with a measured illuminance of 1000 lx. In this way, the material was stimulated under controlled conditions with a radiation distribution similar to solar radiation. The measurements made on the pieces were made with a distance of 50 mm between the instrument and the area to be measured. The illuminated area has a circular shape with a width greater than 50 mm. Values were taken at multiple points (e.g., dot and



PU: [Polyol + Isocyanate + Pigment (black or White) + (Photoluminescent Pigment)]

Fig. 3. Four-layer surface treatment.

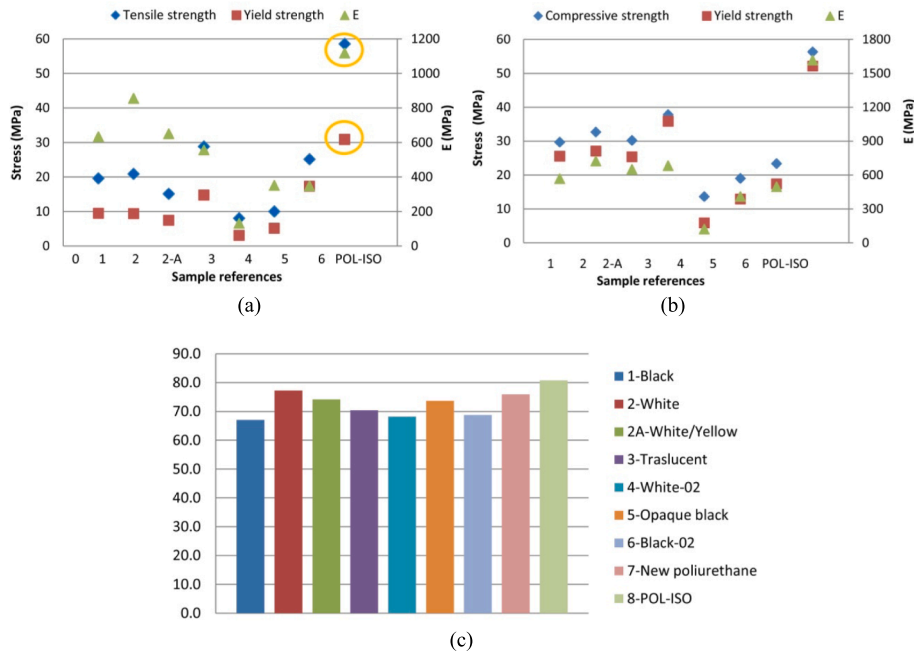


Fig. 4. Test results for unreinforced mixtures of polyurethane mixtures/polyol-isocyanate: a) tensile strength, b) compressive strength, and c) Shore D.

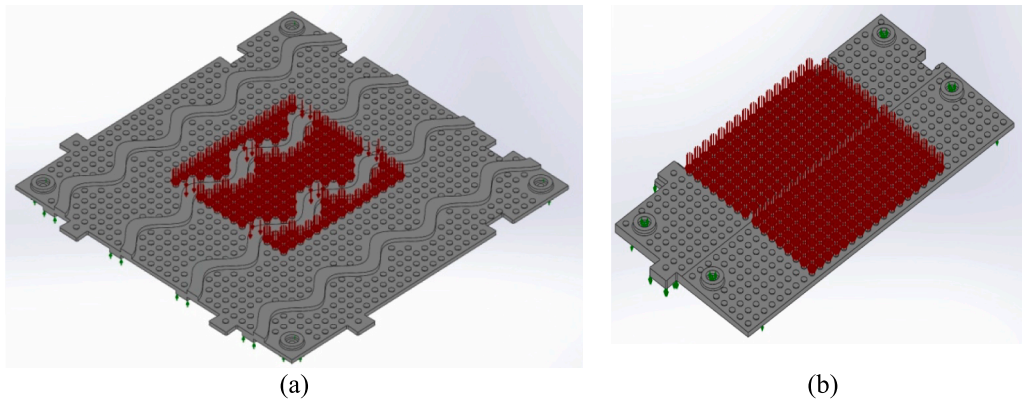


Fig. 5. Load patterns: a) tile, b) ramp.

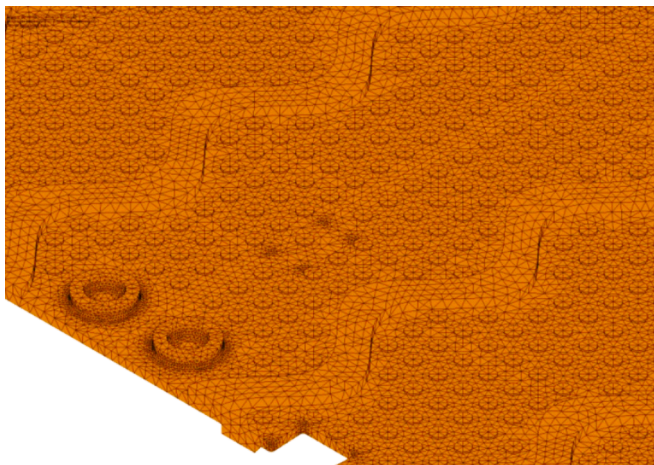


Fig. 6. Mesh detail.

line areas) to accommodate the inherent variability in the manual tile construction process, such as gravity deposition of additives or particle agglomeration. Measurements were conducted under darkroom conditions after light exposure, both in a laboratory and under real operating conditions. Photoluminescence in real environments was measured after 12 h of exposure to natural sunlight (Fig. 9).

The results obtained revealed significant differences in the intensity of photoluminescence among the different resins (Table 6), with PU212 generally exhibiting the lowest values. Furthermore, it was observed that the photoluminescence effectiveness under real operating conditions consistently exceeded the results obtained in laboratory tests, which is a promising finding. A P/I resin containing 9.84 % photoluminescent pigment was selected, which offered a consistent balance between higher photoluminescence and a lower proportion of additives in various situations. This material made it possible to reach a maximum value of 55 mcd/m² and 68 mcd/m² after 20 min of illumination from both artificial and natural sources. This allowed them to be classified as Class A according to the UNE 23035-4:2003 standard. As a reference, the luminous intensity received at a distance of 100 m generated by the high beams of a vehicle on the pavement is approximately 30 mcd/m². This demonstrates the potential that the developed material offers in

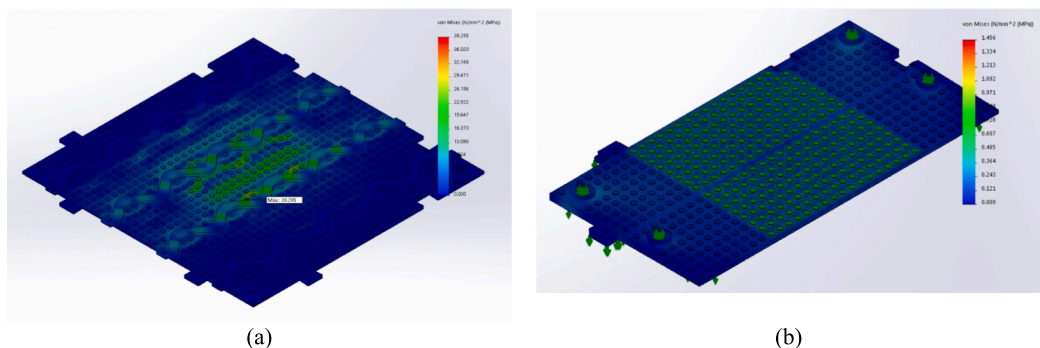


Fig. 7. Von Mises stresses (N/m²): a) tile, b) ramp.

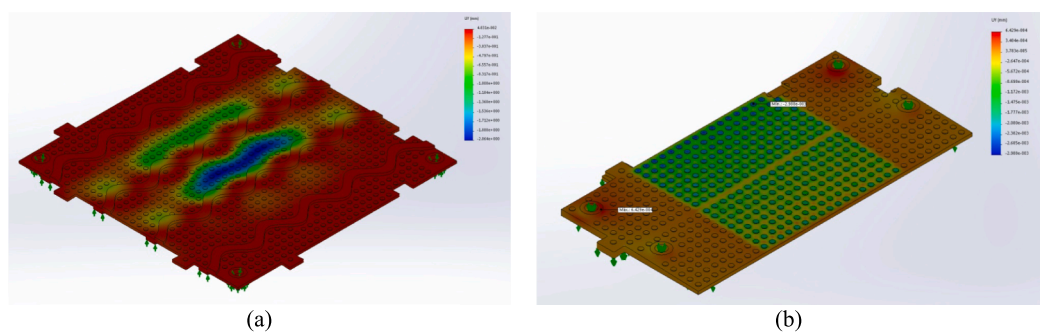


Fig. 8. Vertical deformations (mm): a) tile, b) ramp.

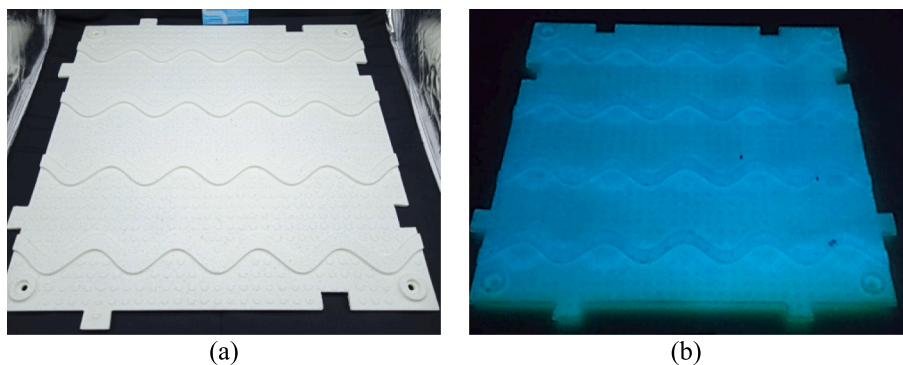


Fig. 9. Tile appearance: a) during the day, b) with absence of light.

practical applications, especially in low-light situations at night, road safety could be improved as long as there is good exposure to sunlight during the day.

4.4. Vibrational and acoustic characterization

Among the works performed, an evaluation of the vibroacoustic properties of the crosswalk was carried out to confirm the design of the surface depicted above in subsection 2.4. This texture manages to alert drivers to the presence of the crosswalk, in addition to warning and alerting pedestrians of the existence of vehicles. The study was conducted on an urban road where the crosswalk was mounted, and which was previously equipped with a common crosswalk (see details of the location in section 5 of this document).

To carry out this process, vibroacoustic data was collected from inside a vehicle and information was recorded around the crosswalk. A three-year-old car with adaptive suspension was used along with a BQ Aquaris V device to perform the measurements. The mobile version of Matlab® was used to collect data from the mobile device's sensors. The

values were then stored in.csv format and analysed using the desktop version of Matlab®. For in-vehicle measurements, the mobile device was mounted on the steering wheel, using a mounting system that allowed data to be taken while driving without interruptions, ensuring the safety of the driver at all times. For measurements outside the vehicle, and aligned with the centre of the crosswalk, the device was placed on the sidewalk at a distance of one meter from the edge.

The test conditions involved driving the vehicle over the crosswalk at constant speeds, with reference velocities set at 20, 30 and 40 km/h. The absence of both internal and external interference was ensured, with the windows closed, the radio turned off and the ventilation switched off. Ten repetitions were conducted for each set speed. Inside the vehicle, audio and vibration signals were recorded on the vertical axis (the Z-axis), and audio signals were collected exclusively outside the vehicle, totalling 90 sets of data overall. The respective sampling sequences were 44,100 Hz for the audio signals, which were captured using the device's microphone, and 100 Hz for the vibration signals, which were recorded using the same device's accelerometer. Further processing of the vibration signals involved filtering the vehicle data during the crosswalk,

Table 6
Photoluminescent characterization.

Sample	20 min (mcd/ m ²)	60 min (mcd/ m ²)	90 min (mcd/ m ²)	Pigment (%)	Resin	Scenario
1	53.17 ± 16.09	23.83 ± 9.20	17.5 ± 7.15	18.1	PU28LE	Lab
1	111.00 ± 24.93	48.4 ± 13.39	35.6 ± 10.06	18.1	PU28LE	Street
2	55.00 ± 31.11	29.5 ± 16.26	22.5 ± 12.02	9.84	P/I	Lab
2	68.00 ± 3.56	27.5 ± 3.00	20.0 ± 2.94	9.84	P/I	Street
3	36.75 ± 6.18	18.00 ± 6.48	12.25 ± 2.06	6.77	P/I	Lab
3	38.00 ± 6.93	18.00 ± 7.94	10.33 ± 1.15	6.77	P/I	Street
4	27.5 ± 3.54	12.00 ± 2.83	8.50 ± 2.12	6	PU28LE	Lab
4	51.00 ± 2.83	21.00 ± 7.07	16.00 ± 5.66	6	PU28LE	Street
5	8.00 ± 0.00	3.00 ± 0.00	2.00 ± 0.00	6	PU212	Lab
5	8.33 ± 8.38	3.33 ± 4.04	2.33 ± 3.21	6	PU212	Street
6	19.00 ± 4.24	7.5 ± 2.12	5.5 ± 0.71	3.09	PU28LE	Lab
6	31.00 ± 2.83	13.5 ± 0.71	9.5 ± 0.71	3.09	PU28LE	Street

removing first and last movements, normalizing the values using the min-max technique, and extracting the relevant features from each sample. As for the sound, the samples were not subjected to a normalization process since this operation was performed by the device itself at the time of data capture. After extracting the attributes of every collection of signals, the corresponding means and variability measures were calculated for analysis.

In relation to audio signal processing, there is an upward trend in the ratio of vehicle speed/bandwidth of the audio level generated by the pedestrian crossing. The trend is the same inside and outside the vehicle, but it is higher outside the vehicle (Fig. 10a). This situation is probably due to the materials used in the interior and the design of the vehicle construction, which, as we know, is intended to isolate the passengers from the sounds produced outside the vehicle. This last detail is very important since a driver's perception of outside sound, the ambient sound, clearly influences the safety of all road users. In addition, the signal strength was evaluated to determine the level of noise generated by traffic over the crosswalk. The results show that it increases with increasing speed (Fig. 10b). The results obtained clearly indicate that the system emits more powerful sounds the higher the speed at which vehicles circulate, implying a certain relevance in terms of road safety since it alerts pedestrians to the existence of vehicles circulating on the roadway.

An increase in the sound level could imply an increase in noise pollution and be an undesirable result, but the analyses performed

indicate that the acoustic level generated by the tested signals remains below acceptable ambient noise levels in urban environments. The evaluation of the acoustic level produced was carried out using the equations of a signal analysis system. Equation (1) calculates the acoustic level of a signal in decibels (dB) from the power spectral density (PSD) and bandwidth (BW), and equation (2) estimates the PSD of a signal using the data in Table 7. In addition, equation (3) is used to calculate the uncertainty in the sound level, taking into account the standard deviations in signal power and bandwidth.

$$\text{Signal level} = 10 \cdot \log_{10}(\text{PSD}) + 10 \cdot \log_{10}(\text{BW}) \quad (1)$$

$$\text{PSD} = \frac{\text{Signal power}}{\text{BW}} \quad (2)$$

$$\sigma_{\text{Signal level}} = 10 \cdot \log_{10}(\sigma_{\text{PSD}}) + 10 \cdot \log_{10}(\sigma_{\text{BW}}) \quad (3)$$

The sound levels recorded on the road vary between 16.33 ± 3.07 dB and 17.62 ± 3.29 dB. According to the WHO guidelines [41], the exterior noise level in residential areas should not exceed 55 dB during the day, while it is recommended that during the night it should not exceed 45 dB to preserve people's rest and health. Therefore, the evaluated signals do not exceed the recommended noise limits, suggesting their suitability for use in urban environments.

Regarding the vibration signal analysis, the findings indicate that, regardless of speed, the bandwidth produced by the vehicle passing over the pedestrian crossing remains constant at 46 Hz (Fig. 11a and Table 8). This consistency could be significant for the well-being and safety of vehicle passengers. Relate to amount, the study revealed that vibration levels are lower when the vehicle is traveling at 30 km/h (Fig. 11b).

4.5. Discussion on characterisation

In relation to the mechanical characterisation and structural analysis, the results indicate that the designed material exhibits strong mechanical features, with suitably high tensile and compressive strength, together with a significant elastic modulus and considerable Shore D

Table 7

Sound attributes of the pedestrian crossing observed both inside and outside the vehicle.

Position	Velocity (km/h)	Bandwidth (Hz)	Signal power (dB)	Sound level (dB)
Inside	20	681.43 ± 49.23	-23.17 ± 1.34	13.65 ± 2.44
	30	633.75 ± 38.05	-18.36 ± 0.29	13.89 ± 2.63
	40	1194.59 ± 129.87	-15.26 ± 0.72	11.66 ± 2.83
Outside	20	4650.47 ± 900.55	-20.27 ± 1.29	17.62 ± 3.29
	30	5180.92 ± 878.67	-17.44 ± 0.48	17.44 ± 3.26
	40	5443.79 ± 617.28	-15.02 ± 0.51	16.33 ± 3.07

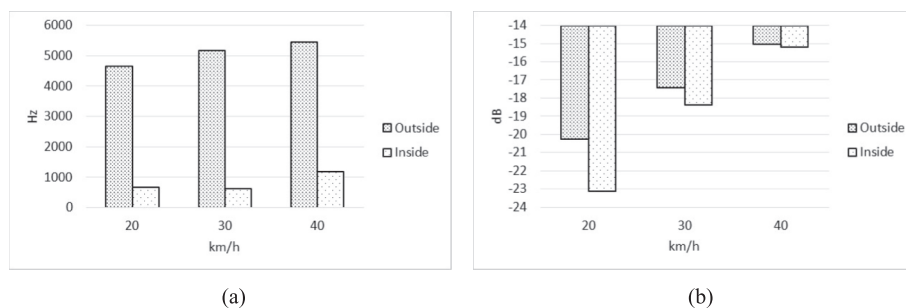


Fig. 10. Audio characteristics: a) bandwidth versus speed, and b) signal power dependent on speed.

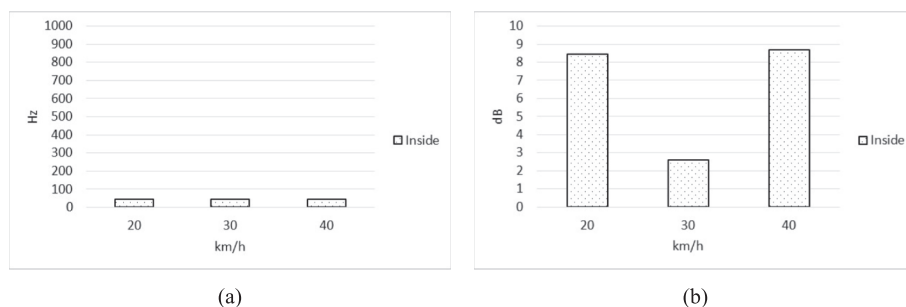


Fig. 11. Vibration profile relationship: a) bandwidth vs. velocity, and b) signal power vs. velocity.

Table 8

Vibration attributes of the pedestrian crossing observed inside the vehicle.

Position	Velocity (km/h)	Bandwidth (Hz)	Signal power (dB)
Inside	20	43.77 ± 1.21	8.45 ± 0.34
	30	45.56 ± 2.07	2.82 ± 0.85
	40	46.07 ± 0.74	8.68 ± 0.98

hardness. Although the vehicle weight of 50 KN may seem relatively low in certain contexts, it is essential to consider the load applied per wheel. This weight could increase on larger vehicles with more axles, resulting in a noticeably higher total weight, even if the weight per wheel remains constant. Therefore, the analysis performed is relevant for such cases.

Concerning photoluminescent features, various important outcomes can be inferred. It should be emphasized that the measurement methodology used made it possible to obtain results that comply with current safety standards, thus ensuring the reliability of the results obtained. In the tests carried out, significant differences were obtained in the photoluminescent intensity between the different resins evaluated, with the P/I resin standing out for presenting generally higher values than the rest of the mixtures. The photoluminescent characteristics were superior in real operating conditions compared to those achieved in controlled laboratory environments, which confirms its actual performance. The selection of the P/I resin, with a 9.84 % content of photoluminescent powder, demonstrated an optimum balance between higher photoluminescence and a lower proportion of additives, classifying it according to UNE standards in the Class A tile category. These tiles achieved an exceptional glow of 68 mcd/m² after 20 min, significantly exceeding the apparent brightness of car headlamps at a considerable distance. These results highlight the capabilities of photoluminescent properties to improve safety in low-light conditions, benefiting both walkers and drivers.

The study conducted confirmed the important benefits of the use of the proposed system. Thus, it was confirmed that an increase in vehicle speed results in better sound perception by pedestrians with respect to vehicles traveling at higher speeds, due to the increase in sound bandwidth and signal power produced when the vehicle passes through the crosswalk. In situations where pedestrians encounter a vehicle, installing soundtracks of the same system before the crosswalk (e.g., a single one) could alert drivers to slow down before reaching the crosswalk. In addition, the potential of vibroacoustic signals goes beyond directly alerting pedestrians at crosswalks. First, these signals could serve as auditory signals to drivers, prompting them to adjust their speed, which would indirectly improve pedestrian safety. Second, in busy traffic scenarios, these signals could assist pedestrians about to cross. In addition, acoustic signals could provide vital alerts for the visually impaired, thus contributing to inclusive urban design.

In addition, the clear distinction between in and vehicle and out-of-vehicle sound bandwidth highlights the relevance of taking into account both vehicle design and road infrastructure to optimize acoustic environments for safety. With respect to vibration, the constant bandwidth of 46 Hz, which remains stable against speed variations, suggests

coherent interactions with the pavement contributing to predictability and safety on roads. The fact that vibrations are minimized traveling at a speed of 30 km/h influences vehicle comfort, indirectly improving road safety by mitigating passenger distractions. This could be attributed, on the one hand, to the arrangement of points and curves designed into the crosswalk surface and, on the other hand, to the vehicle’s adaptive suspension system used. These results provide valuable insight into how vehicles engage with their surroundings, thus contributing to balance both safety on roads and passenger comfort.

5. Experimentation

This section describes a study that compares the effectiveness of a traditional crosswalk with the proposed crosswalk. The first subsection details the experimental setup, explaining the location chosen and the methodology followed to analyze vehicle speeds. The second subsection presents the results. It shows that, in general, vehicles moved more slowly near the new crosswalk than the traditional one.

5.1. Methodology

The experiments took place in an actual setting situated in the university area (37.273202 N, -6.923660 W), adjacent to an educational building housing around 2,150 individuals. This location was selected due to its long track length and the flow of both vehicle and pedestrian traffic at the crosswalk. The road segment spans 270 m with a maximum gradient of 1° and a maximum velocity of 30 km/h. A 4.5 m by 5.5 m pedestrian crossing configuration was tested, monitored with real traffic over 15 days. The street was divided into several sections: S1, S2, and S3 with 37 m, 12 m, and 23 m, respectively (see Fig. 12).

A study using photogrammetry was carried out to analyze 1.5 Gbytes of information collected from 180 moving images along the monitored track sections. Photogrammetric analysis is a method employed to extract geometric data from images, facilitating precise characterization of object movement. By analyzing spatial relationships and temporal variations, this technique enables precise calculation of target velocities, particularly applicable in traffic monitoring scenarios [42]. Consequently, this approach was employed to gauge vehicle speeds in video sequences, leveraging time intervals between frames and distance measurements between road landmarks. A comparative study using photogrammetry was carried out with 1.86 Gbytes of information comprising 174 moving images monitored at the proposed pedestrian crossing. The same photogrammetric analysis method was used to extract geometric data and calculate vehicle speeds in the monitored sections.

5.2. Results

Using the conventional pedestrian crossing, the user profile identified 244 vehicles, comprising 166 automobiles, 60 public transports, 19 persons, 6 cargo vehicles, 4 motorbikes, and 1 car yielding to a pedestrian. An analysis centred on drivers revealed that average velocities in

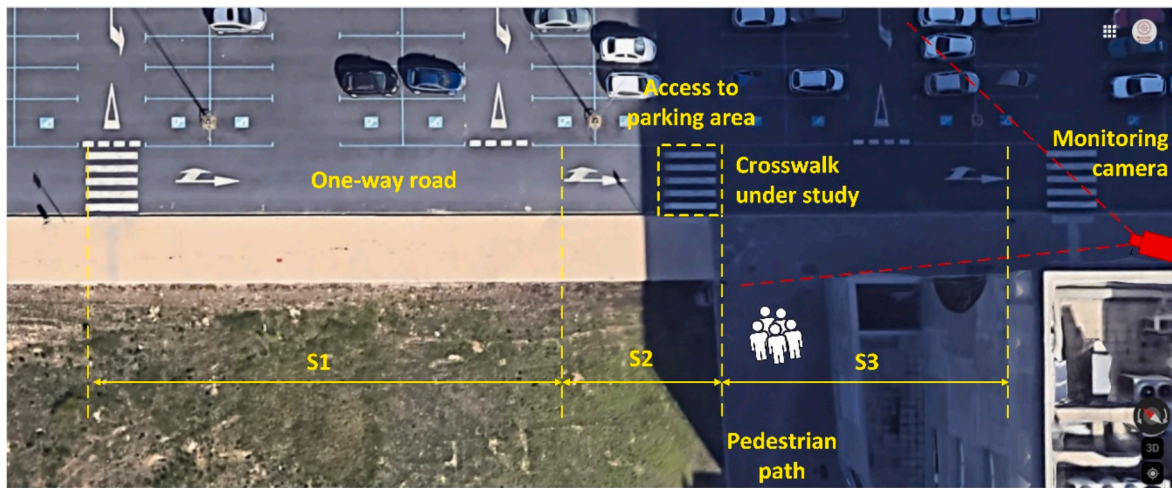


Fig. 12. Configuration of the analyzed system.

segments S1, S2, and S3 were comparable and exceeded the speed limit of the road (refer to Table 9). Motorbikes, cargo vehicles, automobiles, and coaches recorded the highest speeds in descending order. This suggests that the existence of a traditional crosswalk has little impact on vehicle velocity when no pedestrians are present. However, a decreased speed observed in S2 for the vehicle yielding to a person indicates that the pedestrian crossing was acknowledged, and safety measures were enacted by reducing the speed by half until reaching the pedestrian crossing. Nonetheless, 8 drivers were observed exhibiting uncivil behaviour by driving in the wrong direction. These findings may signal the necessity for supplementary safety precautions at pedestrian crossings or increase police surveillance so that drivers comply with traffic regulations.

The analysis identified 244 vehicles with a similar profile including 165 automobiles, 60 public transports, 10 persons, 5 cargo vehicles, 3 motorbikes and a vehicle yielding to pedestrian (refer to Table 10). The study of the vehicles revealed a notable difference between the driver mean velocity in sections S1, S2, and S3 compared to that of the vehicle yielding to a pedestrian. Moreover, the mean velocity change of drivers showed a notable decrease compared to the mean velocity change for a vehicle yielding to a pedestrian when comparing the variations between S1-S2 and S2-S3. This suggests that vehicles reduce speed more when safety takes priority. However, uncivil behaviour was observed in 10 vehicles, including 9 cars that bypassed the proposed crosswalk and 1

Table 9 Speed profile for different vehicles using a conventional pedestrian crossing.

Vehicle	Speed in S1	Speed in S2	Speed in S3	Variation S1 vs. S2	Variation S2 vs. S3
Automobile	35.70 ± 6.38 km/h	35.56 ± 6.99 km/h	38.22 ± 8.29 km/h	-0.40 %	7.50 %
Public transport	34.09 ± 3.65 km/h	35.60 ± 4.54 km/h	39.24 ± 5.43 km/h	4.45 %	10.22 %
Cargo	41.48 ± 5.14 km/h	43.01 ± 5.56 km/h	48.20 ± 7.74 km/h	3.69 %	12.05 %
Motorbike	52.84 ± 19.36 km/h	52.96 ± 19.17 km/h	54.01 ± 18.51 km/h	0.24 %	1.98 %
Car yielding to a pedestrian	32.73 ± 0.0 km/h	14.79 ± 0.0 km/h	32.55 ± 0.0 km/h	-54.82 %	120.17 %
Weighted mean	35.72 ± 6.67 km/h	35.98 ± 7.30 km/h	39.00 ± 8.25 km/h	0.73 %	8.41 %

Table 10 Speed profile for different vehicles using the proposed pedestrian crossing.

Vehicle	Speed in S1	Speed in S2	Speed in S3	Variation S1 vs. S2	Variation S2 vs. S3
Automobile	30.09 ± 5.31 km/h	22.62 ± 6.29 km/h	26.40 ± 7.13 km/h	-24.83 %	16.71 %
Public transport	29.55 ± 2.81 km/h	22.49 ± 6.32 km/h	25.48 ± 7.29 km/h	-23.90 %	13.31 %
Cargo	32.52 ± 10.47 km/h	28.67 ± 13.46 km/h	32.78 ± 15.01 km/h	-11.83 %	14.35 %
Motorbike	25.71 ± 0.14 km/h	19.29 ± 0.49 km/h	21.02 ± 0.45 km/h	-24.98 %	8.96 %
Car yielding to a pedestrian	19.94 ± 0.0 km/h	10.69 ± 0.0 km/h	21.56 ± 0.0 km/h	-46.37 %	101.65 %
Weighted mean	29.96 ± 5.07 km/h	22.69 ± 6.61 km/h	26.25 ± 7.49 km/h	-24.28 %	15.71 %

driving in the opposite direction. This indicates that although the new pedestrian crossing may have influenced a decrease in mean velocity, vehicles may have adopted new risk conducts.

An evaluation comparing vehicle conduct at both traditional and proposed pedestrian crossings revealed several key findings. At the intended pedestrian crossing, mean velocity was found lower in general compared to that at the conventional crosswalk (Fig. 13). In the traditional crosswalk, the highest velocity was recorded in segments S3, S1 and S2 with speeds of 38.22 km/h, 35.70 km/h and 35.56 km/h, respectively. On the contrary, at the new pedestrian crossing, the maximum velocity was observed in segments S1, S3 and S2 with speeds of 30.09 km/h, 26.40 km/h, and 22.62 km/h, respectively. Although both types of pedestrian crossings achieved a notable decrease in velocity as the vehicles approached the S2 section, the new pedestrian crossing presented greater percentage differences in velocity both between S1 and S2 (-24.28 %), and between S2 and S3 (15.71 %). This indicates that the new crosswalk could have more significantly influenced a reduction in velocity as vehicles approached the pedestrian crossing, thus improving traffic flow and pedestrian safety. A notable aspect is the decrease of 46.37 % in velocity observed between S1 and S2 for the vehicle yielding the road to pedestrians with the new system compared to a greater reduction of 54.82 % in the conventional pedestrian crossing. This underlines the effectiveness of the proposed system in smoothing out sudden changes in speed. Although the scope of

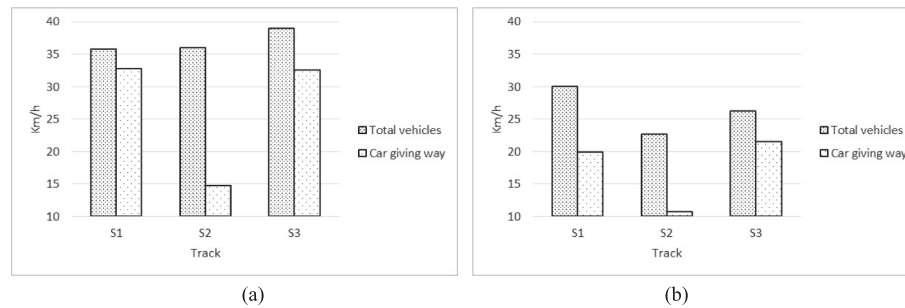


Fig. 13. Average speed: a) conventional crosswalk, b) proposed crosswalk.

the study is limited by the sample size, ongoing research efforts aim to increase the data collection to provide more consistent evidence. Nevertheless, these findings lay a solid foundation for further exploration.

6. Conclusions and future works

Traffic accidents involving pedestrians pose a significant road safety challenge, with 10,461 incidents recorded in Spain according to available statistics. However, current solutions face several limitations, including lack of understanding about the effect of road markings on road safety, lack of proprietary solutions, dependence on energy sources and restricted accessibility of driver assistance systems, and scarcity of studies on photoluminescence properties used in road markings, more specifically at pedestrian crossings. To address these limitations and improve visibility at pedestrian crossings, a solution focused on road systems using photoluminescent materials is proposed. The potential objective is to avoid a significant percentage of injuries and fatalities in line with the “zero casualty” target required by Sweden, Finland and the EU itself, among others.

The present pedestrian crossing aims to substitute traditional pedestrian crossings incorporating long-lasting components that emit eco-friendly and secure lighting in dim or no-light situations. The elements used contain photoluminescent materials, glass microspheres and durable polymers, as well as auditory and vibrating components for driver awareness, slip-resistant characteristics, and effortless removal for maintenance. This photoluminescent pedestrian crossing, in addition to being environmentally sustainable and cost-effective, contributes to energy conservation and a decrease in CO₂ emissions. The design consists of tiles and ramps that are reversible, featuring photoluminescent pigment on white tiles, resulting in a luminous effect for an extended time of more than 12 h. Extensive testing was conducted to demonstrate that the composite material is resistant to tensile and compressive stress, with a high Shore D hardness that ensures durability and strength. To model the crosswalk, SolidWorks software was used considering a 50 kN vehicle with each wheel supporting a weight of 12.5 kN. Photoluminescence tests and vibroacoustic study verified the effectiveness of the selected components for both visual alertness and awareness.

In a real scenario, field tests showed reduced average velocities compared to traditional pedestrian crossings, obtaining a notable decrease in both the average vehicle traffic speed (36.96 %, i.e., 35.98 km/h vs. 22.69 km/h) and the speed when drivers yield to pedestrians (27.73 %, i.e., 14.79 km/h vs. 10.69 km/h). Therefore, the proposed system potentially reduces accident rate by focusing on road conditions and factors that directly relate to the driver.

The proposed system faces several potential limitations to achieving comprehensive and sustainable road safety, including integration with existing road infrastructure, collaboration challenges between traffic technicians, urban planners and local administration, and the need for continuous monitoring. Future work should focus on addressing local conditions to successfully integrate the solution into existing road infrastructure, establishing interdisciplinary committees and guidelines

for coordinated implementation with road safety authorities, and deploying automated monitoring systems with intelligent algorithms to optimize system efficiency (e.g., during peak hours).

The scope of the study is restricted by the sample size, which limits the breadth and generalizability of the findings. A limited sample size may not encompass all variations in driver behavior, traffic flow, and environmental influences. This restriction requires conducting research to improve data collection and gather a more diverse set of samples, thus offering stronger evidence to support the efficiency and reliability of the system. The preliminary research results are valuable but serve only as the beginning for future studies. To extend the results, it is essential to prolong the research by carrying out long-term field tests. Short-term research may not consider seasonal changes, which could affect long-term traffic trends or the development of road users' adaptation to the new system. Expanded studies can provide insight into the system's impact on long-term road safety and pedestrian behavior. Furthermore, it is essential to expand current research to cover different traffic conditions and types of urban environments. For example, the effectiveness of the system may vary depending on whether it is used on wider roads or in areas with more congestion. Each of these configurations poses distinctive obstacles and possibilities for system efficiency. Testing in different environments helps identify any restrictions or modifications necessary to ensure that the system works efficiently in various situations.

Future research will explore additional factors such as driver awareness and compliance with road regulations, which are significant contributors to traffic accidents due to driver distraction, lack of civic education, poor road conditions, and inadequate traffic signalling. By improving drivers' perception of pedestrians and enhancing their compliance with road safety practices, the effectiveness of the proposed system can be significantly increased. This comprehensive approach aims to create a safer road environment, ultimately reducing traffic accidents and improving pedestrian safety. Other potential research areas include further exploring the impact of sound and vibration features on speed reduction, which may lead to innovative designs using 3D geometry to mitigate slipping, particularly for personal mobility devices like scooters and electric bicycles. Another focus could be adapting the surface pattern of pedestrian crossings to incorporate tactile elements aimed at enhancing safety for individuals with visual impairments. Additionally, combining photoluminescent crosswalks with emerging technologies such as smart sensors and real-time data analytics could enhance the system's adaptability to changing traffic conditions. Smart sensors could continuously monitor traffic and environmental factors, including pedestrian presence, vehicle speed, traffic density, and weather conditions. Analyzing traffic patterns and pedestrian behavior could help optimize crosswalk design and placement in future projects and develop predictive models to identify high-risk areas and address additional safety needs.

CRedit authorship contribution statement

J.M. Lozano Domínguez: Writing – review & editing, Writing –

original draft, Software, Formal analysis, Data curation, Conceptualization. **T.J. Mateo Sanguino**: Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Investigation, Funding acquisition, Conceptualization. **M. Redondo González**: Writing – review & editing, Writing – original draft, Methodology. **J.M. Davila Martin**: Writing – review & editing, Writing – original draft, Methodology, Formal analysis.

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.

Acknowledgments

This work has been supported by MCIN/AEI/10.13039/501100011033/FEDER, UE, throughout the project PID2021-1213001033B-I00. Furthermore, we would like to express our deep gratitude to J.M. Corralejo Mora for his valuable inputs that have significantly improved this study.

References

- [1] Snider, A.: New Projection: U.S. Pedestrian Fatalities Reach Highest Level in 40 Years. Governors Highway Safety Association. Tech. Rep. (2022). <https://www.ghsa.org/resources/news-releases/GHSA/Ped-Spotlight-Full-Report22> [accessed on 24 July 2024].
- [2] S. Matus, D. Dostal, R. Risser, Pedestrian-driver communication and decision strategies at marked crossings, *Accid. Anal. Prev.* 102 (2017) 41–50.
- [3] A. Sheykhsfar, F. Haghighi, Performance analysis of urban drivers encountering pedestrian, *Transport. Res. F: Traffic Psychol. Behav.* 62 (2019) 160–174.
- [4] E.M. Acerra, M. Shoman, H. Imine, C. Brasile, C. Lantieri, V. Vignali, The visual behaviour of the cyclist: comparison between simulated and real scenarios, *Infrastructures* 8 (5) (2023) 92.
- [5] T. Schnell, H.T. Zwahlen, Driver preview distances at night based on driver eye scanning recordings as a function of pavement marking retroreflectivities, *Transp. Res. Rec.* 1692 (1) (1999) 129–141.
- [6] M. Infante Francés, T.J. Mateo Sanguino, Method for characterizing obstacles on the road to evaluate their impact on pollution, *DYNA* 97 (4) (2022) 392–397.
- [7] Janice, D.; Chien, S.; Liu, R.: Effectiveness of Certain Design Solutions on Reducing Vehicle Speeds. Federal Highway Administration Report FHWA-NJ-2005-007, 1-133 (2005).
- [8] Traffic Safety Dashboard. Tech. Rep., 2024. <https://opendata.sandag.org/stories/s/Traffic-Safety-Dashboard/5f7y-nefe/> [accessed on 25 July 2024].
- [9] A. William, O.T. Kolawole, O.A. Comfort, A. Francis, Driver compliance and pedestrian safety at zebra crossings in the Cape Coast Metropolis, Ghana, *Urban Plann. Transp. Res.* 9 (1) (2021) 464–478.
- [10] P. Olszewski, P. Szagała, M. Wolański, A. Zielińska, Pedestrian fatality risk in accidents at unsignalized zebra crosswalks in Poland, *Accid. Anal. Prev.* 84 (2015) 83–91.
- [11] E. Krug, J.L. Irigoyen, P. Venter, D. Ward, Pedestrian safety: a road safety manual for decision-makers and practitioners, World Health Organization, 2013.
- [12] S. Suzuki, P. Raksincharoensak, I. Shimizu, M. Nagai, R. Adomat, Sensor fusion-based Pedestrian Collision Warning System with Crosswalk Detection, *IEEE Int. Vehicles Symp.*, IV, 2010.
- [13] D. Olmeda, C. Premevida, A.J.M. Nunes, A. Escalera, Pedestrian Detection in Far Infrared Images, *Integrated Computer-Aided Eng.* 20 (4) (2013) 347–360.
- [14] Ayuso, M.; Sánchez, R.; Santolino, M.: Longevity of Drivers and Age of Vehicles: Impact on the Accidents' Severity. *Anales del Instituto de Actuarios Españoles*, 4^ª época, 25, 33–53 (2019).
- [15] M. Jovanović, T.J. Mateo Sanguino, M. Damjanović, M. Đukanović, N. Thomopoulos, Driving sustainability: carbon footprint, 3D printing, and legislation concerning electric and autonomous vehicles, *Sensors* 23 (22) (2023) 9104.
- [16] T. Zou, D. Chen, Q. Li, G. Wang, C. Gu, A novel straw structure sandwich hood with regular deformation diffusion mode, *Compos. Struct.* 337 (2024) 118077.
- [17] J.M. Lozano Domínguez, T.J. Mateo Sanguino, Design, modelling, and implementation of a fuzzy controller for an intelligent road signaling system, *Complexity* 1849527 (2018).
- [18] J.M. Lozano Domínguez, M.J. Redondo González, J.M. Dávila Martín, T.J. Mateo Sanguino, Using sensor fusion and machine learning to distinguish pedestrians in artificial intelligence-enhanced crosswalks, *Electronics* 12 (23) (2023) 4718.
- [19] COST 331 - Requirements for Horizontal Road Marking. Luxembourg: Office for Official Publications of the European Communities, 153 (1999). [https://www.vegagerdin.is/vefur2.nsf/Files/COST331/\\$file/331-en.pdf](https://www.vegagerdin.is/vefur2.nsf/Files/COST331/$file/331-en.pdf) [accessed on 19 April 2024].
- [20] Impact Assessment of Road Safety Measures for Vehicles and Road Equipment. Tech. Rep. (TREN-04-ST-S07.37022), Harmonisation of road signs and road markings on the TERN from a safety point of view (2006).
- [21] K. Diamandouras, M. Gatscha, Rainvision: the impact of road markings on driver behaviour–wet night visibility, *Transp. Res. Procedia* 14 (2016) 4344–4353.
- [22] T.J. Mateo Sanguino, J.M.L. Domínguez, Photoluminescent Horizontal Road Marking, WIPO, 2018, pp. 1–20. Tech. Rep. WO 2018/224716 A1.
- [23] T. Zou, S. Shangb, C. Simms, Potential benefits of controlled vehicle braking to reduce pedestrian ground contact injuries, *Accid. Anal. Prev.* 129 (2019) 94–107.
- [24] Fredriksson, R.; Rosén, E.: Head Injury Reduction Potential of Integrated Pedestrian Protection Systems Based on Accident and Experimental Data - Benefit of Combining Passive and Active Systems. Proc. International Council on the Biomechanics of Injury (IRCOBI) Conference, IRC-14-69 (2014).
- [25] J. Hu, K.D. Klinich, Toward designing pedestrian-friendly vehicles, *Int. J. Veh. Saf.* 8 (1) (2014) 22–54.
- [26] L.A. Suleymanova, M. Maliukova, A. Koryakina, Architectural and decorative concrete with photoluminescent pigment, *IOP Conf. Series: Mater. Sci. Eng.* 896 (2020).
- [27] F.G. Praticó, S. Noto, A. Moro, Optimisation of photoluminescent painting treatments on different surface layers, CRC Press, *Functional Pavement Design*, 2016.
- [28] F.G. Praticó, R. Vaiana, S. Noto, Photoluminescent Road Coatings for Open-Graded and Dense-Graded Asphalts: Theoretical and Experimental Investigation, *J. Mater. Civil Eng.* (2018).
- [29] C. Villa, R. Brémond, F. Eymond, E. Saint-Jacques, Characterization of luminescent road markings, *Light. Res. Technol.* 55 (2021) 459–473.
- [30] Сайго, К.; Сахан, М.; Яманашин, С.: Photoluminescent material for the highway marking and the highway structure. Patent RU 2 276 702 C2 (2002). <https://patenton.ru/patent/RU2276702C2/en> [accessed on 19 April 2024].
- [31] E.I. Gutiérrez, H.A. Colorado, Development and Characterization of a Luminescent Coating for Asphalt Pavements, Characterization of Minerals, Metals, and Materials 2020 (2020) 511–519.
- [32] R.N. Nurmuhametov, L.V. Volkova, N.I. Kunavin, V.G. Klimenko, Application of luminescent materials for road signs and road markings, *Izvestiya MGTU MAMI* 1 (2) (2007) 199–203.
- [33] General Directorate of Traffic (DGT): European Policies in Urban Mobility, Conferences and Congresses (2014). <https://www.coches.net/noticias/dgt-jornada-de-politicas-de-movilidad-urbana> [accessed on 19 April 2024].
- [34] T.J. Mateo Sanguino, J.M. Dávila Martín, M.J. Redondo González, J.M. Lozano Domínguez, J.M. Corralejo Mora, Manufacturing and characterization of intelligent pedestrian crossings to improve road safety, *DYNA* 98 (2023) 341–345.
- [35] J.M. Lozano Domínguez, M.J. Redondo González, J.M. Davila Martin, T.J. Mateo Sanguino, Using sensor fusion and machine learning to distinguish pedestrians in artificial intelligence-enhanced crosswalks, *Electronics* 12 (2023) 4718.
- [36] T.J. Mateo Sanguino, M.J. Redondo González, J.M. Davila Martin, J.M. Lozano Domínguez, Enhanced road safety with photoluminescent pedestrian crossings in urban contexts, *Infrastructures* 9 (3) (2024) 60.
- [37] J.D. Jiménez Negrete, P.C. Ruiz Parra, Analysis of the behavior of photoluminescent materials applied in horizontal signage, *Int. Eng. Education Meeting* 1–11 (2016).
- [38] Ministry of Public Works: Guide for the Project and Execution of Horizontal Signage Works. Tech. Rep., 1-111 (2012). https://cdn.mitma.gob.es/portal-web-drupal/carreteras/normativa/guia_sh.pdf [accessed on 19 April 2024].
- [39] Topcon Technohouse Corporation: Luminance Meter BM-100. Easy and handy luminance meter for high luminance photoluminescent safety sign. Tech. Rep. (2014).
- [40] JSA (Japanese Standards Association): JIS Z 9096, Safety sign and guidance line of phosphorescent type on floor (2012).
- [41] European Environment Agency, Good Practice Guide on Noise Exposure and Potential Health Effects, Office for Official Publications of the European Communities, Luxembourg, 2002.
- [42] C. Wang, Z. Ye, J. Li, F. Su, Vehicle speed estimation using video-based traffic data, *IEEE Trans. Intelligent Transp. Sys.* 18 (10) (2017) 2827–2837.

J.M. Lozano Domínguez is a Computer Engineer (2020) and Master's degree in Computer Engineering (2021) from the University of Huelva. He was hired as a PhD student in the Department of Electronic Engineering, Computer Systems and Automatics, where he has been a supply teacher in Automatics and System Engineering for 6 years. He also worked as a trainee engineer at the company ONUBA TECHNOLOGY, SL for a year in 2014. He has published 15 papers in national / international conferences and journals, of which a book chapter and 5 journals indexed in JCR stand out. In addition, He has a utility model and a patent on intelligent road safety issued to international PCT.

T.J. Mateo Sanguino is an Industrial Technical Engineer (esp. Electronics), Electronic Engineer, Master's Degree in University Teaching and PhD in Systems Engineering and Automatics from the University of Huelva. He has worked since 1998 as a research fellow and as a freelancer at the National Institute of Aerospace Technology (INTA). In 2003/04 he was hired for a specific project or service in the Higher Council for Scientific Research (CSIC). Since 2004 he has been hired as a teacher at the University of Huelva, being deputy director of the Department of Electronic Engineering, Computer Systems and Automatics since 2014. He has been a founder of a Spin-off (2009/12). He has completed four short pre-doctoral stays, together with a postdoctoral stay at EPFL (Switzerland). He has published around 100 papers in different books, journals and conferences of which more than 50% are indexed in Scopus. He has been a reviewer of 42 working documents in international congresses and journals indexed in JCR, Scopus and the Andalusian Agency for

Evaluation (AGAE), being guest editor of four special issues. He has led 1 international R&D project, 2 national knowledge transfer projects, 3 regional R&D projects and 18 teaching innovation projects, as well as he has obtained other several aids for ~150K€. He participated in the European COST action CA16222. He has also participated in 8 national R&D projects and 3 regional R&D projects. He has three patents extended to international PCT. He has organized 17 events in the Spanish Week of Science and Technology with training talks, workshops and challenges. He has recently completed 13 years of service as an instructor of the CISCO Certified Networking Association.

M. Redondo González is Industrial Technical Engineer from the University of Seville (No. 1 of his class); Technical Engineer in Computer Management (best academic grade of the Faculty of Informatics and Statistics of the University of Seville awarded by the City Council of Seville in 1998/99); Industrial Organization Engineer from the University of Seville; Doctor in Engineering from the University of Huelva (cum laude). He has worked for the last 30 years as a full-time teacher at the University of Seville (1986-1993) and at the University of Huelva since 1993. He has been a professor at the University of Huelva since 2013. He is also a teacher at the Associated Center of Huelva of the National University of Distance Education (UNED) since 1995. He has the Diploma for Teaching Excellence, awarded by the University of Huelva (2002/03); Award to the Teaching Team of Excellence of the University of Huelva as coordinator (2008); Excellent Teaching Professional (2010/11 and 2012/13). He has been an External Evaluator of Educational Innovation Projects of the Andalusian public universities on the Architecture and Engineering area from 2011 to 2014. He is part of the Control and Robotics research group. He has published a total of 12 research papers in scientific journals and book chapters, as well as 13 scientific papers in national and international conferences. He has participated in a

total of 14 research projects of the national R&D plan, the Andalusian Government and the research plan of the University of Huelva. He has coordinated and / or participated in a total of 7 Teaching Innovation Projects. In the field of research transfer, he has a patent. He has participated in an R&D contract with the Invest company (2012).

J.M. Dávila Martín is Architect (University of Seville-2014) with the qualification of outstanding cum laude, completing his training with a postgraduate course and 20 specialization courses. He obtained a predoctoral scholarship financed by the EMAHSA company. He performed postdoctoral stays at the Eloy Alfaro University of Ecuador, the University of Oviedo, the Polytechnic University of Madrid and the Nova of Lisboa. Since the beginning of his research activity, he has joined the Sustainable Mining Engineering Research Group (from 2017) actively collaborating in the design of sampling networks, evaluation of results and writing of the papers. His scientific production exceeds 50 published works: 20 contributions in scientific journals indexed in databases with a relative quality index and clear upward trajectory, of which 6 are Q1 in JCR, 3 are Q2 in JCR, 4 Q3 in JCR, 3 Q3 in SJR, 1 is Q4 in SJR. In addition, he has published 4 books and presented 7 papers in conferences indexed in the Web of Science and another 2 in Scopus; in addition to 13 other works, between presentations and communications, counting in all cases with a peer review for acceptance. He has carried out 25 research projects in different fields and has been awarded a R&D project as Principal Investigator in a competitive call for applications from the Junta de Andalucía (UHUPJ00001). Likewise, he has participated in a cooperation project of a competitive call (Andalusian Agency for International Development Cooperation-2016DEC028). He has carried out 20 professional jobs and worked as a freelance in more than 40 professional projects. He has a patent called Screw-Nut Assembly Threading and Unscrewing Device (P201730656).