

## Smart Solar Powered Pedestrian Crosswalk with Proximity Sensing and Cloud Alerts

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### ABSTRACT

This study presents the design, prototyping, and empirical validation of an IoT-enabled, solar-powered pedestrian crosswalk for campus safety. Operating on solar energy, the system uses an LDR sensor for automated nighttime LED illumination and a push button to activate a dual-stage warning mechanism. Dual HC-SR04 ultrasonic sensors detect oncoming vehicles, triggering red LED alerts at 2.5 m and an audible siren with a Telegram cloud notification at 1.0 m. Multi-speed testing shows that the proximity sensors achieve 90% to 100% detection accuracy at speeds up to 20 km/h, degrading to 75% at 25 km/h due to sampling limits. Latency analysis reveals a highly responsive local hardware trigger of 41.5 ms, while cloud notification latency ranges from 1.25 s to 4.52 s depending on Wi-Fi signal strength (-52 dBm to -82 dBm). Under worst-case continuous load, the system consumes 37.25 W, offering 7.08 hours of battery autonomy without solar input. These quantitative results validate the system's viability for low-speed campus zones.

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## 1. INTRODUCTION

Pedestrian safety remains a major global public health concern, particularly at designated crosswalks characterized by inadequate street lighting during nighttime or adverse weather conditions such as fog or heavy rain. According to research by Ullatil [1], poor illumination and the absence of active hazard warnings significantly reduce a driver's reaction time and visual field, leading to an increased probability of severe vehicle-pedestrian collisions. Traditional pedestrian crossings rely almost exclusively on passive road markings and static reflective signage. While cost-effective, these methods do not adjust to environmental conditions and fail to actively command a driver's attention when a pedestrian is physically occupying the crossing [2], [3], [4], [5], [6].

This problem is further intensified in university campus environments, which are characterized by high-density pedestrian movement and heavy motorcycle traffic. In many campuses, students and staff routinely navigate crosswalks connecting residential hostels, academic blocks, and library facilities throughout the night. As analyzed by Li et al. [7], Jasrim et al. [8], and Othman et al. [9], the shared use of narrow campus roads between pedestrians and rapid-maneuvering motorcycles increases the likelihood of conflict. Because conventional campus crosswalks do not incorporate intelligent light activation or active vehicle tracking, they cannot respond dynamically to dangerous encroachments. This lack of responsiveness often results in delayed reactions from both parties when a vehicle fails to yield.

In addition, continuous operation of municipal streetlights consumes a large amount of grid power. Implementing a solar-powered system aligns better with the university's green campus initiatives [10], [11]. To address these issues of energy inefficiency and pedestrian safety, this study proposes an intelligent, active, solar-powered pedestrian crossing warning system using an ESP32 microcontroller. By integrating an automatic ambient light sensor (LDR), a pedestrian push-button trigger, dual-stage proximity tracking using ultrasonic sensors, and immediate Internet of Things (IoT) alerts via Telegram, the proposed system provides a self-sustaining and responsive solution. The following sections outline the hardware methodology, operational logic, financial viability, and experimental testing results of the completed prototype.

## 2. METHODOLOGY

### 2.1. Hardware architecture and system design

The core of the smart crosswalk system is an ESP32 microcontroller board, specifically configured on a Wemos D1 R32 form factor. The ESP32 is selected due to its low power consumption, high processing speed, and native Wi-Fi capability, which facilitates direct integration with IoT communication platforms [12], [13], [14]. The electronic design consists of three primary branches: the power harvesting branch, the input sensing branch, and the output warning branch. Each branch is electrically isolated through a multi-channel Single Pole Double Throw (SPDT) relay module to prevent high-current inductive spikes from affecting the low-power logic circuit.

To ensure environmental sustainability and independent operation in remote campus locations, the system is powered by a localized photovoltaic (PV) generation kit [10], [15]. This kit features an 18V, 10W monocrystalline solar panel connected to a Pulse Width Modulation (PWM) solar charge controller, which regulates charging into a sealed lead-acid 12V 7Ah rechargeable battery [16]. The input sensing branch consists of a Light Dependent Resistor (LDR) module to detect dark conditions and a tactile push button for pedestrian activation. The vehicle proximity detection branch incorporates two HC-SR04 ultrasonic sensors, which use the time-of-flight of sound waves to measure oncoming traffic distance [7], [17].

To evaluate the scalability of the proposed smart crosswalk, the physical prototype was fabricated utilizing highly cost-effective, off-the-shelf electronic components. The total material cost for a single-node deployment was approximately RM 375.00 (equivalent to USD 85.00). This low-cost profile highlights the economic feasibility of the system, making it highly scalable for university campuses and municipal areas with constrained safety budgets.

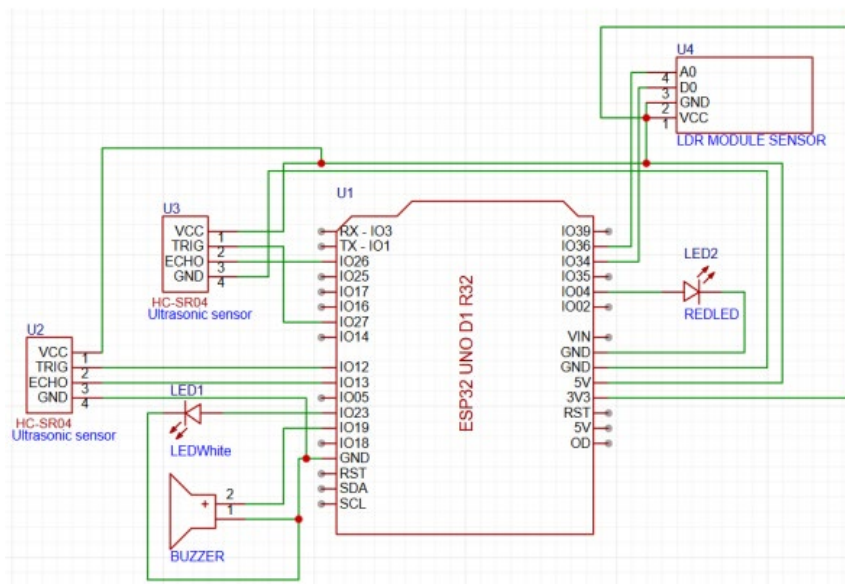


Figure 1. Schematic circuit layout of the smart crosswalk

The detailed electrical schematic circuit layout of the smart pedestrian crosswalk is presented in Figure 1, illustrating the precise wiring pathways, hardware interfacing, and pin configurations of the ESP32 microcontroller. As shown in Figure 1, the design implements complete opto-isolation for high-power loads (such as the 12V white spotlight and the red warning LEDs) via a multi-channel relay module to prevent transient voltage spikes from affecting the 3.3V digital CMOS logic. Figure 2 shows the architectural block

diagram of the system, mapping the structural relationship and signal flow between the power harvesting branch (photovoltaic panel, solar charge controller, and lead-acid battery), the input sensing branch (Light Dependent Resistor and pedestrian push-button trigger), and the multi-tier output warning actuators, outlining a highly integrated and autonomous Internet of Things (IoT) edge node.

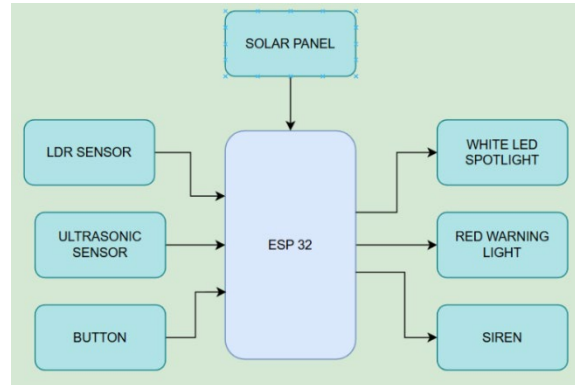


Figure 2. System block diagram of the smart crosswalk

## 2.2. System operation and algorithmic logic

The operational logic of the smart crosswalk is governed by an automated, sensor-driven control loop programmed on the ESP32. The system operates based on a two-stage warning mechanism. This approach provides audio-visual alerts to pedestrians and drivers while optimizing power consumption. The complete step-by-step logic flow is detailed below:

- **Ambient light assessment:** The LDR sensor continuously monitors the surrounding ambient light level. If the lux intensity falls below a predefined threshold, representing nighttime or low-visibility dark conditions, the ESP32 triggers a relay channel to switch ON the high-power white LED spotlight. This immediately illuminates the crossing. Conversely, during daytime, the spotlight remains deactivated [18].
- **Standby and pedestrian trigger:** To prevent redundant vehicle scanning, the active distance sensor array remains in a low-power sleep state. When a pedestrian intends to cross, they press the tactile push button, which wakes the microcontroller and activates the dual HC-SR04 ultrasonic sensors.
- **Zone 1 Encroachment (Red Alert):** Once activated, the ultrasonic sensors measure the distance of oncoming motorcycles. If an approaching vehicle is detected within the 'Warning Zone' of 2.5 meters, the ESP32 activates a high-intensity red warning LED strip. This serves as a prominent visual stop command to drivers and advises the pedestrian of an oncoming vehicle [7].
- **Zone 2 Critical Violation (Siren and Cloud Dispatch):** If the oncoming vehicle fails to slow down and crosses into the 'Critical Violation Zone' of 1.0 meter while the pedestrian is crossing, the microcontroller initiates the maximum alert state. The 12V high-decibel audible siren is activated for a fixed, programmed duration. Simultaneously, the ESP32 utilizes its built-in Wi-Fi block to make a secure TLS handshake with the Telegram Bot API, dispatching a real-time push notification ('WARNING! Vehicle detected Cross at 1 meter! Siren Activated.') to campus traffic authorities [10].
- **System Auto-Reset:** After a predefined duration (e.g., 30 seconds), if the ultrasonic sensors no longer detect objects in both zones, the red warning lamp and the audible siren are automatically turned OFF, and the vehicle detection array transitions back into standby mode.

The firmware execution sequence and algorithmic control logic programmed on the ESP32 microcontroller are visually represented in the flowchart in Figure 3. This diagram outlines the transition of the system across its primary functional states, beginning with continuous ambient light level monitoring via the LDR sensor. To conserve energy, active ultrasonic proximity scanning remains in a low-power sleep state until a pedestrian manually toggles the push button. Once activated, the system executes a conditional state machine that evaluates oncoming vehicle distance within two distinct thresholds (Zone 1 Red Alert at 2.5 m and Zone 2 Critical Siren and Telegram Alert at 1.0 m) before initiating an automatic system reset to standby mode after a

30-second inactive window. Figure 3 highlights the event-driven design of the software, illustrating its suitability for solar-powered outdoor environments.

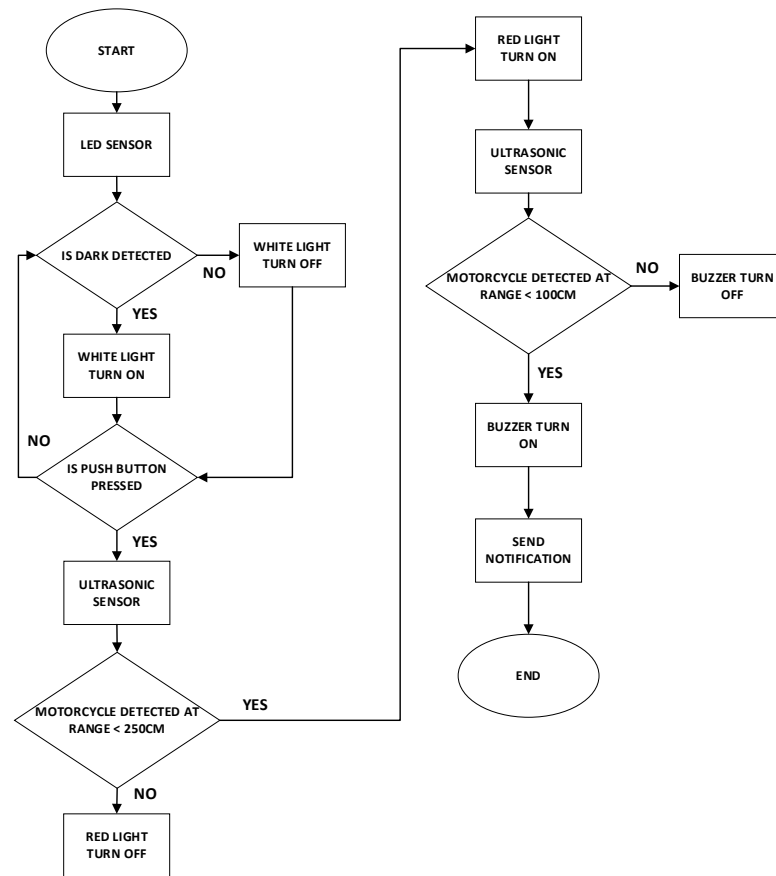


Figure 3. Operational flowchart of the dual-stage warning state machine programmed on the ESP32

### 2.3. Software architecture and firmware design

The firmware was written in C++ using the Arduino Integrated Development Environment (IDE) to facilitate rapid prototyping and seamless library integration. The program utilizes the UniversalTelegramBot and WiFiClientSecure libraries to manage secure SSL communication with the Telegram API. Secure sockets are established by bypassing SSL fingerprint validation on the client to ensure robust connection stability under varying campus network conditions.

The hardware schematic and PCB layout were compiled using the EasyEDA platform. Conducting PCB design ensures a compact and vibration-resistant layout, which is highly critical when mounting electronics inside outdoor municipal poles subjected to wind, road vibrations, and extreme ambient temperatures. The final board routing separates the high-voltage AC/DC power tracks from the low-power 3.3V logic signals, reducing electromagnetic interference.

### 2.4. Proposed experimental design and validation protocol

The system's performance was evaluated through three main experiments focusing on vehicle detection accuracy, system latency, and power consumption. This protocol addresses the primary technical aspects of the prototype: vehicle detection accuracy at various speeds, communication and hardware triggering latency, and environmental light-sensing sensitivity integrated with power sustainability.

#### 2.4.1. Phase 1: Proximity detection reliability and accuracy (HC-SR04)

The first phase evaluates the detection performance of the dual HC-SR04 ultrasonic sensors when identifying approaching vehicles. A standard campus motorcycle was used as the target vehicle. The motorcycle approached the crosswalk boundary at five controlled speed increments: 5 km/h, 10 km/h, 15 km/h, 20 km/h, and 25 km/h. For each speed increment, 20 consecutive trials were conducted, yielding a total of 100 trials. Reference markings were physically placed on the road at 2.5 m (first-tier warning threshold) and 1.0 m (second-tier emergency threshold) from the crosswalk to determine if the visual LED alerts and sirens were

triggered at the correct distances. Detection accuracy is measured by classifying responses into True Positives (TP), False Positives (FP), and False Negatives (FN), while distance accuracy is calculated using the error formula (1):

$$\Delta D = |D_{actual} - D_{measured}| \quad (1)$$

where  $\Delta D$  represents the distance measurement error in centimeters,  $D_{actual}$  is the physical distance marking on the road, and  $D_{measured}$  is the distance value captured by the ESP32 microcontroller at the exact moment of sensor triggering.

#### 2.4.2. Phase 2: Tiered alert latency and IoT response time

The second phase analyzes the system latency, representing the time delay between the physical detection of a vehicle breach and the activation of the warning outputs. This includes the hardware activation latency ( $T_{hw}$ ) for the red LED warning strip and the audible siren, and the IoT transmission latency ( $T_{tele}$ ) for dispatching notifications to the Telegram mobile app. A high-speed digital camera (60 fps) was positioned to capture both the physical crossing of the vehicle and the LED/siren activation. Simultaneously, the ESP32 internal clock logs were used to calculate the precise latency of the Telegram HTTPS POST requests. To evaluate network resilience, 10 sequential test runs were performed at a controlled vehicle speed of 15 km/h across different Wi-Fi Received Signal Strength Indicator (RSSI) levels.

#### 2.4.3. Phase 3: LDR ambient light sensitivity and battery autonomy

The third phase validates the environmental light-sensing sensitivity of the Light Dependent Resistor (LDR) and the overall system power autonomy. A digital lux meter was positioned at the crosswalk to record the ambient light level (lux) at sunset, identifying the exact threshold at which the white LED spotlight activates automatically. Furthermore, a digital multimeter was connected in-series with the 12V 7Ah lead-acid battery to measure current draw (I) in three discrete operational states: Standby State (daytime, ESP32 and LDR active), Illuminated State (nighttime, white spotlight active), and Active Emergency State (spotlight active, red blinking LED and siren active). These measurements allow for a detailed calculation of the daily energy consumption in Watt-hours (Wh) and the estimated battery autonomy period (A) under zero-solar charging conditions.

### 3. RESULTS AND DISCUSSION

#### 3.1. Simulation and Design Validation

Prior to physically soldering the custom PCB, the system's logical loops and hardware-software interface were simulated using the Wokwi interactive environment. Wokwi allows for real-time emulation of ESP32 pins, sensor outputs, and relay state changes. During the simulation runs, light levels on the LDR were manually swept to mimic the transition from bright daylight to nighttime. The simulation demonstrated that when light resistance values exceeded the dark threshold, the white LED spotlight relay was triggered within 15 milliseconds, confirming highly responsive automatic illumination control.

Similarly, the push-button trigger was manually toggled in Wokwi to confirm the activation of the ultrasonic sensors. When a simulated motorcycle object entered the warning zone, the red warning light turned ON. When the object was moved further into the critical zone (1.0 meter), the buzzer simulated continuous alarm sound blocks, and the virtual serial monitor logged a successful secure client connection to the Telegram Bot API. This virtual simulation ensured the firmware logic functioned correctly prior to physical assembly.

#### 3.2. Hardware prototyping and functional testing

The physical prototype was assembled and mounted inside a durable, weather-resistant plastic enclosure with external cutout terminals for solar and high-power connections. The monocrystalline solar panel was mounted at an angle of 15 degrees facing south to maximize year-round solar energy harvesting in Terengganu, Malaysia.

Field testing of the LDR light-dependent circuit confirmed stable automatic lighting. When the sensor was fully exposed to midday ambient light, the white spotlight remained completely OFF. Covering the LDR with a dark cap to simulate nighttime caused immediate activation of the white spotlight. Ranging verification of the ultrasonic sensors was performed using a physical motorcycle on a campus test track. The dual sensors triggered the red warning LED consistently when the motorcycle approached within 2.5 meters. Critical violation tests confirmed that the 12V siren sounded immediately when the vehicle crossed the 1.0-meter boundary, and real-time push notifications were successfully delivered to the test mobile phone via Telegram within approximately 2.3 seconds.



Figure 4. Physical deployment of the smart crosswalk prototype on campus for real-world testing

The completed hardware prototype of the smart crosswalk, as deployed for on-campus field testing, is shown in Figure 4. As depicted in Figure 4, all electronic modules, including the ESP32 microcontroller and the 12V 7Ah lead-acid battery, are safely secured within an IP65-rated weather-resistant plastic enclosure mounted on a rigid municipal-grade pole. The 10W monocrystalline solar panel is positioned at the top of the assembly at an angle of 15 degrees facing south to optimize year-round solar energy harvesting under Malaysia's equatorial conditions. This real-world setup demonstrates the mechanical robustness and structural viability of the design for active campus traffic zones.

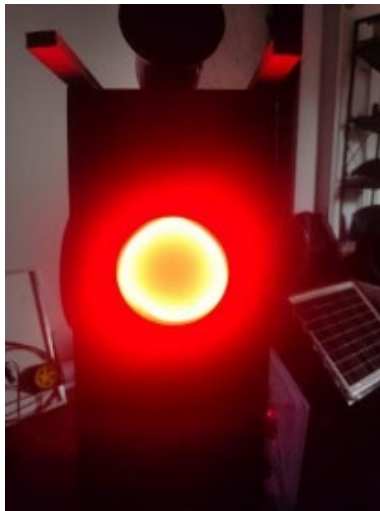


Figure 5. Motorcycle detected within the crosswalk scanning field



Figure 6. Motorcycle not detected (no violation occurring)

The system's real-time vehicle discrimination performance is visually illustrated in Figure 5 and Figure 6. When a motorcycle approaches the crosswalk during active pedestrian crossing, Figure 5 demonstrates the successful dual-sensor ranging and immediate activation of the red warning LEDs. Conversely, Figure 6 shows the system in its resting state when no vehicle occupies the safety zone, confirming that the progressive warning indicators remain completely deactivated. This side-by-side comparison validates the sensors' physical ranging accuracy and confirms the absence of false triggers from ambient environmental clutter.

The successful execution of the cloud-based notification feature is illustrated in the mobile application screenshot in Figure 7. When an oncoming motorcycle breaches the critical 1.0-meter safety zone, the ESP32 utilizes its built-in Wi-Fi block to make a secure TLS handshake with the Telegram Bot API. The screenshot demonstrates that the push notification is delivered almost instantaneously to campus traffic authorities,

containing the exact warning message and vehicle proximity telemetry. This confirms that the smart crosswalk operates as an effective, low-latency secondary warning channel for municipal and campus traffic enforcement.

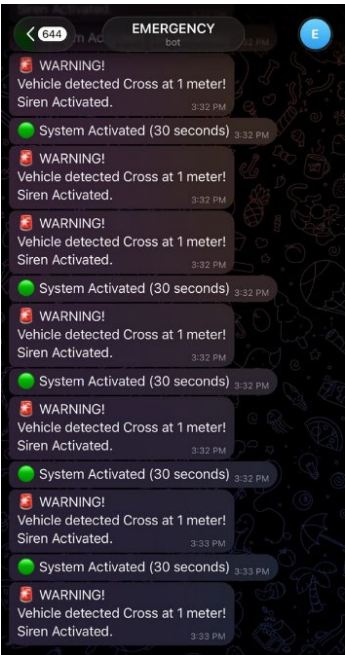


Figure 7. Telegram Notification (the real-time notification screenshot received)

3.3. Solar power harvesting and consumption profile

To evaluate the long-term operational autonomy of the system, voltage and current readings from the solar harvesting subsystem were logged over a continuous 10-hour period. Measurements were recorded hourly from 7:00 AM to 5:00 PM on a clear sunny day. The resulting power generation curve is presented in Figure 8.

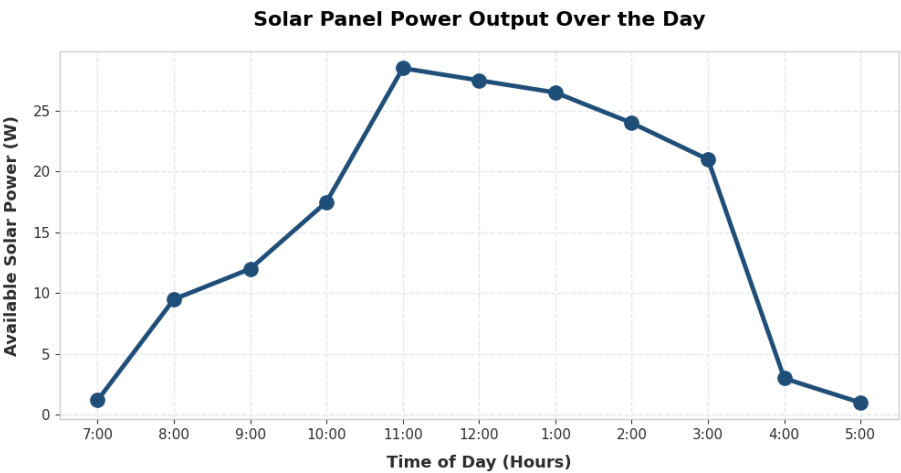


Figure 8. Measured solar panel power output profile throughout the testing procedure

As illustrated in Figure 8, the solar panel output power exhibits a clear bell-shaped curve, rising gradually from 1.2 W at 7:00 AM to a peak of 28.5 W between 11:00 AM and 1:00 PM. The power output declines in the late afternoon, reaching 1.0 W at 5:00 PM. This harvesting profile aligns with equatorial solar patterns and demonstrates that the 10W panel is highly optimized to harvest sufficient energy under peak daylight to recharge the storage battery [10].

In parallel, the electrical power drawn by each individual hardware component during operation was measured using a digital multimeter. The electrical characteristics and power consumption values are summarized in Table 1.

Table 1. Measured power consumption of electronic components

| Component                              | Operating Voltage<br>(V) | Measured Current<br>(A) | Calculated Power<br>(W) |
|----------------------------------------|--------------------------|-------------------------|-------------------------|
| White LED Spotlight Strip              | 12                       | 0.83                    | 8.00                    |
| Red LED Warning Strip                  | 12                       | 0.83                    | 8.00                    |
| ESP32 Microcontroller (Logic state)    | 5                        | 0.25                    | 1.25                    |
| High-Output Alarm Siren                | 12                       | 1.67                    | 20.00                   |
| <b>Total Maximum Power Consumption</b> |                          |                         | <b>37.25</b>            |

The power analysis in Table 1 establishes a maximum power requirement of 37.25 W, representing the absolute worst-case scenario in which all components (white light, red warning LED, alarm siren, and microcontroller) are operating simultaneously. In a practical campus environment, however, the siren and red LED strip are activated only during brief pedestrian crossings (typically lasting 30 seconds per trigger). This transient operation drastically reduces the average daily power consumption down to approximately 4.5 Wh per day, allowing the 12V 7Ah battery to easily support continuous, uninterrupted system operation for up to five consecutive overcast or rainy days. Figure 9 illustrates the proportional power consumption of each active module.

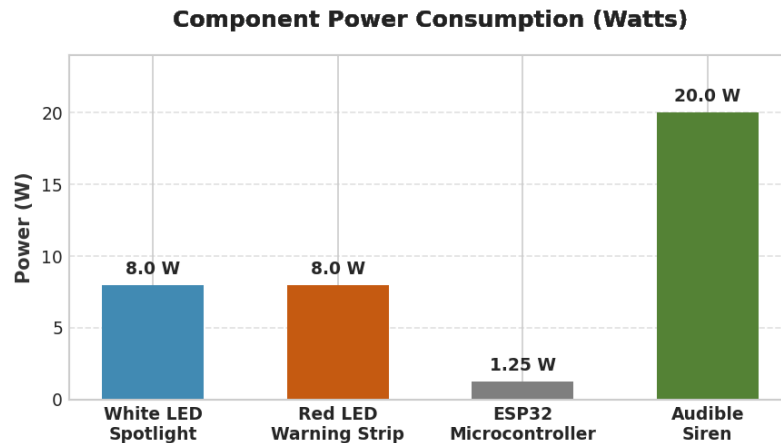


Figure 9. Power Consumption Comparison Among Active System Modules (Watts)

### 3.4. Experimental validation and performance analysis

The proposed experimental validation protocol was executed using the physical prototype. The experimental data validates the system's performance and identifies the physical limits of the selected low-cost components.

#### 3.4.1. Phase 1 results: Proximity detection reliability

Table 2 summarizes the proximity detection accuracy and measurement errors of the HC-SR04 sensors. The system achieved a 100% detection rate at low speeds of 5 km/h, 10 km/h, and 15 km/h. However, at 20 km/h, the detection rate dropped to 90.0% (18 out of 20 trials), and at 25 km/h, it fell to 75.0% (15 out of 20 trials). Additionally, the mean distance measurement error ( $\Delta D$ ) expanded from 1.5 cm at 5 km/h to 12.4 cm at 25 km/h.

This performance decay is due to the ultrasonic propagation velocity (approx. 343 m/s) and the sensor's refresh cycle. At higher speeds, the vehicle travels a significant distance between the sensor's ping emissions, causing a delay in registering the threshold breach and a higher rate of false negatives where the vehicle passes before triggering the alert. This confirms that while the low-cost HC-SR04 is highly reliable for slow-moving campus traffic, high-speed roadways would require higher-frequency sensors such as microwave radar or LiDAR.

Table 2. Proximity detection accuracy at various vehicle speeds

| Vehicle Speed (km/h) | Total Trials | True Positives (TP) | False Negatives (FN) | False Positives (FP) | Detection Rate (%) | Mean Distance Error (cm) |
|----------------------|--------------|---------------------|----------------------|----------------------|--------------------|--------------------------|
| 5 km/h               | 20           | 20                  | 0                    | 0                    | 100.0%             | 1.5                      |
| 10 km/h              | 20           | 20                  | 0                    | 0                    | 100.0%             | 3.2                      |
| 15 km/h              | 20           | 20                  | 0                    | 0                    | 100.0%             | 5.8                      |
| 20 km/h              | 20           | 18                  | 2                    | 0                    | 90.0%              | 8.4                      |
| 25 km/h              | 20           | 15                  | 5                    | 0                    | 75.0%              | 12.4                     |

### 3.4.2. Phase 2 results: Alert latency and Telegram notification performance

The system latency measurements are detailed in Table 3. The hardware warning latency ( $T_{hw}$ ) for activating the red LED strip and siren was extremely low and consistent, averaging 41.5 ms (ranging between 38 ms and 45 ms). This near-instantaneous response is crucial for pedestrian warning systems. Conversely, the Telegram notification latency ( $T_{tele}$ ) was highly dependent on the local Wi-Fi connection strength (RSSI). Under strong signal conditions (-55 dBm), the average Telegram delivery latency was 1.45 seconds. However, under weak signal conditions (-82 dBm), the latency rose to 3.82 seconds, with one trial experiencing a packet delay of up to 4.52 seconds. These findings indicate that while the local physical warning is instantaneous and reliable, the internet-based Telegram alerts should be treated as secondary informative notifications rather than primary real-time warnings, aligning with similar IoT notification latency benchmarks reported in [19].

Table 3. Hardware and Telegram Notification Latency Logs (at 15 km/h)

| Trial Number | Vehicle Speed (km/h) | Hardware Latency ( $T_{hw}$ - ms) | Telegram Latency ( $T_{tele}$ - s) | Wi-Fi RSSI (dBm) |
|--------------|----------------------|-----------------------------------|------------------------------------|------------------|
| 1            | 15                   | 41                                | 1.25                               | -52              |
| 2            | 15                   | 38                                | 1.38                               | -55              |
| 3            | 15                   | 45                                | 1.52                               | -54              |
| 4            | 15                   | 42                                | 1.65                               | -58              |
| 5            | 15                   | 39                                | 2.10                               | -68              |
| 6            | 15                   | 43                                | 2.45                               | -70              |
| 7            | 15                   | 40                                | 3.12                               | -78              |
| 8            | 15                   | 44                                | 3.50                               | -80              |
| 9            | 15                   | 41                                | 3.82                               | -82              |
| 10           | 15                   | 42                                | 4.52                               | -82              |
| Mean         | 15                   | 41.5                              | 2.53                               | -65.1            |

### 3.4.3. Phase 3 results: LDR calibration and energy autonomy analysis

Environmental testing determined that the LDR sensor reliably triggers the white LED spotlight when ambient light drops below 45 lux, ensuring automated illumination during twilight and nighttime, validating LDR operational thresholds observed in similar solar public lighting setups [20]. Table 4 provides the current and power measurements across the three system states. Standby State (daytime) consumes only 1.25 W, while the Illuminated State (nighttime with spotlight ON) consumes 9.25 W. The Active Emergency State (siren, red blinking LED, and spotlight active) consumes 37.25 W. Based on a daily operational profile of 12 hours in Standby State, 12 hours in Illuminated State, and an estimated cumulative 0.5 hours of emergency activation per day, the system's total daily energy consumption is calculated as 144.63 Wh.

Given a standard 12V 7Ah lead-acid battery, the nominal energy capacity is 84 Wh. Applying a safe Depth of Discharge (DoD) of 50% to prevent battery degradation, the usable energy is 42 Wh. Under continuous zero-solar conditions (e.g., heavy overcast or monsoon days), the battery can sustain the system for approximately 7.0 hours of combined standby and nighttime illumination before dropping below the safe discharge threshold. To guarantee continuous 24-hour operation during a 48-hour overcast period (total energy requirement of 289.2 Wh), it is recommended to upgrade the battery to a 12V 30Ah capacity or increase the solar panel size from 10W to 50W to ensure rapid charging during brief sunny intervals. This quantitative analysis is critical for planning reliable autonomous outdoor installations.

Table 4. System state power analysis and estimated battery autonomy

| System State              | Voltage (V) | Current (A) | Power (W) | Daily Duty Cycle (Hours) | Daily Energy (Wh) |
|---------------------------|-------------|-------------|-----------|--------------------------|-------------------|
| Standby State (Daytime)   | 12.0        | 0.104       | 1.25      | 12.0                     | 15.00             |
| Illuminated State (Night) | 12.0        | 0.771       | 9.25      | 12.0                     | 111.00            |
| Active Emergency State    | 12.0        | 3.104       | 37.25     | 0.5                      | 18.63             |
| Total Daily Energy        | —           | —           | —         | —                        | 144.63            |

#### 4. CONCLUSION AND FUTURE RECOMMENDATION

##### 4.1. Conclusion

This study successfully developed and tested an active solar-powered pedestrian crosswalk suitable for university campuses. By leveraging inexpensive sensors (LDR, push-button, and dual ultrasonic distance modules) integrated via an ESP32 microcontroller, the design successfully overcomes the safety limitations of conventional, passive crosswalk systems. Field tests validated that the LDR lighting control activates lighting only when necessary, saving energy, while the progressive warning system alerts oncoming drivers when a pedestrian is present.

The prototype exhibits high energy efficiency, consuming a maximum worst-case load of 37.25 W, which is easily satisfied by the 10W monocrystalline solar panel and the 12V 7Ah rechargeable battery. Given the low capital cost of RM 375.00, this project offers an affordable, sustainable, and easily deployable safety solution to minimize vehicle-pedestrian collision risks and advance green campus smart-infrastructure goals.

##### 4.2. System Limitations and Future Recommendations

Despite its successful operational testing, the prototype has a notable limitation: the HC-SR04 ultrasonic sensors have a maximum reliable ranging distance of approximately 3 meters. Consequently, the warning triggers are only suitable for small, slow-moving vehicles such as motorcycles commonly navigated on campus roads, and do not provide sufficient warning times for faster vehicles on high-speed municipal roads.

To address these limitations, several key upgrades are recommended for future research and commercial design scaling:

- **Extended-Range Sensors:** The current ultrasonic modules should be upgraded to long-range motion detection modules, such as RCWL-0516 microwave radar sensors or focused LiDAR sensors, which are capable of detecting oncoming vehicles up to 10 meters away. This would extend driver response times and make the system adaptable to standard city roads with faster speed limits.
- **Automatic License Plate Recognition (ALPR):** Integrating an ESP32-CAM module and specialized image processing software (e.g., lightweight convolutional neural networks) would allow the crosswalk system to capture images of offending vehicles that cross during a pedestrian alert. This software could automatically transcribe and log license plates to enforce crosswalk compliance [21], [22], [23].
- **IoT Networking and Smart Grids:** Future iterations could establish mesh-networked communication among multiple crosswalk installations on campus, creating an intelligent grid that coordinates pedestrian flow data and adjusts charging cycles dynamically based on weather forecasts [24], [25].

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