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ARTICLE

Modular Design Using Sustainable Luminescent Materials in Energy-Saving Reflective Cat's Eyes for Public Road Safety Planning

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ABSTRACT

Recently, there has been a global movement toward environmental protection and energy conservation through the design and development of new products in accordance with sustainable utilisation. In this study, rare earth luminescent materials were used owing to their active light emission and reusability. Additionally, solar light-emitting diode lights and car-light reflection were utilised to increase the recognition and reliability of reflective cat eyes. Along with carbon reduction, this can save energy and enhance road safety. This study considered the Theory of Inventive Problem Solving and a literature review to analyse the issues in existing products. Then, expert interviews were conducted to screen projects and develop product design policies. Finally, the ratio of light-storage materials was experimentally determined and the prototypes implemented. This cat's eye addresses the shortcomings identified in previous analyses of existing products. We applied energy storage environmental protection materials, together with material proportioning (which balanced warning efficiency against cost-effectiveness) to develop diversified modular kits; these were flexible in terms of quantity and easily assembled. This study achieved four key objectives: (1) reducing the research and development costs of the manufacturer; (2) offering buyers a diverse suite of products; (3) responding to a need to improve diverse road user safety; and (4) reducing government procurement costs for safety warning products. The results provide a reference for the creative modular design of energy-saving products for public road safety planning in various industries.

KEYWORDS

Sustainable luminescent materials; modular design; TRIZ; expert interview; diverse road safety

1 Introduction

At present, the rapid development of science and technology is heavily reliant upon the exploitation of various energy sources and emerging new materials. As many energy sources and raw materials are non-renewable, environmental protection, and energy saving have gradually become primary goals in product design and development. Additionally, sustainable utilisation is the means to cope with the depletion of non-renewable energy sources. In areas that receive abundant sunshine and grapple with insufficient illumination at night, applying self-luminance technology to road safety warning products may save electric energy and improve warning devices. Self-luminous warning products are particularly important for driving on rural roads and hiking with insufficient light. In the "smart future road project" in

Amsterdam, Netherlands, energy storage luminescent materials have been added to marking paints to absorb and store solar energy that is emitted at night. However, paints can be washed away by rain, and these light emissions are not uniform [1]. British company Pro-Teq has developed a product known as "Starpath", which may be sprayed on any solid surface to absorb sunlight and emits a soft blue light at night. This product reduced the demand for complex illumination facilities in parks and streets and improved night safety. Although the low light intensity of Starpath did not increase light pollution [2], its relatively low luminance was unsuitable for roads. Energy storage luminescent coatings on pavements in tourist areas have been tested in Chongqing and Liuzhou, China. Studies have shown that through such approaches, roads can attract user attention while saving energy; however, the associated high costs inhibit their widespread use [3].

Many countries have used energy storage luminescent materials for pavement safety warnings; however, the paints utilised are susceptible to external forces and require further development. Moreover, to the high cost of energy storage luminescent materials, large-scale pavement coatings are not economically feasible [3]. This study improves the design of warning products that use energy storage luminescent materials to address these issues. Based on the input of various experts, embedded reflective cat's eyes, which cover small areas, were identified as a suitable design target.

There are many cases in which traffic safety concerns may arise; these include riding bicycles with faint lights, walking in areas without street lamps, and insufficient nighttime illumination in rural mountain areas and on industrial roads. Commercial reflective cat eyes do not provide multifunctional modules to meet the needs of different users, such as active or passive light emission; as such, this study used multifunctional and creative designs. To improve road safety under various conditions and lower the product development costs, energy storage luminescent functional materials were employed and modular reflective cat's eyes were developed.

The research process involved five key steps: (1) determination of research motivation and purpose through data collection and field observations; (2) review of literature on energy storage luminescent materials and reflective cat's eyes; (3) development of product design policies using the theory of inventive problem solving (TRIZ) and interviewing experts to select the four highest priority qualities for the creative design of modular product kits; (4) the development of the design of prototypes, implementation of experiments on material ratios, the description of application scenarios; and (5) the summary of research results and recommendations for future research.

2 Literature Review

This study aimed to incorporate energy storage luminescent materials into the design of pavement retroreflective warnings. The literature review was divided into 5 main themes: (1) energy storage luminescent materials, (2) pavement warning markings, (3) road safety investigations, (4) application of light-storage warning products, and (5) retroreflective markings. The literature was collected and summarised to inform subsequent prototype design and product application.

2.1 Energy Storage Luminescent Materials

Energy storage luminescent materials refer to materials that store energy and emit light slowly in the dark; these are also referred to as light storage materials. Such materials may be used for safety warnings in districts with insufficient nighttime light, improving the safety of night activities. Light storage materials have been developed over the past hundred years. The earliest self-luminous materials may be traced back to the radium extracted by Madame Curie; however, they are radioactive and highly toxic. Zinc sulfides were the second generation of self-luminous materials that emerged in the mid-20th Century. Their toxicity, radioactivity, and low luminance restricted their application; most were used on clock surfaces. The third generation of self-luminous materials is light storage materials, including strontium aluminates (rare earth-doped aluminates) which are non-toxic and non-radioactive. Their luminescence intensity and duration are 30–50 times that of traditional light-emitting materials; they are also energy-saving, stable, and inclement weather resistant. Strontium aluminates have revolutionised the development and application of light-storage materials [4].

Rare earths are indispensable for producing high-efficiency, energy-saving light sources. They have a clear energy-saving effect and greatly improve lighting quality. The production process using rare earth materials produces less pollution when compared to conventional materials, and rare-earth-doped aluminates provide green lighting [3]. The advantages of rare earth luminescent materials include physical and chemical stability, high-temperature resistance, narrow emission spectra, colours with high saturation and purity, high light conversion efficiency, strong absorptive capacity, and a wide wavelength distribution [4]. The International Maritime Organization (IMO) has developed regulations for the use of light-storage fire safety signs in places such as the German Airport and Telecommunications Centre buildings, the American Boeing aircraft, London subway and ships, and Hong Kong subway cars. These signs also function as guides to escape pathways during an accidental power failure [5,6].

2.2 Warning Pavement Markings

The general visibility or retro-reflectivity of road markings is highly relevant to the field of vision for drivers, particularly under nighttime conditions, which means the degree of road marking luminosity is very important to pedestrian safety [7]. Road markings are mainly classified into reflector-type and reinforced-glass retroreflective; the latter is commonly known as reflective cat's eyes. This name originates from its similarity to a cat's eye in reflecting vehicle lights and is used worldwide. The cat's eyes can function normally with 360° reflection and has a service life exceeding six years, which reduces maintenance costs along with road accidents; this longevity is regardless of whether the double yellow line is worn and rendered useless [8]. As the reflective cat's eyes were designed as a raised structure, their original name was raised pavement markers (RPMs); the vibration of vehicles warned drowsy drivers from driving off lanes [9].

Most new cat's eyes utilize light-emitting (LED) lamps as light sources in which electricity is supplied by pavement power facilities or solar panels [9]. Compared with traditional incandescent lamps, LED lights have a longer service life and lower power consumption. The relevant manufacturing technologies are becoming increasingly sophisticated in terms of improving colour and luminance. As such, the United States (US), Japan, and many European countries have actively adopted LED lights as opposed to incandescent lamps in traffic signs to improve vehicle and pedestrian safety and save energy [10,11].

2.3 Road Safety Investigation and Application of Light-Storage Warning Products

A major issue in road safety, based on analysing public opinions on poor traffic engineering facilities, is the unrepaired/non-updated damages and the inappropriate size and location of facilities. The main issues with road markings were weak reflectivity, luminance, and illumination at night. This means that to some extent, retroreflective markings influence road users. The key factor in traffic safety is re-examining the approaches and locations in the placement of markings and maximising visual performance, specifically in terms of achieving efficient retroreflective markings [9].

There has been extensive use of light storage materials, such as for safety warnings at construction sites and escape warnings in hospitals; recently, their application has expanded to traffic systems. For example, a luminous highway was tested in the Netherlands to replace streetlights. Studio Roosegaarde marked a 500 m road with luminous paints near the city of Oss. The paints stored light energy during the day and emitted light at night, saving electricity and cost; however, the experiment encountered issues related to worn pavements, rain erosion, and non-uniform luminescence [1]. Another example is the development of Starpath to illuminate a city in the United Kingdom (UK). According to the introduction of Arup Group Limited, this product could be sprayed on any solid surface to absorb sunlight, and emit blue light to illuminate the city at night; this would significantly reduce the demand for streetlights and carbon emissions. Moreover, Starpath improves the safety of parks, streets, and alleys, while not creating light pollution due to its low luminance. Researchers have tested its effect in Christ's Pieces Park, Cambridge, UK [2]. Although both product examples save energy and reduce carbon emissions, they are vulnerable to pavement damage and rain erosion. Furthermore, Starpath requires large-scale application due to its low luminance and relatively high cost. In this study, the embedded reflective cat's eyes were identified as suitable design targets to address these issues. They are a light storage material that span small areas and may lower the cost of product development and improve resistance to inclement weather.

2.4 Research on Retroreflective Markings

Previous research studies have focused on the location and colour of retroreflective markings and the effect of these markings on the accident rate. In terms of locations, researchers evaluated the use of raised markers at a sharp curve and a narrow bridge in Kentucky to support recommendations for improved delineation at similar sites on rural roads. The optimal centreline spacing for retroreflective markers was experimentally established under different road conditions for determining the number of markers required and appropriate placement [12]. Another study noted driver responses to raised pavement markers by measuring changes in speed and encroachment distances into the opposing travel lane after varying the spacing of these markers [13].

In terms of colours, a study was conducted to evaluate the understanding of drivers of red-raised RPMs (RRPMs) on undivided and divided roadways. There were 191 participants equally categorised into three groups: (1) drivers from countries with left-hand drive, (2) Hawaii, and (3) the continental US. In general, red RRPMs on one-way divided roads to indicate the wrong direction of travel were found to alert drivers when they were travelling in the wrong direction. Red RRPMs on undivided roadways improved the understanding of the road for drivers from countries with left-hand drive without reducing the understanding of the other two groups [14]. Another study reported that the red colour prompts drivers to avoid the marking; as such, this study selected red retroreflective markers to warn drivers who strayed into unauthorised lanes [15].

In terms of the influence of retroreflective markers on the accident rate, a study analysed the relationship between retroreflective markings and accident prevention from actual measurements on 86 highways; accident reduction was only 2% in the daytime and 13% at night [16]. Another study assessed the safety of wet-weather pavement markings on night crashes using empirical Bayes (EB) and full Bayes (FB) approaches [17]. Both evaluation results supported the positive safety effects of wet-weather pavement markings for crashes that occur under dark and wet conditions. Experts also conducted a similar analysis of wet-weather pavement markings based on data from three US states; Minnesota, North Carolina, and Wisconsin [18]. They found that results for the most relevant target crashes, night crashes, and night wet-road crashes were inconsistent across these three states and were largely insignificant.

Traffic facilities should be centred around human-oriented design, particularly focusing on vision and hearing which significantly impact driving [19]; traditional retroreflective markings do not exhibit good visual performance. Self-luminescence should be employed together with light reflection to improve performance. For instance, solar pavement markings may be installed in areas with sufficient sunlight and insufficient illumination at night [20,21].

In summary, experts state that retroreflective markers mainly function on sufficient luminance; as such, different retroreflective markers should be installed according to the road conditions. Despite this, only few studies have focused on the locations and colours of these markers, and their impact on the accident rate. Retroreflective markers have rarely been developed from a creative modular design basis in which the application of green energy materials is key. This study combined light storage materials and modular retroreflective markers for adaptation under different road conditions, exemplifying the use of innovative materials to save energy and thus reduce carbon emissions. Modular creative products have been developed to enhance competitiveness, reduce mould costs, and improve traffic safety under different road situations.

3 Research on Product Innovation

This study utilised the principle of creative design as a product development method. The feasible direction to develop existing products was analysed using the TRIZ contradiction matrix. Expert interviews were conducted with four general managers and professors in the industrial design, electron control, light storage materials, and new product research and development fields. This informed the evaluation of requirements for the final design principle of new products and ways to improve the practicability of materials, research and development, and production.

3.1 Investigation on Invention Principles by Contradiction Matrix

Unlike traditional innovative research and development, patent mining is an effective method of technology extension and development. By practicing patent mining, manufacturers can defray the high risks, high costs, and lengthy processes usually associated with the original product research and development. In recent years, systematic patent mining methods have gradually gained the attention of researchers and technology developers, and common design processes (e.g., TRIZ, a Russian approach), have emerged as patent mining formats [22].

A common issue in new product development processes is that improvements to a particular product characteristic or engineering property often come at the expense of another product or engineering property. This inspired Genrich Altshulle to sort through 39 general engineering parameters and 40 principles of invention into the contradiction matrix after studying 2.5 million patents; he summarised the innovative principles and rules to solve various technical contradictions [23]. When using the 39 × 39 contradiction matrix table, the "improving engineering parameters" are initially selected from the vertical axis; this is followed by selecting the "worsening engineering parameters" from the horizontal axis. The numbers in the intersecting cell of the contradiction matrix point to the principles of innovation and invention; these overcome the identified contradiction, as shown in Fig. 1.

Improving Feature ↓ / Worsening Feature →		1 Weight of moving object	2 Weight of stationary object	3 Length of moving object	4 Length of stationary object	5 Area of moving object	6 Area of stationary object	7 Volume of moving object	8 Volume of stationary object	9 Speed	10 Force (Intensity)	11 Stress or pressure	12	13
1	Weight of moving object	+		15, 8, 29,34		29, 17, 38, 34		29, 2, 40, 28		2, 8, 15, 38	8, 10, 18, 37	10, 36, 37, 40	10, 14, 35, 40	1, 35, 19, 39
2	Weight of stationary object		+		10, 1, 29, 35		35, 30, 13, 2		5, 35, 14, 2		8, 10, 19, 35	13, 29, 10, 18	13, 10, 29, 14	26, 39, 1, 40
3	Length of moving object	8, 15, 29, 34		+		15, 17, 4		7, 17, 4, 35		13, 4, 8	17, 10, 4	1, 8, 35	1, 8, 10, 29	1, 8, 15, 34
4	Length of stationary object		35, 28, 40, 29		+		17, 7, 10, 40		35, 8, 2, 14		28, 10	1, 14, 35	13, 14, 15, 7	39, 37, 35
5	Area of moving object	2, 17, 29, 4		14, 15, 18, 4		+		7, 14, 17, 4		29, 30, 4, 34	19, 30, 35, 2	10, 15, 36, 28	5, 34, 29, 4	11, 2, 13, 39
6	Area of stationary object		30, 2, 14, 18		26, 7, 9, 39		+				1, 18, 35, 36	10, 15, 36, 37		2, 38
7	Volume of moving object	2, 26, 29, 40		1, 7, 4, 35		1, 7, 4, 17		+		29, 4, 38, 34	15, 35, 36, 37	6, 35, 36, 37	1, 15, 29, 4	28, 10, 1, 39
8	Volume of stationary object		35, 10, 19, 14	19, 14	35, 8, 2, 14				+		2, 18, 37	24, 35	7, 2, 35	34, 28, 35, 40
9	Speed	2, 28, 13, 38		13, 14, 8		29, 30, 34		7, 29, 34		+	13, 28, 15, 19	6, 18, 38, 40	35, 15, 18, 34	28, 33, 1, 18
10	Force (Intensity)	8, 1, 37, 18	18, 13, 1, 28	17, 19, 9, 36	28, 10	19, 10, 15	1, 18, 36, 37	15, 9, 12, 37	2, 36, 18, 37	13, 28, 15, 12	+	18, 21, 11	10, 35, 40, 34	35, 10, 21
11	Stress or pressure	10, 36, 37, 40	13, 29, 10, 18	35, 10, 36	35, 1, 14, 16	10, 15, 36, 28	10, 15, 36, 37	6, 35, 10	35, 24	6, 35, 36	36, 35, 21	+	35, 4, 15, 10	35, 33, 2, 40
12	Shape	8, 10, 29, 40	15, 10, 26, 3	29, 34, 5, 4	13, 14, 10, 7	5, 34, 4, 10		14, 4, 15, 22	7, 2, 35	35, 15, 34, 18	35, 10, 37, 40	34, 15, 10, 14	+	33, 1, 18, 4
	Stability of the object's	21, 35 [illegible]	26, 39 [illegible]	13, 15 [illegible]	[illegible]	2, 11 [illegible]	[illegible]	[illegible]	34, 28 [illegible]	33, 15 [illegible]	10, 35 [illegible]	2, 35 [illegible]	22, 1 [illegible]	

Figure 1: Example showing partial extraction from a contradiction matrix. Table based on TRIZ (2021), and on the 39 engineering parameters in the contradiction matrix, sourced from https://sites.google.com/site/triz5mis/our-solutions

3.1.1 Research Procedure of Contradiction Matrix

First, we investigated issues in previous technologies according to patents and literature on pavement markings and luminous warnings at night; these issues were summarised to establish goals for improvement. Next, invention principles were deduced from the TRIZ contradiction matrix. The feasible invention principle was selected as a prerequisite for product innovation based on analysing parameters that required improvement and those that needed to be prevented from deterioration. Expert interviews were conducted to assess technical requirements and energy-saving needs. This assessment was essential for the creative design of new products; the research procedure for the contradiction matrix is shown in Fig. 2.

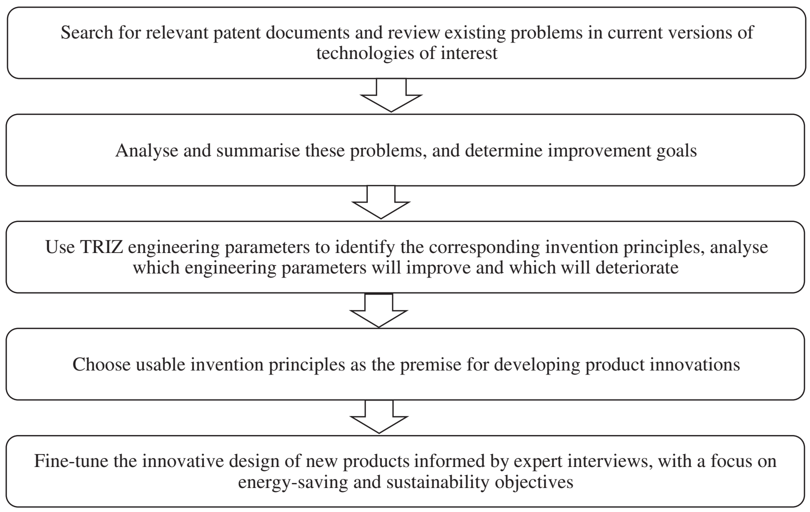


Figure 2: Research procedure for contradiction matrix

Patent Search and Selection of Applicable Invention Principles

Patent literature between 1999 and 2019 was collected from the Republic of China Specialty System; keywords of the search were "pavement markings" and "reflective cat's eyes". Among the 27 and five patents obtained for pavement markings and reflective cat's eyes, nine and two were invention patents, 18 and two were new type patents, and zero and one were a new model of a patent, respectively. As the reflective cat's eyes in the study were developed with light storage materials in response to energy-saving demands across various countries, two patents related to "luminous warning at night" were added to facilitate new product design with luminescent function. Following a detailed examination of patent documents, the 11 most relevant to the research topic were identified for detailed analysis. Key technologies applied in selected patents, together with descriptions of their shortcomings were summarised and transformed into corresponding engineering parameters. "Improving engineering parameters" were obtained from these key technologies, while "worsening engineering parameters" were derived from identified technical deficiencies. The invention principle was deduced from the contradiction matrix after identifying the parameters requiring improvement and those being prevented from deterioration. The applied statistical invention principle was relative plurality and workability, including three principles (10, 35, 40): pre-action, parameter change, and composite materials. Four invention principles were derived based on the discussion with experts, the energy saving and sustainability objectives, and the consideration to the Invention Principle 34 (abandonment and regeneration).

Conversion of Invention Principles to Design Policies

The detailed explanations of the four selected invention principles were converted into implementation policies based on expert interviews.

(1) Invention principle 10: pre-action (a) and (b)

(a) Introduce a useful action into an object or system (either fully or partially beforehand);

(b) Pre-arrange objects or systems such that they may be active at the most convenient time and place.

Expert opinions: Threats to safety occur when vision becomes obscured by darkness or when lighting is insufficient at night. As such, utilising energy storage luminescent materials in safety warning products is a feasible option that is attracting significant international attention. These materials may be applied to anti-slip nosing on stairs, pavement coatings, and escape equipment signage. Some issues still require consideration, such as whether the location has sufficient light, and whether light pollution affects the area during use; this means lighting requirements need to be considered on a case-by-case basis. It is recommended that LED lights are used to complement photoluminescent lighting; this will provide light energy at night, extending the photoluminescence lighting period while saving electricity. This product mix will contribute to the research and development of new energy-saving cat's eyes applicable in a variety of situations.

Design policy 10: pre-action (a) and (b)

(a) Light storage materials employed to store light energy in advance and illuminate at night to supplement exhausted batteries;

(b) When there is insufficient light on rainy days, LED lights or light-reflective parts were one of the key light sources for luminous warning.

(2) Invention principle 34: abandonment and regeneration

Elements of an object or system that have fulfilled their functions disappear (e.g., by dissolving, evaporating), or appear to disappear. Restore consumable or degradable parts of an object or system during operation.

Expert opinions: Energy storage luminescent materials embody energy storage and light-emitting characteristics. They absorb and store ultraviolet (UV) light and luminesce when there is no light source. Light is gradually emitted from the energy storage luminescent material over time and may be used repeatedly. While these energy-saving materials are safe and consistent with the sustainable development objectives, they have never been used in reflective cat's eyes. Cat's eyes link into national transportation infrastructure, creating a relatively broad scope for their deployment. As such, this application represents an important safety breakthrough, also contributing to energy savings and environmental protection. Based on these opinions, the product design policy was transformed, as described in the next section.

Design policy 34: abandonment and regeneration

Light storage luminescent materials absorb energy and emit light repeatedly such that energy may be regenerated for sustainable utilisation.

(3) Invention principle 35: parameter change (b)

(b) Change in concentration or consistency

Expert opinions: Ensuring an effective proportion of energy storage luminescent materials within composite materials is crucial to their luminosity; based on previous experience, a light-emitting layer should be at least 2 mm thick. Increasing the ratio of luminescent powder can extend lighting time and increase its brightness while optimising ratios can reduce costs. Based on these opinions, the product design policy was transformed as described in the next section.

Design policy 35: parameter change (b)

(b) The proportion of luminescent powders was adjusted to improve the luminous time and illuminance of light storage materials.

(4) Invention principle 40: composite materials

Change from uniform to composite (multiple) materials, where each material is optimised for a specific functional requirement.

Expert opinions: Rare earth materials with energy storage functions may be combined with other materials. Although these materials are luminescent with high potential, the brightness of the light they emit decays relatively rapidly. If composites are developed by combining rare earth elements with other materials, luminosity may effectively be improved [24]. Epoxies are an example and contain ingredients that can improve luminosity; these include compounds such as silicon oxide, strontium carbonate, and europium oxide. Combining these two materials (i.e., rare earths and epoxies), has a synergistic effect on luminosity and product robustness; this may expand their applicability while reducing costs. Based on these opinions, the product design policy was transformed as described in the next section.

Design policy 40: composite materials

Products should be made of materials that may be combined with luminescent materials, such as epoxy and poly glue.

3.2 Analysing Product Research and Development Plans

When these design guidelines were summarised, the main development elements include the light storage function, material pouring, and top cover design guidelines, warning modes, and material ratios. Feasibility research and development plans were discussed with experts, and the advantages and disadvantages of each plan were analysed to address the shortcomings of existing products. In particular, this discussion focused on energy consumption and the constraint that each product was only suitable for road usage applications. Through a modular design, energy savings can be achieved, and the scope of the product may be expanded to applications other than road usage.

3.2.1 Light Storage Function

Energy storage luminescent materials with light storing functions were added to safety warning products to include a warning component capable of emitting light in and of itself; relevant feasibility plans are presented in Table 1. After considering the advantages and disadvantages, experts advised that surface coatings, the common form of energy storage luminescent materials, were susceptible to surface wear and reduced performance in inclement weather [1]. As such, we selected Plan (1), in which energy storage luminescent materials were placed inside the top covers of the reflective cat's eyes.

Table 1: Feasibility plans for the light storage function

Feasibility plan (1): To place the energy storage luminescent material inside the top covers of reflective cat's eyes; light may enter and exit through the glass.	
Advantages	Disadvantages
1. The energy storage luminescent material is protected by the top cover, reducing its exposure to damage. 2. Light is emitted through the glass shell, such that it is scattered and amplified.	1. Insufficient transmission by the glass affects the energy absorption and luminosity performance of the energy storage luminescent material. 2. The shape and position of the energy storage luminescent material interfere with the luminous effect of other components in the bottom cover.

(Continued)

Table 1 (continued)

Feasibility plan (1): To place the energy storage luminescent material inside the top covers of reflective cat's eyes; light may enter and exit through the glass.	
Feasibility plan (2): The energy storage luminescent material is embedded into the surface of the top cover; light can irradiate and emit directly.	
Advantage	Disadvantages
The luminosity of the energy storage luminescent material is unaffected by the top cover.	1. The energy storage luminescent material is directly exposed at the surface and is prone to damage by external forces. 2. The energy storage luminescent material directly blocks light produced by other components, reducing their luminosity.

3.2.2 Material Pouring and Top Cover Design

Experts noted that the electronic parts of the product use little space and that the energy-saving design can efficiently use the internal space; the shape may also be modified to reduce the influence of the energy storage luminescent material shape and position on the reflective effect of other product constituents. The energy storage luminescent material may be coated in a 360° circular, planar fashion, or poured in a three-dimensional (3D) manner inside the cover, to perform synergistically with other luminous components under varying road usage situations; the feasibility plans are listed in Table 2. After considering the advantages and disadvantages, the experts suggested that the planar coating method would not allow existing energy storage luminescent materials to function effectively. Furthermore, the traditional, smooth, semi-circular design of top covers may easily lead to cars skidding, endangering passers-by. Therefore, we selected Plan (2), in which the energy storage luminescent material is poured in a 360° circular and 3D manner and the top cover incorporates anti-slip blister patterns. Non-deformable top covers enhance the convenience and stability of the pouring process and are sufficiently thick to encourage more light storage. If material is poured in a triangular segmental manner, material costs may be reduced; this addresses the cost issue in which this method could otherwise be more expensive than flat coating.

Table 2: Feasibility plans for the shape/position of the energy storage luminescent material and for top cover design

Feasibility plan (1): The energy storage luminescent material will be coated in a 360° circular, planar manner, inside a smooth glass shell.	
Advantages	Disadvantages
1. The hollow part of the cat's eye can include other luminous components to improve its practicality. 2. Energy storage luminescent materials are prone to shrinking. A flat coating inside the shell can reduce any associated deformation problems.	1. Energy storage luminescent materials that are too thin affect energy absorption and luminosity. 2. Smooth glass covers may lead to more car skidding incidents, increasing the risk of harm to passers-by.

(Continued)

Table 2 (continued)

Feasibility plan (1): The energy storage luminescent material will be coated in a 360° circular, planar manner, inside a smooth glass shell.	
3. The manufacturing approaches of flat coating and creating smooth covers are simple and cost-effective.	
Feasible plan (2): The energy storage luminescent material is poured in a circular, 3D manner, with the top cover incorporating anti-slip blister patterns.	
Advantages	Disadvantages
1. The hollow part of the cat's eye can include other luminous components, to improve its practicality. 2. A sufficient thickness of energy storage luminescent materials can enhance energy absorption and luminosity. 3. Incorporating anti-slip blister patterns onto the glass shells can reduce skidding, protecting passers-by.	The manufacturing technique of 3D pouring and top cover anti-slip blister patterning is relatively complicated and costly, when compared to flat coating.

3.2.3 Warning Mode

Experts believe that photoluminescent energy storage materials, solar-powered LEDs, and the reflection of reflective components may all be effective warning markers; the feasibility plans are listed in Table 3. Determining the most optimum component combinations on a case-by-case basis can meet the needs of different road use situations and enhance warning and safety outcomes while satisfying energy saving and sustainability objectives; for this reason, we selected Plan (2). Top and bottom covers suitable for component combinations in various situations should also be designed and developed to reduce case-by-case mould manufacturing. As such, modular component designs which are compatible and flexible in terms of quantity may be adopted to facilitate manufacturing and mass production.

Table 3: Feasibility plans for warning modes

Feasible plan (1): To integrate all luminous components (e.g., solar-powered LEDs, energy storage luminescent materials, and reflective components), into one product.	
Advantages	Disadvantages
Such a product would be effective regardless of road type or other situations. During a power outage or major accident, the product would continue to provide a backup light source to protect road users.	Combining all luminous components will increase cost and may contribute to resource depletion.
Feasibility plan (2): Use various combinations of luminous components on a case by case basis.	

(Continued)

Table 3 (continued)

Feasible plan (1): To integrate all luminous components (e.g., solar-powered LEDs, energy storage luminescent materials, and reflective components), into one product.	
Advantages	Disadvantages
Various luminous components are integrated into diversified products as required, on a case by case basis. This responds to the needs and safety concerns of different road users, and expands the product lines of manufacturers. It also supports the energy-saving and sustainability objectives.	Diversified product lines increase the mould manufacturing cost; this is not aligned with economies-of-scale.

3.2.4 Material Mixing and Preparation

Experts believe that luminescent powder proportioning and material thickness are crucial to the luminous efficiency levels. Therefore, the feasibility plans in Table 4 should also be considered to identify suitable luminescent powder/material thickness ratios. This will offer a balance between energy storage luminosity and cost-effectiveness.

Table 4: Feasibility plans for material mixing and preparation

Feasibility plan (1): Increase the proportion of luminescent powder	
Advantages	Disadvantages
Can improve brightness and extend afterglow.	Excess can cause counter-effects and increase cost.
Feasibility plan (2): Increase the thickness of the luminescent material	
Advantage	Disadvantage
Can increase light energy capture capacity.	Excess thickness reduces the absorption capability of the bottom cover light energy.

4 Product Development

First, experts were invited to discuss and modify the light storage function, cover modelling, material preparation, and the warning mode based on the design goals. Then, we conducted experiments on the ratio of luminescent material to understand the luminous effect. Finally, a modular implementation was carried out in accordance with different luminescence scenarios.

4.1 Design of Product Prototype

4.1.1 Design of Covers and Light Storage Castings

The top cover was made of tempered glass; the 45° oblique angle was adopted to reduce the impact of tyre rolling. The surface of the top cover had anti-slip flanges to prevent vehicle slipping. Luminescent materials were cast inside the top cover with a 360° ring shape and a triangular cross-section to prevent damage from exposure to external forces. As they were shrinkable, the materials needed to fit into a rigid cover that could not be easily deformed. The red triangle was gradually cast to a height of 10 mm; the retaining wall design allowed for a convenient and stable casting process. The extra space in the middle was configured with other components. Different modular kits were designed to improve the luminous effect and safety, as shown in Fig. 3.

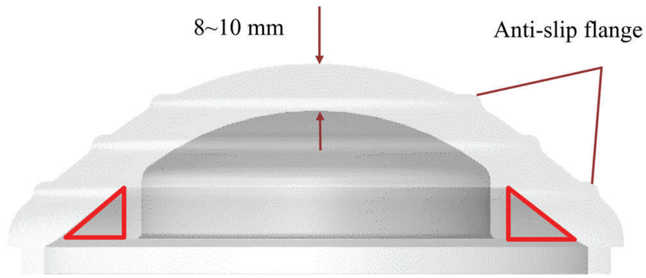


Figure 3: Design of top cover

4.1.2 Material Preparation Design

Experimental Method

The luminous efficiency is dependent on the ratio of the luminescent powder to the material thickness. As such, we tested the effect of the material ratio and thickness on the luminous efficiency to determine the appropriate proportion. Moulds with an area of 2.5 cm × 2.5 cm and different thicknesses (5, 10, and 15 mm), were cast.

Experimental specimens were placed in an open area to absorb natural light energy and receive light energy from a non-energy state; they were then tested to determine the luminous time after sunlight exposure. We included 15 males and females aged around 25 years as subjects. This was because the luminance of energy storage in rare earth elements remains visible to the naked eye when the illuminance meter cannot detect the value, and humans are the target of the luminescence warning of the reflective cat's eye. The test was conducted at 12 m from the specimens (a safe distance of approximately 1 m based on the laws and regulations of road markings [25]. A long-distance conservative test was carried out to reduce the visual bias by including subjects of different ages and eyesight capabilities. Records were taken every 30 min to confirm that each subject agreed with the visual warning effect until it was no longer effective; this was considered the luminous time. Specimens were placed back into the dark box after the measurement to avoid interference from external light.

This study was a collaborative project between industry and academia. The cat's eye material provided by a professional manufacturer was composed of tempered glass commonly used for roads; it was fully sealed and waterproof and complied with the CNS 13762 specifications for reflective road markings used by Taiwanese engineering units. This includes compliance with size, reflectivity, tightness, salt spray, compressive strength, and impact test requirements to ensure the reflective brightness and durability of the reflective cat's eye under harsh conditions [26]. The experiment was conducted to identify the appropriate light storage material and its cost-effective proportion and luminous time. After confirming the optimum proportion, the prototype luminous time of the product was tested by pouring an appropriate proportion of light storage material into the glass photomask.

Experimental Result

When proportioning luminous powder and epoxy A + B, a 30% concentration (luminous powder to epoxy A + B ratio) is the limit for complete dissolution without particles. Initially, we had planned to use luminous powder to epoxy A + B ratios of 10%:90%, 20%:80%, and 30%:70%; to reduce product costs, the proportion of luminous powder was increased to 35–40% and thickness was reduced to 10 mm. A proportion of 35–40% leads to micro-particle formation, although this does not affect the aesthetics as the reflective cat's eye is a long-range warning tool. Further increases to the proportion of luminous power will make it difficult to form and pour a homogenous sample, producing waste; as such, the 35–40% range was given preference. The experimental results in Table 5 show that the suitable ratio of energy storage rare earths to epoxy was 35%:65%–40%:60%, and the casting thickness of 10 mm showed significant improvement in terms of luminous efficiency. For rare earth materials that exhibit medium efficiency, the luminous time could reach 4–4.5 h. We were able to enhance the luminous effect by 1.5–2 times if a rare earth material with longevity was employed; this is shown in Fig. 4.

Table 5: Luminous proportion and time

Luminous layer thickness (mm)	Luminous powder proportion (%)	Luminous time (h)
5	10	1–1.5
5	20	1.5–2
5	30	2.5–3
10	10	2–2.5
10	20	2.5–3
10	30	3.5–4
15	10	2.5–3
15	20	3.5–4
15	30	4–4.5
10	35	4–4.5
10	37	4–4.5
10	40	4–4.5

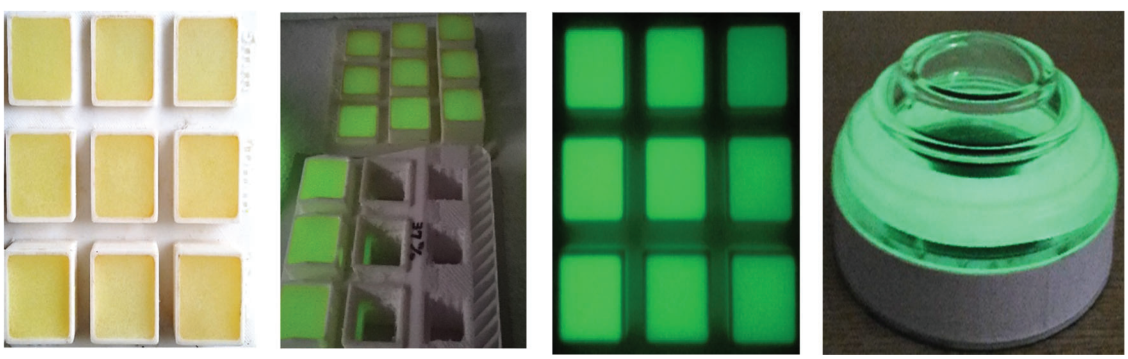


Figure 4: Luminescence experiments of energy storage rare earths

Based on interviews with experts and previous studies, the daylight duration required for energy storage in the rare earths was approximately 2 h; therefore, the difference between 2 h of daylight and a full day was tested. The luminous time at night was the same regardless of whether specimens were exposed to sunlight for 10–12 h or 2 h. This means that the light storage material can fully store energy after 2 h of sunlight; as such, the length of light has little effect on the luminous time of the energy storage material. Typically, the cat's eye material used has been utilised as road-tempered glass and meets the requirements of CNS 13762 Grade 1 for cat's eye reflection performance. The luminous time of the most suitable proportion of the experimental specimen and the luminous time measured by the same proportion of the light-energy material poured on the glass photomask were 4–4.5 h; this indicates that the prototype had a good luminous effect that was unaffected by the glass photomask.

4.1.3 Design of Warning Modes

Fig. 5 presents the configuration and descriptions of materials for all components. The warning design was divided into four modes: (1) active type, (2) passive type, (3) fusion type A, and (4) fusion type B. The active type mode includes self-luminous warnings using light storage materials, composed of a top cover (including rare earth casting), and a die-cast base of aluminium alloy, as shown in Fig. 6. Rare earths can store energy from sunshine or when irradiated by light from passing vehicles. With dim lights, they can luminesce for hours late at night even when no vehicles are passing by. The passive type modes are warnings with reflective components, composed of a top cover (without rare earth casting), a die-cast base of aluminium alloy, and a reflective cover, as shown in Fig. 7. Reflective patches may instantly be luminous (reflective) in response to a light source. Fusion type A includes luminous warnings at night using luminescent materials and reflective components, consisting of a top cover (including rare earth casting), a die-cast base of aluminium alloy, and a reflective cover, as shown in Fig. 8. The reflective patch is illuminated by a light source and instantly becomes luminous (reflective). The rare earths also store energy from sunlight or when irradiated by artificial light sources (e.g., car and street lights); as such, they may be luminous even in poor light. The fusion type B are supplemental warnings using light storage materials and solar LED modules, incorporating a top cover (including rare earth casting), a die-cast base of aluminium alloy, solar LED, and a battery, as illustrated in Fig. 9. Rare earths store energy during the day, and solar-powered LED modules store electricity from sunlight. The photosensitive resistance sensing function on the Printed Circuit Board (PCB) allows the LEDs to be luminous intermittently in dim light; the rare earths can store energy from these emissions. As such, during late-night periods with little car traffic, the combined effect of the rare earths and the LEDs is multiplied, maintaining longer-lasting, luminous warning effects.

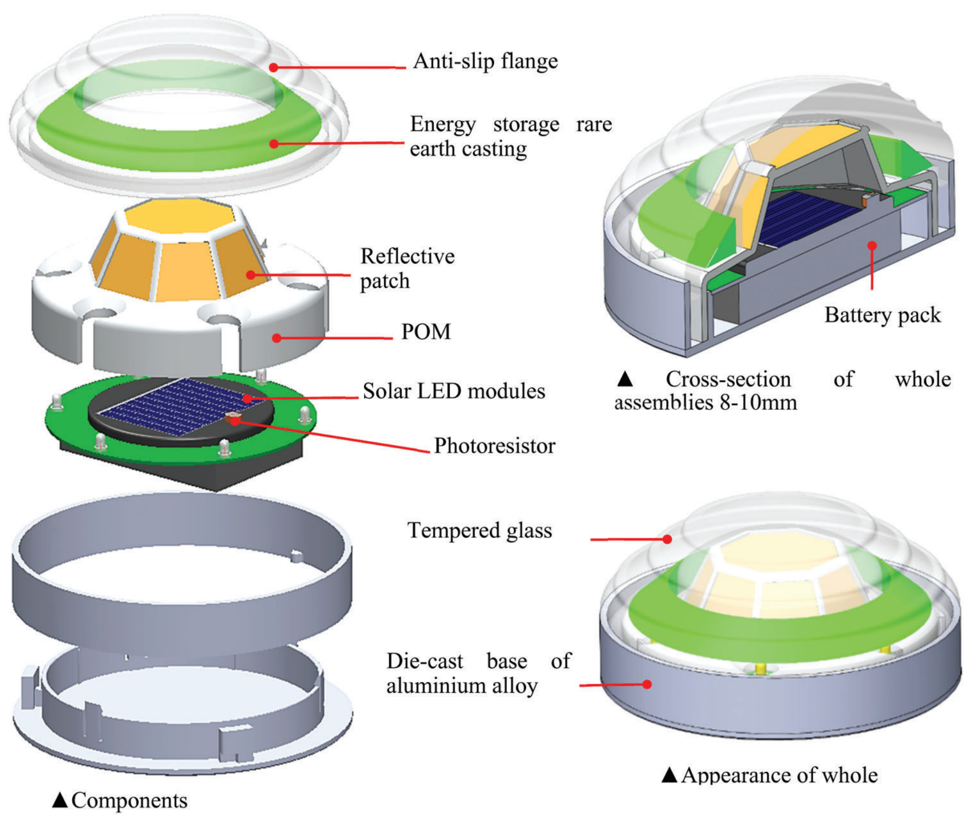


Figure 5: 3D configuration and material description of components

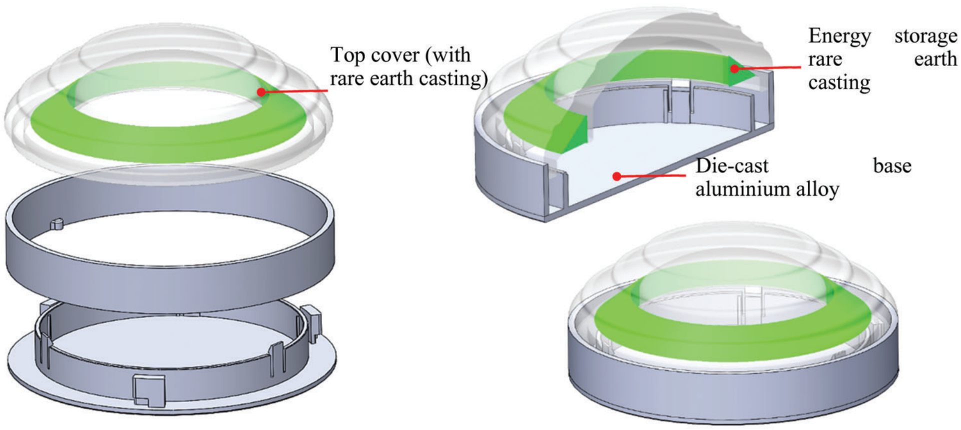


Figure 6: Active luminous warning design

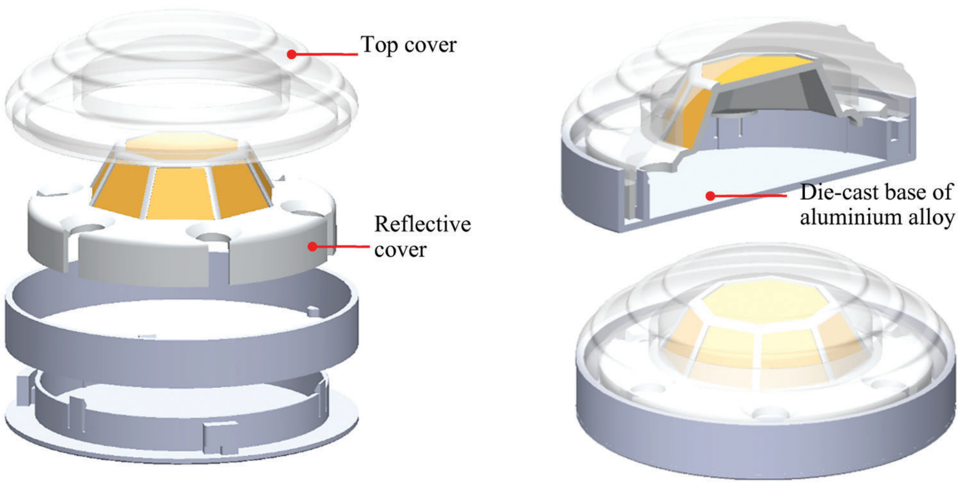


Figure 7: Passive light warning design

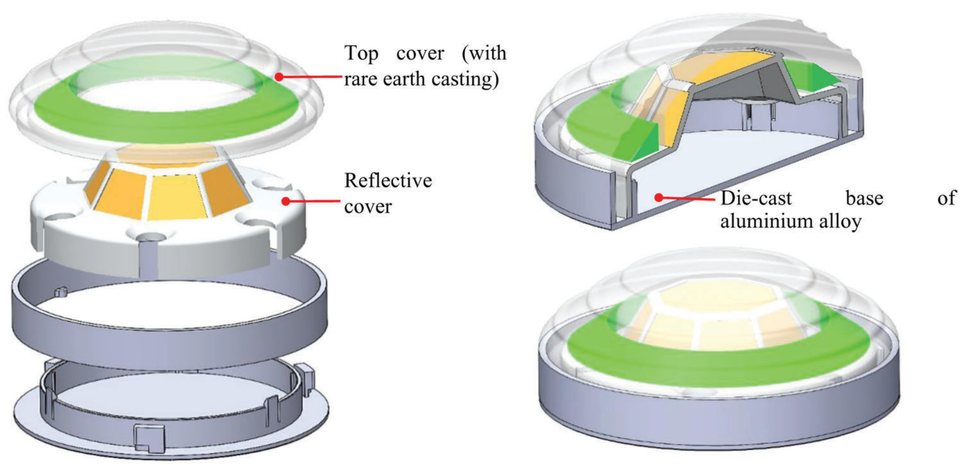


Figure 8: Fusion type A luminous warning design

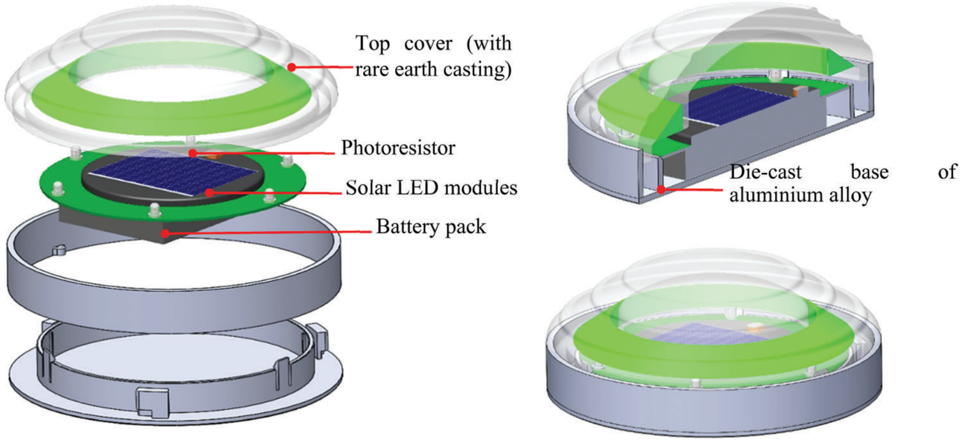


Figure 9: Fusion type B light warning design

4.2 Product Prototype Implementation and Testing

Fig. 10 shows that the prototype is composed of six components: the model shell, luminescent materials, solar LED modules, and PCB, reflective components, rechargeable batteries, and a base. Four combination modes were generated according to the requirements. The luminous effects and applicable scenarios for each mode are described below.

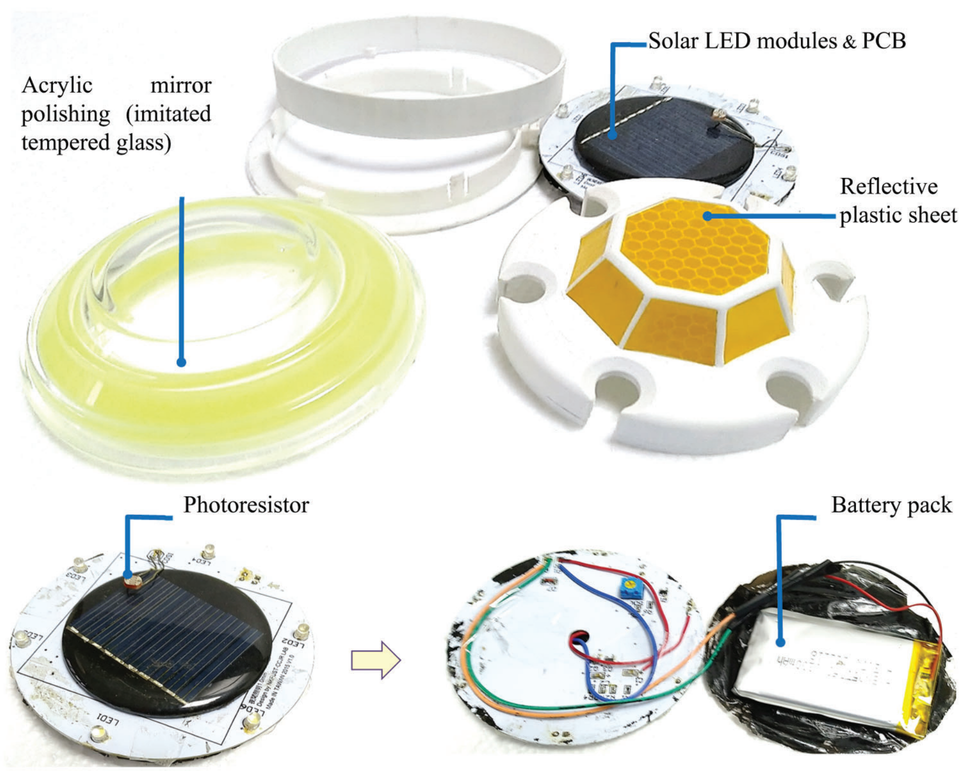


Figure 10: Component prototype

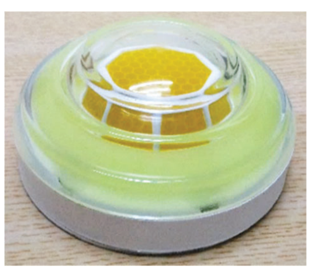
4.2.1 Luminous Effect

The luminous effect is primarily a warning effect detectable by the naked eye. This is because the luminance of energy storage rare earths is visible to the naked eye even when the illuminance meter cannot detect the value, and because humans are the target of the luminescence warning effect of the reflective cat's eye. The experimental results show that the "active type" illumination endures for approximately 4 h when the rare earth is used with medium efficiency and the ratio of rare earth to epoxy is 35%:65%–40%:60%. It can endure for longer than 6 h if the rare earth used has long-term efficiency.

4.2.2 Applicable Scenarios

Table 6 shows that the product prototype in this study was designed with a modular kit that was assembled to develop a variety of warning methods that match different application scenarios. For example, the active type may be adopted in abundant sunlight situations in the morning and insufficient illumination at night; this includes rural and mountainous areas, bicycles with weak lights, or pedestrians on pavements. The fusion type A supplements the night luminescence using car-light reflection and is applicable when there are fast vehicles with car lights shining on speed lanes, locomotive lanes, or heavy traffic roads in urban areas. The fusion type B may be used for urban roads with severe light pollution at night, or forest scenic areas, parks, and mountain areas with a short period of sunlight. This is because its warning time may be extended by supplying the strong LED lights, as a major warning source, with the self-illumination of energy storage materials at night during power failure. The passive type may be used for car light-reflective areas, such as on lane separation lines.

Table 6: Warning modes and applicable scenarios

Warning mode	Prototype	Applicable situation
Active type		-Bicycle lanes -Sidewalks -Rural and mountain roads
Fusion type A		-Urban roads -Locomotive lane -Speed lanes
Fusion type B		-Urban roads -Forest scenic areas, parks, mountain areas

(Continued)

Table 6 (continued)

Warning mode	Prototype	Applicable situation
Passive type		-Separation line of lanes

4.2.3 Product Assembling and Specifications

The product consists of two basic components; the top and bottom covers. These may be assembled through creative design by adding or removing components in the middle. The product was also designed with convex points and guide hooks for positioning and clamping, making the screw fixture redundant. Fig. 11 illustrates that the product may be rapidly assembled and disassembled, has high mobility, and mould development is low cost. Compared with other similar products, this product has reduced protrusion on pavements, improving pedestrian safety. It is also advantageous in terms of design diversity, easy assembly, environmental protection and energy conservation, slope reduction and anti-slip, and low development cost, as shown in Figs. 12 and 13.

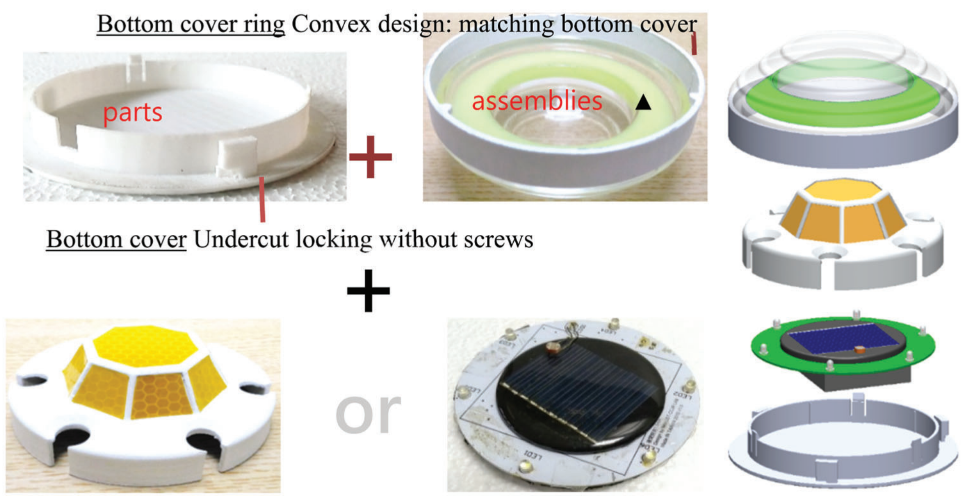


Figure 11: Component assembly

4.2.4 Green Energy Design Related to Road Safety Warning

In addition to developing the energy storage reflective cat's eye in this study, recent studies have reported on green energy design for road safety warnings, such as piezoelectric technology [27–29]. This can instantly convert the vibration energy of passing vehicles into electrical energy for flash LED lights to provide an early warning of oncoming traffic. This approach can enhance traffic safety in remote mountainous areas, at night, or in rain/fog; however, the device is prone to loosening because of long-term rolling of the road surface. This results in weakened power generation performance and a reduced warning life. Vehicle speeds affect the stability and effectiveness of the output-to-input power conversion, and the practical application of this material requires careful calculation and arrangement to compensate for power shortages. The piezoelectric device placed in the road structure is also greatly affected by climate [28]. As such, a road

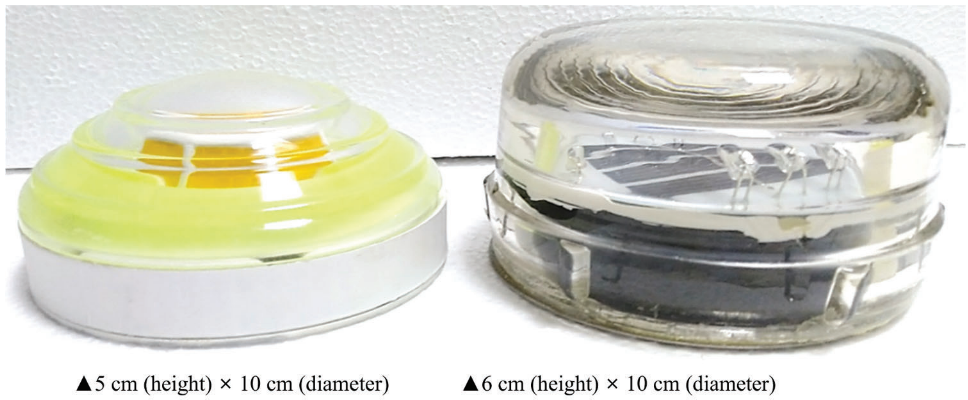


Figure 12: Specifications of the prototype and a competitive product for comparison

Figure 13: Assembly of the prototype and the commercially available product

piezoelectric micro-energy, collection-storage system was designed to enhance the accuracy and energy collection of road piezoelectric technology [29]. Overall, a reflective cat's eye with light storage material was produced using a modular design for various road situations (urban and suburban). The design focused on energy storage and self-luminescence (light storage-light energy), while the piezoelectric technology developed vehicle kinetic energy to enhance the warning effect in mountainous regions or in inclement weather. This technology focused on the conversion of vibration energy to electrical energy (energy storage to electrical energy to light energy). In this study, the reflective cat's eye was waterproof, resistant to inclement weather, and could withstand vehicle runover. Additionally, the signal did not need to be converted to electricity to emit light. It was characterised by a diverse design, easy assemblage and replacement, low development cost, and longevity. These two materials may be used interactively to complement each other depending on the situation.

5 Research Results and Recommendations

A new energy-saving reflective cat's eye was designed; the design was informed by rigorous processes including a literature review, TRIZ patent analyses, and expert interviews. This cat's eye overcomes shortcomings identified in previous analyses of existing products. We applied energy storage environmental protection materials, together with material proportioning (which balanced warning efficiency against cost-effectiveness) to develop diversified modular kits; these kits were flexible in terms of quantity and easily assembled. This design addressed the four key objectives: (1) to reducing manufacturer research and development costs; (2) provide buyers with a diverse suite of product options;

(3) respond to a need for improved road user safety; and (4) reduce government procurement costs for safety warning products. These products are also aligned with energy-saving and sustainability goals. These achievements, together with recommendations for future research, are discussed in the following sections.

5.1 Research Results and Contributions

5.1.1 Critical Design Procedures

Patent analysis and literature review were carried out to determine the disadvantages of existing products using TRIZ. Expert interviews were conducted to select product design policies. These analyses informed the product design which considers user needs and the feasibility of technical applications. Models were built under the technical guidance of experts to effectively eliminate development risks and errors.

5.1.2 Application of Energy-Saving and Environmental Protection Materials

Energy-storage luminescent materials were largely applied to escape signs on a flat surface. This study was the first to employ cast-forming in reflective cat's eyes. As such, it provides various industries with a reference to the innovative application of energy-saving materials.

5.1.3 The Ratio and Thickness of Luminescent Powder Significantly Affect the Luminescence

The experimental results indicate that the suitable energy storage rare earths to epoxy ratio was 35%:65%–40%:60%. The luminous efficiency was significant when casting thickness was approximately 10 mm; this means a thickness with a triangular cross-sectional area (whose volume is half of the quadrangular cross-sectional area) should be adopted to further reduce mass manufacturing costs.

5.1.4 Design and Application of Adding and Removing Modular Kits

The reflective warning mode was designed with modular assemblies, involving the active type, passive type, fusion A type, and fusion B type. The four warning modes provide route prediction, greatly improving the warning effect of the reflective cat's eyes and reducing the risk of cars being driven off lanes on dark roads. The shared size of components was designed to meet the needs of multiple road users and illumination environments, reduce the cost of the mould and reduce the cost of research and development in terms of the manpower and time for commercialisation and mass manufacture; moreover, quality inspection is relatively simple.

5.1.5 Multiple Assembling Options in Comparison with Competitive Products

In addition to the anti-slip design, low angle, low raised road surface, and improved safety, the internal components may also be added or removed according to demand, offering multiple choices and easy assembly. Multiple needs are met by supplying buyers in small quantities and offering diversified choices. Due to the short life cycle of products and the high number of competitors, a diversified product will improve competitiveness with other enterprises. It will also reduce the research and development cost of moulds, offering simple quality control and high yield.

5.2 Research Limitation and Subsequent Development

The actual test of the study was limited by the lack of mass production. The adjustable directions and subsequent applications are described in the next section.

5.2.1 Product Verification Method

As the reflective cat's eye used as part of traffic safety facilities has a large distribution area, its impact is likely to be large if innovative breakthroughs occur in material use and design applications. Therefore, this research primarily focused on conducting patent exploration and expert interviews to discover new green energy materials and innovative designs, improve environmental protection, and propose breakthrough applications. As the product remains at the prototype stage, the experiment mainly focused on exploring the appropriate cost-effective proportion and luminous time of light storage materials. Advanced tests for different passers-by (e.g., drivers, pedestrians), and different usage scenarios may only be carried out following mass production and further research.

5.2.2 Follow-Up Promotion and Application

Only four basic models were provided for the product modules because of limited space to outline the innovative design of the reflective cat's eye combined with green energy materials. This addresses the key objective of multiple options, depending on the usage context; however, the usage situation and product support can be advanced. Fusion type B is suitable for mountainous areas, although the duration of sunlight hours in mountainous areas may vary depending on the openness of the road or the amount of shade. Therefore, manufacturers may use different integration methods to meet the needs of different roads in mountainous areas. The interplay between a reflector with the top hollowed out, light storage material, and solar LED and reflector (Fig. 14) may enhance the inadequate LED lighting of commercially available reflective cat's eyes and eliminate concerns relating to insufficient sunlight. The design and development of modular accessories may progress for versatile applications, allowing a wider range of environmental factors to easily be added, subtracted, or fine-tuned to increase flexibility and applicability.

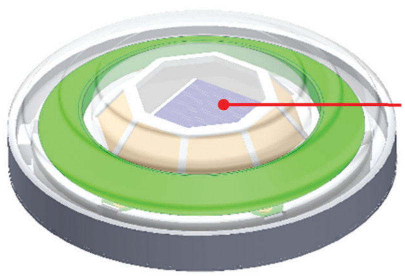


Figure 14: Advanced fusion type B light warning design

In addition, the innovative aspect of this study was the application of energy storage luminescent materials to safety warning products; road safety may improve by sharing development results. Moreover, energy storage materials used in this study may potentially be applied to a wide variety of fields. There is plenty of room to develop night luminescence characteristics for safety, such as in firefighting, emergency rescue equipment, and public safety warnings.

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Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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