This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

New Approach to Intelligent Pedestrian Detection and Signaling on Crosswalks

Tomás de J. Mateo Sanguino, José Manuel Lozano Domínguez, Manuel Joaquín Redondo González, and Jose Miguel Davila Martin

***Abstract*— Traffic signaling systems play a crucial role in improving driver attention and reducing road speed. Nevertheless, most available solutions face challenges such as limited commercial availability, high infrastructure costs, lack of intelligence, and incomplete coverage for all road users. To address these obstacles and bolster road safety, this manuscript introduces an innovative intelligent crosswalk featuring speed bumps with integrated light signaling, facilitating precise pedestrian detection through artificial intelligence. The design methodology incorporates resins, aggregates, and reinforcing fibers, cold-injected into an aluminum mold. Notably, the system operates autonomously on solar power, ensuring sustainability and robust protection against environmental elements. To validate the crosswalk, quantitative indicators of road safety improvement are compared against a conventional crosswalk and a prior system based on fuzzy logic. A comprehensive ROC analysis of the implemented machine learning techniques revealed an accuracy rate of 99.11% in pedestrian detection, representing a substantial leap forward in road safety. In addition, a study assessing the system's impact on user behavior found a 46.5% improvement in pedestrian trajectory, along with speed reductions observed for both pedestrians (10.24%) and drivers (32.83% during the day, and 70.6% at night). The study was further completed with an analysis of the opinion of users who perceived a significant improvement in safety and compliance with regulations with the intelligent crosswalk, highlighting the potential of the system to significantly contribute to the enhancement of road safety.**

***Index Terms*— Artificial intelligence, road safety, pedestrian detection, smart crosswalk.**

I. Introduction

ROAD safety is a major concern in cities, where current data highlights the ongoing vulnerability of pedestrians as the most at-risk road users, particularly at singular road points like crosswalks. According to statistics from the General Directorate of Traffic (DGT), there were 1,818 pedestrian accidents in urban areas in Spain during 2022. Among them, 740 were fatal accidents, accounting for 40.8% of the total. Compared to 2021, the number of urban pedestrian accidents increased by 2.1%. The most common causes of pedestrian accidents were excessive vehicle speed, as well as alcohol or drug consumption [1]. Therefore, it is essential to take actions to improve road safety such as greater surveillance and reduction of vehicle speed, raising awareness among drivers and pedestrians about the importance of respecting traffic rules and providing road safety education from childhood. It is worth noting that this issue is not unique to Spain. For instance, according to a report from the National Highway Traffic Safety Administration (NHTSA), in the United States there were 7,310 hit-and-run accidents with pedestrians in urban areas in 2022. Of these, 6,752 were accidents with injuries and 478 were fatal accidents. Compared to 2021, the number of accidents involving pedestrians in urban areas in the United States increased by 5.1% [2].

These statistics are dramatic, not only due to the high number of accidents but also because they indicate a concerning upward trend. Current data features the need for ongoing initiatives and solutions to reduce accidents and save lives, hence efforts to address pedestrian road safety continue to be of paramount importance. Studies show that more severe traffic calming measures provide greater speed reductions and, therefore, fewer accidents [3]. If light signaling with active control is added in addition to reducing vehicle speed, the necessary attention at crosswalks is achieved. To make progress in enhancing road safety solutions and infrastructure pertaining to crosswalks, this manuscript puts emphasis on traffic signaling systems capable of detecting both pedestrians and vehicles. Despite the wide range of solutions mainly found in intellectual property databases such as Invenes, Espacenet and Google Patent, several drawbacks have been identified within the current state of the art. These limitations encompass the fact that most of these solutions are conceptual and not yet available on the commercial market, often requiring additional infrastructure and civil works for installation, making them susceptible to electrical system disruptions. Additionally, these solutions often lack the sophistication to distinguish between pedestrians and vehicles, resulting in a binary "all or nothing" detection approach that can lead to false positives. Furthermore, a comprehensive architectural framework for the seamless integration of all stakeholders, including pedestrians, vehicles, and the surrounding environment, is notably absent. As a result, traditional methods such as reflectors, illuminated canopies, rubber speed bumps, and

Manuscript received 21 February 2024; revised 22 July 2024; accepted 11 August 2024. This work was supported in part by the General Secretariat of Universities, Research and Technology within the scope of the Andalusian Research, Development and Innovation Plan (PAIDI 2020); in part by European Regional Development Fund; in part by the Mutualidad de la Agrupación de Propietarios de Fincas Rústicas de España (MAPFRE) Foundation through the "Ignacio H. de Larramendi" Research under Grant BIL/15/P3/047; and in part by the University of Huelva under Grant EPIT24. The Associate Editor for this article was H. Han. *(Corresponding author: Tomás de J. Mateo Sanguino.)*

The authors are with the Escuela Técnica Superior de Ingeniería, University of Huelva, 21007 Huelva, Spain (e-mail: tomas.mateo@diesia.uhu.es; jose.lozano@diesia.uhu.es; redondo@uhu.es; jmdavila@dimme.uhu.es).

Digital Object Identifier 10.1109/TITS.2024.3445156

© 2024 The Authors. This work is licensed under a Creative Commons Attribution 4.0 License.
For more information, see https://creativecommons.org/licenses/by/4.0/

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

trapezoidal concrete or cement reliefs continue to be the prevailing and widely adopted solutions for pedestrian crossing signaling.

A. Objectives and Research Hypothesis

Our primary objective is to comprehensively evaluate the performance and impact of an intelligent crosswalk with respect to enhancing pedestrian safety. Building on this, we hypothesize that the proposed intelligent system will significantly contribute to an improvement in road safety by effectively detecting pedestrians and alerting drivers to their presence. Our secondary objective involves a thorough investigation of the system's influence on road user behavior, particularly in terms of vehicle speed and pedestrian flow. In line with this objective, we hypothesize that the introduction of the intelligent crosswalk will result in a noticeable reduction in vehicle speed and a more streamlined pedestrian flow at the crosswalk. Finally, our tertiary objective revolves around assessing user attitudes, perceptions, and experiences pertaining to road safety and the intelligent crosswalk. We hypothesize that the presence of the proposed system will positively shape user attitudes and perceptions related to road safety, as it enhances their experiences and fosters more favorable opinions regarding safety actions.

To this end, this manuscript is structured as follows: Section II reviews the literature on pedestrian road safety and work related to intelligent crosswalks. Section III introduces the intelligent traffic signaling system. Section IV presents the experimentation carried out with the intelligent crosswalk in several scenarios, whilst Section V discusses the improved road safety. Finally, Section VI summarizes the conclusions and future works.

II. State of the Art

Diverse authors shed light on crucial aspects of the analysis of safety at crosswalks and pedestrian behavior, emphasizing the need for improved safety interventions. In this context, an initial study underscored the importance of pedestrian safety, especially in urban areas, and highlighted key factors contributing to accidents, including the design of pedestrian crossings and driver behavior. In this regard, the study found that although signal countdown timers are likely to improve efficiency at signalized crosswalks, they can lead to risky driver behaviors such as errors and violations that could increase the potential for pedestrian accidents [4]. As a solution, another study suggested the necessity of modernizing crosswalk design to lower speeds and enhance driver visibility [5]. Additionally, another work addressed the high pedestrian fatality rate in its country and presented findings such as active signage and speed cushions at crosswalks. These approaches were found to reduce vehicle speeds and positively impact driver behavior, which could potentially contribute to pedestrian safety [6]. Another study examined pedestrian safety on urban roads and found low driver compliance at crosswalks. It reported a significant number of pedestrian crashes with a considerable portion resulting in hospitalization or fatalities. The study recommended coordinated efforts by stakeholders to enhance pedestrian safety and driver compliance at these crossings [7]. Furthermore, an additional work delved into pedestrian behavior at crosswalks in the same city and identified factors influencing risky behaviors. It was discovered that most pedestrian accidents occurred outside of crosswalks and pedestrians often exhibited risky behaviors (e.g., using smartphone while crossing). The findings underlined the need for educational campaigns by traffic authorities to promote safer pedestrian use of crosswalks despite their right-of-way [8]. In relation to this, other study addressed the emerging issue of pedestrian distraction related to smartphone use and explored its associations with risky crossing behaviors and safety outcomes. As the main result, this research provided insight into the complex relationship between distraction and safety for pedestrians [9].

Other authors explored the interactions between pedestrians and vehicles. For instance, a study assessed conflicts between vehicles and pedestrians in areas with and without zebra crossings using naturalistic driving data. The study found that drivers adjusted speed and direction to avoid collisions, while pedestrians performed actions such as returning to the sidewalk or increasing walking speed [10]. Regarding driver-safe evasive actions, another study was carried out in various urban and non-urban areas with the goal of mitigating the risk of pedestrian accidents. The study showed that changing lanes is the key evasive action employed by drivers to avoid pedestrian crashes in suburban and unmarked crossing areas, while drivers rely on soft evasive actions such as deceleration in urban and marked crossing areas [11]. Other researchers also studied the interactions between pedestrians and vehicles, proposing threshold risk indicator values for severe pedestrian-vehicle interactions. This research is valuable in evaluating the severity of interactions at uncontrolled intersections and improving pedestrian safety [12].

Attention to safety on suburban roads was the focus of a recent study conducted to understand how factors influence pedestrian decisions. The results indicated that waiting time, average traffic speed, headway between vehicles, size of available space, and type and speed of approaching vehicle were significant [13]. In line with this topic, a recent work explored risk behavior profiles of pedestrians, particularly in low-income countries, by examining sociodemographic factors associated with risky conduct. As a conclusion, this work emphasized the need for road safety education and strategies designed with profile information in mind to reduce pedestrian risk [14]. Also aligned with this topic, another study deepened into the psychological factors influencing child-pedestrians' decisions when crossing roads and aims to create a safer urban environment for them. It examined attitudes, beliefs, and perceptions to understand and improve child-pedestrian safety [15]. All these studies show the importance of dealing with pedestrian safety at crosswalks through a combination of design improvements, safety solutions, and public awareness campaigns. They also offer a comprehensive perspective on pedestrian safety analysis, behavior, and interventions at pedestrian crossings.

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

A. Related Work on Intelligent Crosswalks

The research landscape surrounding intelligent crosswalks has witnessed significant developments, each contributing to the enhancement of pedestrian road safety. Such landscape has been addressed by a study that conducted a broad analysis of safety trends in urban transportation systems. It offered valuable insights into global safety trends. Nevertheless, it lacks specific technical implementation details for smart pedestrian crossings, thus limiting its contribution in terms of direct impact on pedestrian safety [16]. Similarly, an innovative vision of pedestrians in future smart cities is described with an emphasis on personalized travel and metamorphic crosswalk styles. However, it remains in the visionary phase, lacking technical application details [17]. In this sense, a comprehensive review of devices aimed at enhancing safety at pedestrian crossings was presented. This work, while providing a valuable overview, also lacks specific technical implementation details, placing it behind the present manuscript regarding the practical application and impact on road safety [18].

Focusing on real applications, an ongoing initiative on implementing pedestrian detectors at crosswalks to improve safety was described in a forefather work. These detectors activate flashing lights to alert drivers when pedestrians are present in the crosswalk. While this work provides a practical example of the implementation of this type of smart systems, it only describes underway efforts without covering implications for pedestrian safety [19]. Also, a sophisticated system was proposed to address the collision between pedestrians and vehicles during traffic light transitions. The system employs a braking distance model that considers human-vehicle characteristics, significantly improving pedestrian crossing safety. However, the complexity of the system, involving multiple modules and wireless communication, may pose challenges in terms of implementation and maintenance compared to simpler approaches [20]. Similarly, an analytical model that takes advantage of video sequences for risk analysis was introduced. This work offers valuable information on possible risk scenarios at pedestrian crossings. However, its reliance on video data and the need for extensive analysis may limit real-time application compared to the more immediate intervention approaches [21]. Likewise, a solution to improve pedestrian safety at crosswalks by taking advantage of real-time data and the use of IoT technology was described. The proposal involves collecting data from various sources, including observations and previous research, to develop a prototype model. Although promising, the proposal was presented in the conceptual phase and requires specific implementation details [22]. Other works also used IoT technology and CCTV with object tracking to provide safety for pedestrians. Although it presented a valuable approach, this work may require more complex and expensive infrastructure, including advanced tracking sensors and communication systems [23]. In contrast, an approach based on visible flashing lights can be effective in slowing vehicles and reminding pedestrians of the importance of crossing carefully. As another example, a system focused on pedestrian safety that uses alarms generated by sensor signals and a flat laser projection was introduced. This offers a unique approach to improving road safety for pedestrians. Nonetheless, the reliance on specialized sensors and laser technology may pose challenges in terms of scalability and cost-effectiveness compared to the approach described in this manuscript [24].

Artificial intelligence (AI) has been a convenient approach used as in a study that explored its use to improve the regulation of road traffic, with special attention to unregulated and poorly lit crosswalks. The study emphasized the need to address the significant number of deaths that occur in such areas through smart technology capable of recognizing moving vehicles, warning pedestrians, and notifying drivers of the presence of people on the road. Although this proposal highlights the importance of using AI to address road safety issues, particularly to crosswalks, it focuses on early detection and timely alerts for both pedestrians and drivers, which distinguishes it from the immediate detection capabilities of the present approach [25]. Another study explored the potential of intelligent driver support systems to lower accidents by detecting pedestrians and predicting collisions. It emphasized the importance of understanding the environment, vehicle, and driver conditions for enhanced safety and discussed machine learning (ML) techniques for pedestrian detection. It highlighted the potential limitations of relying solely on vehicle-based sensors for pedestrian detection and proposes a more interconnected and standardized approach. However, this work does not provide a specific technical solution [26]. Also related to AI, a work presented a novel algorithm that uses Fourier transform and other techniques for pedestrian crossing detection. This research provided valuable insights into pedestrian detection but focuses specifically on the algorithm rather than a comprehensive pedestrian crossing system [27].

AI has also been the focus of a study that delved into the critical aspect of understanding pedestrians' behavior regarding autonomous vehicles in urban environments. By using multimodal input data, including human poses, bounding boxes, and image-based features, the study aims to predict crosswalks through AI. While this research addresses a crucial aspect of road safety, it pays attention on prediction rather than direct intervention, distinguishing it from the practical approach of the present work [28]. An additional work discussed the concept of smart crosswalks for potential implementation in future road infrastructure. It addressed the issue of frequent road accidents in pedestrian areas and the growing regulations on harmful emissions, coupled with the increasing traffic flow. Similarly to the present work, the authors investigated pedestrian behavior through online surveys and observations at test sites, suggesting that smart crosswalks could reduce time delays and enhance pedestrian safety. In contrast, it distinguishes by focusing on the impact of improved traffic signal systems and pedestrian behavior at controlled intersections, especially when equipped with time-counting traffic lights [29]. In this context, another work investigated the impact of different traffic light configurations on pedestrian behavior. This study provided important insights into signal design but focused on influencing pedestrian behavior rather than immediate detection and intervention [30].

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

While the present literature contributes significantly to the field of pedestrian safety, several research gaps can be identified. Firstly, there is a need for more comprehensive studies that address the real-world implementation and scalability of the proposed systems. Additionally, the long-term effectiveness and sustainability of these intelligent crosswalk solutions require further investigation. Moreover, research should also explore the social and psychological aspects of pedestrian behavior in relation to these technological interventions. Lastly, considerations of legal and regulatory frameworks surrounding the deployment of intelligent crosswalks are crucial for their widespread adoption and integration into urban environments.

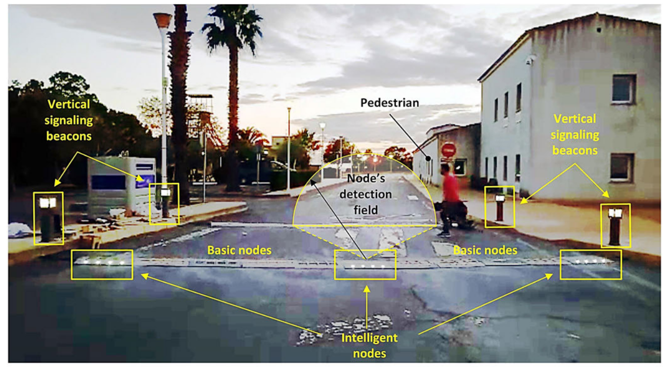


Fig. 1. Overview of the intelligent crosswalk at work.

B. Vision-Based Pedestrian Detection

Identifying people is an essential part of intelligent transport systems (ITS). In recent years, person re-identification has become one of the most important research hotspots where neural network-based computer vision has been used to determine whether there is a pedestrian in an image. However, person re-identification still faces significant difficulties due to the impact of occlusion, illumination and pose, among other factors [31]. Machine vision based on neural networks has been successfully used in pedestrian detection also for autonomous driving systems. Current research seeks to improve results with thermal imaging in low-light night driving scenarios, which have a significant impact on conventional RGB cameras [32]. The rise of deep convolutional neural networks (CNNs) has made notable progress in pedestrian detection, which still needs to deal with poor visual appearance and noisy representation caused by the intrinsic structure of small targets [33]. This is the case of a research that proposes the use of SODA-A and SODA-D benchmarks for the detection of small objects using faster recurrent CNNs [34]. Another study also introduced a deep sense network for small-scale pedestrian detection, generating effective regions for better identification. The authors designed a novel function to enhance detection and introduced a new evaluation metric for location precision. Their method showed strong performance on different pedestrian datasets, which was constructed from various road conditions [35].

Video data combined with reinforcement learning techniques have been used to simulate an adaptive traffic signal model with the aim of minimizing road user delays [36]. The intelligent vehicle pedestrian light model made it possible to manage the flows of users, demonstrating superior performance than conventional activated traffic lights. Video data has been used for pose estimation as well, enabling prediction of pedestrians' intention to cross at red lights through machine learning models. This method can be incorporated into infrastructure-to-vehicle alert systems to prevent collisions, although it still needs to address improvements in accuracy for long prediction horizons [37]. Recent studies suggest that pedestrian crossing intention lacks comprehensive consideration and mathematical modeling of social interaction. To this end, a recent work introduced the concept of social interaction force to predict crossing intention. It collected a large dataset of pedestrian-vehicle interactions and extracted high-dimensional features to improve prediction accuracy 1.0 second ahead [38]. Detecting abnormal events in large-scale video sequences from cameras in ITS is another current challenge. Recent research proposes video event description and retrieval methods that significantly improve efficiency and accuracy while reducing video event retrieval time [39].

The existing literature makes a significant contribution to the safety of road users in the field of ITS. Computer vision-based methods are explored to improve pedestrian detection and re-identification, as well as techniques to predict behavior and avoid collisions. Furthermore, the development of AI models for efficient traffic management and detection of anomalous events in large-scale video sequences is investigated. However, research in ITS has significant challenges. These include persistent difficulties in accurately re-identifying people due to problems such as occlusion, variations in lighting, and complicated poses. Furthermore, pedestrian detection remains vulnerable, especially on small targets and in adverse conditions (e.g., nighttime environments). Despite advances in traffic modeling and pedestrian intention prediction using AI-based computer vision, challenges remain in improving accuracy, especially in long-term predictions.

III. System Description

This paper introduces an intelligent crosswalk with TRL8 maturity level, that comprises a speed bump system based on a network of smart nodes that independently detect objects and operate in a coordinated manner [40]. The system consists of a variable set of speed bumps that can cover the entire road width, with the division into autonomous nodes offering several advantages, including redundancy and adaptability to various types of pedestrian crossings. Notably, it does not require substantial infrastructure or connection to the power grid, as it is self-sustained through solar panels and lithium polymer batteries up to 8 days with a consumption of 22.63 Wh per day (Fig. 1).

The system consists of two types of nodes: basic and intelligent, the latter equipped with sensors for target detection and light signaling elements for both drivers and pedestrians [41]. It is capable of object discrimination through the application of AI techniques, wireless network synchronization, and activation of a visual warning barrier when

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

pedestrians are detected, signaling to drivers with warning lights [42]. The AI software of the system differentiates the presence of pedestrians and vehicles at the crosswalk either moving, stopped, or parked [43]. This is achieved through a sensory fusion process, integrating information cooperatively from different sensors and redundantly with sensors from other nodes [44]. Specifically, the sensory fusion process is executed by a hierarchical classifier that uses One-Class support vector machine (SVM) for RADAR sensors and fuzzy logic for a magnetic field sensor [45].

A. Design and Materials

Current traffic regulations specify that a speed bump should have a cross-section resembling a circular segment with a maximum height of 70 mm and a depth ranging from 600 to 1200 mm for roads with a speed limit of 50 km/h [46]. With this aim, we proposed a curved surface with a maximum height of 40 mm and a minimum height of 5 mm on a 600 × 720 mm base. Both smart and basic nodes share the same shape when placed on the road, differing in their electronics; intelligent nodes incorporate circuitry and twelve solar panels, while basic nodes feature catadioptric stickers. These nodes are connected via a "dovetail" tongue and groove system (Fig. 2).

The nodes were built using ISO-ORTO polyester resin with calcium carbonate added, providing flexibility and mechanical strength. Smart nodes have cavities to house electronics and batteries, while a transparent epoxy resin layer safeguards the solar panels and reflectors. Because the nodes house all the electronics inside, the system requires high resistance to humidity and good electrical insulation. Furthermore, the nodes placed on the asphalt are subject to the passage of vehicles, so they must have great mechanical resistance, chemical resistance and temperature resistance. To do this, reinforcing fibers were integrated to provide improved performance in terms of strength and lightness to the epoxy resins [47].

Various tests, including tensile, compression, and Shore hardness, were performed on different resin mixtures to strike a balance between mechanical properties and production cost. The cavities intended for the placement of the electronics are areas of stress concentration. However, the zone of maximum stress due to the bending effect is located above the cavities, just where the solar panels are placed. These solar panels are covered by a layer of epoxy resin that behaves like a rectangular piece supported by a perimeter edge. The maximum stress has been obtained in the center of these pieces, specifically values of 15.34 MPa, and a maximum deformation of 0.08 mm. This stress value is lower than the 31 MPa that the epoxy resin material can withstand. Based on results, a 50-50% resin mixture was chosen for the system's body as the most suitable option, with some parts reinforced with carbon fiber and fiberglass for enhanced performance. For more information, see reference [47].

Design considerations and protective measures of the system included robust sealing to protect internal electronics from extreme weather conditions (e.g., heavy rain, snow, and extreme cold). To ensure the system reliability and performance in various environmental conditions, we conducted a series of tests in a third-party laboratory focusing on both stain resistance and ingress protection (IP). The tests served to evaluate the stain resistance using various coloring agents typically found on roads (e.g., oil, gasoline, or tire rubber). Testing ensured easy cleaning (typically with water) while maintaining system integrity. Moreover, the nodes were tested in a dust chamber for 8h under varying internal pressure, ensuring that no dust penetrated the electronic compartment. Additionally, the nodes were submerged to a depth of 1m for 24h and post-test inspections confirmed that no water entered the electronic compartment. The smart nodes achieved an IP68 rating, the highest level of protection against dust and water. These design considerations and tests ensure the system maintains accuracy and functionality in various weather conditions, guaranteeing reliable performance and long-term durability [47].

The total price of a prototype crosswalk for a two-way street (e.g., 6 intelligent nodes and 12 basic nodes) manufactured manually with epoxy resin and an aluminum mold could be around 6180 €, including material, electronics and mold with an estimated lifetime of 800 pieces. In the case that the parts were industrially manufactured with hot injected polypropylene pellets of similar characteristics, this cost would be 2478 € considering an aluminum mold with a lifetime of 1200 pieces and 2050 € for a steel mold with a lifetime of $1\cdot10^6$ pieces.

B. Sensory Fusion Process

The sensory fusion process is based on the correlation of sensors of the same type and their integration with sensors of different types, coinciding with the third level of abstraction of Dasarathy's model [48]. The sensory fusion process begins with the acquisition and normalization of data from each RADAR sensor. Then, the short time Fourier transform (STFT) is applied to this data, allowing spectral analysis to be performed in search of patterns related to vehicle motion and human walking. Subsequently, a number of features are extracted from the STFT analysis that serve as input to the one-class SVM algorithm. These features include skewness, kurtosis, as well as the mean and standard deviation of the points that make up the signal spectrum, among others. The one-class SVM has been selected as the preferred classifier over other options because it is based on unsupervised learning and only needs to be trained with the target class (e.g., pedestrians). The rest of the actors on the public road (e.g., vehicles, motorcycles, bicycles, etc.) are considered outliers or anomalies for this classifier, whose strategy is considered an advantage in our case study [49]. This strategy has been adapted to determine the presence of pedestrians or vehicles by training two different classifiers using different RADAR sensors. The first RADAR is oriented towards the inside of the crosswalk to detect the presence of pedestrians, while the other is oriented towards the outside of the pedestrian crossing to determine the approach of vehicles. Figure 3 shows a diagram of the hierarchical classifier.

The fuzzy vehicle presence detector monitors the presence of ferromagnetic elements that cause disturbances in the

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

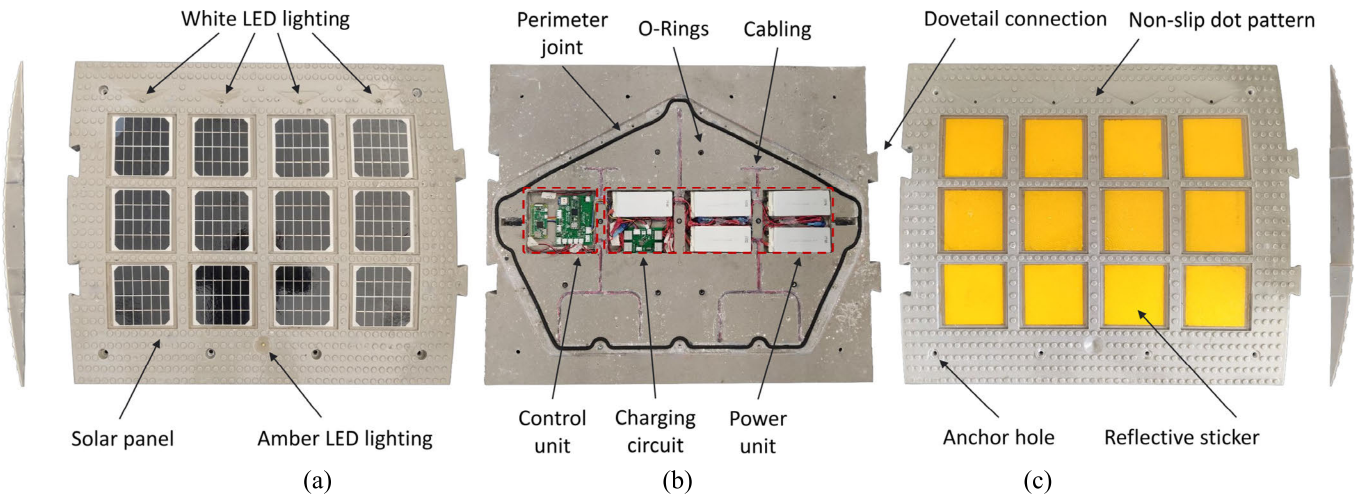


Fig. 2. Representation of the traffic signaling system: a) profile/top view of an intelligent node; b) interior layout of an intelligent node; and c) profile/top view of a basic node.

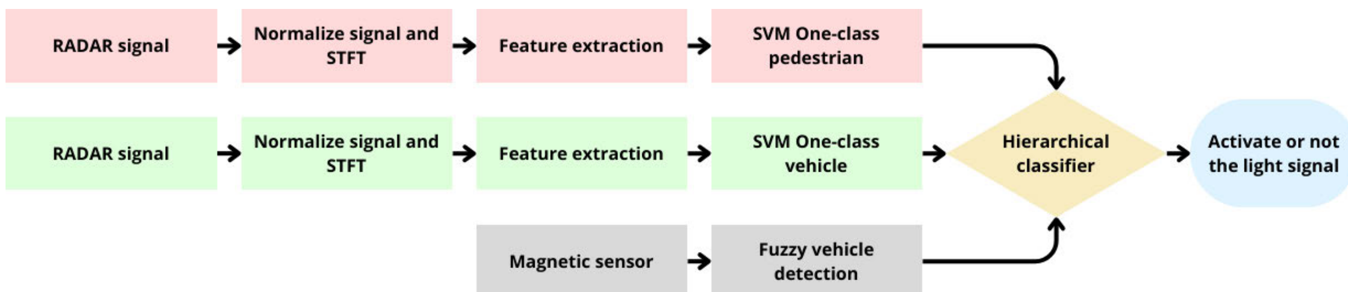


Fig. 3. Sensory fusion process carried out from the sensors to the output of the hierarchical classifier.

crosswalk. The main function of this detector is to determine whether a vehicle is moving or stopped at the crosswalk based on the magnetic field disturbances and the duration of these disturbances. The detector is based on the Mamdani fuzzy inference system [50], using the T-norm of the minimum as conjunction and implication operators [51]. In turn, the defuzzification process is based on the "first infer, then aggregate" (FITA) method and applies the maximum weighted value point (MVP) as an operator to obtain the result [52].

Once the detectors announce the presence of vehicles or pedestrians, a hierarchical classifier determines whether it is necessary to activate the lights signal of the crosswalk. This is done according to the following main rule: if a pedestrian is detected by a one-class SVM classifier and the magnetic sensor does not detect the presence of a vehicle, the light signal is activated independently of the output of the one-class SVM classifier for vehicles. Thus, the presence of pedestrians on the crosswalk is prioritized over the presence of vehicles. In the event that a one-class SVM classifier indicates the presence of a vehicle, the activation of the light signal is inhibited.

IV. Experimentation

Pedestrian safety has been intricately associated with the proposed system through three distinct approaches. Primarily, the system's capacity to indicate the presence of pedestrians at crosswalks was evaluated through an experiment conducted to assess the intelligent detection capabilities. Secondly, the system's influence on road users, particularly in terms of its impact on vehicle speed and pedestrian flow, was examined through a comprehensive analysis. Thirdly, the system's effects on user attitudes, perceptions pertaining to road safety, and their experiences with the proposed intelligent system were examined through the administration of a user survey to gather their perspectives and opinions. According to this, Subsection IV-A explains the experimental design, data collection and data description. Subsection IV-B introduces a ROC analysis. Subsection IV-C includes safety-relevant indicators on traffic conflicts and pedestrian/vehicle violations. Subsection IV-D provides the results of the questionnaire administered to road users.

A. Methodological Approach

The experimentation was carried out on a real scenario located on the University Campus of La Rábida, Huelva (37.2N, -6.92W). This environment was selected because it is frequently used by around 3,600 people —between students and staff— passing through different administrative spaces (e.g., classrooms, offices, parking lots) and a residential area. Specifically, the location of the crosswalk under the experiment has been chosen because it has a large influx of both pedestrians and vehicles, is in a poor state of maintenance and lacks road signs. The crosswalk is located at the confluence of two straight sections of road measuring 60 and 90 meters

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

Fig. 4. Detail of the scenario under study.

TABLE I
USER PROFILE IN THE DIFFERENT SCENARIOS UNDER STUDY

	Pedestrians	Cars	Others
Conventional crosswalk	59	118	4
Previous intelligent system	227	17	-
Proposed intelligent system	21	162	2

respectively with a speed limit of 30 km/h, being an ideal scenario to be monitored (Fig. 4).

The crosswalk was monitored 24/7 using a 1.3 MP TrendNet camera with infrared vision up to 20 meters of range. To detect incoming objects, a region of interest (ROI) was delineated to initiate the recording of a complete video sequence upon activation, spanning 3 seconds preceding and following the object's presence within the scene. The sequences recorded underwent post-processing filtration through an expert system to discard any spurious element such as animals, insects, rain, or wind moving vegetation. Subsequently, a photogrammetric analysis was performed to ascertain the flow and speed of the identified objects. The target flow was inspected through field observations, while the vehicle speed was achieved by measuring the time difference between reference points along the roadway at a consistent rate of 30 frames per second.

Three types of crosswalks were considered to carry out the experimentation: *i*) conventional crosswalk, *ii*) intelligent system based on fuzzy logic previously developed by the authors, and *iii*) current intelligent system based on machine learning. The subjects were randomly selected, whose user profile for each of the scenarios is detailed in Table I. Pedestrians included people, groups of people and strollers. Cars included only passenger vehicles, whilst others included bicycles, motorcycles, medium-weight vehicles such as delivery vehicles and large-weight vehicles such as garbage trucks. It should be noted that although the classes seem unbalanced in the two intelligent systems; the reason is that the detection of people was prioritized in the previous system, while the detection of vehicles was chosen in the current system due to the new functionalities incorporated.

B. Efficacy of the Intelligent Detection Feature

The validation of the previous prototype encompassed an extensive evaluation period, involving 240 hours of hardware and software integration, followed by 160 hours of rigorous testing conducted within controlled laboratory settings [45]. Additionally, the experimentation phase extended to 65 hours of practical trials in real-world environment. Following the experimentation phase, a Receiver Operating Characteristic (ROC) analysis was conducted to ascertain the prototype's sensitivity in relation to its specificity. To this end, a positive discrimination threshold was defined when pedestrian detection transpired within the initial 2/3 portion of the crosswalk. Conversely, pedestrian detection in the final third of the crossing was deemed negative, as it failed to meet the requisite safety criteria for secure operational performance. For the ROC analysis, true positive rate (TPR) or sensitivity metrics were used, which are described as follows:

$$TPR = \frac{TP}{TP + FN} \tag{1}$$

where TP represents the number of true positives (i.e., the target class detected correctly) and FN represents the number of false negatives (i.e., the target class categorized as non-target). Similarly, the false positive rate (FPR) was also used, standig for the ratio of false alarms generated by the system according to the following equation:

$$FPR = \frac{FP}{FP + TN} \tag{2}$$

where FP is the number of false positives (i.e., another non-target class detected as a target class) and TN is the number of true negatives (i.e., objects correctly detected as a non-target class). Finally, the accuracy (ACC) is defined as follows:

$$ACC = \frac{TP + TN}{P + N} \tag{3}$$

where P and N represent the total positive and negative elements observed, respectively.

The findings showed a mean accuracy of 94.64%, indicating a high test accuracy = [0.9, 0.97) based on ROC analysis, with a precision of 100% as no false positives were recorded (Table II). After analyzing various case studies, we discovered that vehicles were detected most effectively, with bicycles, strollers, and groups of people following closely behind. In contrast, we observed poorer outcomes in both detecting a single individual and multiple individuals crossing in the opposite direction. This implies that the prototype is more effective when detecting larger volumes of objects, such as bicycles or strollers, compared to just a single person. This may result from the sensors being positioned low on the asphalt, which decreases their accuracy in detecting smaller body parts compared to larger ones like the torso. However, the research suggests that sensors, especially those based on ultrasound, do not face problems when bicycles and motorcycles pass by.

The system currently being proposed was tested in actual traffic conditions for 15 days to make comparisons. The success rate of the experiment varied depending on the shape and speed of the target. Due to this, the data has been split into individuals and cars with speeds ranging from 0-10 km/h, 10-20 km/h, 20-30 km/h, 30-40 km/h, and over 40 km/h (Table III). Specifically, an excellent success rate was obtained when the target is a person (99.11%). When it comes to

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

TABLE II
ROC ANALYSIS OF THE PREVIOUS PROTOTYPE SYSTEM BASED ON FUZZY LOGIC

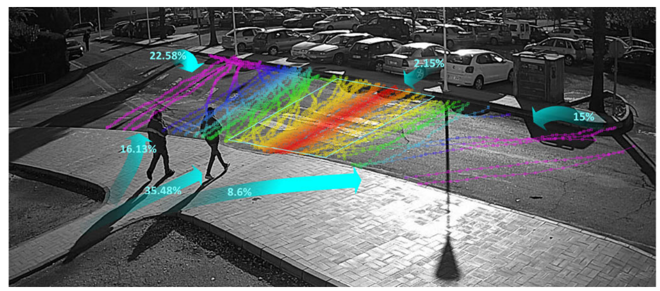
Target	Tests	Speed (km/h)	TPR	FPR	ACC (%)
Person	148	3.168 ± 0.14	0.8133	0	81.33
Stroller	33	3.02 ± 0.18	0.972	0	97.20
People in the same direction	17	3.38 ± 0.18	0.95	0	95.00
People in opposite direction	16	3.78 ± 0.14	0.9433	0	94.33
Bicycle as pedestrian	13	6.77 ± 0.50	1	0	100
Car, bicycle or motorcycle	17	≥ 7.99 < 19.98	1	0	100
Weighted average	244	4.25 ± 1.55	0.9464	0	94.64

Test: number of occurrences observed; TPR: true positive rate; FPR: false positive rate; ACC: accuracy

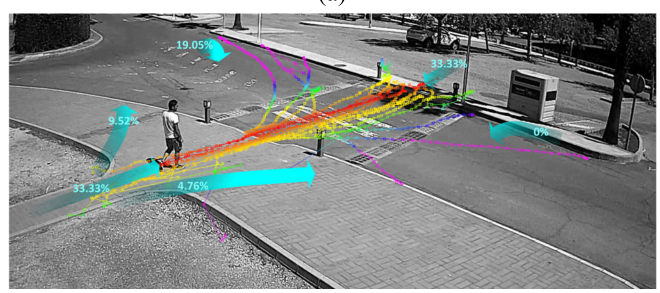
TABLE III
ROC ANALYSIS OF THE CURRENT SYSTEM BASED ON ML ALGORITHM

Target	Tests	Speed (km/h)	TPR	FPR	ACC (%)
Person	19	3.43 ± 0.85	1	0	99.11
Car [0-10) km/h	20	7.58 ± 1.36	1	1	47.37
Car [10-20) km/h	66	15.46 ± 2.80	1	0.55	56.63
Car [20-30) km/h	49	24.34 ± 2.49	1	0.11	91.94
Car [30-40) km/h	21	33.45 ± 2.09	1	0	100
Car over 40 km/h	4	42.55 ± 1.58	1	0	100
Weighted average	175	20.31 ± 8.58	1	0.4	64.57

Tests: number of occurrences observed; TPR: true positive rate; FPR: false positive rate; ACC: accuracy



(a)



(b)

Fig. 5. Analysis on pedestrian trajectories: a) conventional crosswalk; b) intelligent crosswalk.

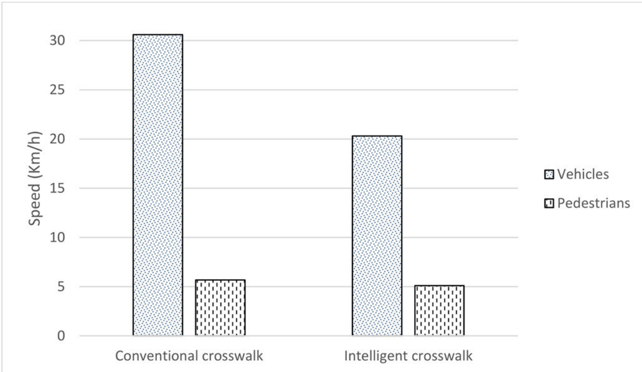
vehicles, we observed that the success rate increases as the speed increases. The findings indicate that the AI algorithm used effectively distinguishes between targets based on their varying speeds. This results in a notable enhancement of the TPR overall when comparing the current ML algorithm to the previous development using Fuzzy logic. On the other hand, it fails to distinguish between targets effectively when the speed is consistent (such as cars traveling at speeds similar to humans). Additionally, the outcomes achieved in actual settings significantly vary from those achieved in controlled training, testing, and validation environments (64.57% vs. 91.20%, respectively). This discrepancy indicates that the one-class SVM model could be operating in a different setting from the one it was initially trained on. This could be due to drivers slowing down vehicles when they perceive the system. Even though the overall outcome of the system is average, this creates an opportunity for further research to enhance the ML algorithm in low-speed situations by increasing data to create a stronger model or exploring alternative techniques like Random Forest or Tree Bagger, which showed promising results in lab validation and test [53].

C. Impact on Road User Behavior

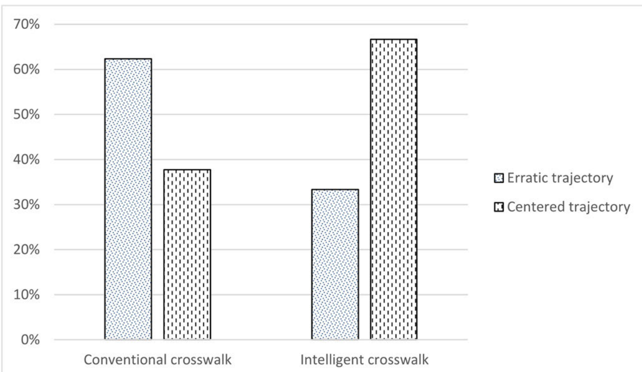
A comparison on the behavior of pedestrians and vehicles was carried out between a conventional crosswalk and the proposed intelligent crosswalk. To this end, Figure 5a shows a photogrammetric analysis of 294 video sequences taken at a conventional crosswalk after processing 1.12 GB of data with pedestrians, cars, trucks, motorcycles and others. Regarding pedestrians, we found an average speed of 5.69 ± 0.94 km/h with a large dispersion in their trajectories when crossing the crosswalk (62.31% erratic). Regarding drivers, we observed an average vehicle speed of 30.94 ± 4.41 km/h and 38.04 ± 4.98 km/h during daytime and nighttime hours, respectively ($\Delta = 22.95\%$). The significant dispersion observed in pedestrian trajectories and driver speeds reflect a low level of awareness of road safety among users. Regarding other safety-relevant indicators, the analysis encountered several traffic conflicts such as a car parked in the yellow zone just before the pedestrian crossing, a car driving the wrong way, four cars parked on the crosswalk, a motorcycle traveling at 68.10 km/h and two people crossing while handling their smartphone. In addition, we found a pedestrian/vehicle violation consisting of a car passing the crosswalk without stopping in front of two pedestrians.

Figure 5b shows a photogrammetric analysis of 393 video sequences taken over the intelligent crosswalk for comparative purposes. The processing of 1.69 GB of data encountered a lower average speed of 5.11 ± 1.25 km/h for pedestrians, whose trajectories were narrower and less erratic than for pedestrians using the conventional crosswalk (66.6% centered vs. 33.33% erratic). The speed reduction by 10.24% and the improvement of the trajectory within the limits of the

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.



(a)



(b)

Fig. 6. Quantitative indicators on improvements in road safety: a) average speed of vehicles and pedestrians under study; b) dispersion of pedestrian trajectories.

crosswalk by 46.5% suggests that people could feel safe and comfortable when crossing the intelligent crosswalk (i.e., less rushed), positively influencing on how pedestrians cross the road. Moreover, an analysis of 162 vehicles circulating on the intelligent crosswalk got an average speed of 20.78 ± 8.36 km/h during the day and 11.16 ± 8.02 km/h at night ($\Delta =$ -46,29%). When comparing the average speed of vehicles with the conventional crosswalk, we found a decrease of 32.83% in speed during the day and 70.6% at night. This suggests that the presence of the intelligent traffic signaling system decreased the car speed significantly, being greater in situations of higher lighting contrast (i.e., at night). Regarding other safety-relevant indicators, the analysis encountered only one car parked on the crosswalk. This suggests that the number of traffic conflicts and pedestrian/vehicle violations were significantly reduced because of the proposed intelligent crosswalk. A summary of the quantitative indicators on average speed and dispersion of the pedestrian trajectories can be consulted in Figure 6.

D. Opinion of Road Users

With the aim of assessing user attitudes, perceptions, and experiences with the proposed intelligent crosswalk regarding road safety, a comprehensive survey was conducted, providing invaluable insights into the system's impact on user opinions. With this goal, a group of 18 voluntaries were consulted on several lines of action. The diverse group of participants represented a balanced cross-section of society, consisting of 50% men and 50% women with a mean age of 43.5 years and a standard deviation of 18.29 years. This set encompassed various life stages and roles with 16.67% being students, 11.11% homemakers, 38.89% employees, 16.67% currently unemployed, and another 16.67% enjoying their retirement years. In their daily transportation choices, a significant 72.22% preferred walking, while the remaining 27.78% opted for the convenience of cars or motorcycles.

A list of 33 questions was administered considering aspects of road safety education, road maintenance, risk perception, road attitude, motivation/interest, usability/practicality and viability of the solution. The survey was assessed using a Likert scale (1 = strongly disagreed, 5 = strongly agreed) and the dataset was analyzed employing the Cronbach's alpha coefficient. This yielded a value of 0.9808, indicating that the questionnaire exhibits acceptable internal consistency (i.e., $\alpha > 0.7$). The average values and standard deviations obtained for each question are explained below.

In relation to road education, users stated to have a high level of knowledge on traffic regulations referring to pedestrians (Q1 = 4.44 ± 0.98) although they considered that both pedestrians and drivers moderately respect the regulations in general (Q2 = 2.33 ± 0.84, Q3 = 2.88 ± 0.58). However, users had a good impression of themselves, rating positively their respect for regulations both as a pedestrian and as a driver (Q4 = 3.66 ± 1.08; Q5 = 4.05 ± 0.53).

In relation to road maintenance, the subjects considered that both horizontal and vertical signage was deficient in general (Q6 = 1.88 ± 0.90; Q7 = 1.83 ± 0.70), discreetly assessing visibility due to obstacles (Q8 = 2.66 ± 1.74) and slight compared to the road lighting (Q9 = 1.55 ± 0.92).

Regarding the risk perception, pedestrians stated to frequently use the conventional crosswalk under study (Q10 = 4.22 ± 0.80), being considered highly dangerous (Q11 = 4.72 ± 0.57). For this reason, users consider necessary to regulate conventional crosswalks by means of traffic lights (Q12 = 4.72 ± 0.75). These responses are contrasted affirmatively when pedestrians stated to perceive poor safety on the conventional crosswalk (Q13 = 1.55 ± 0.78).

Regarding the road attitude, pedestrians affirmed that they mostly cross the crosswalk properly towards their destination, although not always (Q14 = 3.55 ± 1.09). In this sense, pedestrians stated to take the crosswalk in a straight line in general, but not always (Q15 = 3.27 ± 1.48). Pedestrians mostly stated to look around before crossing (Q16 = 4.77 ± 0.64). This answer is contrasted affirmatively with the following question in which the subjects do not cross immediately because they think they have no preference (Q17 = 1.77 ± 0.94). Moreover, the pedestrians affirmed to use personal devices sometimes (e.g., smartphone or music player) at the conventional crosswalk (Q18 = 1.94 ± 1.39). Regarding the driver attitude at the conventional crosswalk, the subjects stated that they do not always stop and wait when they see a person (Q19 = 2.5 ± 0,78).

In relation to motivation and interest, those surveyed consider that the use of an intelligent traffic regulation system significantly promotes both aspects (Q20 = 4.77 ± 0.54). Likewise, they considered to the same degree that the proposed

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

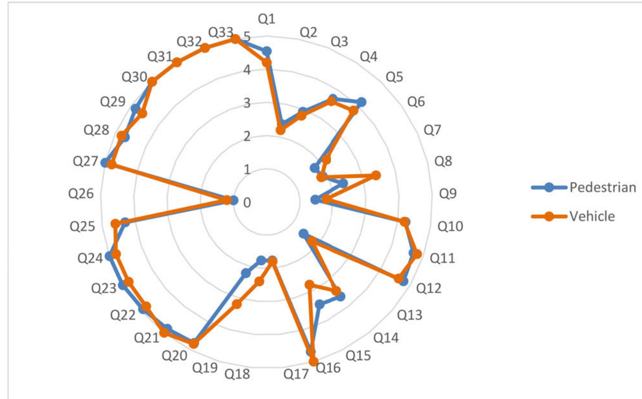
system promotes respectful use and road awareness (Q21 = 4.88 ± 0.47).

Considering aspects of usability and practicality, the volunteers considered that both installation and location of the intelligent system were adequate (Q22 = 4.88 ± 0.23). In this sense, they significantly highlighted the simplicity and understanding of its operation, as well as its level of interactivity between user/road (Q23 = 4.94 ± 0.23; Q24 = 4.94 ± 0.23). Regarding the appearance, the subjects remarkably highlighted this aspect (Q25 = 4.38 ± 0.69). Moreover, users perceived few technical problems during its operation (Q26 = 1.05 ± 0.23).

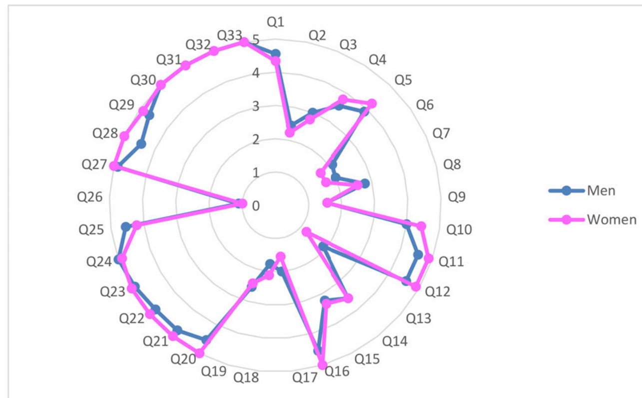
Finally, regarding the results and feasibility of the intelligent crosswalk, most participants believed that the approach speed of vehicles was reduced with the use of the intelligent system (Q27 = 4.94 ± 0.24). In this sense, people tend to believe that the stopping distance of vehicles was greater when the intelligent system was used compared to when it was not available (Q28 = 4.72 ± 0.96). Likewise, the wait time for vehicles was perceived to be longer with the intelligent system compared to when not present (Q29 = 4.7778 ± 0.55). Furthermore, users highlighted a greater safety perception (Q30 = 5.00 ± 0.00), a useful regulation of conventional crosswalks (Q31 = 5.00 ± 0.00) and therefore suitability for implementation in a real context (Q32 = 5.00 ± 0.00). In summary, the last question contained a positive general assessment of the proposed system (Q33 = 5.00 ± 0.00).

The two-sample Welch's t-test was employed to assess significant distinctions among user profiles within the opinion survey. This statistical test is recommended when the analyzed groups exhibit considerable differences in standard deviations, when sample sizes are unequal, or when the sample size is less than or equal to 10 values [54]. The analysis revealed no noteworthy disparities in how drivers and pedestrians perceived aspects such as road education, maintenance, risk perception, attitude, motivation/interest, usability/practicality, and viability of the solution (i.e., p = 0.93 for all questions). Furthermore, the examination yielded no substantial disparities between men and women (i.e., p = 0.99 for all questions), signifying an absence of statistical evidence to support gender-related distinctions in the aspects under investigation. In summary, the Welch's t-test analysis determined that all the groups shared similar perceptions regarding road safety. For further details, Figure 7 shows the users' opinion about the proposed system.

Based on the responses provided by the subjects who tested the intelligent crosswalk, it is inferred that they perceive that the system effectively enhances pedestrian safety, mitigating the risk of accidents at crosswalks. The system's capacity to improve visibility, particularly in low-light conditions, and its ability to alert drivers to the presence of pedestrians are key factors contributing to its positive reception. Furthermore, the subjects' comments underscore the inadequacy of conventional painted crosswalks in ensuring pedestrian safety, as they are often disregarded by drivers. In summary, the consensus among participants supports the implementation and adoption of the intelligent crosswalk as a valuable solution for enhancing road safety and preventing pedestrian accidents.



(a)



(b)

Fig. 7. Users' opinion about the system evaluated.

V. Discussion

The research's three core studies, encompassing the ROC analysis to assess the system's detection capabilities (Subsection IV-B), the evaluation of its impact on road user behavior (Subsection IV-C), and the examination of user attitudes and perceptions (Subsection IV-D), collectively bolster the benefits of the proposed system regarding the reduction of accidents and injuries in three critical domains: a) road conditions, b) driver-related factors, and c) pedestrian behavior. Firstly, the analysis of the system's intelligent detection capabilities corroborates its effectiveness in enhancing road conditions, as it directly addresses the challenge of improving visibility and potentially reducing accidents at the crosswalk. Secondly, the evaluation of the system's impact on road users underscores its potential to mitigate driver-related accidents by influencing vehicle speed and pedestrian flow in a manner that aligns with road safety objectives. Thirdly, the examination of user attitudes and perceptions, as derived from the survey, reinforces the discussion's premise that active signaling through an intelligent crosswalk can positively shape pedestrian behavior, as it enhances user experiences and fosters favorable attitudes towards road safety.

In consequence, the advantages of using active signaling through the proposed system would potentially reduce the casualty rate in three lines of action: a) state of the road as the cause, b) driver as the cause, and c) pedestrian as the

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

cause. In the area of road conditions, official statistics on accidents involving vehicles and pedestrians demonstrate that nighttime signposting of crosswalks yields a 26.26% reduction in injuries and a 35.4% reduction in fatalities [55]. Additionally, it potentially mitigates a 9.68% injury and a 14.28% in deaths by ameliorating poor visibility caused by inclement weather. Furthermore, it results in a 41.18% decrease in injuries and a 0.81% decrease in fatalities by enhancing the perception of obstacles, such as urban buses. In terms of driver-related factors, the Nilsson model [56] establishes a 2% reduction in injury-related accidents and a 4% reduction in fatal collisions for every 1% decrement in the average speed of vehicles. The application of this model to our findings suggests that the speed reduction achieved with the proposed intelligent crosswalk can avert 6.07% of daily injuries and 12.15% of daily deaths, along with a substantial 42.46% reduction in injuries and a remarkable 84.52% reduction in fatalities during nighttime, relative to conventional crosswalks. This underscores the significant advantage of active signaling, which is further pronounced in high-contrast scenarios, such as nighttime, sunrise, and sunset. Consequently, with respect to pedestrian-related factors, the results of the survey indicate that road re-education actions would prevent 2.44% of injuries and 9.38% of deaths by discouraging incorrect crosswalk usage. Additionally, this enhanced security would mitigate 52.56% of injuries and 79.91% of deaths among individuals over 55 years of age while addressing the protection of vulnerable populations, including 7.39% of people with limited vision/low vision and 5.67% of people with hearing impairments/hard of hearing in the population.

VI. Conclusion

Certain locations on the road demand special attention from drivers, necessitating reduced speeds for safety. In addition to conventional road signs, various approaches like speed bumps can contribute to achieving these objectives. Nevertheless, most solutions found in the literature tend to face challenges such as commercial availability, high infrastructure costs, a lack of intelligence, or limited inclusivity for all road users. This work details the materials and methodologies employed in the creation of a cost-effective speed bump, which has reached a maturity level of TRL8. This innovative speed bump is adaptable to various road types, including one-way and two-way roads, with the primary aim of enhancing road safety. Its applications extend to locations such as garage entrances/exits and low-visibility intersections.

The intelligent speed bump is composed of discrete nodes, each equipped with an embedded electronic system featuring an array of sensors and wireless communication devices. This intelligent system employs AI techniques to accurately discern vehicles and individuals on a crosswalk. In cases where pedestrians are detected, the system alerts oncoming drivers through light signals. A key innovation of this system lies in the use of a composite material comprising resins, aggregates, and reinforcing fibers, applied through a cold infusion process within an aluminum mold. Remarkably, it can operate autonomously for up to 8 days with a theoretical daily energy consumption of 22.63 Wh. Furthermore, the system does not rely on a connection to the power grid, offering significant energy savings.

Preliminary operational tests involving 155 vehicles per day, with an average speed of 20.31 ± 8.58 km/h, and exposure to sunlight for 15 days, confirmed the system's robust protection of its internal electronics. In terms of road safety, experimentation revealed a substantial improvement in pedestrian detection accuracy compared to a previous prototype (99.11% vs. 81.33%). However, vehicle detection accuracy in low-speed scenarios (47.37%, 56.63%, 91.94%) suggests the need for further research to develop more robust algorithms and expand the dataset to bridge the gap between laboratory and real-world results.

A comparative analysis of pedestrian and vehicle behavior at a conventional crosswalk and the proposed intelligent crosswalk revealed substantial differences. The assessment, based on video sequences, encountered a speed reduction of pedestrians by 10.24% and an improvement of their trajectories within the limits of the crosswalk by 46.5%. In addition, the study found a decrease of 32.83% in vehicle speed during the day and 70.6% at night. The presence of the intelligent signaling system promotes safer and more comfortable behavior of pedestrians while reducing the speed of vehicles, resulting in a notable reduction in road conflicts and violations.

User attitude tests demonstrated that the intelligent crosswalk significantly reduced pedestrian erratic trajectories outside the crosswalk (33.33% with the intelligent crosswalk vs. 62.31% with a conventional crossing) and led to reduced driving speeds (a decrease of 32.83% during the day and 70.6% at night). According to models, implementing illuminated crosswalks at night could prevent 26.26% of injuries and 35.4% of fatalities. In this context, the system is estimated to prevent 6.07% of injuries and 12.15% of fatalities during the day due to reduced vehicle speeds, and a significant 42.46% reduction in injuries and an impressive 84.52% reduction in fatalities at night. Additionally, pedestrian re-education efforts would prevent 2.44% of injuries and 9.38% of fatalities, a proportion that significantly increases, especially in the case of individuals over 55 years of age, with potential reductions of 52.56% in injuries and 79.91% in fatalities. These findings underline the system's substantial potential in advancing road safety and addressing the limitations of existing road signaling systems.

Although the system was not tested in extreme cold weather conditions, it was tested for 15 days in summer in southern Spain with maximum ambient temperatures of 35-40°C (i.e., typically 50-65°C for asphalt). The system functionality during testing was not compromised and maintained the level of performance described in the results. Nevertheless, the system will be subject to extreme cold conditions in future research (e.g., during winter). It is expected that, just as the system worked well at high temperatures, it will also do so at low temperatures, thus confirming the results obtained in the laboratory tests. Future work should be also directed towards improving the accuracy of vehicle detection in low-speed scenarios, potentially through the development of more robust algorithms and the expansion of the dataset to bridge the gap between laboratory and real-world results. In addition, broader

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

and more extensive experimentation will be carried out to include more actors on public roads (e.g. buses, trucks, vans, bicycles). Moreover, research efforts should explore ways to make the intelligent crosswalk even more effective and adaptable for various road and environmental conditions. Future research endeavors should also delve into the user attitudes and perceptions surrounding road safety. Assessing the long-term effects of the intelligent crosswalk on user behavior, such as pedestrian compliance and driver response, can inform strategies for enhancing road safety education and awareness. These aspects will be vital for shaping the development of intelligent crosswalks that not only perform effectively but are also well-received and supported by the individuals who use them, ultimately contributing to safer road environments.

Acknowledgment

The authors would like to thank J. M. Corralejo Mora and I. J. Fernández de Viana González for their valuable and constructive work that helped to improve this research.

References

[1] *Balance De Las Cifras De Siniestralidad Vial*, Ministerio del Interior de España, Dirección Gen. de Tráfico (DGT), Paseo de la Castellana, Madrid, Spain, 2022.

[2] *Fatality Analysis Reporting System (FARS)*, Nat. Highway Traffic Saf. Admin. (NHTSA), Washington, DC, USA, 2022.

[3] M. Infante Francés and T. D. J. M. Sanguino, "Method for characterizing traffic calming measures to evaluate their impact on pollution," *Dyna*, vol. 97, no. 4, pp. 392–397, Jul. 2022.

[4] A. Sheykhfard, F. Haghighi, E. Papadimitriou, and P. Van Gelder, "Exploring the influence of signal countdown timers (SCTs) on driver behaviour: An analysis on pedestrian-vehicle conflicts at signalized intersections," *SSRN Electron. J.*, vol. 2678, no. 4, pp. 865–880, Aug. 2023.

[5] D. Antov, T. Rõivas, and H. Roeuk, "Investigating the driver's behaviour at zebra crossings and their vicinity," in *Proc. 18th Int. Cooperation Theories Concepts Traffic Saf. (ICTCT)*, Helsinki, Finland, Oct. 2005.

[6] I. Buttler, W. Czajewski, and P. Olszewski, "Safety assessment of pedestrian crossings with video analysis," *Transp. Res. Procedia*, vol. 14, pp. 2044–2053, 2014.

[7] A. William, O. T. Kolawole, O.-A. Comfort, and A. Francis, "Driver compliance and pedestrian safety at zebra crossings in the cape coast metropolis, Ghana," *Urban, Planning Transp. Res.*, vol. 9, no. 1, pp. 464–478, Jan. 2021.

[8] T. Ojo, C. O. Adetona, W. Agyemang, and F. K. Afukaar, "Pedestrian risky behavior and safety at zebra crossings in a Ghanaian metropolitan area," *Traffic Injury Prevention*, vol. 20, no. 2, pp. 216–219, Feb. 2019.

[9] L. T. Truong, N. H. Thai, T. V. Le, and A. K. Debnath, "Pedestrian distraction: Mobile phone use and its associations with other risky crossing behaviours and conflict situations," *Saf. Sci.*, vol. 153, Sep. 2022, Art. no. 105816.

[10] A. Sheykhfard, F. Haghighi, S. Bakhtiari, and L. Pariota, "Safety margin evaluation of pedestrian crossing through critical thresholds of surrogate measures of safety: Area with zebra crossing versus area without zebra crossing," *Transp. Res. Rec., J. Transp. Res. Board*, vol. 2677, no. 1, pp. 396–408, Jan. 2023.

[11] A. Sheykhfard, F. Haghighi, S. Das, and G. Fountas, "Evasive actions to prevent pedestrian collisions in varying space/time contexts in diverse urban and non-urban areas," *Accident Anal. Prevention*, vol. 192, Nov. 2023, Art. no. 107270.

[12] L. Govinda, M. R. S. K. Raju, and K. V. R. R. Shankar, "Pedestrian-vehicle interaction severity level assessment at uncontrolled intersections using machine learning algorithms," *Saf. Sci.*, vol. 153, Sep. 2022, Art. no. 105806.

[13] A. Sheykhfard, F. Haghighi, S. Kavianpour, S. Das, P. S. Farahani, and G. Fountas, "Risk assessment of pedestrian red-light violation behavior using surrogate safety measures: Influence of human, road, vehicle, and environmental factors," *IATSS Res.*, vol. 47, no. 4, pp. 514–525, Dec. 2023.

[14] D. Osorio-García, G. Hernández-Pulgarín, and D. A. Escobar, "Profiles of pedestrian risk behavior while crossing the street," *Saf. Sci.*, vol. 163, Jul. 2023, Art. no. 106120.

[15] A. Meir, H. Tapiro, and T. Oron-Gilad, "Towards safer, more walkable urban environments for child-pedestrians—Application of the theory of planned behavior," *Saf. Sci.*, vol. 164, Aug. 2023, Art. no. 106148.

[16] I. Makarova, K. Shubenkova, V. Mavrin, and P. Buyvol, "Improving safety on the crosswalks with the use of fuzzy logic," *Transp. Problems*, vol. 13, no. 1, pp. 97–109, 2018.

[17] P. S. Townsend and C. F. Oakley, "Innovative provision for pedestrians in future intelligent cities," in *Proc. IET Conf. Future Intell. Cities*, Dec. 2014, pp. 1–6.

[18] K. Kowalski et al., "Intelligent warning systems as devices improving safety at pedestrian crossings," in *Zeszyty Naukowe Pro Publico Bono*, vol. 1, no. 1, pp. 245–257, 2022.

[19] P. A. Davis, "New 'intelligent' crosswalks aimed at pedestrian safety," Washington Post, Tech. Rep., 2002.

[20] D. Qu, H. Li, H. Liu, S. Wang, and K. Zhang, "Crosswalk safety warning system for pedestrians to cross the street intelligently," *Sustainability*, vol. 14, no. 16, p. 10223, Aug. 2022.

[21] B. Noh, D. Ka, D. Lee, and H. Yeo, "Vision based pedestrian potential risk analysis based on automated behavior feature extraction for smart and safe city," 2021, *arXiv:2105.02582*.

[22] P. Porouhan and W. Premchaiswadi, "Proposal of a smart pedestrian monitoring system based on characteristics of Internet of Things (IoT)," in *Proc. 18th Int. Conf. ICT Knowl. Eng. (ICT&KE)*, Nov. 2020, pp. 1–4.

[23] K. An, S. W. Lee, Y. J. Jeong, and D. Seo, "Pedestrian-safe smart crossing system based on IoT with object tracking," in *Advances in Computer Science and Ubiquitous Computing* (Lecture Notes in Electrical Engineering), vol. 474, J. Park, V. Loia, G. Yi, and Y. Sung, Eds. Singapore: Springer, 2018.

[24] M. Pogatsnik, D. Fischer, L. Nagy, and S. Dora, "Autonomous pedestrian crossing in smart city environment," in *Proc. IEEE 24th Int. Conf. Intell. Eng. Syst. (INES)*, Jul. 2020, pp. 37–42.

[25] I. E. Agureev, K. P. Andreev, E. V. Ionov, A. Y. Svistunova, and V. V. Terentyev, "The use of intelligent systems when regulating road traffic," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 832, Nov. 2020, Art. no. 012090.

[26] T. Gandhi and M. M. Trivedi, "Computer vision and machine learning for enhancing pedestrian safety," in *Computational Intelligence in Automotive Applications* (Studies in Computational Intelligence), vol. 132, D. Prokhorov, Ed. Berlin, Germany: Springer, 2008.

[27] S. Sichelschmidt, A. Haselhoff, A. Kummert, M. Roehder, B. Elias, and K. Berns, "Pedestrian crossing detecting as a part of an urban pedestrian safety system," in *Proc. IEEE Intell. Vehicles Symp.*, Jun. 2010, pp. 840–844.

[28] D. Schörkhuber, M. Pröll, and M. Gelautz, "Feature selection and multi-task learning for pedestrian crossing prediction," in *Proc. 16th Int. Conf. Signal-Image Technol. Internet-Based Syst. (SITIS)*, Oct. 2022, pp. 439–444.

[29] M. Štrumbelj, "Smart pedestrian crossings," U.G. thesis, Faculty Civil Geodetic Eng., Univ. Ljubljana, Ljubljana, Slovenia, 2016.

[30] L. L. Di Stasi, A. Megías, A. Cándido, A. Maldonado, and A. Catena, "The influence of traffic signal solutions on self-reported road-crossing behavior," *Spanish J. Psychol.*, vol. 17, Jan. 2014, Art. no. E103.

[31] M. Wang, H. Ma, and Y. Huang, "Information complementary attention-based multidimension feature learning for person re-identification," *Eng. Appl. Artif. Intell.*, vol. 123, Aug. 2023, Art. no. 106348.

[32] K. Dasgupta, A. Das, S. Das, U. Bhattacharya, and S. Yogamani, "Spatio-contextual deep network-based multimodal pedestrian detection for autonomous driving," *IEEE Trans. Intell. Transp. Syst.*, vol. 23, no. 9, pp. 15940–15950, Sep. 2022.

[33] G. Cheng et al., "Towards large-scale small object detection: Survey and benchmarks," *IEEE Trans. Pattern Anal. Mach. Intell.*, vol. 45, no. 11, pp. 13467–13488, Nov. 2023.

[34] X. Yuan, G. Cheng, K. Yan, Q. Zeng, and J. Han, "Small object detection via coarse-to-fine proposal generation and imitation learning," in *Proc. IEEE/CVF Int. Conf. Comput. Vis. (ICCV)*, Oct. 2023, pp. 6294–6304.

[35] B. Han, Y. Wang, Z. Yang, and X. Gao, "Small-scale pedestrian detection based on deep neural network," *IEEE Trans. Intell. Transp. Syst.*, vol. 21, no. 7, pp. 3046–3055, Jul. 2020.

[36] M. Yazdani, M. Sarvi, S. A. Bagloee, N. Nassir, J. Price, and H. Parineh, "Intelligent vehicle pedestrian light (IVPL): A deep reinforcement learning approach for traffic signal control," *Transp. Res. C, Emerg. Technol.*, vol. 149, Apr. 2023, Art. no. 103991.

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

[37] S. Zhang, M. Abdel-Aty, Y. Wu, and O. Zheng, "Pedestrian crossing intention prediction at red-light using pose estimation," *IEEE Trans. Intell. Transp. Syst.*, vol. 23, no. 3, pp. 2331–2339, Mar. 2022.

[38] Z. Zhou, Y. Liu, B. Liu, M. Ouyang, and R. Tang, "Pedestrian crossing intention prediction model considering social interaction between multi-pedestrians and multi-vehicles," *Transp. Res. Rec., J. Transp. Res. Board*, vol. 2678, no. 5, pp. 80–101, May 2024.

[39] S. Wan, X. Xu, T. Wang, and Z. Gu, "An intelligent video analysis method for abnormal event detection in intelligent transportation systems," *IEEE Trans. Intell. Transp. Syst.*, vol. 22, no. 7, pp. 4487–4495, Jul. 2021.

[40] T. J. M. Sanguino, M. A. R. Roman, and J. M. L. Dominguez, "System and autonomous device for road signage and detection," WO Patent 2018 050 945, Mar. 22, 2018.

[41] J. M. L. Domínguez, F. Al-Tam, T. D. J. M. Sanguino, and N. Correia, "Vehicle detection system for smart crosswalks using sensors and machine learning," in *Proc. 18th Int. Multi-Conf. Syst., Signals Devices (SSD)*, Mar. 2021, pp. 984–991.

[42] J. M. L. Domínguez, T. J. M. Sanguino, M. J. R. González, and I. J. F. de Viana González, "Over-the-air programming system for IoT devices with a non-native wireless update service," *J. Phys., Conf. Ser.*, vol. 2224, no. 2022, pp. 1–8, Art. no. 012078.

[43] J. M. L. Domínguez, T. J. M. Sanguino, M. J. R. González, and I. J. F. de Viana González, "Performance analysis of an embedded system for target detection in smart crosswalks using machine learning," in *Proc. 17th Int. Conf. Softw. Technol. (ICSOFT)*, 2022, pp. 382–389.

[44] J. M. L. Domínguez, T. D. J. M. Sanguino, D. M. Véliz, and I. J. F. de Viana González, "Multi-objective decision support system for intelligent road signaling," in *Proc. 15th Iberian Conf. Inf. Syst. Technol. (CISTI)*, Jun. 2020, pp. 1–6.

[45] J. M. L. Domínguez and T. D. J. M. Sanguino, "Design, modelling, and implementation of a fuzzy controller for an intelligent road signaling system," *Complexity*, vol. 2018, no. 1, Jan. 2018, Art. no. 1849527.

[46] *Instrucción Técnica Para La Instalación De Reductores De Velocidad y Bandas Transversales de Alerta En Carreteras De La Red De Carreteras Del Estado*, document FOM/3053/2008, Ministerio de Fomento, 3053.

[47] T. D. J. M. Sanguino, J. M. Davila, M. R. Gonzalez, and J. M. L. Dominguez, "Manufacturing and characterization of intelligent pedestrian crossings to improve road safety," *Dyna*, vol. 98, no. 4, pp. 341–345, Jul. 2023.

[48] B. V. Dasarathy, "Sensor fusion potential exploitation-innovative architectures and illustrative applications," *Proc. IEEE*, vol. 85, no. 1, pp. 24–38, Jan. 1997.

[49] M. Amer, M. Goldstein, and S. Abdennadher, "Enhancing one-class support vector machines for unsupervised anomaly detection," in *Proc. ACM SIGKDD Workshop Outlier Detection Description (ODD)*. New York, NY, USA: Association for Computing Machinery, 2013.

[50] E. H. Mamdani, "Applications of fuzzy set theory to control systems: A survey," in *Fuzzy Automata and Decision Processes*, vol. 10. Amsterdam, The Netherlands: North Holland, 1997, pp. 247–259.

[51] R. A. Aliev, "Fuzzy sets and fuzzy logic," in *Fundamentals of the Fuzzy Logic-Based Generalized Theory of Decisions* (Studies in Fuzziness and Soft Computing), vol. 293. Berlin, Germany: Springer, 2013, pp. 1–64.

[52] J. J. Buckley and Y. Hayashi, "Can approximate reasoning be consistent?" *Fuzzy Sets Syst.*, vol. 65, no. 1, pp. 13–18, Jul. 1994.

[53] J. M. L. Domínguez, F. Al-Tam, T. D. J. M. Sanguino, and N. Correia, "Analysis of machine learning techniques applied to sensory detection of vehicles in intelligent crosswalks," *Sensors*, vol. 20, no. 21, p. 6019, Oct. 2020.

[54] J. H. McDonald, *Handbook of Biological Statistics*, 3rd ed. MD, USA: Sparky House, 2014, pp. 127–131.

[55] J. M. Menéndez, "Velocidad, 20 preguntas y respuestas," *Tráfico y Seguridad Vial*, vol. 230, pp. 18–23, Jan. 2015.

[56] G. Nilsson, "Traffic safety dimensions and the Power Model to describe the effect of speed on safety," Lund Inst. Technol., Lund, Sweden, Tech. Rep. 221, 2004.

Tomás de J. Mateo Sanguino received the master's degree in computer engineering. He is currently a Technical Industrial Engineer and an Electronic Engineer. He has demonstrated leadership and innovation as a Teacher at the University of Huelva, where he also served as the Deputy Director of the Department of Electronic Engineering, Computer Systems, and Automatics. He has made significant contributions to research and academia throughout more than two decades of his career, holding various roles at esteemed Spanish institutions, such as the National Institute of Aerospace Technology and the Higher Council for Scientific Research. He is a seasoned researcher with a substantial publication record, including numerous indexed papers in renowned journals and conferences. In addition, he has excelled in project management, securing funding for international, national, and regional research initiatives. His contributions extend beyond academia, with involvement in technology transfer projects, patents, and organizing educational events. His dedication is further exemplified by his participation in professional associations and training programs, such as the CISCO Certified Networking Association.

José Manuel Lozano Domínguez received the bachelor's and master's degrees in computer engineering from the University of Huelva, Spain, in 2020 and 2021, respectively, where he is currently pursuing the Ph.D. degree with the Department of Electronic Engineering, Computer Systems and Automatics. He has been a Supply Teacher in automatics and system engineering for six years. He also worked as a Trainee Engineer at the company Onuba Technology S.L., for a year in 2014. He has published 15 papers in national/international conferences and journals, of which a book chapter and five journals indexed in JCR stand out. Also, he has a utility model and a patent on intelligent road safety issued to international PCT.

Manuel Joaquín Redondo González is currently a Distinguished Industrial Technical Engineer with the University of Seville, recognized for his academic excellence. With over three decades of experience, he has dedicated his career to teaching and research, holding positions at the University of Seville and the University of Huelva. He is known for his exceptional teaching prowess for earning accolades, such as the Diploma for Teaching Excellence and the Award to the Teaching Team of Excellence. He is actively involved in research as part of the Control and Robotics Research Group, contributing to numerous projects and publications. In addition, he has made significant contributions to educational innovation, coordinating, and participating in various teaching innovation projects. He is also engaged in research transfer, holding a patent and collaborating on research and development contracts with industry partners.

Jose Miguel Davila Martin is an accomplished Architect with outstanding academic qualifications, including a postgraduate course and numerous specialization courses. He has a diverse research background, including pre-doctoral and post-doctoral scholarships, and stays at prestigious institutions. Actively contributing to the Sustainable Mining Engineering Research Group, he has authored over 50 publications, including contributions to indexed scientific journals and conference papers. His research covers various fields, with notable achievements, such as being awarded a Principal Investigator role in a competitive research and development project and participating in cooperation projects. In addition, he has extensive professional experience, having worked on numerous professional projects and holding a patent for a Screw-Nut Assembly Threading and Unscrewing Device.