UDC 681.5

DOI: 10.20535/2523-4455.mea.354779

Development of a Bidirectional Road User Warning System Based on the ESP32 Microcontroller

I. Bryka, 0009-0004-9735-6659
N. Yu. Filipova, PhD, Assoc. Prof., 0000-0002-9723-8562
Department of Acoustic and Multimedia Electronic Systems, Faculty of Electronics
National Technical University of Ukraine “Igor Sikorsky Kyiv Polytechnic Institute”, 00syn5v21
Kyiv, Ukraine

Abstract–This paper considers the task of improving road traffic safety through the development of a bidirectional warning system for road users. The proposed system provides mutual information interaction between a vehicle driver and a pedestrian or animal located near the roadway. The system generates warning signals for both parties based on the spatial position of the detected object and the level of potential danger.

The developed system is based on a multisensor approach using sensors of different physical principles and a two-factor detection algorithm, which reduces the number of false activations. The operating area is divided into warning and critical zones with corresponding modes of visual and acoustic notification.

To validate the effectiveness of the proposed model, simulation modeling was performed in the MATLAB environment, which made it possible to evaluate the dependence of the correct detection probability on sensor reliability. The obtained results demonstrate an improvement in system reliability when using the multisensor approach and confirm the feasibility of applying the developed solution in intelligent road infrastructure.

Keywords – road traffic safety; bidirectional warning system; sensor fusion; simulation modeling; road infrastructure; pedestrian; vehicle; object detection

I. Introduction

The issue of road traffic safety remains relevant, especially at uncontrolled pedestrian crossings and road sections with limited visibility. A significant number of road accidents are associated with the delayed detection of pedestrians or animals by vehicle drivers. Additional risks are created by electric vehicles, which may be less noticeable to pedestrians due to their low noise levels.

Existing warning systems mainly provide information only to the driver, which limits their effectiveness in preventing hazardous situations. The lack of feedback information for pedestrians creates an information imbalance between road users.

This paper proposes a bidirectional warning system that provides simultaneous notification of the driver about the presence of an object within the risk zone and informs the pedestrian about an approaching vehicle. The system is based on the use of a multisensor detection unit and a logical signal processing algorithm for generating warning messages.

The aim of this work is to develop and evaluate the effectiveness of the proposed system under the influence of sensor noise and measurement errors.

II. Overview of existing solutions

Existing systems for warning about potential collisions with pedestrians are implemented as onboard vehicle modules. Such solutions belong to the class of Advanced Driver Assistance Systems (ADAS) and involve pedestrian detection using sensors (cameras, radars, etc.), evaluation of the approaching trajectory, and generation of a warning signal for the driver.

In particular, the Pedestrian Collision Warning system describes a solution that generates alerts when hazardous driving conditions are detected. This approach operates by installing corresponding hardware and software modules directly in the vehicle, while warnings are provided through the driver interface [3].

The known solution is mainly focused on informing the driver, while the pedestrian acts as a detected object rather than an active participant in the information exchange process. The disadvantage of such solutions is their dependence on the hardware equipment of road users required for notification, without which the system cannot operate properly.

Another solution similar to the proposed utility model in terms of technical concept and functional

Copyright (c) 2026 І. Брика, Н. Ю. Філіпова

DOI: 10.20535/2523-4455.mea.354779

purpose is the Smart Road Infrastructure for Vehicle Safety and Autonomous system. This approach involves the installation of multiple road infrastructure modules along the roadway that interact with vehicles and are capable of transmitting and receiving signals to improve road safety. The system enables information exchange between road infrastructure and vehicles in order to provide warnings about potentially hazardous situations or changes in road conditions [2].

The main disadvantages of this analogue include: focus on information exchange with vehicles rather than external visual and acoustic warning of all road users; the warning system is mainly oriented toward informing drivers about traffic-related road conditions (traffic flow, road accidents, road surface conditions), without considering hazards caused by the presence of pedestrians or animals in the roadside area; the absence of a fully autonomous power supply architecture for long-term independent operation without an external power source; and one-way or insufficiently bidirectional communication channels between the road infrastructure system and all road users, which is related to the fact that not every vehicle is equipped with such onboard warning systems.

Solutions known as “smart pedestrian crossings” use a sensor unit to detect a pedestrian approaching the roadway and automatically activate a notification unit, for example, the Smart Pedestrian Crossing System Using Intelligent Lighting and Detection Sensors. The technical principle of such solutions is that, after the sensor unit is triggered, a control signal is generated that activates the notification unit, thereby increasing the contrast and visibility of the crossing area and providing road users with information about a potential collision hazard [1].

The disadvantage of the described solution is the lack of sufficient technical information required for the complete implementation of the system. In particular, the author does not specify the exact types of sensors used in the sensor unit and does not provide signal processing algorithms for each of the proposed activation methods. This makes it impossible to evaluate the accuracy of object identification and the reliability of the system under complex weather conditions. In addition, the solution is designed exclusively for urban infrastructure with possible intervention into the road surface for marker installation, which limits its application on suburban road sections and does not address the issue of complete power autonomy.

The closest analogue is a roadside animal detection system designed to reduce the risk of vehicle collisions with wild animals – Roadside Animal Warning System. This system is installed permanently along the roadway and includes a microcontroller, a sensor unit with a thermal sensor, a notification unit represented by a light module, and an autonomous power supply unit. The operating principle of the system is based on the detection of thermal radiation from objects (large animals) within the monitored area by the sensor unit, followed by activation of the light module to visually inform drivers about the risk of collision [4].

The main disadvantages of the closest analogue are the narrow specialization of the system for detecting potential collision hazards exclusively with large animals and the one-way nature of the notification process, which is aimed only at vehicle drivers and leaves other road users unaware of the danger.

Furthermore, the exclusive use of thermal sensors without additional verification channels (such as sensors and detectors of other types) may lead to false activations caused by external heat sources or loss of the target under conditions of minimal temperature contrast and challenging environmental conditions.

In addition, the system lacks the capability for object classification and analysis of object dynamics, since it operates according to a threshold-based activation principle without measuring speed and distance, making algorithmic determination of the actual hazard level impossible.

The conducted analysis shows that existing safety systems implement a one-way interaction model: either the driver is warned, or the pedestrian is informed. The absence of synchronized bidirectional information exchange reduces the effectiveness of hazardous situation prevention, especially under conditions of limited visibility and complex road environments.

III. Development of a Mathematical Model

A. Problem Statement

The developed bidirectional warning system is intended to reduce the risk of collisions between vehicles and pedestrians or animals in areas with an increased probability of hazardous situations. The main objective of the system is to provide timely detection of potentially dangerous objects and ensure effective information exchange between all road users involved in a possible collision scenario.

The system provides detection of vehicles approaching the potential interaction zone, as well as identification of pedestrians or animals located near the roadway. When a potential collision risk is detected, warning information is generated simultaneously for both the vehicle driver and the detected object located within the hazardous area. An important requirement of the proposed approach is the reduction of false activations by generating warning signals only when an actual threat is identified.

Copyright (c) 2026 І. Брика, Н. Ю. Філіпова

DOI: 10.20535/2523-4455.mea.354779

B. Object Detection and Classification Model

For algorithmic processing of sensor data, the system uses object classification based on the characteristics of detected objects and their movement parameters. Vehicles (V) are defined as objects moving at a speed of 15 km/h or higher. Pedestrians (P) are classified as objects corresponding to human movement patterns, with a speed of up to 5 km/h and additional confirmation by a thermal sensor. Animals (A) are identified as warm-blooded objects characterized by irregular movement trajectories.

Object detection is performed using a multisensor approach that combines data from several independent sources. The main detection module includes a millimeter-wave radar, which provides information about object movement, speed, and trajectory. A thermal sensor or PIR sensor is used as an additional verification channel to confirm the presence of a living object. If necessary, a ToF sensor can also be integrated into the system to improve the accuracy of distance measurement.

The use of several independent sensing technologies increases detection reliability and reduces the probability of incorrect system activation caused by sensor errors, environmental factors, or external interference.

The probability of correct activation when using two sensors:

$$P = P_{radar} \times P_{thermal}$$

When using three sensors:

$$P = \prod P_i$$

where P_i — probability of correct operation of the i-th sensor.

The multisensor approach reduces the influence of random noise and decreases the frequency of false activations by combining data obtained from different detection channels.

C. Spatial Zoning

The operating area of the system is divided into two main zones depending on the distance to the roadway and the level of potential danger. The first zone, Z1, represents the warning zone located at a distance of approximately 10–20 meters from the edge of the road. When an object is detected within this area, a visual warning signal is generated to prepare the driver for a possible hazardous situation.

The second zone, Z2, represents the critical zone located within a range of 0–8 meters from the roadway. In this area, a combined notification mode is activated, including both visual and acoustic warning signals. This type of notification is perceived by the driver and pedestrian as an indication of an immediate potential threat.

The staged response algorithm makes it possible to reduce the number of sudden and unnecessary activations while maintaining effective warning capabilities.

D. Functional Requirements

The developed system must provide reliable detection of moving objects using a combination of radar-based monitoring and thermal analysis. Object classification is performed according to movement speed, thermal profile, and trajectory characteristics.

The system implements bidirectional notification, where the driver receives a visual signal and a short acoustic warning, while the pedestrian is informed through visual or sound notification methods. Intelligent filtering algorithms are used to suppress noise, eliminate false detections caused by small objects, and improve the reliability of system operation.

Additional functional capabilities include automatic adjustment of light intensity and sound level depending on environmental conditions, autonomous operation using a solar panel with a backup battery, and the possibility of connecting multiple modules into a single communication network using LoRa or BLE technologies.

E. Technical Implementation

The hardware architecture of the proposed system is based on the ESP32 controller [5], which provides sensor data processing, control of warning modules, and communication functions. The detection subsystem includes the HLK-LD2410 radar module for movement analysis, the AMG8833 thermal sensor for thermal object detection, and the VL53L1X ToF sensor for accurate distance measurement.

The power supply system operates at 12 V with energy consumption not exceeding 0.5 W in standby mode and 3 W in alarm mode. Visual notification is provided by 12 V LED indicators with a luminous intensity of at least 100 cd [7]. The acoustic notification module has an output power of 3–5 W and provides a sound pressure level of 85–95 dB at a distance of 1 meter.

Communication between system components is implemented through standard interfaces, including UART for the radar module, I^2C for sensors, and I^2S for audio signal processing.

The system enclosure provides an IP65 protection rating, ensuring resistance to dust and water exposure. The operating temperature range of the device is from −30 °C to +50 °C, allowing stable operation under various environmental conditions.

F. Operating Conditions

The system is activated only when a confirmed collision risk is detected based on the analysis of sensor data and verification algorithms.

Copyright (c) 2026 І. Брика, Н. Ю. Філіпова

DOI: 10.20535/2523-4455.mea.354779

Stable operation is ensured under normal weather conditions; however, during heavy fog or snowstorms, the effective detection range may be reduced due to environmental limitations affecting sensor performance. System maintenance is limited to periodic cleaning of the sensor modules to maintain detection accuracy.

The device must be resistant to impulse overvoltages and electromagnetic interference, ensuring reliable operation near road infrastructure and vehicle electronic systems.

The main expected technical and operational parameters of the developed system are presented in Table 1.

G. System Structure

The proposed system is implemented as an autonomous intelligent warning post installed near the roadway.

The block diagram of the proposed system is shown in Fig. 1.

In general, the proposed architecture is based on a modular principle and consists of five main functional units: the sensor unit, microcontroller, light module, power supply module, and acoustic module.

Sensor Unit

The sensor module implements multisensor detection based on the sensor fusion approach. The use of several independent detection channels increases the reliability of object identification and reduces the influence of external interference.

TABLE 1 EXPECTED TECHNICAL AND ECONOMIC INDICATORS

Indicator	Estimated Value	Comment
Average power consumption	1.3 W	Autonomous operation using a solar panel
Response time	≤ 1 s	From the moment of object entering the detection zone
Probability of correct activation	≥ 90 %	Combination of radar and thermal sensor
False activation rate	≤ 5 %	Due to signal filtering
Environmental noise level	<3 dB above background level	Environmental criterion
Prototype component cost	≤ 70 USD	5–10 times lower compared to commercial systems

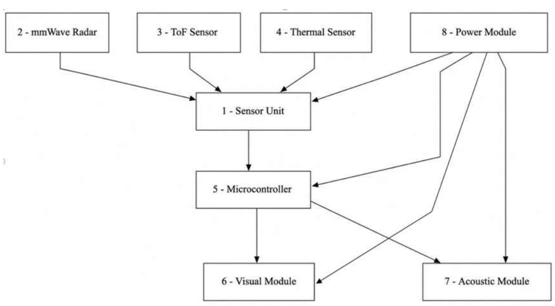

Fig. 1. Block Diagram of the System

The HLK-LD2410 radar module [9], operating at a frequency of 24 GHz, is used as the primary detection channel. It provides object detection within a range of approximately 10–20 meters and enables the determination of movement parameters, including object speed and distance. The radar module is mainly responsible for detecting approaching vehicles.

The VL53L1X Time-of-Flight (ToF) sensor is used as an additional distance measurement module. It provides accurate distance estimation within a range of up to 4 meters and is mainly applied for object position refinement in the critical zone Z2.

The AMG8833 thermal sensor [10] or PIR sensor is used to confirm the presence of warm-blooded objects. This detection channel allows the system to distinguish living objects from non-living obstacles and reduce false activations.

Additional sensors may also be integrated into the system, including the BH1750 light sensor for automatic brightness adjustment according to environmental lighting conditions and a magnetic sensor for auxiliary detection of metallic objects.

The final decision regarding object presence is made only when detection is confirmed by at least two independent sensors [8].

Microcontroller or Computing Module

The central processing element of the system is the ESP32 microcontroller. It performs sensor data acquisition through UART, I^2C, and GPIO interfaces, processes incoming information, filters noise, and performs object classification into predefined categories: vehicle (V), pedestrian (P), or animal (A).

The microcontroller also determines the current risk zone (Z1 or Z2), generates commands for activating warning modules, and controls power consumption using the Deep Sleep mode.

The ESP32 platform was selected due to the availability of integrated wireless communication interfaces, sufficient computing performance, and low energy consumption in standby mode.

Light Module and Acoustic Module

The warning system is implemented separately for vehicle drivers and pedestrians in order to provide effective bidirectional notification.

For drivers, the warning module uses red LED indicators with a power of 3–5 W [6]. The light signal operates in flashing mode with a frequency of 2–5 Hz to increase visibility and attract the driver's attention. In addition, a short acoustic signal with a duration of 200–300 ms can be generated to enhance the warning effect.

Copyright (c) 2026 І. Брика, Н. Ю. Філіпова

DOI: 10.20535/2523-4455.mea.354779

For pedestrians, the system provides a separate visual indicator combined with an acoustic or voice notification. To reduce noise impact in urban environments, automatic adjustment of the sound level is implemented, including volume reduction during nighttime operation.

Audio signal generation is performed using the MAX98357A amplifier connected through the I²S interface.

Power Supply Module

The power supply module ensures autonomous operation of the system without the need for a permanent external power source. The energy subsystem consists of a 20–30 W solar panel, a 12 V battery with a capacity of 7–12 Ah, and a charge controller.

The system is optimized for low energy consumption. In standby mode, power consumption does not exceed 0.5 W, while in the active warning mode it remains below 3 W. The average daily power consumption is approximately 1.3 W.

The power module includes protection against overvoltage and impulse interference, which increases the reliability of operation under outdoor conditions. The estimated autonomous operating time without additional charging reaches up to 5 days.

The system also supports a network configuration, allowing multiple warning modules to be combined into a distributed road safety infrastructure.

Operating Sequence

The detailed operating sequence of the proposed system is presented in Fig. 2.

The general operating sequence of the system can be described as follows. Initially, the sensor modules detect an object within the monitored area and collect information about its movement parameters. The obtained data are transmitted to the microcontroller, where signal processing, object classification, and risk zone determination are performed.

Based on the processed information, the system selects the appropriate warning mode according to the detected threat level. If a hazardous situation is confirmed, the corresponding visual and acoustic notification modules are activated to warn road users.

After the detected object leaves the monitored area and the potential threat disappears, the system returns to the energy-saving mode to minimize power consumption and ensure long-term autonomous operation.

IV. ZONE GEOMETRY AND DETECTION PARAMETERS

For object classification, a combination of movement speed, temperature characteristics, and trajectory parameters is used. The object classes used in the proposed system are presented in Table 2.

All object classes undergo double verification using at least two independent sensors. This approach reduces the probability of false activations caused by shadows, movement of tree branches, or small objects.

V. MATHEMATICAL MODEL OF HAZARD DETERMINATION

Object detection is performed by combining signals from multiple sensors into a unified logical decision-making system. The probability of correct system activation can be represented as:

Thus, the system confirms an event only when at least two sensors detect the presence of an object simultaneously.

A. Kinematic Calculations

To determine the appropriate activation moment, the system calculates the Time-To-Collision (TTC) parameter:

$$T_{tc}\frac{R}{v},$$

R – distance to the object, v – its speed.

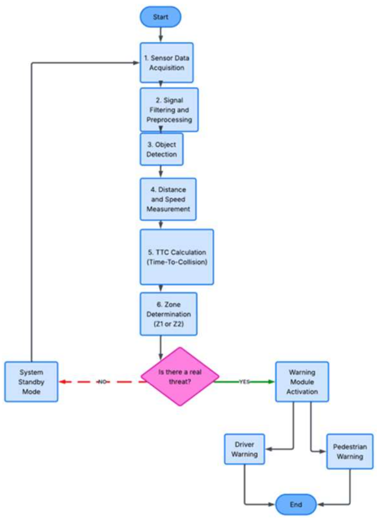

Fig. 2. Operating Sequence

TABLE 2 OBJECT CLASSES

Class	Designation	Characteristic Features	Sensor Type
Vehicle	V (vehicle)	Speed ≥15 km/h; stable trajectory; possible metal mass	Radar + magnetic sensor
Pedestrian	P (pedestrian)	Speed ≤5 km/h; stable thermal radiation	Radar + thermal sensor
Animal	A (animal)	Irregular speed; variable trajectory; thermal signature	Radar + thermal sensor + speed variation analysis

Copyright (c) 2026 І. Брика, Н. Ю. Філіпова

DOI: 10.20535/2523-4455.mea.354779

If TTC ≤ 1.5 s, the system switches to the critical warning mode with activation of the Z2 zone.

If TTC > 1.5 s, but the detected object continues moving toward the roadway, the warning zone Z1 is activated.

Example: A vehicle is moving at a speed of 50 km/h (approximately 13.9 m/s), and the radar detects an object at a distance of 20 m:

$$T_{tc} = \frac{20}{13{,}9} \approx 1{,}44s$$

which indicates an immediate transition of the system into the critical warning mode.

B. Sensor Geometric Arrangement

For correct system operation, the sensors are positioned according to the triangular coverage principle. The mmWave radar is directed at an angle of 5–10° relative to the roadway, allowing effective detection of approaching moving objects.

The ToF sensor is positioned horizontally along the road edge to provide accurate distance measurements within the monitored area. The PIR or thermal sensor is installed at a height of 1.2–1.5 m with a slight inclination toward the roadside area to improve the detection of pedestrians and animals.

This sensor arrangement minimizes blind zones and prevents mutual interference between detection channels.

C. Signal Processing

The obtained data undergo several stages of digital processing. First, noise filtering is performed using a digital averaging filter to reduce the influence of random disturbances. The next stage includes event detection by comparing sensor values with predefined activity thresholds.

After that, the system performs data integration by combining features obtained from different sensors. Based on the processed information, the object class is determined, and a decision regarding warning activation is made.

Additionally, an anti-fluttering function is implemented: short signal peaks lasting less than 0.3–0.5 s are ignored as random disturbances.

The division of the monitored area into two zones (warning and critical), combined with the use of a multisensor detection system and time-based activation thresholds, enables the creation of an adaptive safety model in which the warning level corresponds to the actual degree of risk.

Such zoning increases the reliability of the notification process and ensures a balance between system efficiency and environmentally friendly operation.

TABLE 3 ZONE PARAMETERS AND SENSITIVITY LIMITS

Parameter	Designation	Value	Note
Radar detection range	Rmax	10–20 m	Depends on module type
ToF sensor range	RToF	Up to 4 m	Z2 zone
Confirmation delay	Δtconf	0.5–0.8 s	Anti-fluttering
Signal holding time	Δthold	3 s	After object disappearance
Radar viewing angle	αR	90°	Optimal Z1 control
PIR / thermal sensor viewing angle	αT	100°	Area coverage

VI. DETECTION MODEL AND SYSTEM OPERATION ALGORITHM

A. Model Design Principle

The main concept is based on multisensor detection, where the decision regarding a potential hazard is made according to the combined results of several sensor modules rather than a single detection source.

This approach improves object identification reliability and reduces the number of false activations under challenging environmental conditions, such as rain, fog, moving vegetation, or animal movement.

The system operates according to a conditional voting principle: a warning signal is generated only when at least two independent sensors confirm the presence of an object within the monitored area.

B. Sensor Fusion

Let: E_R– event “the radar has detected an object”; E_T – event “the thermal sensor has confirmed the presence of a living object”; E_D – event “the ToF sensor has detected an object within the critical zone”; E_M – event “the magnetometer has detected a metallic mass”.

The decision about the presence of a real event is made according to the following rule:

$$E_{real} = (E_R \wedge E_T) \vee (E_R \wedge E_M) \vee (E_T \wedge E_D)$$

Thus, the system responds only when at least two signals from sensors with different physical operating principles coincide. For example, simultaneous activation of the radar and thermal sensor indicates with high probability that a pedestrian or animal has appeared within the detection area.

C. Probabilistic Model

The probability of correct detection by the system is defined as:

$$P_{true} = 1 - (1 - P_R)(1 - P_T)$$

When P_R – reliability of radar readings, P_T – reliability of thermal sensor readings.

Copyright (c) 2026 І. Брика, Н. Ю. Філіпова

DOI: 10.20535/2523-4455.mea.354779

For three sensors, the model expands to:

$$P_{true} = 1 - (1 - P_R)(1 - P_T)(1 - P_D)$$

If the probability of each sensor is ≈ 0.8, then the combined result is:

$$P_{true} = 1 - (1 - 0{,}8)^3 = 0{,}992$$

which corresponds to a reliability of 99.2% when using three independent sensors.

D. Object Classification Algorithm

For each detected object, the system calculates the following parameters: movement speed (v), distance (R), thermal profile stability, and speed variance.

Object classification is performed according to the following rules:

$$If\ v \geq v_0 \vee E_m \Rightarrow Automobile(V)$$
$$If\ v < v_0 \wedge E_t \wedge \sigma v < \sigma_{пор} \Rightarrow pedestrian(P)$$
$$If\ E_T \wedge \sigma v > \sigma_{пор} \Rightarrow animal(\mathrm{A})$$

where v0=15 km/h, and σpor is the threshold value of motion instability.

E. Logic of determining the level of danger

After identifying the object, the system determines its current zone: Z1 – warning; Z2 – critical.

For each object class, the time to potential collision (TTC) is calculated:

$$T_{tc}\frac{R}{v},$$

If TTC < 1.5 s, the system switches to the critical warning mode (Z2).

If TTC ≥ 1.5 s, the system operates in the warning mode (Z1).

At the same time, the system checks whether objects are present on both sides of the roadway (vehicle + pedestrian). In this case, the bidirectional warning mode (Dual Alert) is activated.

F. Protection Against Noise and False Detections

The system uses several levels of signal verification.

The confirmation time window ensures that an event is considered valid only if its duration exceeds 0.5 s.

Distance hysteresis determines that an object is considered to have disappeared only after moving 2–3 m outside the detection zone.

The stability filter rejects an event if the deviation of radar measurements exceeds 30% during the last 0.3 s.

The anti-fluttering algorithm prevents repeated activation earlier than 2 s after the previous warning.

G. Model Summary

Thus, the developed model combines signals from three different sensors into a unified logical analysis system, provides decision-making based on a probabilistic approach, considers the temporal dynamics of movement and the spatial position of the detected object, and generates the appropriate warning level according to the actual degree of danger.

The implementation of this model as a software algorithm for the ESP32 microcontroller enables the creation of a next-generation intelligent warning system that operates autonomously and adaptively, providing a higher level of safety compared with traditional one-way warning solutions.

VII. ALARM LOGIC AND ALARM MODES

A. General Warning Principle

The warning system is implemented using two communication channels: visual and acoustic. The signal intensity depends on the detected hazard level and the corresponding operating zone (Z1 or Z2).

In the Z1 warning zone, only visual notification is activated to inform road users about a possible hazardous situation. In the Z2 critical zone, a combined visual and acoustic warning mode is used. If a vehicle and a pedestrian are simultaneously detected within the Z2 zone, the system activates the bidirectional emergency alert mode.

B. Driver Warning Channel

In the Z1 zone (10–20 m), the driver warning system generates a red flashing signal with a frequency of 2 Hz. The LED brightness is maintained at approximately 60–70%, and the signal shutdown delay is up to 3 s. Acoustic notification is not activated in this mode.

In the Z2 zone (0–8 m), the system switches to the critical warning mode. The red LED indicators operate with a flashing frequency of 5 Hz, and an acoustic pulse with a frequency of 1000 Hz and a duration of 200 ms is generated. To prevent excessive activation, signal repetition is limited to no more than once every 2 s using an anti-fluttering algorithm.

In the Dual Alert mode, when both a vehicle and a pedestrian are simultaneously detected in the Z2 zone, the system generates three visual pulses with a duration of 250 ms and three corresponding acoustic pulses. After activation, the system switches to the COOLDOWN mode for 5 s to prevent repeated unnecessary warnings.

C. Pedestrian Warning Channel

For pedestrians in the Z1 zone, a yellow indicator operates with a flashing frequency of 1 Hz using diffused light. After the object leaves the detection area, the shutdown delay is approximately 2 s.

In the Z2 zone, a red flashing signal with a frequency of 3 Hz is activated. Additionally, a voice notification with a duration of no more than 1 s can be generated.

Copyright (c) 2026 І. Брика, Н. Ю. Філіпова

DOI: 10.20535/2523-4455.mea.354779

The acoustic output level is automatically adjusted depending on environmental conditions.

D. Adaptation to Lighting and Noise Conditions

The system uses the BH1750 light sensor and an environmental noise monitoring microphone to adapt warning parameters.

The output sound level is determined as:

$$Lout = \min(Lmax, Lbackground + \Delta L)$$

where: Lbackground – average environmental noise level; ΔL = 10 dB during daytime operation and 5 dB during nighttime operation.

The LED brightness is adjusted proportionally according to the ambient illumination level, ensuring sufficient visibility while reducing unnecessary energy consumption.

VIII. Modeling the Efficiency of a Multisensor System

To validate the performance of the proposed sensor fusion model, simulation modeling was performed in the MATLAB environment. The purpose of the simulation was to evaluate the probability of correct object detection when using the coordinated sensor voting rule.

The model used the same events that were previously introduced: E_R, E_T, E_D, E_M

$$E_{real} = (E_R \wedge E_T) \vee (E_R \wedge E_M) \vee (E_T \wedge E_D)$$

The simulation was performed using the Monte Carlo method with the number of iterations ($N = 10^5$). In this model, each sensor was represented as an independent random source with a specified probability of correct detection:

$$P_R = P_T = P_D = 0.8$$

During each iteration, a combination of sensor activations was generated, after which the logical condition of “at least two confirmed sensor detections” was verified.

The probability of correct system detection was determined as:

$$P_{sim} = \frac{N_{\text{detected}}}{N}$$

N_{detected} – the number of iterations in which the system recorded the object.

According to the simulation results, we obtained:

$$P_{sim} \approx 0.89$$

For comparison, the analytical estimate for independent sensors has the form:

$$P_{true} = 1 - (1 - P_R)(1 - P_T)(1 - P_D)$$

which, with the same parameters, gives:

$$P_{true} = 0.992$$

The obtained difference is explained by the fact that the analytical formula describes the probability of activation of at least one sensor, whereas the proposed system uses a stricter signal confirmation rule requiring activation of at least two sensors.

Additionally, a generalized graph showing the dependence of the correct detection probability of the system on the reliability of individual sensors was created in the MATLAB environment. The following sensor types were used during the simulation:

- radar module;
- thermal sensor;
- ToF distance sensor.

All sensors were modeled as independent signal sources with the same probability of correct detection, which varied within the range of 0.5–0.95.

The graph representing the dependence of the multisensor system performance on sensor reliability is shown in Fig. 3.

As can be seen from the graph, with an increase in the reliability of individual sensors, the overall probability of correct system detection increases nonlinearly. This confirms the effectiveness of using a multisensor approach and the coordinated voting algorithm for improving object detection reliability.

Conclusions and Practical Value

In this work, a bidirectional warning system for road users was developed, providing detection of vehicles, pedestrians, and animals on both sides of the roadway and generating adaptive visual and acoustic notifications depending on the level of potential danger.

During the research, the following tasks were completed:

- modern road safety systems were analyzed, and the limitations of existing solutions were identified, particularly the lack of bidirectional information interaction between road users;

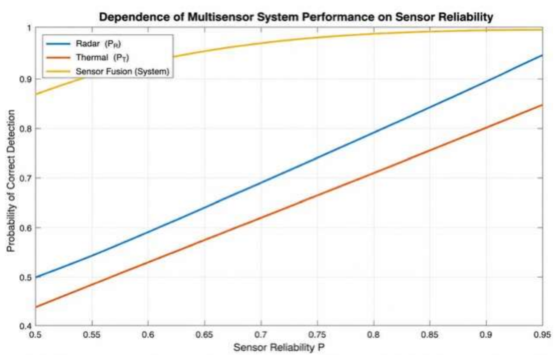

Fig. 3. Dependence of the Multisensor System on Sensor Reliability

Copyright (c) 2026 І. Брика, Н. Ю. Філіпова

DOI: 10.20535/2523-4455.mea.354779

- a functional model of the system was developed using a multisensor approach based on radar, thermal sensor, ToF sensor, and the ESP32 microcontroller;
- a sensor fusion model based on a logical signal confirmation rule was implemented, which reduces the number of false activations;
- an object classification algorithm and hazard level determination method were developed, with the monitored area divided into the warning zone (Z1) and the critical zone (Z2).

To validate the effectiveness of the proposed model, simulation modeling was performed in the MATLAB environment. During the simulation, the dependence of correct detection probability on sensor reliability was investigated.

The obtained graph confirmed the nonlinear increase in system efficiency and demonstrated the advantages of the multisensor approach compared with the use of individual sensors.

The developed system can be applied:

- at uncontrolled pedestrian crossings, suburban roads, and areas with limited visibility;
- in high-risk zones such as schools, hospitals, parking areas, and territory exits;
- as an element of Smart City intelligent infrastructure;
- as a component of IoT monitoring systems.

Energy autonomy and low implementation cost (approximately 70–80 USD) provide the possibility of large-scale deployment of the system.

The proposed bidirectional warning system is an effective and technically justified solution that combines sensor integration, adaptive notification, and autonomous operation. It can serve as a basis for further development of intelligent road traffic safety systems.

References

[1]. G. Mouna, E. Nagaveni, M. Nishanth, D. Srisha, and A. R. Gopinath, “Smart pedestrian crossing system”, International Research Journal of Engineering and Technology (IRJET), vol. 8, no. 7, pp. 1110–1113, Jan. 2021. URL: https://www.irjet.net/archives/V8/i7/IRJET-V8I7187.pdf

[2]. I. Fermon "Smart road infrastructure for vehicle safety and autonomous drivingю" USA, US11981337B2, 2022

[3]. D. Rosenbaum, A. Gurman, Y. Samet, G. P. Stein, D. Aloni "Pedestrian collision warning system", USA, US10300875B2, 2018.

[4]. H. Hykawy "Roadside animal warning system", USA, US20020145519A1, 2002

[5]. Espressif Systems. ESP32 Technical Reference Manual URL: https://www.espressif.com

[6]. G. Shahzad, H. Yang, A. W. Ahmad, and C. Lee, “Energy-Efficient Intelligent Street Lighting System Using Traffic-Adaptive Control”, vol. 16, no. 13, pp. 5397–5405, Jul. 2016. doi: 10.1109/JSEN.2016.2557345

[7]. I. Chew, V. Kalavally, C. P. Tan, and J. Parkkinen, “A Spectrally Tunable Smart LED Lighting System With Closed-Loop Control”, IEEE Sensors Journal, vol. 16, no. 11, pp. 4452–4459, Jun. 2016. doi: 10.1109/JSEN.2016.2542265

[8]. D. Caicedo and A. Pandharipande, “Sensor-Driven Lighting Control With Illumination and Dimming Constraints”, IEEE Sensors Journal, vol. 15, no. 9, pp. 5169–5176, Sep. 2015. doi: 10.1109/JSEN.2015.2436338

[9]. Texas Instruments. Automotive mmWave radar sensors. – URL: https://www.ti.com/product-category/sensors/mmwave-radar/automotive/overview.html.

[10]. AMG8833 : Infrared Array Sensor Grid-EYE. URL: https://industrial.panasonic.com/ww/products/pt/grid-eye/models/AMG8833.

Надійшла до редакції 15 березня 2026 року
Прийнята до друку 25 квітня 2026 року
Опублікована 04 травня 2026 року.

Copyright (c) 2026 І. Брика, Н. Ю. Філіпова

УДК 681.5

DOI: 10.20535/2523-4455.mea.n

Розробка двонаправленої системи попередження учасників дорожнього руху на основі мікроконтролера ESP32

І. Брика, 0009-0004-9735-6659
Н. Ю. Філіпова, канд. техн. наук, доц., 0000-0002-9723-8562
Кафедра акустичних та мультимедійних електронних систем, Факультет електроніки
Національний технічний університет України
"Київський політехнічний інститут імені Ігоря Сікорського" 00syn5v21
Київ, Україна

Анотація–У цій роботі розглядається завдання підвищення безпеки дорожнього руху шляхом розробки двонаправленої системи попередження учасників дорожнього руху. Запропонована система забезпечує взаємну інформаційну взаємодію між водієм транспортного засобу та пішоходом або твариною, що знаходиться поблизу дорожнього полотна. Система генерує попереджувальні сигнали для обох сторін на основі просторового положення виявленого об'єкта та рівня потенційної небезпеки.

Розроблена система базується на мультисенсорному підході з використанням датчиків різних фізичних принципів та двофакторного алгоритму виявлення, що зменшує кількість помилкових спрацьовувань. Робоча зона поділена на зони попередження та критичні зони з відповідними режимами візуального та акустичного сповіщення.

Для перевірки ефективності запропонованої моделі було проведено імітаційне моделювання в середовищі MATLAB, що дозволило оцінити залежність ймовірності правильного виявлення від надійності датчиків. Отримані результати демонструють покращення надійності системи при використанні мультисенсорного підходу та підтверджують доцільність застосування розробленого рішення в інтелектуальній дорожній інфраструктурі.

Ключові слова – безпека дорожнього руху; двонаправлена система попередження; об'єднання датчиків; імітаційне моделювання; дорожня інфраструктура; пішохід; транспортний засіб; виявлення об'єктів.

Copyright (c) 20XX Прізвище І. П., Прізвище І. П. і т.д.