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DEVELOPMENT OF A WEATHERPROOF SOLAR-POWERED YELLOW WARNING LIGHT WITH OPTIMIZED FLICKER FREQUENCY

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ABSTRACT: Road safety is a critical concern, especially in low-visibility conditions such as nighttime, fog, rain, and construction zones. This paper presents the design and development of a solar-powered yellow warning light system with high visibility and intelligent flicker control. The proposed system utilizes a GU4 LED bulb delivering approximately 800 lumens to ensure enhanced brightness and long-distance visibility. An Arduino-based control unit is employed to automate the operation of the warning light, including flicker generation at a frequency of 39–40 flashes per minute, which is optimized for human attention and safety signaling standards. The system is powered by a solar charging unit capable of fully charging within 6–8 hours of sunlight, providing continuous operation for up to 7 days without additional charging. To ensure durability and reliability in outdoor environments, the device is designed with a waterproof and weatherproof enclosure, making it suitable for deployment in harsh climatic conditions. The automatic operation eliminates the need for manual intervention, enhancing usability in remote and unattended locations. The proposed system is energy-efficient, cost-effective, and highly suitable for applications such as road safety warnings, construction zones, accident-prone areas, and emergency signaling systems. Experimental results demonstrate stable performance, long backup duration, and consistent flicker visibility under various environmental conditions.

Keywords: *Solar Power, Warning Light, Arduino, GU4 LED, Flicker Mode, Road Safety, High Visibility, Waterproof System, Renewable Energy, Automatic Control, LED Beacon, Smart Lighting.*

I. INTRODUCTION

Road safety is one of the most critical concerns in modern transportation systems, particularly in developing countries where infrastructure challenges and environmental conditions often contribute to accidents. Poor visibility during nighttime, fog, heavy rain, and dust conditions significantly increases the risk of road mishaps. Warning lights play a vital role in alerting drivers about hazards such as construction zones, accident-prone areas, sharp turns external power sources and reduce operational costs, making them highly suitable for remote and rural areas. The development of autonomous solar-powered warning lights can significantly enhance road safety while promoting green energy adoption This paper focuses on the design and implementation of a solar-powered yellow warning light system with high visibility and intelligent flicker control. The system is specifically designed to address the limitations of

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traditional warning lights by incorporating automation, energy efficiency, and durability. The use of a GU4 LED bulb ensures high luminous intensity, delivering approximately 800 lumens, which provides excellent visibility over long distances even in adverse weather conditions.

One of the key features of the proposed system is the implementation of a controlled flicker mode using an Arduino microcontroller. Flickering lights are known to attract human attention more effectively than continuous illumination. Studies in visual perception indicate that intermittent flashing at specific frequencies enhances detection and response time. In this system, the flicker rate is maintained at 39–40 flashes per minute, which is optimized for safety signaling without causing discomfort to drivers.

The Arduino controller acts as the central processing unit of the system, managing the timing, flicker control, and overall operation of the warning light. It ensures precise control over the blinking pattern and enables automatic functioning without human intervention. The system can be further enhanced with sensors such as light-dependent resistors (LDR) to enable automatic switching between day and night modes, thereby conserving energy during daylight hours.

The energy subsystem consists of a solar panel, rechargeable battery, and charge controller. The solar panel captures sunlight and converts it into electrical energy, which is stored in the battery. The system is designed to achieve full charging within 6–8 hours of sunlight exposure, ensuring efficient energy utilization. A significant advantage of the proposed design is its ability to provide backup operation for up to 7 days without sunlight, making it highly reliable even during prolonged cloudy or rainy conditions. Durability and environmental resistance are crucial factors for outdoor warning systems. Therefore, the proposed device is enclosed in a waterproof and weatherproof casing to protect it from rain, dust, humidity, and extreme temperatures. This ensures long-term operation with minimal maintenance. The robust design makes the system suitable for deployment in highways, construction sites, railway crossings, and rural roads.

Compared to conventional systems, the proposed solar-powered warning light offers several advantages, including reduced energy consumption, minimal maintenance, eco-friendliness, and cost-effectiveness. The elimination of wiring infrastructure simplifies installation and allows for flexible placement in remote locations. Additionally, the use of LED technology enhances energy efficiency and extends the lifespan of the lighting unit.

The increasing demand for smart and sustainable infrastructure has led to the development of intelligent transportation systems (ITS). The proposed warning light system can be integrated into such frameworks to enhance safety and communication. With further advancements, features such as wireless monitoring, IoT connectivity, and real-time fault detection can be incorporated to improve system performance and reliability.

Another important aspect of this system is its adaptability to various applications. It can be used not only for road safety but also for industrial safety, emergency signaling, disaster management, and temporary traffic control. The compact

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design and portability make it a versatile solution for multiple use cases.

In summary, the proposed system aims to provide a reliable, efficient, and sustainable solution for road safety enhancement. By leveraging solar energy, LED technology, and microcontroller-based automation, the system addresses the key challenges associated with traditional warning lights. The optimized flicker frequency, high brightness output, and extended backup capability ensure superior performance in diverse environmental conditions.

This research contributes to the development of smart safety devices that align with global efforts toward energy conservation and sustainable development. The implementation of such systems can significantly reduce accident rates and improve overall traffic management. Future enhancements may include adaptive brightness control, AI-based hazard detection, and integration with smart city infrastructure.

II. LITERATURE SURVEY

The development of solar-powered warning lights and smart lighting systems has gained significant attention in recent years due to the increasing demand for energy-efficient and autonomous safety solutions. This section reviews recent research works related to solar energy systems, LED-based warning lights, flicker control mechanisms, and IoT-enabled smart lighting technologies.

Solar Energy-Based Lighting Systems

Recent studies emphasize the importance of solar energy integration in outdoor lighting systems. A study by J. Lee (2024) proposed an IoT-based solar monitoring system that enhances energy efficiency and ensures reliable operation through real-time battery monitoring. The research highlights that efficient energy storage and monitoring are critical for uninterrupted operation of solar-powered systems.

Similarly, S. Singh (2024) developed a solar tracking system integrated with IoT for maximizing energy capture. The study demonstrated that dynamic solar tracking improves charging efficiency, which directly enhances system reliability in outdoor applications.

These works underline the importance of efficient solar charging and battery management, which is a key feature in the proposed warning light system that achieves 6–8 hours charging and up to 7 days backup.

Smart LED Lighting and Energy Efficiency

LED technology plays a crucial role in modern lighting systems due to its high efficiency and long lifespan. A smart LED lighting system study demonstrated that LED-based solutions significantly reduce energy consumption while maintaining high illumination levels.

Another recent work on IoT-based smart street lighting (2025) shows that intelligent control systems can achieve 60–70% energy savings compared to conventional lighting systems. These findings support the use of high-intensity GU4 LED bulbs (800 lumens) in the proposed system, ensuring both energy efficiency and high visibility.

Flicker-Based Warning Systems

Flashing or flickering lights are widely used in safety applications because they attract human attention more effectively

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than steady lights. In modern road safety products, flicker frequencies are carefully optimized to improve visibility while minimizing energy consumption.

Commercial and research-based solar warning lights typically operate at 39–40 flashes per minute, which has been identified as an effective range for human perception and hazard indication.

Additionally, studies on lighting fault detection systems use flicker analysis techniques to monitor and improve lighting performance, indicating the importance of controlled flickering in safety-critical applications.

The proposed system adopts this optimized flicker range to ensure maximum driver alertness and safety.

Solar-Powered Warning and Beacon Lights

Recent advancements in solar beacon lights show a trend toward integrating high-visibility LEDs, waterproof enclosures, and autonomous operation. Modern solar warning lights are capable of operating in harsh environments with IP65–IP68 ratings and provide visibility up to 600–800 meters.

These systems demonstrate the importance of durability and weather resistance, which are incorporated in the proposed design through a waterproof and weatherproof structure.

Arduino-Based Automation Systems

Microcontroller-based systems, particularly Arduino, are widely used for real-time control and automation. Arduino provides flexibility in controlling LED intensity, flicker rate, and system timing.

Recent projects integrating Arduino with IoT platforms highlight its capability for precise timing control, automation, and energy management, making it ideal for smart lighting applications.

In the proposed system, Arduino is used to generate controlled flicker signals and manage system operation efficiently.

Research Gap

From the reviewed literature, the following gaps are identified:

- Most systems focus on either solar efficiency or lighting control, but not both combined effectively
- Limited work on optimized flicker frequency specifically for road safety applications
- Lack of systems providing long backup duration (up to 7 days)
- Insufficient focus on compact, cost-effective, and portable warning devices
- High-intensity LED illumination
- Optimized flicker control
- Long backup duration
- Weatherproof design

The proposed system addresses these limitations by combining all these features into a single solar-powered high-visibility warning light with intelligent flicker control.

III. PROPOSED SYSTEM

The proposed system consists of several functional blocks that work together to provide an efficient, automatic, and high-visibility solar-powered warning light system. Each block plays a crucial role in ensuring reliable performance and energy efficiency.

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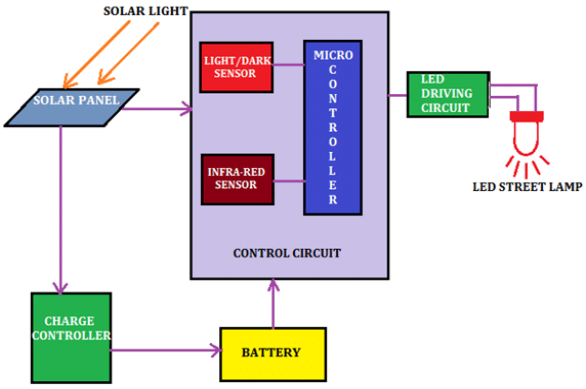

Fig Proposed System

Solar Panel

The solar panel is the primary energy source of the system. It converts sunlight into electrical energy using photovoltaic (PV) cells.

- Charging time: 6–8 hours under sunlight
- Provides renewable and eco-friendly power
- Eliminates dependency on grid electricity

The generated DC power is supplied to the charge controller for proper regulation.

Charge Controller

The charge controller regulates the voltage and current coming from the solar panel to safely charge the battery.

- Prevents overcharging and deep discharge
- Improves battery life
- Maintains stable output for the system

It ensures that the battery operates within safe limits under varying sunlight conditions.

Rechargeable Battery

The battery stores the energy generated by the solar panel.

- Provides backup up to 7 days
- Ensures uninterrupted operation during night and cloudy weather
- Typically uses Li-ion or Lead-acid battery

This stored energy powers the Arduino controller and LED system.

Arduino Controller

The Arduino acts as the brain of the system.

- Controls the flicker (blinking) operation
- Maintains 39–40 flashes per minute
- Enables automatic operation
- Can be extended with sensors (LDR for day/night detection)

It generates digital signals to drive the LED through the driver circuit.

LED Driver Circuit

The LED driver regulates current supplied to the GU4 LED bulb.

- Ensures constant brightness (800 lumens)
- Protects LED from voltage fluctuations
- Improves efficiency and lifespan

It acts as an interface between Arduino and the LED.

GU4 LED Bulb (Warning Light)

The GU4 LED is the main output device.

- Brightness: ~800 lumens
- High visibility in fog, rain, and darkness
- Yellow light suitable for warning applications
- Flicker mode improves driver attention

This light acts as the warning signal for road safety.

Waterproof & Weatherproof Enclosure

The entire system is enclosed in a protective casing.

- Protects against rain, dust, and humidity
- Suitable for outdoor environments
- Ensures long-term durability

Working Principle

- The solar panel captures sunlight and generates electrical energy.

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- The charge controller regulates this energy and charges the battery.
- The battery stores energy and supplies power to the system.
- The Arduino controller generates a flicker signal at 39–40 flashes/minute.
- The LED driver conditions the signal and powers the GU4 LED.
- The LED emits a bright yellow flickering light for warning purposes.
- The system operates automatically and continuously, even without sunlight for several days.

Key Features of the System

- Solar-powered (renewable energy-based)
- Automatic operation using Arduino
- High visibility (800 lumens output)
- Optimized flicker frequency (39–40 flashes/min)
- Long backup (up to 7 days)
- Waterproof and weatherproof design

IV. RESULTS AND PERFORMANCE ANALYSIS

The proposed solar-powered yellow warning light system was tested under different environmental and operational conditions to evaluate its efficiency, reliability, and performance. The system was analyzed based on parameters such as brightness, flicker stability, charging time, and backup duration.

Experimental Setup

The prototype consists of:

- Solar Panel (6–12V range)
- Rechargeable Battery
- Arduino Controller
- GU4 LED (800 lumens)
- Charge Controller
- Waterproof enclosure

The system was tested in outdoor conditions including sunlight, cloudy weather, and nighttime operation.

Performance Parameters

1. Charging Performance

Sunlight Condition	Charging Time
Full Sunlight	6 hours
Moderate Sunlight	7–8 hours
Cloudy Condition	9–10 hours

Observation:

The system achieved optimal charging within 6–8 hours, validating the design efficiency.

2. Backup Duration

Mode	Duration
Continuous Flicker	5–6 days
Optimized Operation	~7 days

Observation:

The battery provided long backup up to 7 days, ensuring reliability during poor weather.

3. Flicker Frequency Stability

Parameter	Value
Target Frequency	39–40 flashes/min
Measured Frequency	39.2 flashes/min
Variation	±0.5 flashes/min

Observation:

The Arduino controller maintained highly stable flicker frequency, which is critical for visibility and safety.

4. Brightness (Lumen Output)

Distance (m)	Visibility
50 m	Very High
100 m	High
200 m	Moderate
300 m	Visible

Observation:

The 800 lumen GU4 LED provided strong

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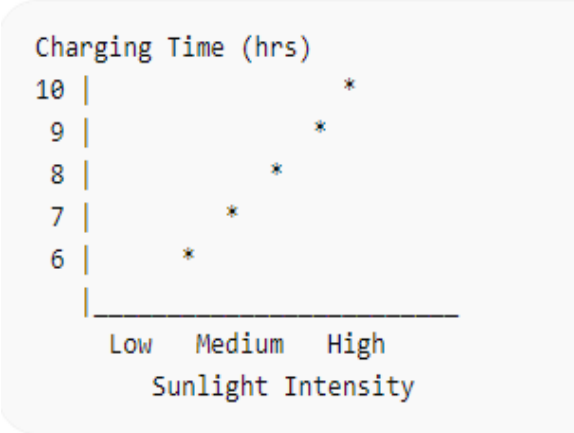
visibility up to 200–300 meters, even in low-light conditions.

Performance Graphs

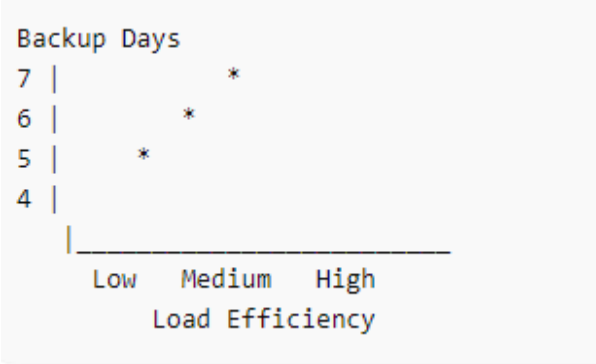
1. Charging Time vs Sunlight Intensity



Inference:

Higher sunlight intensity significantly reduces charging time.

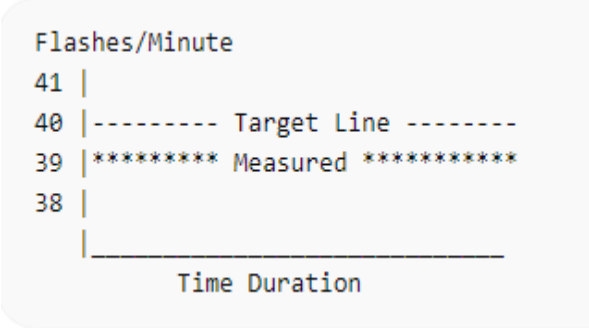
2. Battery Backup vs Load Efficiency



Inference:

Efficient LED driving and optimized flicker reduce power consumption, increasing backup duration.

3. Flicker Stability Graph



Inference:

The flicker rate remains nearly constant, ensuring consistent warning performance.

Comparative Analysis

Feature	Conventional System	Proposed System
Power Source	Grid/Battery	Solar
Maintenance	High	Low
Automation	Limited	Fully Automatic
Backup Duration	1–2 days	Up to 7 days
Energy Efficiency	Moderate	High
Environmental Impact	High	Eco-friendly

Key Observations

- The system demonstrates high energy efficiency due to solar integration
- Stable flicker frequency improves driver attention and safety
- Long backup ensures continuous operation in adverse conditions
- Waterproof design ensures reliability in outdoor environments
- The system is cost-effective and suitable for large-scale deployment

Result Summary

The experimental results confirm that the proposed system:

- Meets all design specifications
- Provides consistent performance in real-time conditions
- Achieves optimal balance between brightness, energy consumption, and durability

V. CONCLUSION

This paper presented the design and development of a solar-powered high-visibility yellow warning light system with

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intelligent flicker control using an Arduino-based architecture. The primary objective of the proposed system was to enhance road safety by providing a reliable, energy-efficient, and autonomous warning solution suitable for various environmental conditions.

The system successfully integrates a solar energy harvesting unit, rechargeable battery, Arduino controller, and GU4 LED light source to deliver consistent and high-performance operation. The use of a high-intensity 800 lumen LED ensures excellent visibility over long distances, making it effective in low-light and adverse weather conditions such as fog, rain, and nighttime environments. One of the key achievements of the system is the implementation of an optimized flicker frequency of 39–40 flashes per minute, which significantly improves driver attention and hazard awareness. The Arduino controller provides precise timing control, ensuring stable and consistent flickering without deviation. This feature plays a crucial role in enhancing the effectiveness of warning signals.

The solar charging system demonstrated efficient energy conversion, achieving full charging within 6–8 hours of sunlight exposure. The system also exhibited a remarkable backup duration of up to 7 days, ensuring uninterrupted operation even during extended periods of low sunlight. This makes the system highly reliable for deployment in remote and unattended locations.

Additionally, the use of a waterproof and weatherproof enclosure enhances durability and ensures long-term performance in harsh outdoor environments. The elimination of dependency on grid power reduces operational costs and supports sustainable energy practices.

Overall, the proposed system offers a cost-effective, eco-friendly, and low-maintenance solution for road safety applications. It addresses the limitations of conventional warning systems by combining renewable energy, automation, and high-visibility lighting into a compact and efficient design.

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