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Innovative E-Paper-Based Traffic Display Modules for Sustainable Urban Infrastructure

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Abstract: This study explores the potential of electronic paper(e-paper) technology in traffic signals and road information displays as a sustainable alternative to traditional LED systems. E-paper's ultra-low power consumption, high readability in sunlight, and flexibility make it well-suited for outdoor applications. The research designs a system integrating e-paper into traffic lights, pedestrian curb tiles, and road information boards, utilizing encapsulation technology and matrix driving to enhance durability. Results demonstrate reduced energy consumption and improved sustainability, suggesting that e-paper could contribute significantly to smart city infrastructure.

Keywords: Electronic Paper (E-paper), Traffic Signals, Energy-saving, Road Information Displays, Sustainability, Electrophoretic Technology, Environmental Protection

1. Introduction

As the process of urbanization accelerates, the effectiveness and sustainability of traffic display systems have become a core challenge in smart city construction. Although traditional LED traffic display systems are widely used, their high energy consumption significantly impacts the environment, making the exploration of new low-energy display technologies a trend. E-paper, with its ultra-low power consumption and excellent readability in sunlight, offers a potential solution for traffic display systems.

E-paper is a bi-stability display technology that utilizes Microcapsules electrophoretic technology. Its working principle involves using an electric field to control the distribution of colored particles within the Microcapsules to display images [1]. Even without a power source, the images on e-paper remain visible, and power is only consumed when updating the display content. It maintains good visibility in strong light and provides high visual comfort without producing harsh light, making it more eye-friendly [2]. This study explores the feasibility of applying e-paper technology to traffic display systems, focusing on its material properties, design innovations, and technical advantages, with an emphasis on its potential for large-scale application in smart city infrastructure, promoting more sustainable traffic management solutions.

2. Materials and Methods

E-paper, as a new generation display technology, utilizes bi-stability display technology, microcapsules electrophoretic technology, and low power consumption, showing its unique advantages as a material.

2.1. Bi-Stability Display Technology

Bi-stability display technology is one of the core features of e-paper. It refers to the ability of the display to remain in one of two stable states without requiring continuous power supply to maintain the displayed content. This significantly reduces energy consumption, as power is only needed when updating the display content. Technically, bi-stability relies on a special molecular structure within the material, which changes its alignment when exposed to an electric field and retains the new alignment even after the electric field is removed, thus locking the content and further reducing power consumption.

2.2. Microcapsules Electrophoretic Technology

The realization of e-paper displays depends on microcapsules electrophoretic technology. This technology uses microcapsules, each containing a transparent fluid medium with charged black and white particles. These particles are typically made from titanium dioxide (white) and carbon black (black), each carrying opposite charges. When an electric field is applied, the positively charged white particles and negatively charged black particles move toward the front or back of the display screen according to the direction of the electric field. The movement and aggregation of these particles allow each pixel to appear as either black or white, thus forming images and text. The encapsulation quality of the microcapsules directly affects the performance of e-paper. High-quality microcapsules must have good sealing and stability to prevent leakage of particles and fluids. Furthermore, the size and distribution uniformity of the microcapsules determine the resolution and contrast of e-paper. Additionally, to achieve color displays, color filters or multi-colored charged particles can be introduced based on this technology.

2.3. Low Power Consumption

The low power consumption characteristic of e-paper primarily stems from its bi-stability display and reflective display principles. Unlike traditional display technologies that require a backlight, e-paper relies on ambient light to display content, eliminating the need for additional lighting equipment. This not only reduces energy consumption but also minimizes heat generation and cooling requirements for the device. Additionally, since e-paper does not require continuous power to maintain the displayed content after refreshing, it is particularly suitable for applications requiring long-term static image displays, such as e-readers, electronic signage, and electronic price tags.

2.4. Comparison with Traditional Display Technologies

- **Energy Consumption:** Liquid crystal displays (LCD) require continuous backlight illumination and consume energy regardless of whether the display content changes. Organic light-emitting diode (OLED) displays, while self-luminous, consume less energy when displaying black but more when displaying bright or white colors. E-paper, in contrast, only consumes power when refreshing and almost no power during static displays, making it highly energy-efficient.
- **Visual Comfort:** LCD and OLED displays use active lighting or transmissive displays, which may cause eye strain during prolonged viewing and have poor readability under strong sunlight. E-paper, using reflective display technology, mimics the reading experience of paper, providing good readability under bright light and reducing visual fatigue.
- **Material Properties**: LCD and OLED typically use rigid glass substrates, making flexible and foldable designs difficult. E-paper can use flexible substrates like plastic films, enabling bendable and foldable display devices, expanding design and application possibilities.
- **Environmental Adaptability**: E-paper is more stable than LCD and OLED, capable of operating within a wider temperature range.

3. Literature Review

3.1. Previous Applications of E-Paper

Since its inception, e-paper technology has demonstrated its unique advantages in various applications. Early e-paper applications primarily focused on e-readers, such as Amazon's Kindle, which utilize e-paper's ultra-low power consumption and high contrast characteristics to provide a reading experience close to that of paper books, significantly extending battery life. Additionally, e-paper has been widely used in the retail industry, with electronic price tags being a typical example. These tags can dynamically update pricing information, saving labor costs associated with replacing paper tags and aligning with energy-saving and environmental protection trends.

The Joan meeting room reservation system is another successful application of e-paper. Joan combines interactive and touch interface functionality with energy-efficient design, with each charge lasting up to three months [3]. PhutureMed's smart pillbox is another exemplary solution, designed for pharmaceutical packaging. It can detect environmental changes during drug transportation and storage to ensure quality, record patient medication history, and assist in adhering to medical instructions [4].

In the travel and transportation sectors, RIMOWA's smart luggage with electronic tags showcases the potential of e-paper applications. These tags, built into the luggage, display flight and baggage information, allowing travelers to track their luggage via smartphones, reducing paper tag usage and enhancing convenience and safety in luggage handling [5]. RFID UHF e-paper tags further demonstrate e-paper technology's application in logistics and warehouse management. These tags can update panel

information in real-time, with a reading distance of up to 8 meters, operating without batteries by wirelessly updating the display through transmitted power, significantly reducing paper tag waste, saving labor time, improving efficiency, and lowering costs [6].

These diverse applications illustrate the wide applicability and low energy consumption advantages of e-paper technology, which is why this study focuses on its application.

3.2. Design of Traffic Display Systems

The design of traffic display systems significantly impacts road safety and traffic flow management. Traditional traffic display systems primarily rely on LED technology, which, although excellent in brightness and color performance, is energy-intensive and less readable in direct sunlight. Statistics show that traditional LED traffic displays consume substantial amounts of power annually, posing a significant challenge for energy-conscious urban management.

In recent years, with advancements in e-paper technology, researchers have begun exploring its application in traffic display systems. E-paper's high contrast feature ensures good visibility even in bright outdoor conditions. Furthermore, e-paper only requires power when updating content, needing no power to maintain the display, which has already been utilized in dynamic information boards at bus and train stations in some countries, displaying real-time arrival times and route information, significantly reducing energy consumption and improving passenger convenience.

For instance, the Massachusetts Bay Transportation Authority (MBTA) in the United States is testing solar-powered E Ink e-paper signs to provide arrival times and system alert information for trains and buses. During the pilot phase, MBTA is evaluating the durability and performance of these signs and collecting customer feedback, planning future expansion to bus and subway stations without power access. Additionally, some bus stops in Taiwan have installed e-paper displays showing real-time arrival information [7].

Moreover, the E Ink Kaleido 3 Outdoor e-paper display has been used in Sydney, Australia, for smart parking signage. This device employs color-printed e-paper technology with solar charging capabilities to dynamically adjust parking notifications, demonstrating the potential for digital transformation and net-zero carbon emissions. Mercury Innovation's integrated system design allows these signs to provide highly visible information while consuming minimal power, suitable for various weather conditions [8].

These practical examples demonstrate that e-paper technology in traffic display systems not only effectively reduces energy consumption but also enhances readability and durability of information displays, providing a feasible and environmentally friendly solution for smart city development. The majority of existing research focuses on e-paper applications in information boards, with fewer studies on its use in traffic display systems. This study aims to explore further possibilities in traffic system applications.

3.3. E-paper in Other Public Systems

E-paper's potential is also evident in various public systems, closely related to the United Nations Sustainable Development Goals (SDGs) for energy conservation and environmental protection. E Ink collaborated with Sharp to launch the ePaper Poster application, addressing the issue of installing digital billboards in areas without power supply. Traditional paper posters are still widely used, but e-paper digital posters not only consume no power when displaying content but also use reflective display technology to show images by reflecting ambient light. The brighter the environment, the better the display effect, making it more advantageous than traditional LCD and LED screens [9].

In the healthcare system, e-paper is also utilized to integrate all patient care data through software systems, wirelessly transmitting medical care information to devices like ward signs, bedside cards, and medical care information boards. This enhances information accuracy, reduces error risks, and alleviates the workload of medical staff. Ward signs can display visitor restrictions, allergies, or medical precautions, reminding healthcare workers and visitors of important information. Bedside cards provide patient information, medication reminders, and medical precautions, combined with a nursing call system for care data analysis, improving care quality and efficiency. Medical care information boards show examination schedules, pain levels, medication, or treatment information, and can display emergency messages and evacuation procedures even during power outages [10].

In education and corporate sectors, e-paper is increasingly used for interactive whiteboards and electronic whiteboards. E-paper whiteboards provide a familiar pen-and-paper feel, supporting real-time remote content updates and wireless connections. Large 42-inch e-paper can be made into interactive whiteboards, replacing traditional chalkboards and whiteboards, reducing dust or odor pollution, and enhancing teaching efficiency and experience. Teaching content can be stored and accessed from the cloud or downloaded from the cloud, further improving teaching efficiency. E-paper's bi-stability feature allows written content to remain without consuming additional power, making it more energy-efficient and environmentally friendly compared to traditional LCDs

[11].

These examples show the broad application potential of e-paper technology in various public systems, especially in scenarios requiring long-term display of static information where energy consumption is a critical consideration. E-paper's low power consumption and high readability make it an ideal choice, enhancing system sustainability and providing effective technical support for achieving the United Nations SDGs.

In summary, e-paper technology in various public systems, particularly in energy-saving and environmental protection fields related to the SDGs, shows broad application prospects and significant environmental benefits. This study builds on this foundation to further explore its application in traffic display systems, aiming to provide a low-energy, high-efficiency traffic management solution.

4. Research Methodology

4.1. Technical Feature Analysis

To evaluate the potential of e-paper technology in a new traffic display system, this study conducted three analyses of its core technical features as follows:

- **Visibility:** The visibility of e-paper under different lighting conditions, especially in strong light, was tested. The study found that e-paper exhibits excellent readability in strong light, with high contrast and brightness, making it very suitable for outdoor display applications.
- **Durability:** By selecting appropriate encapsulation technology and materials, the durability of the e-paper module can be effectively improved, ensuring its stability and longevity under various environmental conditions.
- **Power Consumption:** Compared to LED display technology, e-paper significantly reduces power consumption when displaying stable content. This study conducted a quantitative analysis of the hourly power consumption of a 12-inch traffic signal light used in Taiwan and an E Ink Prism3™ e-paper module [12–14].

Table 1. Power Consumption Comparison Data

	12-inch LED Traffic Light	E-paper
Specifications and Power Consumption	• Red light power consumption: 15 W • Green light power consumption: 9 W • Total power consumption: 24 Wh	• Area: 1 m^2 • Power consumption per color change: 2.4 W, duration: 0.25 seconds • Assumes 3 color changes per second, with 3,600 seconds in an hour
Area Calculation	• Diameter: 12 inches = 0.3048 meters • Total area of two circular lights: ≈ 0.146 m^2	Area: 1 square meter
Power Consumption per Square Meter	24 Wh / 0.146 m^2 ≈ 164.4 Wh/m^2	[(2.4 W × 0.25 seconds) × (3 times x 3600 seconds)] / 3600 seconds = 1.8 Wh/m^2

From the data above:

- The power consumption per square meter of a 12-inch LED traffic signal light is 164.4 Wh/m^2.
- The power consumption per square meter of e-paper is 1.8 Wh/m^2.

It can be seen that the power consumption of e-paper is far lower than that of traditional LED display technology, at only about 1.1% of its power consumption. This significantly reduces operating costs, making e-paper a highly efficient and energy-saving display technology, very suitable for traffic display systems.

4.2. E-Paper Technology Application Design

- **E-Paper Aluminum Frame Waterproof Module Design:** The research team designed an aluminum assembly frame with LED light strips, which is easy to resize according to the size of the e-paper, as shown in Figure 1. The module uses light guide glass and low-reflection glass to encapsulate the waterproof e-paper module, as shown in Figure 2. This design addresses the durability and non-self-luminous characteristics of e-paper in outdoor environments and allows for frame size adjustments according to different e-paper sizes, avoiding the need for a frame that only fits one size of e-paper. During the day, the high

contrast of e-paper ensures visibility, while at night, the LED light strips and light guide glass maintain readability. These designs increase the application range of the waterproof module, solve the non-self-luminous problem, and improve visibility, achieving energy-saving goals.

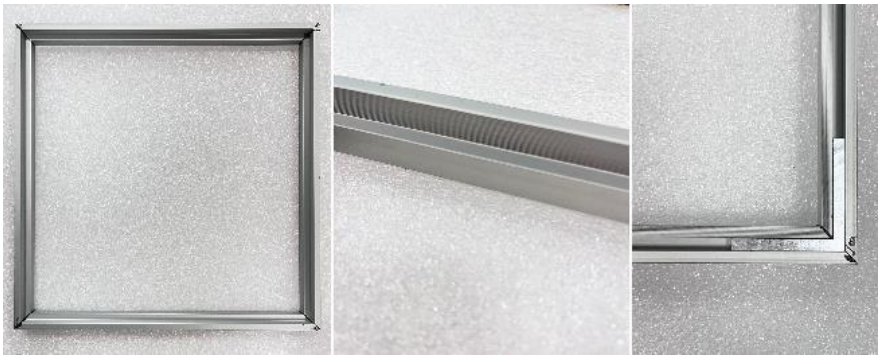

Figure 1. Detailed waterproof design of the aluminum frame. The fine grooves and ridges on the frame enhance the waterproof effect after filling with waterproof glue.

Figure 2. E-paper aluminum frame waterproof module with LED light strips.

- **E-Paper Matrix Driving Technology:** This technology utilizes e-paper combined with conductive copper foil on top, segmented into multiple blocks on a circuit board. The coloration of each block is controlled by powering each piece of copper foil, as shown in Figure 3. This method is suitable for forming large display boards or custom shapes as needed.

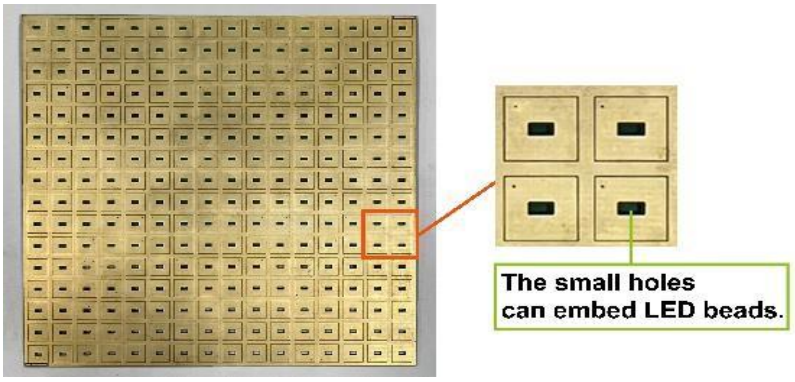

Figure 3. Circuit board segmented with conductive copper foil matrix. Small holes on top can embed LED beads.

- **Embedded LED E-Paper Module:** The research team developed a module combining e-paper and LED lights, called the "Embedded LED E-Paper Module." The module segments e-paper into a dot matrix with an LED bead embedded in the middle of each small piece of e-paper. This design aims to solve the problem of insufficient central brightness due to inadequate illumination from surrounding LED strips when the e-paper area is large. This issue affects display visibility and clarity in low light condition.
  To address this, the research team developed this hybrid module. In bright daylight, the LED lights can be turned off, using only e-paper for display; at night or in low light, the LED lights can be turned on to illuminate the necessary display patterns or text. The LED lights in this module require only half the brightness of regular full-LED displays to achieve sufficient clarity, resulting in lower power consumption. In the future, it may be possible to introduce solar power modules to store energy during the day for nighttime LED use, as shown in Figure 4.

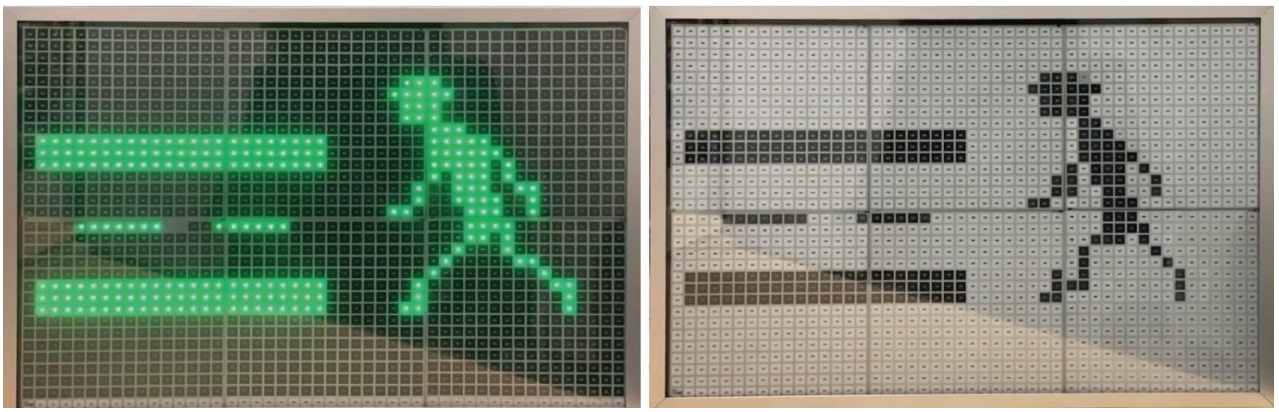

Figure 4. Real-world testing of the embedded LED e-paper module.

The aluminum frame waterproof module addresses durability and visibility issues in outdoor environments. The e-paper matrix driving technology enables the creation of large display boards. The embedded LED e-paper module effectively improves display clarity, especially in low light conditions. These e-paper-related designs and technologies enhance the application effectiveness and energy efficiency of e-paper in traffic display systems.

4.3. New Traffic Display System Design

This study designed a new traffic display system based on e-paper technology, covering traffic lights, color-changing pedestrian curb tiles, and road information display boards. The specific design steps are as follows:

- **Requirement Analysis:** Determine the functional and performance requirements of the traffic display system, particularly regarding visibility, durability, energy consumption, and cost-effectiveness.
- **System Architecture Design:** Construct the overall architecture of the e-paper traffic display system, including hardware design, e-paper module design, encapsulation technology, and control system design. Design corresponding e-paper modules for different application scenarios.
- **Module Design:**
  - **Traffic Lights:** The novel traffic light design features a rectangular column with e-paper installed on all four sides, increasing the display area. Utilize the high contrast feature of e-paper to make signal changes more noticeable, including dynamic displays to assist colorblind or color-weak users in better recognizing the current signal state. The design incorporates the e-paper aluminum frame waterproof module and matrix driving technology to improve readability during both day and night and enhance energy efficiency, as shown in Figure 5.

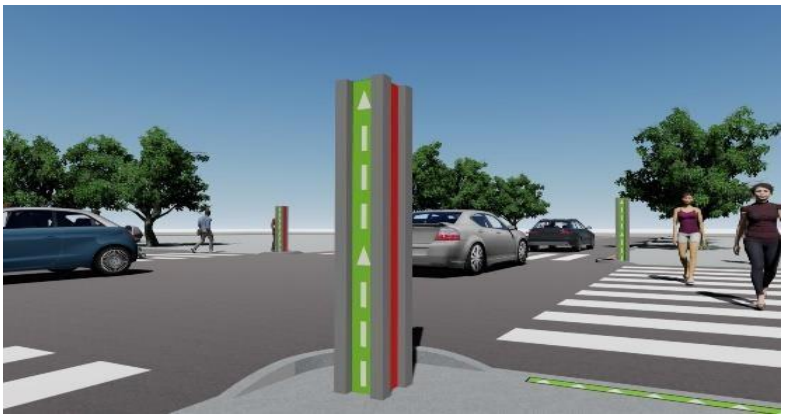

Figure 5. Simulation of the new traffic light.

- **Color-Changing Pedestrian Curb Tiles:** Design color-changing pedestrian curb tiles to replace existing "LED ground-type traffic lights." This design targets pedestrians looking down at their devices, using color changes in the curb to indicate safe crossing and reduce accident risks. The module also employs e-paper aluminum frame waterproof technology.

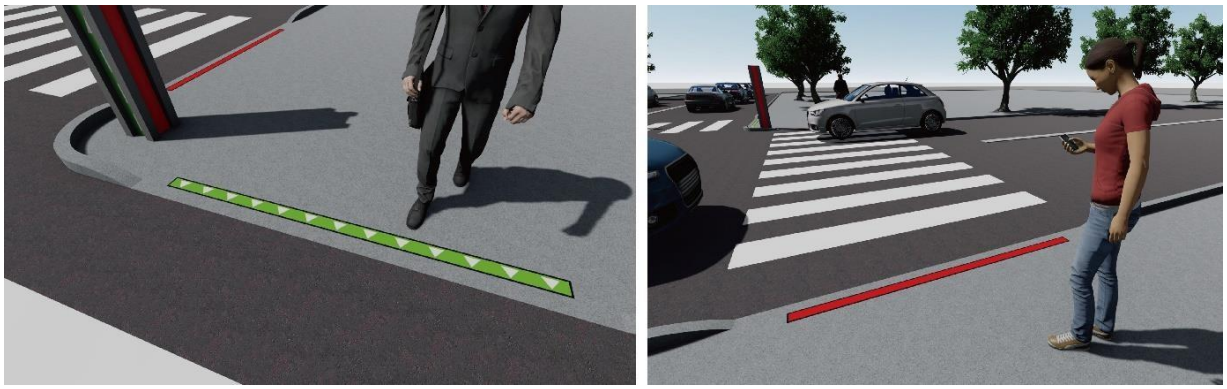

Figure 6. Simulation of the color-changing pedestrian curb tiles.

- **Road Information Display Boards:** Utilize e-paper matrix driving technology to create large subtitle boards through splicing. This module leverages the low energy consumption feature of e-paper and matrix driving technology, suitable for the current road information boards' need to display one or two key pieces of information alternately. This approach avoids the drawback of e-paper's slow pattern change speed, as shown in Figure 7.

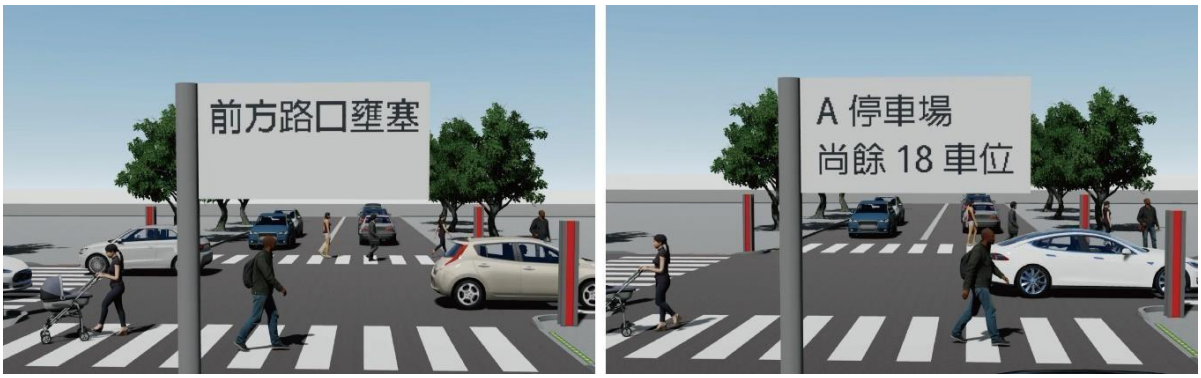

Figure 7. Diagram of the road information display board.

Through the design and application analysis above, this study proposes a new traffic display system based on e-paper technology, aiming to explore its potential in energy saving, environmental protection, and improved display effectiveness. These designs not only address the non-luminous nature of e-paper but also enhance signal visibility during changes, achieving energy-saving and environmental goals.

5. Conclusions

This study explored the application of e-paper technology in traffic signals and road information displays, aiming to replace traditional LED traffic lights and road information boards to achieve energy-saving and carbon-reduction goals. Through detailed analysis of the technical characteristics of e-paper technology and the design of a new traffic display system, the following conclusions were drawn:

- **Technical Feasibility:** E-paper technology possesses advantages such as high contrast, excellent readability in sunlight, and ultra-low power consumption, making it highly suitable for outdoor traffic display applications. By integrating modular designs, it can maintain good readability both day and night, offering stable and durable display performance.
- **Design Innovation:** The new traffic display system designed in this study, including traffic lights, color-changing pedestrian curb tiles, and road information display boards, fully utilizes the features of e-paper. Through the combination of aluminum extrusion frames, LED light strips, light guide glass, and the embedded LED e-paper module design, e-paper can remain clearly visible under various lighting conditions. This effectively addresses the non-luminous issue of e-paper and enhances the intuitiveness and safety of traffic displays.
- **Energy Efficiency and Environmental Protection:** E-paper technology significantly reduces power consumption when displaying stable content, consuming only about 1.1% of the power required by traditional LED technology. This greatly reduces operating costs. The application of e-paper in traffic display systems not only lowers energy consumption but also improves system sustainability and operational efficiency, aligning with the green development concept of smart cities.
- **Application Potential:** The successful application of e-paper technology in dynamic bus stop information boards and supermarket electronic price tags demonstrates its feasibility and practical value. These cases prove the broad application prospects of e-paper technology in various traffic management scenarios.

6. Challenges and Future Prospects

While this study showcases the immense potential of e-paper technology in traffic display systems, there are still some challenges and future development directions in practical application and promotion:

- **Multicolor E-Paper:** Currently, e-paper can display only a limited range of colors due to technical constraints. The development of full-color e-paper in the future is expected to diversify its applications.
- **Improvement in Response Speed:** E-paper has a relatively slow pattern-changing speed, which may limit its ability to display dynamic information. Future advancements in e-paper technology are needed to enhance its refresh rate and display performance to meet more diverse display needs.
- **Enhancing Reliability:** There is insufficient experimental data on the durability of e-paper in outdoor environments. E-paper's biggest issues are its susceptibility to UV radiation and moisture. To extend its durability and lifespan in outdoor settings, further design improvements, experiments, and validations are necessary to mitigate the impact of external factors.
- **Cost Control:** The production cost of e-paper technology is relatively high, which limits its large-scale application and promotion to some extent. Future efforts should focus on technological innovation and scaled-up production to reduce costs and enhance market competitiveness.
- **Application Expansion:** The application of e-paper technology in traffic display systems is still in its initial stage. Future research should continue to explore its potential applications in more traffic management scenarios, such as intelligent parking systems and smart traffic signal systems, to promote the green development of smart cities.

The application prospects of e-paper technology in traffic display systems are vast, but in-depth research and exploration are required in areas such as technological improvement, reliability enhancement, cost control, and application expansion. As the technology matures further in the future, e-paper is expected to become an important component of smart city traffic management, contributing to the achievement of sustainable development goals.

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