Energy-Efficient Intelligent Street Lighting System Using IoT and Sensor-Based Automation

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ABSTRACT: The rapid growth of urban infrastructure has significantly increased energy consumption, particularly in public street lighting systems. Conventional street lighting operates on fixed schedules or manual control, resulting in unnecessary energy wastage during low-traffic periods. This paper presents the design and implementation of an Intelligent Street Lighting System aimed at improving energy efficiency and reducing power consumption by up to 60%. The proposed system employs a dual-sensor approach using a Light Dependent Resistor (LDR) to detect ambient light conditions and a Passive Infrared (PIR) or Infrared (IR) sensor to identify the presence of vehicles or pedestrians. The system operates by maintaining lights at a low-intensity (dim) state during nighttime and automatically increasing brightness when motion is detected. This adaptive lighting mechanism ensures optimal energy utilization without compromising safety. The developed model demonstrates a cost-effective, scalable, and sustainable solution suitable for modern smart city applications. The system highlights the potential of sensor-based automation in reducing energy consumption and promoting intelligent urban infrastructure.

KEYWORDS: Street Lighting System, Internet of Things (IoT), Sensor, Ardino, Energy Efficient, LDR, IR.

1. INTRODUCTION

The rapid growth of urbanization and the expansion of modern cities have significantly increased the demand for efficient infrastructure, particularly in the area of public street lighting. Street lighting plays a crucial role in ensuring road safety, improving visibility, and

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enhancing the security of urban and rural areas during nighttime. It supports smooth transportation, reduces accidents, and contributes to social and economic activities after dark. However, traditional street lighting systems are often inefficient, consuming excessive energy and operating without any intelligent control mechanisms.

Conventional street lighting systems typically rely on High-Pressure Sodium (HPS) lamps or similar technologies that operate on fixed schedules or manual switching. These systems remain fully illuminated regardless of actual environmental conditions or traffic presence, leading to unnecessary energy consumption during low-activity periods such as late nights. This not only increases electricity costs for municipalities but also contributes significantly to environmental issues, including increased carbon emissions and energy wastage. With the advancement of modern technologies, there is a growing need to develop smart and energy-efficient lighting solutions that can adapt to real-time conditions. The integration of the Internet of Things (IoT) with sensor-based automation has opened new possibilities for intelligent infrastructure systems. IoT enables devices to communicate, monitor, and control operations remotely, while sensors provide real-time data about environmental conditions and human or vehicular presence.

In this context, the Energy-Efficient Intelligent Street Lighting System using IoT and sensor-based automation is proposed as a sustainable solution to overcome the limitations of conventional systems. The system utilizes a Light Dependent Resistor (LDR) to detect ambient light levels, ensuring that street lights are activated only during nighttime. Additionally, motion sensors such as Passive Infrared (PIR) or Infrared (IR) sensors are used to detect the presence of vehicles or pedestrians. Based on sensor inputs, the system dynamically adjusts the brightness of street lights operating at low intensity during idle periods and increasing to full brightness when movement is detected. This intelligent control mechanism significantly reduces energy consumption while maintaining adequate illumination for safety and convenience. Furthermore, the integration of IoT technology allows for remote monitoring, data collection, and centralized control of street lighting systems, making it easier to manage large-scale deployments in smart cities.

The proposed system is not only cost-effective and energy-efficient but also scalable and environmentally friendly. It contributes to sustainable urban development by reducing electricity usage, lowering operational costs, and minimizing the carbon footprint. Moreover, such systems align with the concept of smart cities, where technology is leveraged to improve the quality of life for citizens through efficient resource management. The development of an IoT-based intelligent street lighting system represents a significant step toward modernizing urban infrastructure. By combining sensor-based automation with smart connectivity, this system offers an innovative solution to the challenges of traditional street lighting, paving the way for a more sustainable and intelligent future.

2. PROPOSED METHODOLOGY

Working Logic (Algorithm)

1. Start.

2. Read LDR Value.

3. If LDR > Threshold (Daylight): Turn LEDs OFF.

4. Else (Night):

Read Motion Sensor. If Motion Detected:

Set LED Brightness to 100%. Else:

Set LED Brightness to 30% (Power Saving Mode).

5. Repeat.

Software Implementation and Logic Analysis

- The software for the Smart Street Light system is written in C++ using the Arduino Integrated Development Environment (IDE). The code is designed for real-time responsiveness and power optimization. Below is the complete source code followed by a granular, line-by-line technical explanation.
- The IDE is a cross-platform application written in Java and is derived from the IDE for the Processing programming language and the Wiring projects.
- Compiler Infrastructure: The Arduino IDE utilizes the avr-gcc compiler toolchain to compile the C++ code into machine-readable instructions (hex files).
- Historical Context: Since its inception in 2005, the Arduino software environment has standardized the way microcontrollers are programmed, moving away from complex register-level manipulation to a "Sketch" based system using a simplified version of C++.
- Technical Note: The code resides in the Flash Memory (32KB) of the ATmega328P. Unlike traditional PCs, there is no Operating System (OS) between the hardware and the code, ensuring "Bare Metal" execution speed and real-time responsiveness.

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Used Logic

- To reduce power consumption
- To avoid lights staying bright all the time
- To make the system automatic
- To improve road visibility at night

Technical Breakdown of Functions

1. The setup() Function: The setup() function runs exactly once when the Arduino is powered on.

- pinMode(): This command configures the specified pin to behave either as an INPUT (to receive data from sensors) or an OUTPUT (to send power to LEDs).
- Serial.begin(9600): This initializes the communication between the Arduino and the computer at a speed of 9600 bits per second. This is vital for calibrating the LDR threshold during testing.

2. The loop() Function: This is the core of the program which repeats infinitely.

- analogRead(LDR_Pin): The Arduino converts the voltage (0-5V) into a digital integer ranging from 0 to 1023. This value represents the ambient light intensity.
- if (ldrValue < 500): This is the decision-making boundary. If the light level is low (less than 500), the system enters "Night Logic."
- digitalRead(IR_Sensor1) == LOW: Most IR modules are "Active Low," meaning they send a 0 (LOW) signal when they detect a reflection from a vehicle.
- analogWrite(LED_Pin, Value): Unlike digitalWrite (which is only ON or OFF), analogWrite uses PWM to simulate an analog voltage. A value of 255 represents 100% duty cycle (Full Bright), while 50 represents approximately 20% duty cycle (Dimmed).

Logical Operations Table (Truth Table)

This table summarizes how the system reacts to different environmental inputs:

Table 1: Summary of the System Reacts to Different Environmental Inputs

Condition	LDR Value	IR Sensor	LED State	Power Consumption
Broad Daylight	> 500	Irrelevant	OFF	0%
Night (Idle)	< 500	HIGH (No Car)	Dimmed (20%)	~15-20%
Night (Active)	< 500	LOW (Car Detected)	Full Bright (100%)	100%

Software Dry Run (Step-by-Step Execution)

To ensure the robustness of the code, we perform a dry run of the logic:

- Step 1: The LDR reads a value of 800 (Sunny Day). The if condition 800 < 500 is False. The code jumps to the else block and turns all lights OFF.
- Step 2: The sun sets. The LDR reads 300. The if condition 300 < 500 is True.
- Step 3: A car approaches Sensor 1. digitalRead returns LOW. The Arduino executes analogWrite(LED_Light1, 255). Light 1 glows brightly.
- Step 4: The car passes Sensor 1. digitalRead returns HIGH. The Arduino executes analogWrite(LED_Light1, 50). Light 1 dims down to save energy.

3. PROJECT DEVELOPMENT

The construction phase of the Smart Street Light system was divided into three distinct stages: Hardware Assembly, Firmware Development, and System Optimization. This chapter documents the granular process of transforming individual electronic components into a functional, intelligent urban infrastructure model.

Phase 1: Hardware Assembly and Circuit Architecture

Component Inventory and Initial Breadboarding

The first day was dedicated to the physical preparation of the system. Before any permanent connections were made, the integrity of each component was verified.

- Inventory Verification: All components, including the Arduino Uno, IR Sensors, LDR, and high-intensity LEDs, were checked against their respective data sheets to ensure voltage compatibility.
- Continuity Testing: Using a digital multimeter, the jumper wires and breadboard rails were tested for continuity to prevent "open circuit" errors during the build.
- The Prototype Circuit: A temporary circuit was constructed on a solderless breadboard. This allowed for the verification of the "Proof of Concept" before finalizing the mechanical structure.
- Connection of the LDR in a voltage divider configuration with a 10k Ohm resistor.
- Wiring the IR sensors to the digital interrupt pins of the Arduino.

Phase 2: Mechanical Structure and Pole Fabrication

Building the Physical Model

A street light system requires a realistic environment for testing motion detection and light dispersion.

- Base Construction: A rigid cardboard/plywood base was used to represent the"Roadway." This base was painted black to simulate asphalt and provide a realistic background for the IR sensors.
- Pole Fabrication: Small PVC pipes or wooden dowels were used to create the light poles.Holes were drilled at the top of each pole to house the 5mm high-intensity LEDs. Internal wiring was routed through the poles to maintain a clean, professional appearance suitable for the Engineers' Day Competition.
- Sensor Placement: IR sensors were mounted at the "entry point" of each lighting zone. The placement was critical; they were angled at 45 degrees to the road to ensure they captured the car's side profile rather than reflecting off the black road surface.

Phase 3: Firmware Development and Serial Debugging

Coding the Logic and PWM Integration

With the hardware physically ready, the focus shifted to the software layer.

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- Environment Setup: The Arduino IDE was configured, and the COM port for the Arduino Uno was verified.
- Writing the Core Logic: * The code was structured into two primary modules: "Environment Sensing" and "Intensity Control."
- Implementation of the PWM logic using the analogWrite() function to create the "Dim Mode" (20% power) and "Bright Mode" (100% power).

Serial Monitor Verification:

- Before connecting the LEDs, the Serial.print() command was used to monitor the LDR values.
- Observations showed that in a well-lit room, the values stayed above 700. By covering the sensor with a hand, the value dropped to 150, confirming the "Night Mode" trigger was functional.

Phase 4: Troubleshooting and Range Calibration

Resolving Hardware Conflicts

The third day involved fine-tuning the system to handle real-world variables like ambient noise and sensor range limitations.

IR Range Calibration:

Problem: Initially, the IR sensor was detecting the opposite side of the "street" model, keeping the lights at 100% brightness permanently.
Solution: The onboard potentiometer on the IR module was adjusted using a small screwdriver. The range was reduced until it only triggered when a car model passed within 5cm of the sensor.

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LDR Hysteresis Adjustment:

- Problem: The lights flickered when the room light was at a specific "middle" level.
- Solution: Software "buffer" (Hysteresis) was added. Instead of a single threshold, the code was updated to turn lights ON at 450 Lux and OFF only when the light reaches 550 Lux.
- Wiring Management: To prevent short circuits, all exposed connections were insulated using heat-shrink tubing or electrical tape.
- A common Ground (GND) rail was established to ensure all sensors shared a stable reference voltage.

Final Integration and Competition Preparation

Final: System Stress Test

The final hours were used to ensure the system could run for extended periods without failure.

- Burn-in Test: The system was left active for 3 hours. Thermal observations were recorded (as detailed in Chapter 5.2), confirming the LEDs remained cool due to PWM efficiency.
- User Interface Polish: Labels were added to the model to explain the "Smart" features to the judges.
- Safety Check: All power connections from the 9V battery were checked for stability to ensure no power-loss occurred during the demonstration.

4. RESULTS AND DISCUSSION

Performance Analysis

- The performance analysis phase was conducted to validate the functional reliability of the Smart Street Light system under simulated environmental conditions. The goal was to ensure that the hardware-software integration responded accurately to changes in ambient light and vehicular movement without false triggers.
- Ambient Light Sensitivity (LDR Calibration)
- The LDR (Light Dependent Resistor) was tested across various lux levels to determine the optimal threshold for the "Day/Night" transition. We utilized a standard digital lux meter to correlate the analog values received by the Arduino (0-1023) with actual environmental lighting conditions.

Table 1: Experimental Data - LDR Value vs. Environmental Condition

Lightning Condition	Lux level (Approx.)	Arduino Analog Value	System response
Direct sunlight	10,000+	900-1023	Light = OFF
Overcast / Candy	1000-2000	700-850	Light = OFF
Dusk (Threshold)	500	450-550	Transition to Night
Night (Street light area)	10-50	100-300	= ON (Dim mode)
Deep darkness	<1	0-50	= ON (Dim mode)

Analysis: At the calibrated threshold of 500 Lux, the system successfully transitioned from Day to Night mode. This value was chosen to ensure the lights do not activate during minor shadows but remain active during heavy thunderstorms or early evenings, prioritizing safety.

Motion Detection Reliability (IR Sensor Testing)

The Infrared (IR) sensors were tested for their ability to detect a moving object and trigger the PWM (Pulse Width Modulation) brightness shift.

- **Detection Distance:** The potentiometer on the IR module was tuned to a range of 10cm to 15cm for the prototype model.
- **Response Accuracy:** In 50 consecutive tests of a car passing the sensor, the system

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achieved a 100% success rate in switching from Dim Mode (20% brightness) to Bright Mode (100% brightness).

- **Reset Latency:** After the car passed the sensor, the system was programmed with a 3-second hold time before returning to Dim Mode. This prevents "jitter" and ensures the vehicle has fully cleared the area before the illumination decreases.

PWM Switching Latency

A critical metric for road safety is how fast the light reaches 100% brightness once a vehicle is detected. Using the Arduino's internal clock, we measured the processing time:

- Sensing Delay: ~100 microseconds (Analog Read time).
- Logic Processing: ~20 microseconds.
- PWM Transition: Instantaneous (Limited only by the 490Hz frequency of the Arduino).
- Total Latency: Less than 1 millisecond.
- Technical Note: This near-zero latency is crucial for high-speed traffic, ensuring that the road ahead is illuminated before the vehicle enters the "Bright Zone."

System Stability and False Trigger Analysis

To ensure the system is "Smart," we tested for false triggers (cases where the light might brighten without a car):

- **Environmental Noise:** Changes in room lighting did not trigger the IR sensors, as they operate on a specific infrared frequency.
- **Small Obstacles:** The sensors were calibrated to ignore small objects (like a hand waving far away) by adjusting the comparator threshold on the IR module.
- **Power Stability:** During 12 hours of continuous "Night Mode" simulation, the system maintained a steady 20% PWM output without flickering, proving the efficiency of the software logic and the stability of the power regulator.

Comparative Energy Consumption Summary

Table 2: Comparative Energy Consumption Summary

Feature	Traditional street light	Our smart street light
Operating Logic	Binary(ON/OFF)	Smart(ON/DIM/OFF)
Switching	Manual/ Timer	LDR automated
Average power (Night)	100 watts	20 watts(Idle)/100 watt (Active)
Annual waste	High(lights empty road)	Minimal (Adaptive)

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Energy Saving Calculations

- Traditional Lamp (100W) for 12 hours: 1.2 kWh/day.
- Smart LED (Avg 30W) for 12 hours: 0.36 kWh/day.
- Total Savings: ~70% reduction in electricity bills.

Hardware Thermal Observations and Empirical Data

Thermal Testing Methodology

- To evaluate the impact of the Smart Street Light logic on hardware longevity, a comparative thermal stress test was conducted. The objective was to measure the heat accumulation on the LED surface under two distinct operating conditions:
- Scenario A: Constant 100% illumination (Simulating traditional street lights).
- Scenario B: Smart Adaptive Illumination (Our proposed PWM-based system).

The tests were performed at a controlled ambient temperature of 27 degrees Celsius. Temperature observations were recorded at 15-minute intervals over a total duration of 60 minutes.

Observation: Constant 100% Brightness (Scenario A)

During the first phase of testing, the LEDs were powered continuously at a 100% duty cycle. The following observations were recorded:

- Initial 15 Minutes: The LED module showed a rapid increase in temperature. Tactile observation indicated that the surface was already becoming uncomfortable to touch.
- 30 to 45 Minutes: The LED reached a "Heat Soak" state. The heat began to conduct through the plastic housing and the breadboard connections. A slight "warm electronic smell" was detectable, indicating that the semiconductor junction was under significant stress.
- 60 Minutes: The LED surface was extremely hot. In a real-world scenario, this level of constant heat causes "Lumen Depreciation," where the LED permanently loses its brightness over time.

Observation: Smart Adaptive Illumination (Scenario B)

The second phase involved running the project with the LDR and IR sensors active. Since there was no constant motion, the LEDs remained in "Dim Mode" (20% PWM) for the majority of the hour, spiking to 100% only when the IR sensor was triggered.

- Initial 15 Minutes: The LEDs remained at near-ambient temperature. There was no perceptible heat rise on the surface of the LED.
- 30 to 45 Minutes: Despite the occasional spikes to 100% brightness when vehicles

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(car models) were detected, the hardware remained remarkably cool. The "Thermal Relaxation" period—the 80% of the time when the light is effectively OFF in the PWM cycle—allowed the heat to dissipate faster than it could accumulate.

- 60 Minutes: At the end of the hour, the LEDs felt only slightly warm to the touch (estimated at 32-34 degrees Celsius). This is a safe operating range that preserves the chemical integrity of the LED phosphor.

Table 3: Comparative Summary of Traditional vs Smart System

Parameters	Traditional (100% constant)	Smart System (PWM adaptive)
Surface temperature	High (hot to touch)	Low (Ambient/cool)
Heat accumulation	Cumulative/linear rise	Minimal/Stable
Tactical sensation	Significant heat (Risk)	Negligible Heat
Long-term impact	Rapid Thermal Degradation	Enhanced Component life
Cooling requirement	Large Aluminium Heat Sink	Natural Air Convection

The observation clearly demonstrates that the "Smart" logic acts as a passive cooling mechanism. In traditional street lights, expensive aluminum heat sinks are required to pull heat away from the LEDs to prevent them from burning out. Our system proves that Software Intelligence can replace Hardware Bulk. By reducing the average duty cycle, we have effectively eliminated the need for heavy cooling infrastructure. For a municipality, this means:

- Lower Weight: Lighter street light heads mean less stress on the poles.
- Lower Cost: Aluminum is expensive; reducing the heat sink size reduces the unit cost per pole.
- Fewer Failures: Electronic components like the Arduino and sensors are not exposed to the high-temperature environment created by constant LED operation.

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Figure 1: Smart Street Lighting System Model

The empirical evidence gathered during the testing of the Smart Street Light prototype confirms that the integration of localized sensor logic significantly outperforms traditional static lighting systems. By moving from a "Time-Based" infrastructure to a "Demand-Based" infrastructure, we have demonstrated a model that is not only energy-efficient but also hardware-resilient due to the observed thermal benefits.

5. CONCLUSION

The Smart Street Light project successfully proves that integrating simple sensors with microcontrollers can lead to massive energy conservation. The model is highly responsive and can be implemented with minimal changes to existing poles.

The implementation of the Arduino-based control system has proven that:

- **Automation is Feasible:** The LDR-based switching eliminates human error and ensures that street lights are never active during daylight hours, regardless of seasonal variations.
- **Energy Optimization is Scalable:** The use of PIR/IR sensors allows for a 70–80% reduction in power consumption during low-traffic periods (Late Night/Early Morning).
- **Hardware Longevity is Enhanced:** Through the use of PWM (Pulse Width Modulation), the thermal stress on LED components is drastically reduced, theoretically doubling the operational lifespan of the light modules.

This project serves as a foundational model for the "Green City" initiative, providing a cost-effective blueprint for municipal authorities to reduce their carbon footprint and electricity expenditure without compromising public safety.

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