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Photonic Materials for Smart Roads: Intelligent Pavement Monitoring, Energy Harvesting and Adaptive Road Safety

Islom Mamadaliev¹, Sardor Uktamov², Sanjarbek Makhmudov³, Diyorbek Mirsaidov⁴

1,2,3,4 Department of Automobile Roads, Namangan State Technical University, Namangan city, Uzbekistan

* Correspondence: islombeek1987@gmail.com¹, sardoroktamov29101991@gmail.com²,
msanjabek1003@gmail.com³

Abstract: This paper presents a conceptual review of photonic materials and optical sensing technologies for smart road infrastructure. The focus is placed on three mutually reinforcing functions: real-time pavement condition monitoring, local energy harvesting, and adaptive road-safety communication. Fiber Bragg Grating (FBG) sensors are considered as a practical photonic sensing element for measuring traffic-induced strain and temperature inside pavement layers. Photovoltaic and other pavement energy-harvesting approaches are discussed as potential sources for autonomous sensor nodes, while long-afterglow and active luminous materials are considered for adaptive nighttime guidance. A conceptual monitoring chain is proposed in which vehicle loading produces a pavement structural response, the response is converted into an optical wavelength shift, and the resulting data are transmitted to an analytical platform for pavement-health assessment. The paper also formulates a Photonic Smart-Road Architecture that links embedded optical sensing, IoT communication, artificial-intelligence-based analysis and maintenance decision support. The study is conceptual and literature-based; therefore, no unverified experimental performance values are claimed.

Keywords: Photonic materials, smart roads, fiber Bragg grating, pavement monitoring, optical fiber sensing, energy harvesting, luminous road markings, intelligent transportation systems.

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1. Introduction

Road infrastructure is increasingly expected to operate not only as a load-bearing transportation facility but also as an information, energy and safety platform. Conventional pavement management is largely based on periodic visual surveys and instrumented inspections. Although these methods remain essential, they provide discrete observations and can miss short-duration structural responses caused by individual vehicle axles, temperature variation or rapidly developing defects. Embedded optical sensing provides a different pathway because the road can be observed continuously while normal traffic remains in operation.

Fiber Bragg Grating sensors are particularly attractive for this purpose because the sensing principle is optical and the sensing element can be multiplexed along a fiber. Demonstrations on real road structures have shown that embedded FBG sensors can measure traffic-induced strain and temperature and distinguish responses associated with different vehicle classes [1]. Earlier FBG research also established the theoretical basis for grating-based strain and temperature sensing [2].

At the same time, the road surface represents a large exposed area that can potentially host energy-generating or energy-harvesting materials [3]. Photovoltaic pavement

research has investigated multilayer road modules that combine a transparent protective surface, a functional photovoltaic layer and a protective structural layer [4]. However, long-term stability, cost-effectiveness, contamination and mechanical durability remain important barriers to large-scale deployment [5].

A second photonic-material pathway concerns the visual communication function of the road. Long-afterglow phosphors and electrically active luminous markings can produce visible guidance without relying exclusively on conventional continuous illumination. Recent reviews classify active luminous road markings into fluorescent, persistent phosphorescent and electrically luminous approaches and emphasize their potential for improved nighttime recognition while also identifying durability and economic challenges [6].

The combination of these technologies suggests a transition from a passive pavement to a cyber-physical road system. In such a system, the pavement contains sensing elements, communication interfaces and functional materials that interact with traffic, the environment and maintenance services. The objective of this paper is therefore to organize the main photonic technologies into an engineering framework and to show how they can be combined without presenting speculative experimental results as established facts.

Photonic Materials and Technologies for Smart Roads

Fiber Bragg Grating sensing principle

An FBG is a periodic modulation of the refractive index in the core of an optical fiber. When broadband light propagates through the fiber, the grating reflects a narrow spectral band centered at the Bragg wavelength. The fundamental relationship is:

$$\lambda_B = 2n_{eff}\Lambda \quad (1)$$

where λ_B is the Bragg wavelength, n_{eff} is the effective refractive index of the fiber core, and Λ is the grating period.

Mechanical strain and temperature alter the effective refractive index and grating period, producing a measurable wavelength shift. For small changes, the response can be represented in a linearized form:

$$\Delta\lambda_B = K_\varepsilon\varepsilon + K_T\Delta T \quad (2)$$

where K_ε is the strain sensitivity coefficient, ε is strain, K_T is the temperature sensitivity coefficient, and ΔT is temperature change.

For pavement applications, the important engineering point is that the optical wavelength is not itself a pavement-health indicator. It is a measured physical response that must be calibrated, temperature-compensated and interpreted together with traffic and environmental information.

Embedded optical sensing in pavement

FBG sensors can be placed at selected depths and orientations within pavement layers. The placement should correspond to the structural response of interest, such as tensile strain near the bottom of asphalt layers, compressive response in treated bases, or thermal response at a reference location. In a documented field implementation, optical sensors were embedded in a cement-treated reclaimed asphalt pavement layer and monitored with an optical interrogation unit under real traffic and controlled loading [7]. This demonstrates the feasibility of moving FBG monitoring from laboratory testing toward permanent road infrastructure.

Conceptual Monitoring Chain

The proposed smart-pavement monitoring chain translates a physical traffic event into a digital maintenance signal. The logic is deliberately simple: vehicle loading causes a structural response; the embedded optical sensor converts that response into a wavelength shift; the interrogator digitizes the optical information; IoT communication transports the

data; and analytical algorithms convert measurements into a pavement-health indicator. The complete chain is shown in Figure 1.

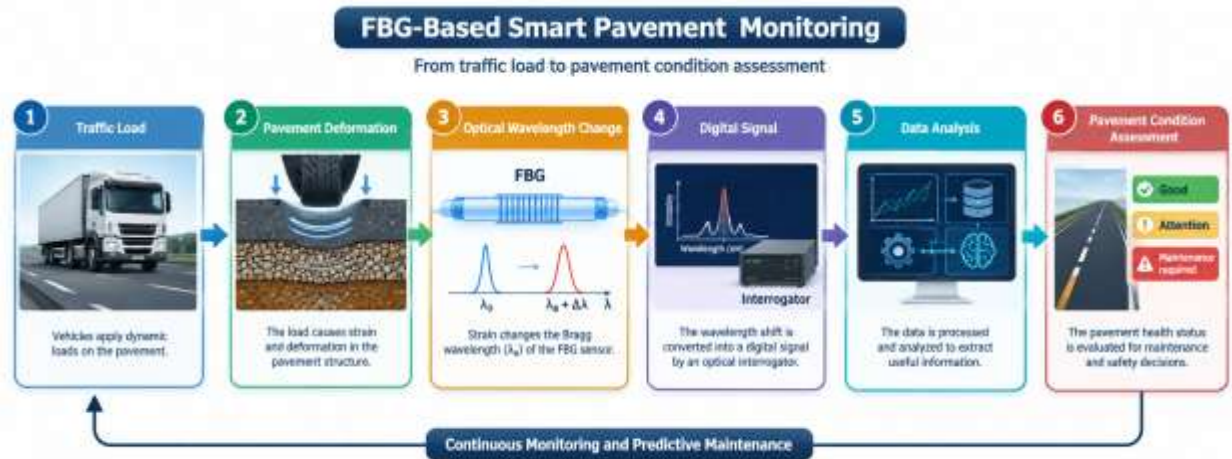


Figure 1. FBG-based smart pavement monitoring: from traffic loading to pavement condition assessment.

The architecture in Figure 1 emphasizes the physical measurement pathway. It should not be interpreted as a claim that every road requires all components at once. A practical deployment may begin with FBG strain and temperature sensing and later add wireless communication, machine learning and adaptive safety functions.

Information Flow and Decision Support

A more detailed monitoring chain is presented in Figure 2. Here the embedded FBG or optical fiber is treated as the sensing interface between the physical pavement and the digital infrastructure. The optical interrogator identifies the spectral response, after which the data can be sent through an IoT gateway to a central or edge-computing platform. AI-based algorithms can then identify patterns, anomalies or changes in the baseline response. The final output is expressed as a pavement-health indicator and a maintenance recommendation.



Figure 2. Conceptual monitoring chain from vehicle loading to maintenance decision.

Such a chain supports condition-based rather than purely calendar-based maintenance. The engineering benefit is not simply a larger volume of data; it is the

possibility of linking a specific structural response to a specific traffic or environmental event and retaining that information for trend analysis.

Intelligent Pavement Monitoring

Structural response and traffic loading

Traffic loads produce transient stress and strain fields that depend on axle configuration, tire contact pressure, vehicle speed, pavement temperature, material properties and structural geometry. Embedded FBG sensors can capture these responses at the sensor location. In field research, measured FBG responses were associated with passenger cars, minibuses and trucks, demonstrating that vehicle-induced strain can contain information about traffic loading [8].

The practical interpretation should be probabilistic rather than deterministic. A single wavelength shift does not uniquely identify a vehicle or a defect. Instead, a sequence of measurements can be compared with calibrated baseline behavior. Changes in amplitude, duration, frequency or spatial distribution may indicate a change in structural response and can become inputs to an anomaly-detection model.

Temperature compensation

Temperature is a major source of cross-sensitivity in optical pavement monitoring. A reference FBG that is mechanically isolated but exposed to the same thermal environment can be used to estimate the temperature-induced wavelength shift. The strain-related component can then be written as:

$$\Delta\lambda_{strain} = \Delta\lambda_{measured} - \Delta\lambda_{temperature} \quad (3)$$

This compensation step is essential for long-term monitoring because pavement temperature can vary substantially between day and night and across seasons. Without compensation, a temperature trend may be incorrectly interpreted as structural deterioration.

Pavement Health Indicator

To transform sensor data into a management variable, a composite pavement-health indicator can be defined. At the conceptual level, the indicator may depend on strain, temperature, cumulative traffic, load level and response history:

$$PHI = f(\epsilon, T, N, L, R) \quad (4)$$

where PHI is the Pavement Health Indicator, ϵ is measured strain, T is temperature, N represents cumulative traffic exposure, L represents load characteristics, and R represents response history or a reference baseline. The function f should be calibrated with field observations and pavement performance data rather than assigned an arbitrary universal form.

From monitoring to predictive maintenance

Once a sufficiently long time series is available, AI and statistical methods can be used to detect deviations from the baseline, classify traffic events, estimate deterioration trends and prioritize inspections. The output should remain decision support rather than an automatic replacement for engineering judgment. Thresholds can be linked to safety, serviceability and maintenance levels.

Energy Harvesting for Smart Roads

Photovoltaic pavement

Photovoltaic pavement integrates solar-energy conversion into a road or pavement module. Reviews describe a general multilayer arrangement in which a transparent or protective surface is combined with a photovoltaic functional layer and a structural/protective layer [9]. The concept is attractive because roadways have extensive exposed surface area, but the road environment is substantially harsher than a conventional rooftop PV installation.

Mechanical loading, skid resistance, contamination, shading, optical transmission, water ingress and thermal cycling all affect performance. Consequently, photovoltaic pavement should be considered a specialized infrastructure component rather than a direct replacement for conventional solar panels. Current literature continues to identify long-term stability and cost-effectiveness as major barriers [10].

Energy for autonomous sensing

Energy harvesting can nevertheless be valuable when its role is defined narrowly: supplying low-power sensing, local processing or communication nodes. Roadway energy-harvesting research covers photovoltaic, thermal, thermoelectric, piezoelectric and other mechanisms [11]. For an FBG-based system, the optical sensing element itself is passive, but the interrogator, communication module and processing electronics require energy. Therefore, harvested energy could support distributed sensor nodes or reduce dependence on wired power, provided that storage and power management are engineered for intermittent energy availability

Lifecycle cost perspective

Future research should compare smart-road technologies using lifecycle rather than initial cost alone. A conceptual lifecycle-cost expression is:

$$LCC = C_{initial} + C_{maintenance} + C_{energy} + C_{replacement} - C_{benefit} \quad (5)$$

where LCC is lifecycle cost and the terms represent initial investment, maintenance, energy, replacement and monetized benefits. The expression is a framework for future economic evaluation; it does not imply that a specific smart-road technology is already economically superior.

2. Materials and Methods

Long-afterglow materials

Persistent luminescent materials can store excitation energy and release part of it as visible light after the external light source is removed. Such materials are being investigated for self-luminous pavement and road-marking applications. A 2026 review highlights SrAl_2O_4 -based systems as one of the most studied material families and notes that real-road validation is still needed because laboratory conditions differ from field conditions [12].

Active luminous road markings

Active luminous road markings provide another pathway for adaptive visual communication. The literature identifies persistent phosphorescent and electrically luminous road markings as promising technologies, while durability, brightness retention and cost remain important research issues [13]. In a smart-road architecture, luminous markings could be controlled according to traffic state, weather, work zones or detected hazards rather than operating as static decoration.

Photonic Smart-Road Architecture

The proposed architecture combines three functional domains: perception, intelligence and adaptive response. The perception layer contains embedded FBG or distributed optical sensing elements. The intelligence layer contains optical interrogation, data communication, storage and analytical models. The adaptive layer contains maintenance decision support, warning systems and potentially luminous road-safety elements.

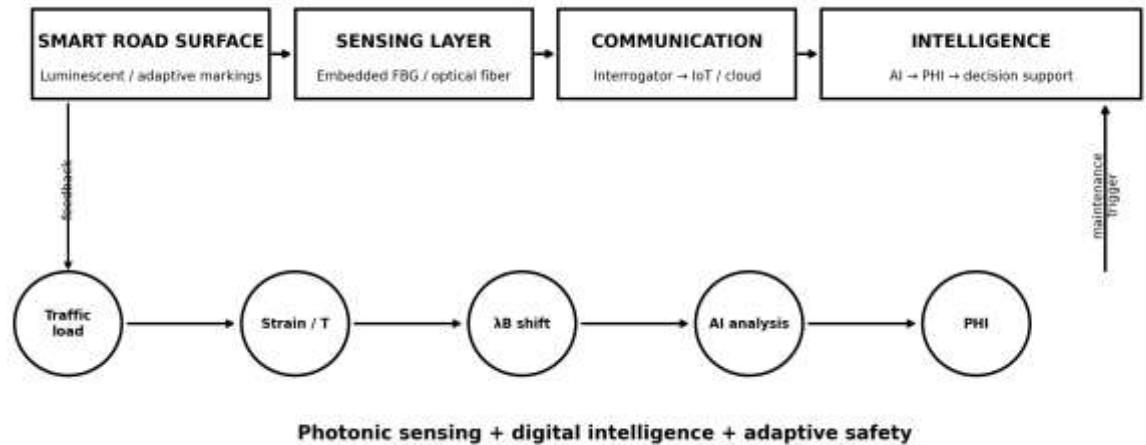


Figure 3. Conceptual Photonic Smart-Road Architecture integrating sensing, communication, intelligence and adaptive response.

The architecture is intended as a modular framework. A pilot project can implement only the sensing and interrogation layers, while later stages can add IoT connectivity, edge analytics, AI-based prediction and adaptive safety elements. This staged approach reduces the risk of attempting to deploy every emerging technology simultaneously.

Comparative Analysis of Photonic Technologies

Table 1. Comparative role of selected photonic technologies in smart-road infrastructure.

Technology	Primary function	Main advantage	Main limitation	Smart-road role
FBG sensing	Strain / temperature	Passive, precise, multiplexable	Requires interrogation and calibration	Structural monitoring
Distributed optical fiber	Spatial monitoring	Long sensing reach	Complex interpretation	Continuous condition mapping
Photovoltaic pavement	Energy generation	Uses road surface area	Durability and cost	Power supply / energy harvesting
Persistent luminescent materials	Night guidance	Passive afterglow	Brightness and durability	Adaptive visibility
Active luminous markings	Traffic communication	High visual recognition	Power, cost, durability	Dynamic safety information

Table 1 shows that no single technology performs all smart-road functions. FBG and optical-fiber systems are strongest for sensing; photovoltaic systems are relevant to energy supply; and luminous materials are relevant to human-facing safety communication. Their value increases when the technologies are integrated through a common digital architecture.

3. Results and Discussion

The literature synthesis supports three main conclusions. First, embedded optical sensing has moved beyond a purely laboratory concept. Field research has demonstrated that FBG sensors can be installed within pavement layers and used to observe real traffic-induced strain and temperature responses [14]. Second, energy-harvesting pavement is technically diverse but remains constrained by durability, cost and environmental exposure [15]. Third, luminous road materials can enhance nighttime visual

communication, but field durability and long-term optical performance require further validation [16].

These findings support the proposed monitoring chain: Vehicle loading → pavement structural response → embedded FBG/optical fiber → optical interrogation → IoT communication → AI-based analysis → Pavement Health Indicator → maintenance decision. The chain is useful because it separates measurement from interpretation. The sensor produces a physical signal; the digital system converts it into information; and the engineer uses that information to support a maintenance action.

Challenges and Future Research

- Long-term durability of embedded optical fibers under repeated traffic loading, moisture, freeze-thaw cycles and pavement rehabilitation.
- Reliable temperature compensation and calibration procedures for seasonal monitoring.
- Standardized datasets linking FBG responses to pavement structure, traffic characteristics and observed deterioration.
- Low-power optical interrogation and communication architectures for distributed field deployment.
- AI models that remain interpretable enough for engineering decision support and are validated on geographically diverse roads.
- Economic assessment using lifecycle cost, maintenance savings, energy yield and safety benefits rather than initial cost alone.
- Field validation of photoluminescent and electrically luminous road markings under dust, water, UV exposure and mechanical abrasion.

4. Conclusion

Photonic materials provide a promising technological basis for transforming conventional pavements into intelligent infrastructure. FBG sensors can provide direct optical measurements of traffic-induced strain and temperature, while photovoltaic and other energy-harvesting technologies can potentially support distributed electronics. Long-afterglow and active luminous materials can extend the smart-road concept toward adaptive visual safety. The most important opportunity is not any individual material but their integration into a coherent cyber-physical architecture.

The proposed Photonic Smart-Road Architecture connects physical traffic loading to optical sensing, digital analysis, pavement-health assessment and maintenance decision support. The framework is intentionally conceptual and should be validated through controlled laboratory testing, pilot road sections and long-term field monitoring. Future work should focus on calibration, durability, lifecycle cost, AI-based prediction and interoperability with existing intelligent transportation systems.

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