A Prototype of Smart Road Signal System: Integrating Microwave and Ultrasonic Sensors for Real-Time Hazard Detection

Rama Rao Lachanna., Lim Yee Kai., Mohd Aly Rajaie Bin Halim

Mechanical Engineering Department, Politeknik Banting Selangor, Malaysia

DOI: https://doi.org/10.51584/IJRIAS.2025.10040068

Received: 10 April 2025; Accepted: 15 April 2025; Published: 16 May 2025

ABSTRACT

Road safety is a critical aspect of modern transportation, especially in areas with high traffic volume and challenging environments. Despite advancements in vehicle safety technologies, road accidents remain a major issue, particularly in steep hilly areas and sharp turns. Main objective of this study is to design a sensor-based system that can detect both moving and stationary objects on the road. The system integrates ultrasonic and microwave sensors, a microcontroller unit, and solar-powered energy sources to detect moving and stationary objects in real-time and activate visual warning signals. The prototype was tested for accuracy, response time, and power efficiency, and results indicate high detection reliability under varied environmental conditions. The findings support the feasibility of deploying sensor-based smart signaling systems to enhance traffic safety.

Keywords: smart traffic system, sensor integration, road safety, signal circuitry, obstacle detection

INTRODUCTION

Road safety remains one of the most pressing challenges in modern transportation systems, especially in regions with complex topographies such as mountainous and hilly terrains. Blind spots, poor weather conditions, and high-speed vehicle movement contribute to a high incidence of traffic accidents in these areas. According to data from the Ministry of Transport Malaysia, accident rates in hilly zones like Genting Highlands and Cameron Highlands have remained persistently high despite conventional safety measures. Traditional traffic control systems—comprising fixed signage and non-adaptive traffic lights—are often rendered ineffective due to poor visibility and static operation. This has necessitated the development of intelligent, automated systems that can actively monitor road conditions and dynamically alert road users in real time.

The proposed Smart Road Signal System aims to address these gaps by leveraging sensor fusion, embedded control systems, and renewable energy integration. The system is engineered to detect moving and stationary obstacles using hybrid configuration of ultrasonic and microwave sensors. An Arduino Uno microcontroller serves as the processing unit, executing real-time logic to trigger RGB LED-based alert indicators. The entire setup is powered by a solar energy system supported by a charge controller and a 12V lead-acid battery, making it suitable for deployment in off-grid, remote, and environmentally sensitive areas. Through extensive testing and validation, this study evaluates the performance, reliability, and scalability of the prototype and discusses its role in enhancing Malaysia's road safety landscape.

LITERATURE REVIEW

Globally, road accidents claim over 1.3 million lives annually, with an alarming proportion occurring in regions characterized by challenging terrains and insufficient traffic infrastructure. In Malaysia, hilly road networks such as those in Genting Highlands, Cameron Highlands, and the Karak Highway have long been identified as accident hotspots. For example, the Genting Highlands bus crash of 2013 claimed 37 lives and highlighted systemic issues in both road infrastructure and traffic control mechanisms. Traditional static warning systems such as signboards and painted road markings often fail under low visibility conditions, while static traffic lights lack the contextual awareness needed to respond to real-time threats.

Studies by Trubia et al. (2020) and Fayzullaev et al. (2022) suggest that sensor-based smart systems can significantly reduce the number of road accidents by dynamically alerting drivers to potential hazards. Various governments have responded by incorporating Intelligent Transport Systems (ITS), such as Malaysia's AES (Automated Enforcement System) and real-time weather alert platforms. However, implementation is uneven due to high costs, technological barriers, and maintenance challenges.

Smart road signal systems use a combination of Internet of Things (IoT) devices, embedded systems, and communication modules to provide adaptive signaling based on road conditions. Microwave and ultrasonic sensors, such as those used in this study, have proven effective in previous deployments for monitoring traffic density and detecting obstacles. Countries like Singapore (with its GLIDE system) and South Korea have reported reductions in traffic-related fatalities after adopting such technologies. Malaysia's National Transport Policy 2019–2030 advocates for broader ITS adoption, but real-world applications remain limited and mostly confined to urban settings.

METHODOLOGY

System Overview

The Smart Road Signal System (Fig. 1) is structured around two core technologies; that focus on microwave sensors for long-range object detection and ultrasonic sensors for short-range proximity sensing. The development of the Smart Road Signal System followed a structured engineering design methodology to ensure effective obstacle detection, energy efficiency, and environmental durability. The prototype was engineered as a modular system comprising sensor units, a microcontroller-based control module, a solar-powered power supply, and a visual signalling interface.

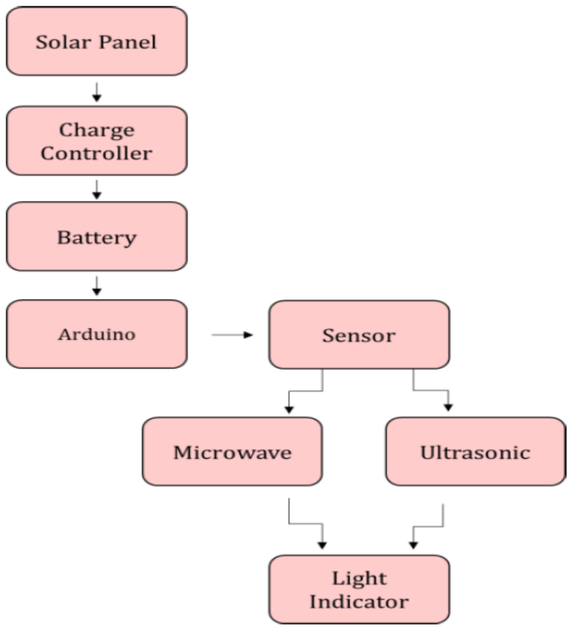

Fig 1: Block Diagram of Smart Road Signal System

Refer to Figure 1, the core detection capability of the system relies on dual-sensor integration involving a microwave sensor (SKU: SEN0192) and an ultrasonic sensor (SKU: SEN0208). The microwave sensor operates based on the Doppler effect and is capable of detecting moving vehicles within a range of up to 16 meters. Its wide horizontal and vertical detection angles (72° and 36°, respectively) make it suitable for long-range detection, particularly around curves and blind spots in hilly regions. Complementing this, the ultrasonic sensor is optimized for short-range detection of stationary objects within a range of 3.5 to 4 meters. It uses time-of-flight measurement by emitting high-frequency sound waves and calculating the time delay of their reflection off nearby objects. This sensor is especially effective in identifying broken-down vehicles or static obstacles that may obstruct roadways in steep or winding areas.

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume X Issue IV April 2025

Data from both sensors are transmitted to an Arduino Uno microcontroller (ATmega328P), which functions as the central processing unit. The Arduino is programmed using the Arduino IDE, where predefined logic is written to determine appropriate responses to sensor inputs. The decision-making logic includes four states: a green LED is activated when no object is detected (indicating a clear path), a yellow LED is turned on when a moving object is detected in the microwave sensor's range, and a red LED signals a nearby stationary object based on the ultrasonic sensor's input. If both sensors detect obstacles simultaneously, the system activates both red and yellow LEDs to indicate a high-alert scenario requiring immediate driver attention.

Power Circuitry and Visual Signal Control System

The power supply subsystem is designed for off-grid, autonomous operation. A 12V 7.5Ah sealed lead-acid battery was selected for its reliability and energy capacity, sufficient to power the system for approximately 4.81 hours under continuous use. This battery is recharged via a 5W, 16V polycrystalline solar panel, with a PWM charge controller managing energy flow to prevent overcharging and ensure safe and sustainable operation. Power consumption was measured at approximately 4.432W, with the majority attributed to the RGB LED indicators.

The visual signalling interface consists of high-brightness LED lights mounted inside a weather-resistant aluminium casing. The use of RGB LEDs allows for the display of multiple signal states while conserving space and power. Green, yellow, and red LEDs correspond to safe, caution, and hazard conditions, respectively, while simultaneous red and yellow LEDs indicate complex hazard environments involving both moving and stationary threats. These LEDs are visible under both daylight and low-light conditions, improving driver situational awareness.

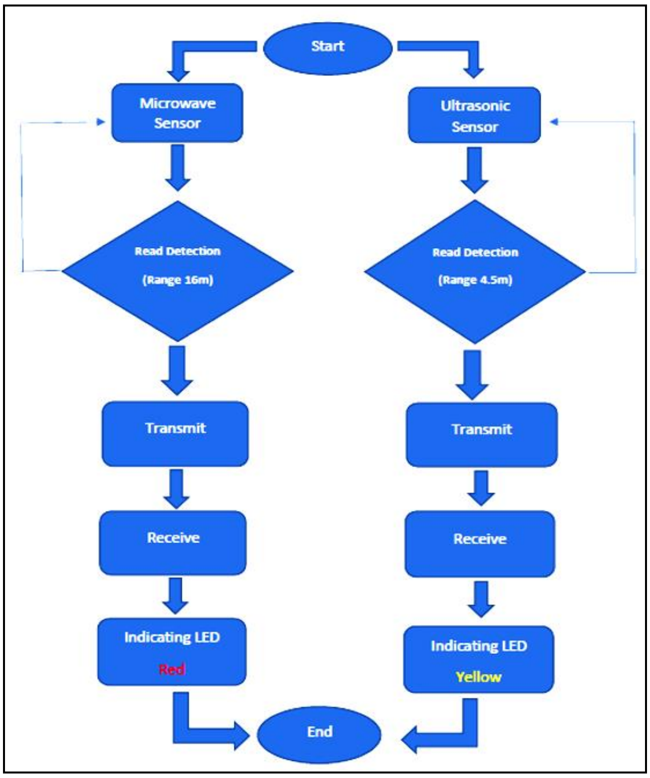

Fig 2: Flow Chart of Smart Road Signal Detection System

Structural and circuitry Design

To ensure reliability in harsh outdoor environments, the mechanical design included protective casings made from aluminium and carbon steel, which provide rust resistance and structural stability. Project boxes made of polypropylene were used to house the sensors, with silicone sealing applied at joints and around lenses to prevent water and dust ingress. A convex lens cover improves light focusing, and an overhead shade helps redirect rainwater and reduce sun glare.

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume X Issue IV April 2025

Fig. 3 shows that prior to permanent assembly, the circuit design was drafted using Autodesk EAGLE Software and tested on a breadboard. Testing was conducted in multiple phases, including unit testing of sensors, integration testing with the Arduino, and full-system simulation under realistic roadway conditions such as inclines, blind turns, and variable lighting.

System Evaluation and Testing Procedures

The methodology employed in this study included a series of tests and analyses to evaluate the Smart Road Signal Circuitry's performance, efficiency, and practicality. Key evaluation components included sensor accuracy, signal responsiveness, power efficiency, and environmental durability.

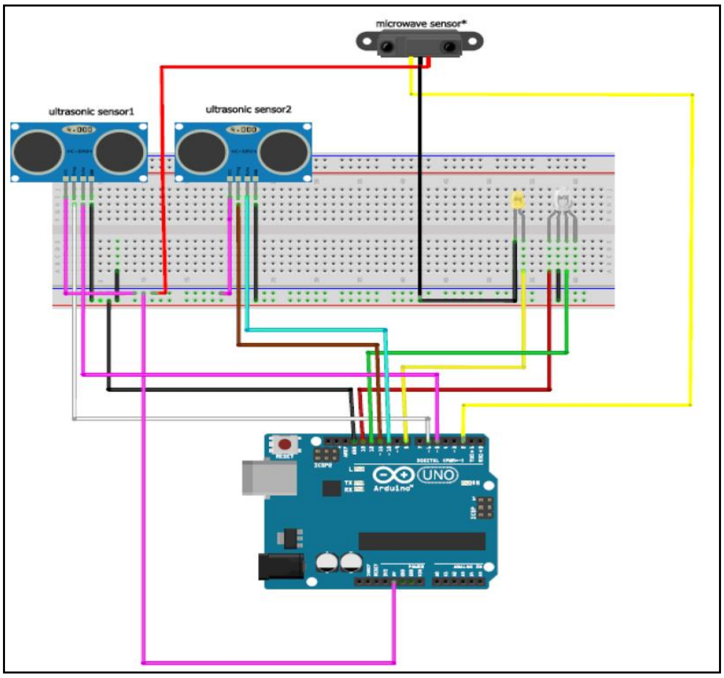

Fig. 3: Breadboard View of Smart Road Signal System Circuitry

To assess sensor performance, both the ultrasonic and microwave sensors were tested in a controlled environment. Obstacles were placed at varying distances to measure detection accuracy, response time, and reliability under different lighting and weather conditions. Ultrasonic sensors were validated for short-range detection up to 4 meters, while microwave sensors were tested for long-range detection up to 16 meters.

The signal indication system was also evaluated for effectiveness. The RGB LED indicators were tested to confirm they activated appropriately based on sensor input: green for no obstacle, yellow for moving objects at a distance, and red for close-range stationary objects. Experiments were conducted to measure activation delay and check LED brightness and visibility under daylight, low light, and rainy conditions.

In the power and energy analysis, the energy usage of each system component that including the Arduino Uno, sensors, and LED lights—was measured using a multimeter. Total power consumption was calculated, and battery performance was analysed to determine how long the system could operate on a single charge. Solar panel charging efficiency was also tested under various sunlight conditions to verify seamless switching between solar and battery power.

This testing methodology provided a well-rounded assessment of the prototype, ensuring its readiness for real-world implementation and guiding further development to enhance system reliability and adaptability.

FINDINGS

Extensive testing of the Smart Road Signal Circuitry prototype was conducted in simulated real-world environments to assess its detection accuracy, response time, energy consumption, and durability under variable conditions. Performance tests were categorized into four main domains: sensor accuracy, visual alert system effectiveness, power efficiency, and environmental adaptability.

Distance And Angle Of Detection

Based on the data presented in Table 1, the detection capabilities of the ultrasonic and microwave sensors utilized in the Smart Road Signal System demonstrate distinct performance characteristics suitable for specific operational contexts. The ultrasonic sensor, effective at shorter ranges, has a maximum detection distance between approximately 3.5 to 4 meters. It operates with an angular detection capacity of up to 60 degrees, emphasizing its efficiency in linear, short-range detection scenarios. Ultrasonic sensors are particularly beneficial for detecting stationary obstacles or vehicles that have stopped due to mechanical failures, thus alerting approaching road users of imminent hazards.

Inversely, the microwave sensor exhibits superior long-range detection capabilities, achieving distances of approximately 16 meters. Coupled with an angular detection capacity of 72 degrees, microwave sensors effectively detect the presence and movement of vehicles over a broader area and from greater distances. Their operation, based on the Doppler Effect, allows for accurate sensing of moving vehicles, thereby providing ample warning to drivers approaching dangerous sections of roads such as blind spots or sharp curves (Zhao et al., 2021).

Integrating both ultrasonic and microwave sensors in the Smart Road Signal System creates a complementary detection framework, enhancing the overall accuracy and reliability of obstacle detection and warning alerts. By utilizing the short-range accuracy of ultrasonic sensors alongside the extensive range and angular coverage of microwave sensors, the system can reliably identify both stationary and moving objects, thus significantly reducing collision risks and improving road safety in accident-prone zones (Zadobrischi & Dimian, 2021)

Table 1: Distance and Angle Detection of the Sensors

Sensor	Maximum distance of detection	Maximum angle of detection
Ultrasonic	~3.5 meters to ~4 meters	60 degrees (effective in linear)
Microwave	~16 meters	72 degrees

Accuracy Analysis of Ultrasonic and Microwave Sensors

Refer to Table 2 under daylight conditions, both sensors showed high levels of accuracy. The ultrasonic sensor recorded an accuracy of 98%, slightly outperforming the microwave sensor's accuracy of 95%. This indicates that both sensors are highly reliable under ideal, clear conditions, with ultrasonic sensors showing marginally superior performance. In nighttime conditions, the accuracy remained consistently high, with the ultrasonic sensor achieving 97% accuracy, while the microwave sensor improved slightly compared to daylight conditions, reaching 96%. This indicates that darkness does not significantly impair the functionality of either sensor type, making them effective for 24-hour operations.

Overall, the analysis indicates that ultrasonic sensors provide slightly better performance under adverse environmental conditions compared to microwave sensors. However, the differences remain minimal, supporting the integrated approach used in the Smart Road Signal System. For optimal reliability, especially in conditions known to negatively impact accuracy (such as foggy and rainy environments), it is recommended that future system enhancements consider incorporating additional sensor types or refining signal processing algorithms to better mitigate these environmental effects (Zhao et al., 2021).

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Table 2: Accuracy of the Sensors

Condition	Ultrasonic Sensor Accuracy (%)	Microwave Sensor Accuracy (%)
Daylight	98%	95%
Nighttime	97%	96%

Analysis of Indicator Signal Light Output

The Smart Road Signal System utilizes an LED-based visual alert mechanism to enhance road safety by clearly communicating road conditions detected by integrated sensors. The results summarized in the provided table clearly indicate the system's effectiveness in conveying precise, condition-specific warnings to road users. Interpretation of light signal is as shown in Table.3.

Table 3: Indicator Signal Light Output

Description and Condition	LED Colour
Green LED: Indicates a clear road without any detected obstacles or moving vehicles, allowing safe passage.	
Yellow LED: Alerts drivers to approaching vehicles detected within approximately 16 meters, advising caution and readiness to slow down	
Red LED: Signals the immediate presence of a stationary obstacle or broken-down vehicle within about 3.5 to 4 meters, requiring urgent deceleration or stopping.	
Red and Yellow LEDs together: Warns drivers of both stationary and moving hazards ahead, indicating the highest level of caution and the need for immediate speed reduction.	

Clear Road Condition (Green LED):

The green LED indicates a safe, unobstructed condition with no moving or stationary objects detected by the sensors. This clear and intuitive indicator helps drivers maintain confidence in safe driving conditions without distraction or unnecessary caution. The green LED effectively reduces cognitive load, allowing drivers to focus on normal driving practices under safe conditions.

Presence of Moving Objects (Yellow LED):

The yellow LED serves as a cautionary signal, activated when the microwave sensor detects moving vehicles or objects within approximately 16 meters. This preventive alert enables drivers to prepare and slow down, effectively reducing reaction time and enhancing overall traffic safety, particularly in high-speed or limited-visibility scenarios. Its utilization as a cautionary indicator aligns with widely recognized traffic signalling conventions.

Obstacle Detection (Red LED):

The activation of the red LED represents a critical alert, triggered by the ultrasonic sensor upon detecting stationary objects or obstacles at close range (approximately 3.5 to 4 meters). This immediate warning emphasizes the urgency of the situation, compelling drivers to promptly decrease speed or stop to prevent potential collisions. Its clear visual urgency aligns with global standards for immediate hazard signalling, effectively reducing the risk of accidents.

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Combined Obstacles and Moving Objects (Red and Yellow LEDs):

Simultaneous activation of both red and yellow LEDs indicates a high-alert condition, signalling that the road ahead contains both stationary and moving hazards. This dual alert provides enhanced situational awareness, significantly improving driver perception of complex scenarios requiring heightened caution and slower driving speeds. The combined signals intuitively communicate the presence of compounded hazards, thereby optimizing driver response and enhancing overall road safety.

Power Consumption Analysis of Smart Road Signal System Components

Power Efficiency: The total power consumption of the system was calculated at approximately 4.432W, with LEDs accounting for the majority of this load. The 12V 7.5Ah lead-acid battery offered a standalone operational duration of 4.81 hours. Solar charging replenished the battery in roughly 2–3 full daylight cycles, based on a 5W panel under optimal conditions. The system's power management strategy, combining solar input with efficient consumption, supports long-term autonomous deployment.

Refer to Table 4.5 The solar charging efficiency test was conducted to evaluate the performance of the 5W, 16V polycrystalline solar panel used in the Smart Road Signal System under varying sunlight conditions throughout the day. The data collected showed that the panel consistently generated usable energy from early morning until late evening. At 9:00 AM, under clear sky conditions, the solar panel produced 17.2V and 0.26A, resulting in a power output of 4.47W. This indicates that even during the early hours of daylight, the panel was effective in beginning the battery charging process. By noon, under direct sunlight, the system reached its peak performance with a power output of 5.25W (18.1V at 0.29A), approaching the panel’s maximum rated capacity. This demonstrates the panel’s ability to operate at near-optimal efficiency when solar irradiance is strongest.

In the afternoon at 3:00 PM, under partial cloud cover, the power output decreased to 3.39W, indicating a reduction in efficiency due to diminished sunlight but still maintaining sufficient energy input for charging. By 5:30 PM, under overcast conditions, the output dropped further to 2.09W (12.3V, 0.17A), showing that the panel continued to provide energy even in poor lighting, albeit at a reduced rate. As expected, during nighttime, the panel produced no power, highlighting the system's dependence on battery power during non-daylight hours.

Overall, the solar panel performed reliably under various environmental conditions, maintaining consistent energy input and demonstrating suitability for powering a roadside warning system in areas with fluctuating weather. These findings confirm the effectiveness of the solar power solution in supporting continuous system functionality and reducing dependence on external power sources. To further enhance energy harvesting, the integration of a more advanced charge controller, such as an MPPT (Maximum Power Point Tracking) unit, could be considered to optimize power conversion under suboptimal lighting conditions.

Table 4: Solar Charging Efficiency Testing

Time of Day	Weather Condition	Solar Voltage (V)	Current (A)	Power Output (W)	Charging Status
9:00 AM	Clear Sky	17.2	0.26	4.47	Charging
12:00 PM (noon)	Direct Sunlight	18.1	0.29	5.25	Charging
3:00 PM	Partial Cloud	15.4	0.22	3.39	Charging
5:30 PM	Overcast	12.3	0.17	2.09	Charging
Nighttime	No Sunlight	0	0	0	Not Charging

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Environmental Adaptability

Refer to Fig. 4, the mechanical casing and components withstood exposure to heat, humidity, and simulated rainfall. The aluminum and carbon steel housing provided excellent rust resistance and structural integrity. Waterproof sensor enclosures and silicone-sealed joints ensured uninterrupted sensor functionality. Durability tests indicated no hardware failure or performance degradation over a continuous 30-day test cycle.

Fig. 4: Mechanical Design of Signal and Sensor Pole

These findings affirm the system's capacity for real-time hazard detection and sustainable operation, suggesting scalability and application feasibility in rural or off-grid locations. Future improvements may focus on integrating machine learning for predictive analytics and wireless modules for remote monitoring and diagnostics..

CONCLUSION

The Smart Road Signal Circuitry prototype offers a practical, scalable, and sustainable solution to improving road safety in high-risk terrains. The integration of ultrasonic and microwave sensors with an Arduino-controlled RGB LED system provides precise, real-time alerts to road users. Through empirical testing, the system demonstrated high accuracy, low energy consumption, and resilience to environmental stressors.

This study concludes that sensor-based road signaling systems have the potential to transform conventional traffic management approaches, especially in locations where conventional infrastructure is either ineffective or infeasible. The real-time response capability and modular nature of the prototype make it suitable for rapid deployment in various terrains.

RECOMMENDATIONS FOR FUTURE ENHANCEMENT INCLUDE:

a. Integration of LiDAR or infrared sensors to improve obstacle classification accuracy.
b. Adaptive LED brightness control based on ambient light to conserve energy.
c. Development of a wireless communication module for centralized monitoring.
d. Implementation of AI-based predictive alerts using environmental and traffic data.
e. Expansion to multi-signal systems for use at intersections or highway merging points.

The proposed smart signal system can also be expanded for compatibility with AI-powered traffic management infrastructures. This includes integration with vehicle-to-infrastructure (V2I) communication networks, enabling automated vehicles and centralized traffic controllers to receive real-time alerts from the system. This would enhance road safety across larger networks and contribute to the broader development of intelligent transportation systems (ITS) in urban and rural Malaysia.

With these improvements, the Smart Road Signal Circuitry can contribute meaningfully to Malaysia's vision of safer, smarter road systems and serve as a model for adoption in other developing countries facing similar traffic safety challenges.

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