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INNOVATIVE APPROACHES IN ROAD MARKINGS FOR ENHANCING TRAFFIC SAFETY

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Abstract: Road markings are a critical component of transport infrastructure, directly influencing driver behavior and lane discipline. However, traditional markings often suffer from rapid wear, poor wet-night visibility, and incompatibility with modern vehicle sensors. This paper explores innovative approaches in road marking applications designed to enhance traffic safety.

Keywords: Traffic safety, road marking.

1. INTRODUCTION

Road markings are an element of road infrastructure visible to drivers at all times while driving, ranking among the most widespread and cost-effective tools for managing traffic safety (Babić, 2020). Although often viewed as a routine, almost inconspicuous feature, road markings serve multiple functions: they visually guide road users, regulate traffic flow, warn of hazards, and provide essential information for safe decision-making.

Previous research indicates that nearly half of all traffic accidents occur between dusk and dawn. Nighttime fatality rates, when adjusted for distance traveled, are significantly higher, and injury severity is greater (Mosböck & Burghardt, 2016). Inattention and a failure to timely perceive the road scene are primary accident catalysts. Because driving relies heavily on visual inputs, clearly visible, highly retroreflective road markings directly reduce accident rates by providing natural focal points for nighttime navigation.

Furthermore, data from the European Union Road Federation (ERF) and the US Federal Highway Administration show that investments in high-quality road markings yield a benefit-to-cost ratio (BCR) of up to 60:1 (Carlson et al., 2009). The financial outlay for advanced materials is negligible compared to the socio-economic costs of preventable accidents. Research confirms that introducing edge and center lines can reduce total accidents by up to 20%, while widening longitudinal markings from 100 mm to 150 mm reduces all accidents by up to 30% and injury-causing crashes by up to 38% (Mosböck & Burghardt, 2016). Similarly, markings at pedestrian crossings can reduce accidents by up to 78% (He et al., 2026) while simultaneously reducing vehicle speeds for both light and heavy vehicles.

In light of these factors, road markings should no longer be viewed as static, traditional infrastructure elements. Instead, they represent a dynamic field constantly evolving under the pressure of new materials, detection technologies, and the demands of automated traffic.

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Therefore, this paper investigates innovative approaches in horizontal signage application, analyzing how smart materials and behavior-modifying geometries can bridge the gap between human driver safety and next-generation autonomous mobility.

2. CLASSIFICATION AND MATERIALIZATION OF ROAD MARKINGS: TRADITIONAL FRAMEWORKS AND TECHNOLOGICAL TRANSITIONS

Road markings consist of a set of specially shaped geometric elements, such as lines, shapes, symbols, and text, that are combined during the design phase and applied directly to the pavement or other traffic surfaces (sidewalks, internal parking facilities etc.) (Mi et al., 2021). Working in tandem with vertical signs, traffic lights, and barriers, horizontal markings form a unified traffic control system. Its primary functions are to regulate traffic flow, guide road users, warn of hazards, and secure work zones.

2.1. Geometric classification and functional purpose

The fundamental classification of road markings is based on their geometric configuration, application method, and position relative to the longitudinal axis of the roadway. Using this criterion, markings are divided into three primary groups:

- Longitudinal Markings: Dividing lines, edge lines, and guide lines that run parallel to the axis of the roadway. A dividing line separates traffic lanes by direction of travel or purpose, whereas an edge line delineates the outer boundary of the drivable surface or isolates special-purpose lanes (e.g., dedicated public transit lanes).
- Transverse Markings: Stop lines, pedestrian crossings, bicycle path crossings, diagonal markings, and limit lines. These markings are applied at an angle relative to the road axis and span across one or more traffic lanes.
- Other Markings: Arrows, text messages on the pavement, traffic channeling islands, parking space layouts, and other specialized symbols not covered by the first two groups.

Based on durability, horizontal signage is further classified into temporary (short-term) markings, typically colored yellow and deployed within construction zones, and permanent (long-term) markings, which are traditionally white.

2.2. Road marking materials and the evolution toward smart infrastructure

The selection of materials directly dictates the durability, retroreflectivity, and skid resistance of horizontal signage, thereby determining its impact on traffic safety. Standard regulatory frameworks identify four basic material categories, all of which are currently undergoing technological transformations to meet modern safety demands:

- Paints (Single-Component Coatings): Liquid-state materials composed of pigments, binders, fillers, and solvents, typically finished with a drop-on application of retroreflective glass beads. Due to their limited service life (6–12 months), innovative practices are increasingly replacing traditional solvent-based formulas with waterborne traffic paints to significantly reduce volatile organic compound (VOC) emissions.
- Thermoplastics: High-quality, specialized compounds applied to the road surface in a molten state at temperatures ranging from 180°C to 210°C. Upon cooling, they form a thick, cohesive bond with the asphalt matrix. This provides exceptional mechanical resistance, making them ideal for high-volume corridors with heavy traffic loads.

- Cold Plastics (Two-Component Resins): Multi-component materials that cure via a chemical reaction (polymerization) after mixing with a catalyst. They offer extreme resistance to mechanical wear and are highly adaptive, allowing engineers to create structured (profiled) markings that generate tactile and acoustic warnings (rumble strips) for drivers.
- Prefabricated Application Tapes: Multi-layer materials based on rubber or high-performance plastics that are adhered or thermally fused to the pavement. Beyond delivering immediate, high-level retroreflectivity, modern tapes are utilized for temporary detours due to their clean removal properties, as well as for permanent 3D optical illusions at pedestrian zones.

Despite the well-defined standards and established benefits of these traditional materials, modern safety challenges and the rise of automated mobility necessitate further material and structural modifications.

Transitioning toward smart infrastructure requires markings that not only last longer but also actively respond to environmental shifts and optimize visibility under critical conditions. This paradigm shift, transforming horizontal signage from passive lines into high-functioning pavement components, serves as the foundation for the innovative approaches.

3. DIRECTIONS IN INNOVATION

The modernization of road markings is driven by the dual necessity of accommodating human visual limitations and meeting the digital demands of automated driving. Innovation in this sector no longer targets incremental durability improvements; instead, it focuses on systemic advancements across four interconnected domains: technological integration, material science, geometric design, and driver perception.

3.1. Technological integration and infrastructure readability

Technological development represents one of the most dynamic avenues of innovation in the field of road markings, as it goes beyond merely altering the material or shape of the marking to introduce entirely new functional layers: electronics, sensor technology, and connectivity with digital traffic management systems.

The transition toward Connected and Automated Vehicles (CAVs) requires a fundamental shift from human-visible markings to machine-readable infrastructure. Advanced Driver Assistance Systems (ADAS), such as Lane Departure Warning (LDW) and Lane Keeping Assist (LKA), rely heavily on steady, high-contrast visual data feeds captured by vehicle cameras.

Modern innovations introduce specialized pigments that enhance the contrast ratio not only in the visible spectrum but also under near-infrared (NIR) light, which is commonly used by automotive sensors. This ensures reliable lane tracking even during adverse weather conditions when human visibility fails.

Experimental setups embed localized data directly into the markings. By incorporating radar-reflective particles or micro-RFID tags within the polymer matrix, road markings act as physical data nodes, transmitting critical geometric and hazard information directly to the vehicle's onboard computer (Fig. 1) (He et al., 2026).

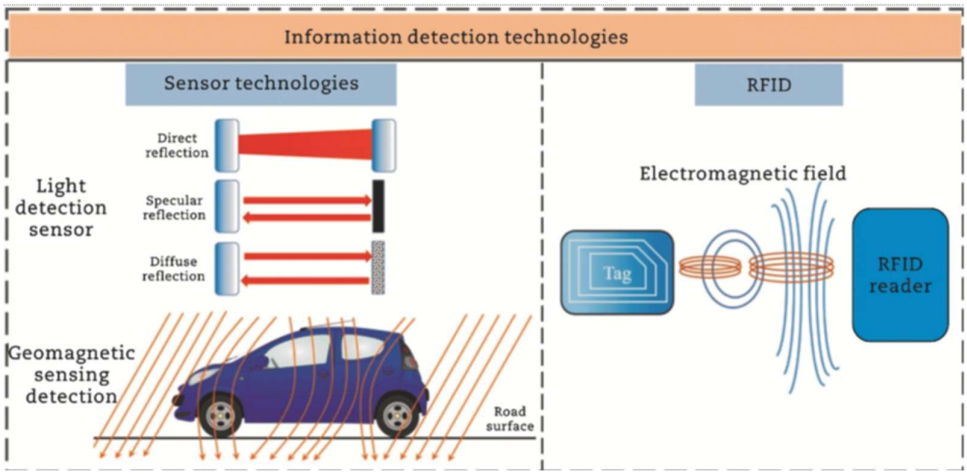


Fig. 1 Principles of information sensing technology (He et al., 2026)

3.2. Material science and photoluminescent advancements

Material innovation focuses on breaking the dependency of road markings on external light sources, such as vehicle headlights, while simultaneously improving environmental sustainability.

The application of Active Luminescent Road Markings (ALRM) introduces self-illuminating capabilities to the pavement. Utilizing advanced strontium aluminate crystals embedded within solvent-free polyurethane bases, these markings absorb solar energy during the day and emit a sustained glow for up to six hours after dark. This significantly lowers nighttime accident rates on unlit rural corridors.



Fig. 2 Display of photoluminescent road markings (https://canada.constructconnect.com)

Replacing crude-oil derivatives with sustainable alternatives, such as pine-derived bio-resins (e.g., Kraton REvolution technology), maintains high thermal stability and structural whiteness while drastically shrinking the carbon footprint of manufacturing and installation.

The operating principle is based on the material's ability to store energy in the form of excited electrons after exposure to daylight or vehicle headlights, and subsequently release it gradually as light during the night (Fig. 2), a phenomenon known as prolonged photoluminescence (Wang et al., 2023). Unlike retroreflection, which requires an external light source (vehicle headlights) for the marking to be visible, a photoluminescent marking emits light independently, representing a shift from passive to active road illumination (Lin et al., 2023).

3.3. Geometric design and optical interventions

Beyond technological and material advancements, a critical frontier in road marking innovation lies in perceptual and geometric design—specifically altering the shape, color palette, and visual patterns to heighten driver alertness and modify behavior in high-risk zones. Unlike technological or material innovations, which primarily enhance core parameters like visibility and durability, design-driven interventions introduce entirely new visual concepts; while this renders them highly appealing to the public and the media, it simultaneously elevates the risks associated with regulatory compliance and quantifiable safety effectiveness.

Traditional linear patterns are increasingly supplemented by innovative geometric configurations designed to subconsciously regulate driver behavior at high-risk zones, such as sharp horizontal curves and school approaches.

The most well-known example of design innovation in the last decade is the so-called three-dimensional pedestrian crossing (3D crossing) (Fig. 3), which is based on the principle of anamorphic projection. Anamorphosis involves a distorted projection that, when viewed from a specific vantage point, creates the impression of perspective and spatial depth on a flat surface (Cerema, 2021). In practice, this effect is achieved by adding grey and black blocks around the standard white stripes; when viewed from the intended angle, this creates the illusion of "hovering" blocks above the roadway.



Fig. 3 Three-dimensional pedestrian crossing (https://www.thestar.com)

In addition to three-dimensional pedestrian crossings, other less radical design innovations are being implemented to enhance visibility and encourage appropriate driver behavior through visual perception.

These primarily include non-standard color schemes on the roadway—such as fully colored intersections or school approach zones in contrasting hues—and the use of optical effects. One prime example is the illusion of a narrowing roadway (so-called "optical narrowing," achieved via transverse lines with decreasing spacing) to induce vehicle deceleration before critical sections.

Unlike 3D crossings, these approaches generally do not deviate from the basic geometric shapes prescribed by existing standards; instead, they combine permitted elements (color, layout, and line spacing) in novel ways. Consequently, the path toward their potential inclusion in regulations is significantly simpler than for entirely new concepts, such as anamorphic projections.

4. CONCLUSION

The integration of innovative design solutions in road markings represents a highly effective, cost-efficient, and psychologically sound approach to modern traffic safety management. As demonstrated, while radical implementations like three-dimensional pedestrian crossings offer substantial visual impact, subtler modifications, such as optical narrowing and contrasting color schemes, provide a more seamless path toward regulatory approval due to their adherence to existing geometric frameworks. Leveraging driver psychology through visual perception proves that infrastructure does not always need physical restructuring to induce safer driving habits and significantly reduce deceleration response times before critical road sections.

To fully maximize the potential of these innovations and ensure their long-term viability, the following steps are proposed for further improvement:

- Standardization of driver familiarity limits: Future research should systematically investigate the "habituation effect," determining how long drivers remain responsive to 3D and optical illusions before the novelty wears off and its effectiveness decreases.
- Harmonization with Autonomous Vehicle infrastructure: New marking designs must be co-engineered with machine-vision algorithms, ensuring that optical illusions meant for human eyes do not cause misinterpretations or positioning errors for LiDAR and ADAS camera systems.
- Development of Smart, Adaptive Markings: Transitioning from static designs to dynamic or responsive markings, such as pavement materials that change color or luminosity based on real-time weather conditions, temperature, or pedestrian presence, could drastically improve night and wet-weather visibility.
- Establishment of Unified regulatory frameworks: Transnational guidelines should be created to simplify the legal transition of proven experimental designs into official traffic signs and markings manuals, removing bureaucratic barriers for local municipalities.

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