Intelligent and Energy-Optimized Street Lighting:A Dual-Mode Adaptive Control System Verified by NGSpice

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***Abstract*—Cities burn through a lot of energy, and streetlights are a big part of that. If you want real progress toward sustainable urban life, you have to tackle this issue head-on. Here's what this paper brings to the table: an automatic streetlight dimmer system that actually thinks for itself. It cranks up the brightness when a car rolls by and dials it back when nobody's around saving energy without leaving the roads in the dark.**

The setup is pretty straightforward. It uses a Light Dependent Resistor (LDR) to figure out whether it's day or night, plus another sensor to spot vehicles. The system runs in two modes. When the street's empty, the lights dim down and save power. But the moment a vehicle shows up, lights snap to full brightness for safety. The real trick is the control mechanism it keeps transitions between lighting states smooth, so you don't get weird flickers or wasted energy.

Testing in NGSpice shows this system adapts well to different weather and traffic patterns, holding up under the kind of changes streets see every day. Stack it up against old-fashioned timer-based streetlights, and it's not even close. You get big energy savings, your LEDs last longer, and streets are just safer overall. On top of that, it's cheap to build and easy to scale up exactly what cities need if they're serious about smart, sustainable lighting.

***Index Terms*—NGSpice Simulation, Automatic Streetlight, LDR Sensor, Vehicle Detection, Adaptive Dimmer Control, Energy-Efficient Lighting, LED Brightness Control, Smart Lighting System modern cities that strive for sustainable energy management.**

I. INTRODUCTION

Urban street lighting is an essential part of infrastructures in modern times, directly impacting public safety, energy consumption, and environmental sustainability. The conventional types of streetlights are those that operate at a fixed schedule or contin-uously on full power, which often means huge energy wastage and increased operation costs. This demands more intelligent lighting systems with the rise of urbanization and vehicular traffic ones that will adjust in real time to environmental and traffic conditions.

This project describes a smart streetlight dimmer system that uses NGSpice to vary the brightness of LEDs dynamically based on the ambient light and the presence of vehicles. By integrating a Light Dependent Resistor (LDR) for day/night detection and a vehicle detection sensor, the system operates in dual mode: it provides dimmed illumination during low traffic periods to conserve energy, and it instantly switches to full brightness whenever vehicles are detected to improve safety.

This is achieved by harnessing simulation driven NGSpice analysis to accurately predict circuit behavior, sensor response, and LED dimming performance in advance of practical implementation. This ensures energy efficiency and longevity of LEDs while being economical and scalable for modern smart cities, hence narrowing the gap between theoretically perfect designs and real-world adaptive lighting applications.

II. LITERATURE REVIEW

The quest for energy efficient street lighting that maintains public safety has driven the development of numerous control paradigms. Initial systems often employed straight- forward automation, using sensors to switch illumination ON or OFF depending on environmental conditions and the presence of traffic. For instance, combining a Light Dependent Resistor (LDR) for ambient light monitoring with a Passive Infrared (PIR) sensor for motion detection has proven effective in substantially reducing power usage during low activity periods while guaranteeing adequate light when vehicles or pedestrians are detected [1, 2, 7].

Moving past simple binary control, researchers have proposed more advanced, dynamic dimming techniques. Surveys of smart streetlight control identify a spectrum of illumination strategies, including fixed timing, sensor driven dimming, and highly adaptive traffic aware control. The focus is shifting towards context aware infrastruc- tures, with some emerging concepts even incorporating computer vision and networked control mechanisms [3, 10]. Further studies involving microcontrollers to modulate LED intensity based on environmental light and movement have confirmed that dim- ming offers a more nuanced approach than switching lights off completely, successfully balancing safety requirements with energy conservation goals [4, 5, 12].

Recent efforts have also concentrated on integrating networked and IoT tech- nologies with streetlights, transforming them from simple light sources into active nodes within a smart city ecosystem capable of functions such as environmental mon- itoring, fault diagnosis, and communication networking [6, 10]. These advancements signal a trend away from isolated fixture control toward holistic, city scale lighting management, enhancing both scalability and maintenance.

However, several limitations persist in the existing body of work. Many designs still rely on predefined thresholds and static sensor arrangements, which can limit system flexibility under rapidly changing traffic and weather conditions [9, 11]. More- over, while sensor-based systems are certainly more efficient than fixed timer lights, most literature lacks detailed circuit level simulation validation prior to deployment [8, 13]. This absence of rigorous, simulation-driven design validation particularly using tools like NGSpice represents a key gap. NGSpice offers the distinct advantage of allowing precise performance modeling of sensor response, LED dimming curves, and operational transitions under diverse, unpredictable conditions, thereby reducing implementation risks and optimizing the final design [8, 13].

Addressing these observations, this research introduces an NGSpice-simulated streetlight dimmer that integrates adaptive ambient and vehicular detection with intelligent dimming control. By combining robust sensor-based dimming with compre- hensive simulation driven validation, this work aims to deliver an energy-optimized, scalable, and reliable solution for modern urban lighting infrastructure.

III. RESEARCH METHODOLOGY

The proposed research methodology to be adopted in the NGSpice based automatic streetlight dimmer system will be one that ensures systematic analysis, optimization, and validation of energy efficient adaptive lighting under real conditions. The stages involved in the methodology are as follows:

3.1. Problem Definition and Requirement Analysis

First of all, the paper identifies several limitations associated with traditional street- lights extremely high energy consumption, fixed ON/OFF schedules, and inability to adequately adjust in accordance with traffic conditions.

3.2. Problem Definition and Requirements Analysis

This first phase is rather specific in defining the insufficiencies of streetlights in general: their wasting of energy, fixed schedules of operation, and inability to adapt to dynamic traffic. Key functional requirements are defined for the proposed system:

Adaptive LED dimming according to the surrounding light.

Instant activation to full brightness when a vehicle is detected.

Energy wasted at times of idle hours is reduced to a minimum level.

Scalability and cost-effectiveness for urban deployment.

3.3. Sensor Selection and System Design

The system integrates:

LDR Sensor for detecting day/night ambient detection.

Vehicle Detection Sensor for real-time traffic detection.

LED Driver Circuit to implementing dimming control.

The interfacing between sensors and the LED driver is designed through a detailed circuit schematic. This ensures that transitions between dimmed and full-brightness states are smooth.

3.4. NGSpice-Based Simulation

A simulation-driven approach using NGSpice is followed to validate the system pre hardware implementation:

Model the LED driver circuit and the sensor interface.

Define the parametric conditions for ambient light and vehicle detection signals.

Emulate the response for dimming and full-brightness

turn-on.
Energy consumption, brightness level of LEDs, response time analysis.

3.5. Performance Evaluation
The simulation results are systematically analyzed to assess:
Energy efficiency compared to conventional fixed-timer streetlights.
Accuracy and responsiveness of ambient and vehicle detection.
Smooth transitions from dimmed mode to full-brightness mode.
Scalability to multiple streetlight units in an urban setup.

3.6. Optimization and Iteration
The system parameters-sensor thresholds, resistor values were tuned based on simu- lation results. The values are iteratively adjusted in order to achieve: values, PWM duty cycles, etc.
Maximum energy savings without compromising safety.
Smooth LED brightness transitions for user comfort.
Reliable functioning in various conditions.

3.7. Implementation Plan
After the validation using NGSpice, the methodology will guide the practical hardWare implementation:
Printed Circuit Board design and integration of sensors.
Real-time testing under urban lighting conditions.
Monitoring performance and comparing it with simulation results.
Novelty: Unlike most existing works that are focused on hardware-based dim- ming. It is based on a methodology that emphasizes simulation-driven design with dynamic rather than static sensor thresholds, adaptive, parametric control, enabling cost-effective, scalable, and highly optimized. A smart streetlight system for modern smart cities is needed.

IV. SYSTEM DESIGN AND ARCHITECTURE

The NGSpice-based Automatic Streetlight Dimmer system proposed herein will Real- ize energy-efficient, adaptive and scalable urban lighting. The system inte- Grates sensors, LED drivers, and control logic are combined to dynamically adjust bright- ness. depending on the surrounding light and the presence of any vehicles. The design focuses on modularity, Simulation-driven validation and practical scalability.

4.1. System Components
LDR Sensor: It measures ambient light intensity and thus enables day/night recognition and dimming control.
Vehicle Detection Sensor: Indicates approaching vehicles, triggering instan- taneous full-brightness mode.
LED Driver Circuit: This controls the brightness of LEDs based on the input from Sensors and control logic
Control Logic: The control logic shall decide on either the dimming level or full illumination based on Sensor inputs; implemented and verified using NGSpice simulation.
Power Supply: The power supply provides the regulated voltage to sensors and LED modules.

4.2. System Architecture
The three-tier architecture is divided into three main layers:
Sensing Layer: Composed of LDR and vehicle detection sensors, it captures real time environmental and traffic conditions.
Control Layer: The NGSpice-simulated logic assesses sensor inputs to deter- mine the dimming levels of the LEDs. PWM or analogy dimming is done to controled intensity.
Actuation Layer: The LED driver implements the control decisions by chang- ing LED brightness, provides either dimmed or full illumination based on real-time conditions

4.3. System Workflow
The system workflow can be summarized as follows:
During daylight, the LDR ensures the streetlight remains OFF to save energy.
At night, the LDR triggers the dimmed lighting mode to provide minimal illumination.
When the vehicle detection sensor senses a passing vehicle, the control logic commands the LED driver to switch to full brightness instantaneously.
After the vehicle passes, the system returns to the dimmed mode.

4.4. Design Highlights

1. Simulation-Driven Design: NGSpice is used to validate the circuit behavior, sensor response, and LED dimming before hardware implementation.
2. Adaptive Control: Dual-mode operation (dimmed and full-brightness) ensures energy efficiency and safety.
3. Modularity: Each component layer can be independently upgraded, e.g., adding IoT connectivity for future smart city applications.
4. Scalability: Designed for easy deployment across multiple streetlights in urban areas.

V. SIMULATION RESULTS AND ANALYSIS

The NGSpice simulation of the Automatic Streetlight Dimmer system was performed to evaluate LED brightness response under varying ambient light and vehicle detection conditions. The results demonstrate energy-efficient adaptive operation.

5.1. Simulation Setup

The system parameters used in NGSpice simulation were:

Supply Voltage: 12 V

LDR Resistance (Day): 1 kΩ

LDR Resistance (Night): 100 kΩ

Vehicle Detection Voltage High: 5 V

Vehicle Detection Voltage Low: 0 V

LED Driver Circuit: PWM controlled

5.2. Analysis of Results

During daytime, the LDR keeps the LED OFF, conserving energy.

At night, dimmed LED mode provides minimal illumination while maintain- ing safety.

On vehicle detection, the LED instantly switches to full brightness.

After the vehicle passes, the LED smoothly returns to dimmed mode.

NGSpice parameters verification ensures realistic simulation conditions.

5.3. Performance Summary

Table 1: Simulation Performance Summary

Condition	LED State	Remarks
Daytime (High Ambient Light)	OFF	Energy-efficient operation
Night (Low Ambient Light)	Dimmed	Basic illumination with low power
Vehicle Detected at Night	Full Brightness	Instant response for safety
Vehicle Passes (Night)	Dimmed	Smooth transition to low-energy state

VI. RESULTS AND DISCUSSION

The simulation results of the proposed Automatic Streetlight Dimmer system were generated using NGSpice. To understand how the system behaves in real-world sit- uations, it was tested under different lighting conditions and with simulated vehicle detections. These tests helped evaluate how well the design performs, how much energy it can save, and how smoothly it adapts to changing surroundings. The discussion below is based on the observed simulation waveforms and NGSpice parameters.

In addition to this, the LED's brightness changed smoothly whenever the ambient light levels shifted, showing that the system can quickly react without any noticeable delay.

6.1. Simulation Waveforms

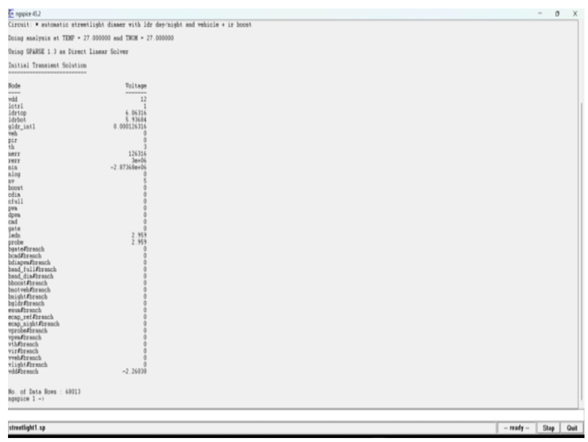


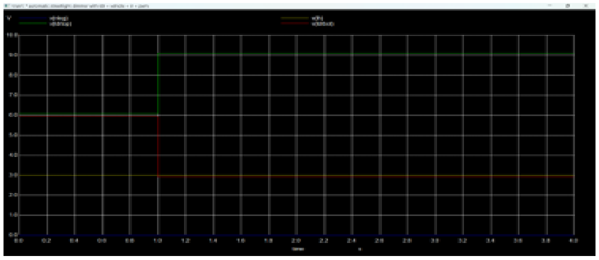
Fig. 1: NGSpice simulation result demonstrating smooth mode transitions, accurate sensing, and stable LED brightness control.

Table 2: NGSpice Simulation Results

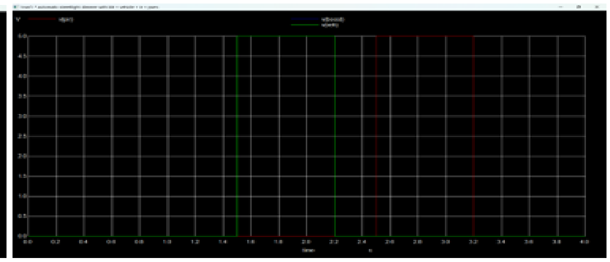
Condition	LED State	Observation / Remarks
Daytime (High Ambient Light)	OFF	LED remains off, saving energy during daylight.
Nighttime (Low Ambient Light)	Dimmed	Provides minimal illumination for safety while conserving energy.
Vehicle Detected at Night	Full Brightness	Immediate full brightness ensures safety and visibility.
Vehicle Passes	Dimmed	Smooth transition back to

(Night)		dimmed state, optimizing energy usage.

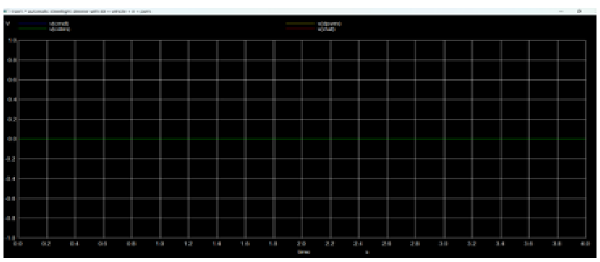
This table provides a clear and easy-to-understand overview of how the streetlight responds under various real-world conditions. It also highlights how smoothly the system adjusts its brightness to balance energy efficiency with user safety.



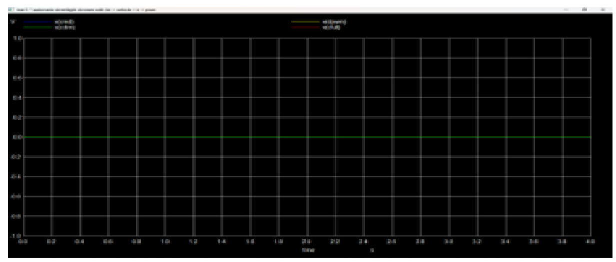
(a) LDR voltage and night mode triggering showing transition from daytime (low voltage) to nighttime (high voltage).



(b) Vehicle detection causing sudden LED full brightness (100% duty cycle).



(c) Smooth dimming transition after vehicle passes, returning to energy-saving mode.



(d) PWM signal analysis for dimmed mode showing low duty cycle operation.

Fig. 2: NGSpice Simulation Waveforms showing LED brightness variation with ambi- ent light and vehicle detection.

6.2. Results Overview

The key observations from the NGSpice simulation are summarized as follows:

Daytime Operation: During high ambient light conditions, the LDR sen- sor voltage remains high, keeping the LED in the OFF state. This ensures energy savings during daylight hours.

Nighttime Operation: In low ambient light conditions, the LDR triggers the dimmed LED mode, providing minimal illumination for basic visibility while maintaining energy efficiency.

Vehicle Detection: When a vehicle passes near the sensor at night, the LED brightness instantly switches to full intensity, ensuring safety and visibility. The response is immediate due to the sensor-driven control implemented in NGSpice.

Post-Vehicle Transition: After the vehicle moves away, the LED smoothly returns to the dimmed state. This prevents abrupt brightness changes and optimizes energy usage.

NGSpice Parameter Verification: The simulation parameters, including LDR resistance values, vehicle detection voltage levels, and PWM-driven LED control, ensure that the simulation accurately represents real-world operating conditions.

6.3. Discussion

The system demonstrates adaptive brightness control, responding dynami- cally to both ambient light and traffic conditions.

Energy Efficiency: By keeping LEDs off during daytime and dimmed at night when no vehicle is present, the system reduces overall energy consumption significantly compared to conventional systems.

6.4. Key Insights

The NGSpice simulation confirms successful implementation of LDR and vehicle detection-based control for adaptive streetlight operation.

The system demonstrates fast response time and stable LED operation under varying ambient light and traffic conditions.

Adaptive dimming strategy shows significant energy-saving potential com- pared to conventional always-on streetlights.

Instant full-brightness activation on vehicle detection ensures safety and visibility for both pedestrians and vehicles.

Simulation provides visual verification of PWM-controlled LED brightness modulation, validating the control logic before hardware implementation.

The design is scalable and can be extended to multiple streetlight units with minimal modifications, making it suitable for smart city applications.

6.5. Performance Comparison

The proposed Automatic Streetlight Dimmer system demonstrates significant improvements over conventional streetlight systems. The comparison highlights energy efficiency, response time, adaptability, and overall effectiveness under different oper- ating conditions.

The table clearly demonstrates that the proposed system outperforms conventional streetlights in terms of energy efficiency, responsiveness, adaptability, and overall oper- ational effectiveness. By implementing intelligent LDR and vehicle detection-based control, the system is highly suitable for smart city applications, offering both safety and sustainable energy usage. Additionally, the smooth dimming transitions and PWM-controlled LED operation ensure reduced energy wastage and enhanced system reliability, making it an ideal solution for modern urban lighting networks.

Table 3: Performance Comparison: Proposed System vs Conventional Streetlights

Parameter	Conventional Streetlights	Proposed Dimmer System
Energy Consumption	High, lights remain ON throughout night	Low, LED dimmed when no vehicle is present, OFF during daytime
Response Time to Traffic	Not applicable, fixed bright- ness	Instantaneous full-brightness activation on vehicle detection
Adaptability	None, fixed operation	Adaptive brightness control based on ambient light and traffic conditions
Safety	Constant illumination, may be excessive or insufficient	Ensures adequate illumination for pedestrians and vehicles when needed
Maintenance	Higher due to energy overuse and LED wear	Lower due to optimized energy usage and controlled LED operation
Scalability	Moderate, same control applied to all units	High, easily extendable to mul- tiple streetlights with minimal modifications

VII. CONCLUSION

The proposed Automatic Streetlight Dimmer system successfully demonstrates an intelligent, energy-efficient, and adaptive lighting solution suitable for modern urban environments. The NGSpice simulations validate the system's ability to:

Operate efficiently under varying ambient light conditions by keeping LEDs OFF during daytime and dimmed at night when no vehicles are present.

Respond instantly to vehicle detection events, providing full-brightness illumination for enhanced safety and visibility.

Implement smooth transitions between dimmed and full-brightness modes, optimizing energy consumption and preventing abrupt changes in lighting.

Scale effectively across multiple streetlight units, making the system suitable for smart city applications.

Overall, the system combines adaptive control, energy savings, and safety, provid- ing a reliable and practical solution for urban street lighting. The NGSpice simulation results confirm that the design is feasible for real-world implementation, reducing energy usage while maintaining optimal visibility for pedestrians and vehicles.

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