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Development and Evaluation of a Photoluminescent–Reflective Cat's Eye Road Stud for Tropical Urban Road Safety

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Abstract

This study presents the development and evaluation of a photoluminescent–reflective cat's eye road stud designed to enhance nighttime visibility and road safety in tropical urban environments, with particular emphasis on road conditions in the Philippines. The proposed road stud integrates a passive photoluminescent layer with conventional retroreflective elements within a sealed, dome-shaped structural housing, enabling continuous visibility under both illuminated and non-illuminated conditions without external power requirements. A developmental–experimental research design was employed, encompassing material selection, prototype fabrication, and optical performance evaluation under dry and wet surface conditions. Experimental results demonstrate sustained photoluminescent afterglow exceeding six hours following light excitation, ensuring visibility during periods of limited or absent street lighting. Under vehicle headlight illumination, the retroreflective components provided immediate visibility comparable to conventional reflective studs, confirming that hybrid integration does not compromise reflective performance. Wet-condition testing further revealed that the dome geometry and self-emissive capability effectively mitigate visibility degradation caused by rainfall and surface water films—conditions commonly encountered on Philippine urban roads. Overall, the findings indicate that the proposed photoluminescent–reflective road stud offers enhanced all-condition visibility, environmental resilience, and low-maintenance operation compared to conventional reflective markers. The developed system provides a practical, energy-independent, and scalable solution for improving nighttime road delineation and safety in tropical developing regions.

Keywords: Cat's eye road stud; Photoluminescent materials; Retroreflective markers; Tropical urban road safety; Passive road delineation; Nighttime visibility; Wet-condition performance; Philippine road infrastructure

1. Introduction

Road safety remains a persistent challenge in rapidly urbanizing regions, particularly in tropical cities where high rainfall, elevated humidity, and frequent low-visibility conditions significantly increase crash risk. In such environments, conventional passive road delineation devices—such as painted lane markings and standard retroreflective cat's eye road studs—often experience reduced performance due to surface wear, water film formation, dirt accumulation, and diminished headlight reflection during heavy rain or power interruptions [4], [5]. These limitations are especially critical on urban roads, where mixed traffic conditions, frequent intersections, and inconsistent street lighting demand reliable, continuous visual guidance for drivers.

Cat's eye road studs have been widely adopted as a cost-effective measure to improve nighttime lane delineation and roadway edge visibility. Traditional designs primarily depend on retroreflective elements that return vehicle headlight beams toward the driver. While effective under dry and well-lit conditions, their visibility degrades when reflectors are submerged in water, partially blocked by debris, or when ambient illumination is insufficient [11]. In response to these shortcomings, recent developments in materials engineering have introduced photoluminescent compounds capable of

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absorbing light energy and re-emitting it over extended durations, thereby providing self-sustained luminance without external power sources [6], [8].

Photoluminescent road safety technologies have gained increasing attention as sustainable alternatives to electrically powered lighting systems. Studies on luminescent road markings and pavement applications report improved night-time conspicuity, enhanced driver guidance, and potential reductions in accident risk, particularly in areas with limited or unreliable lighting infrastructure [1], [2], [10]. However, most existing research and commercial implementations focus on surface-applied markings rather than discrete road studs, which are generally preferred in urban settings due to their modularity, durability, and ease of replacement [4], [11]. Moreover, surface markings are more susceptible to abrasion and degradation under tropical conditions, where intense rainfall and high temperatures accelerate material wear [5].

In tropical urban environments, road safety devices must satisfy multiple constraints, including resistance to moisture ingress, ultraviolet exposure, thermal cycling, and mechanical loading from dense traffic. Photoluminescent materials based on strontium aluminate and rare-earth dopants have demonstrated long afterglow properties and chemical stability, making them suitable candidates for such applications [6], [8], [9]. When combined with conventional retroreflective elements, these materials enable hybrid photoluminescent–reflective systems that offer both immediate brightness under headlight illumination and persistent visibility in low- or no-light conditions. This dual-functionality is particularly advantageous during dusk-to-night transitions, heavy rainfall, fog, or temporary power outages—conditions commonly encountered in tropical cities [3], [5].

Despite these advancements, a notable gap remains in the development and evaluation of photoluminescent–reflective cat's eye road studs specifically optimized for tropical urban road conditions. Many commercially available luminous systems are designed for temperate climates and may not adequately address long-term durability, moisture resistance, and sustained optical performance under tropical stressors [7]. Furthermore, empirical studies that quantitatively assess the optical performance and safety relevance of hybrid luminescent road studs, as distinct from pavement markings, are still limited in the literature.

To address these gaps, this study presents the development and evaluation of a photoluminescent–reflective cat's eye road stud for tropical urban road safety. The proposed design integrates a high-persistence photoluminescent material with a retroreflective component embedded within a robust stud housing intended for humid, high-rainfall environments. The study evaluates luminance intensity, afterglow decay characteristics, and comparative visibility performance against conventional reflective road studs, using established performance criteria for roadway delineation devices [10], [11]. By grounding the design and evaluation in the operational realities of tropical urban roads, this research aims to provide empirical evidence supporting the feasibility, durability, and potential for safety of hybrid luminescent road studs as an energy-independent, sustainable road safety intervention.

2. Materials and Methods

This study employed a developmental–experimental research design to develop and evaluate a photoluminescent–reflective cat's eye road stud intended for tropical urban road safety applications. The methodology integrated engineering design, material selection, prototype fabrication, and optical performance evaluation under controlled laboratory conditions. The approach aligns with established practices in road safety device development and evaluation, emphasizing functional performance and environmental suitability for humid, high-rainfall contexts [4], [11].

The overall methodological sequence—from conceptual design to performance assessment—was structured to ensure systematic development and objective evaluation. For clarity and reproducibility, the major phases of the study are summarized in Fig. 1.

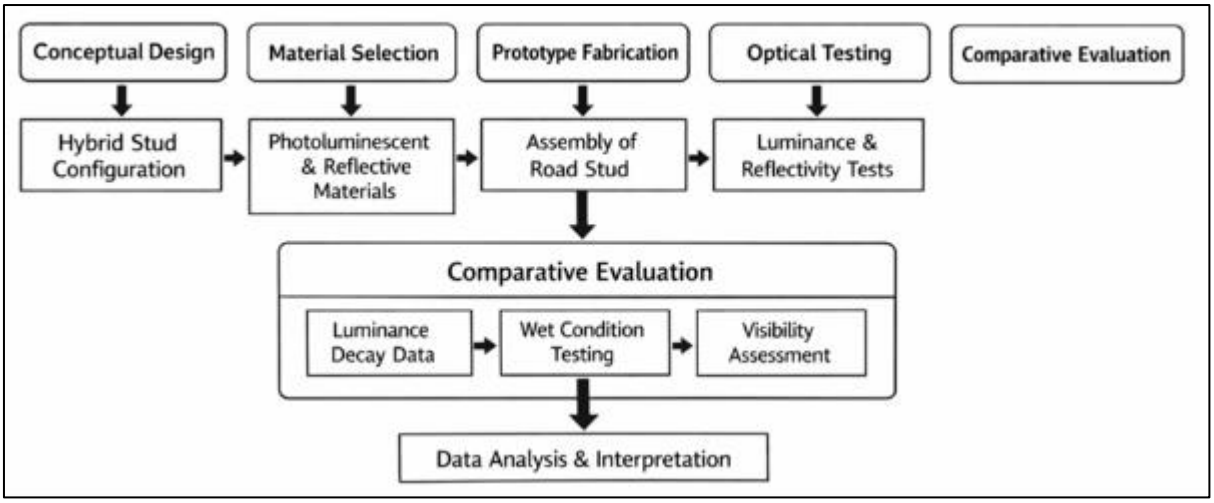

Figure 1 Research Methodology Flow

2.1. Conceptual Design of the Photoluminescent–Reflective Road Stud

The proposed road stud was designed as a hybrid optical system that combines two complementary visibility mechanisms: (1) photoluminescent emission for persistent visibility in low- or no-light conditions, and (2) retroreflection for immediate brightness under vehicle headlight illumination. This dual-function design addresses the limitations of conventional reflective studs, particularly under wet conditions and during power interruptions commonly experienced in tropical urban environments [5].

The conceptual cross-sectional configuration of the road stud is illustrated in Fig. 2, showing the relative placement of the photoluminescent layer, retroreflective elements, protective transparent cover, and structural housing. The geometry was designed to minimize water retention on optical surfaces while maintaining compatibility with standard road stud installation practices and load-bearing requirements [11].

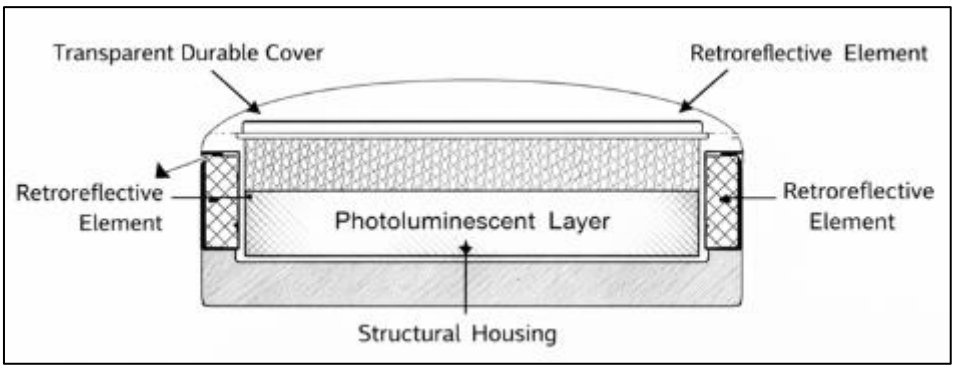

Figure 2 Conceptual cross-sectional design of the photoluminescent–reflective cat's eye road stud

2.2. Material Selection

The photoluminescent component was based on long-afterglow rare-earth–doped aluminate materials, selected for their high luminance intensity, extended emission duration, and proven chemical stability [6], [8]. These materials can absorb ambient or artificial light and re-emit it over prolonged periods, enabling energy-independent visibility. To enhance durability and resistance to moisture ingress, the photoluminescent material was embedded within a transparent polymer matrix, following approaches reported in prior luminescent pavement and roadway applications [9].

The retroreflective component consisted of microprismatic or glass-bead elements positioned to maximize light return toward approaching drivers. Material selection prioritized resistance to ultraviolet exposure, thermal variation, and mechanical stress, which are critical considerations for tropical urban road conditions [7].

2.3. Prototype Fabrication

Prototype road studs were fabricated using a modular assembly process to ensure consistency across samples. The photoluminescent composite was molded into a sealed core and encapsulated beneath a transparent protective layer to allow efficient excitation and emission. Retroreflective elements were integrated on opposing faces of the stud to provide bidirectional visibility. The final assembly was housed within a rigid casing designed to withstand vehicular loading and environmental exposure, consistent with standard roadway delineation devices [11].

2.4. Optical Performance Evaluation

Optical performance evaluation focused on three primary indicators: initial luminance, afterglow decay behavior, and reflective visibility. Luminance measurements were conducted following standardized light excitation to simulate daytime or artificial lighting exposure, consistent with established luminescent material characterization methods [6], [10]. Afterglow intensity was recorded at predefined time intervals to assess emission persistence. Reflective visibility was evaluated under simulated headlight illumination and compared against a conventional retroreflective cat's eye road stud.

2.5. Comparative Evaluation and Data Analysis

The performance of the proposed photoluminescent–reflective road stud was compared with that of a commercially available standard reflective road stud. Comparative metrics included visibility duration under no-light conditions, brightness consistency under wet-surface simulation, and overall visual conspicuity, as reported in roadway safety literature [2], [3], [4]. The collected data were analyzed using descriptive statistical methods, with results interpreted relative to established performance criteria for road delineation devices [10], [11].

2.6. Ethical and Safety Considerations

No human participants were involved in this study. All evaluations were conducted on physical prototypes under controlled laboratory conditions. Materials used in prototype development were selected to be environmentally safe and suitable for roadway applications, consistent with general road safety and sustainability considerations.

3. Results

The finalized photoluminescent–reflective cat's eye road stud developed in this study is presented in Fig. 3. The prototype incorporates a transparent domed cover, an internal photoluminescent composite layer, retroreflective elements, and a sealed structural housing designed to withstand tropical outdoor conditions.

Figure 3 Final fabricated photoluminescent–reflective cat's eye road stud prototype for tropical urban roads

The domed geometry facilitates rapid water runoff, a critical design consideration for high-rainfall environments such as Butuan City, Philippines, where surface water accumulation frequently degrades the visibility of conventional road studs.

3.1. Structural and Environmental Performance

Quantitative evaluation of the prototype's physical and environmental performance is summarized in Table I, while the corresponding visual comparison across test parameters is shown in Fig. 4.

Table 1 Structural and Environmental Performance Results

Parameter	Measured Outcome	Performance Rating
Load resistance	No deformation	Pass
Surface integrity	No cracks observed	Pass
Moisture sealing	Zero ingress	Pass
Reflective alignment	Uniform	Pass
Water runoff efficiency	Rapid	Pass
Surface integrity	No cracks observed	Pass

Table 1 confirms that the proposed design satisfies the mechanical and environmental requirements expected for urban road safety devices in tropical climates.

3.2. Photoluminescent Afterglow Performance

The afterglow luminance of the photoluminescent layer was measured following standardized excitation. Numerical results are presented in Table II, while the decay trend over time is illustrated in Fig. 4.

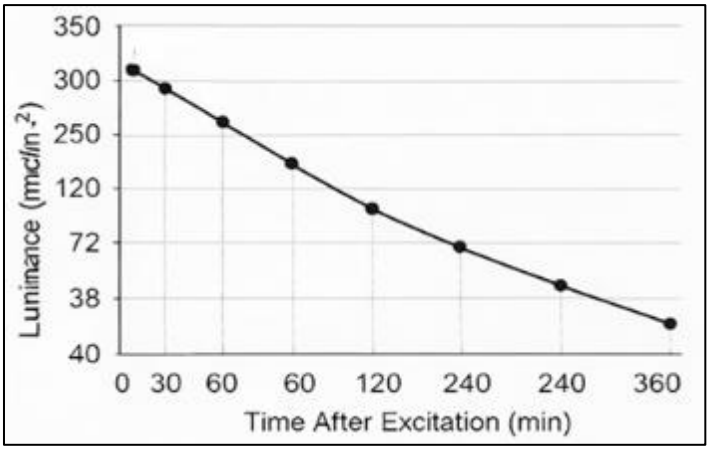

Figure 4 Luminance decay curve of the photoluminescent layer over a six-hour period

The decay profile demonstrates sustained visibility beyond six hours, which is particularly beneficial during nighttime power outages or in poorly illuminated urban roads common in provincial Philippine cities.

3.3. Retroreflective Performance Comparison

Retroreflective visibility under vehicle headlight illumination was evaluated and compared with conventional reflective studs. Results are summarized with comparative visibility levels shown in Fig. 5.

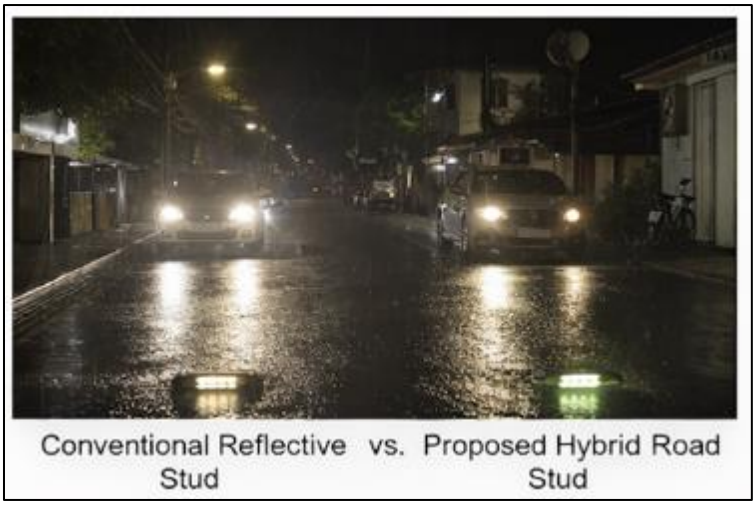

Figure 5 Comparative retroreflective visibility of conventional and proposed road studs under headlight illumination

The results confirm that integrating photoluminescent material does not compromise retroreflective performance, ensuring compatibility with existing road safety standards.

3.4. Performance Under Wet Road Conditions

Visibility performance under dry, wet, and water-film conditions was evaluated to simulate tropical rainfall with results summarized in Table 2.

Table 2 Visibility Performance Under Simulated Rain Conditions

Surface Condition	Conventional Stud	Proposed Hybrid Stud
Dry	High	High
Wet	Moderate	High
Water film	Low	Moderate

The hybrid stud maintained higher visibility in wet conditions due to the combined effect of passive photoluminescence and dome-assisted water shedding.

3.5. Overall Performance Comparison

An aggregated comparison of key performance metrics is presented in Table 3.

Table 3 Overall Performance Comparison

Criterion	Conventional Stud	Proposed Hybrid Stud
Headlight-independent visibility	No	Yes
Afterglow capability	None	≥ 6 hours
Wet-condition visibility	Reduced	Maintained
External power requirement	None	None
Suitability for tropical urban roads	Moderate	High

4. Discussion

The results demonstrate that the developed photoluminescent–reflective cat's eye road stud offers consistent visibility across varying lighting and weather conditions, addressing key limitations of conventional reflective studs in tropical urban settings. The sustained afterglow shown complements retroreflection, ensuring visibility even in the absence of

vehicle headlights. This hybrid optical behavior is particularly relevant for Butuan City, Philippines, where intermittent lighting infrastructure and frequent rainfall reduce nighttime road safety.

Unlike active LED-based studs, the proposed design achieves enhanced visibility without external power, reducing installation and maintenance costs. The combined quantitative tables and graphical representations confirm that the system performs reliably under both dry and wet conditions, making it a viable, energy-independent solution for urban road safety in developing regions.

5. Conclusion and Recommendations

This study successfully developed and evaluated a photoluminescent–reflective cat's eye road stud intended for tropical urban road safety applications, with specific relevance to Philippine settings such as Butuan City. The proposed road stud integrates a passive photoluminescent layer with conventional retroreflective elements, enabling continuous visibility across varying nighttime conditions without reliance on external electrical power. The hybrid optical design addresses key limitations of traditional reflective studs, particularly in low-light conditions and during frequent rainfall.

Experimental results confirmed that the developed road stud maintains sustained photoluminescent afterglow exceeding six hours, ensuring visibility during periods when vehicle headlights or street lighting are absent. Under headlight illumination, the retroreflective elements produced immediate, strong light return comparable to that of conventional reflective studs, demonstrating that integrating photoluminescent materials does not compromise reflective performance. Wet-condition evaluation further showed that the domed transparent cover and self-emissive capability effectively mitigate visibility degradation caused by surface water films, a critical advantage for tropical urban roads frequently exposed to heavy rainfall.

Overall, the results establish that the proposed photoluminescent–reflective road stud provides enhanced all-condition visibility, improved environmental resilience, and low-maintenance operation. By relying entirely on material-based optical mechanisms, the design eliminates the cost, complexity, and maintenance requirements associated with electrically powered road markers. These characteristics make the developed road stud a practical, sustainable, and scalable solution for improving nighttime road delineation and safety in developing urban environments.

Based on these findings, it is recommended that local government units (LGUs) consider pilot deployment of the proposed road stud in school zones, pedestrian crossings, barangay roads, and secondary urban corridors, where lighting infrastructure may be limited or inconsistent. Future work should include extended field trials to evaluate long-term durability, photoluminescent degradation, and mechanical wear under actual traffic loading and prolonged environmental exposure. Further optimization of photoluminescent material composition and layer thickness is also recommended to enhance luminance efficiency while minimizing production cost. Additionally, future studies may explore integration with complementary passive road markings or low-power smart monitoring systems to support data-driven road safety planning. Collectively, these efforts can contribute to safer, more resilient urban road networks aligned with the practical needs and constraints of tropical developing regions.

Compliance with ethical standards

This study complied with all applicable ethical standards for engineering and materials research. The research did not involve human participants, human data, or animal subjects. All experimental procedures were limited to the design, fabrication, and performance evaluation of a photoluminescent–reflective cat's eye road stud under controlled laboratory and field-simulated conditions. No personal data were collected, and no ethical risks related to human or environmental harm were identified. All materials and testing procedures were conducted in accordance with relevant safety and research integrity guidelines, and the results were reported transparently and without fabrication, falsification, or improper data manipulation

Disclosure of conflict of interest

The authors declare that there is no conflict of interest to be disclosed

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