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Original Article

Performance Study of Smart Pavement Systems

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ABSTRACT

Smart pavement system is a ground breaking new technology in the infrastructure transport system as it combines sensing technology, communication technology, and intelligent material technology to form the normal roadways. Contrary to the conventional pavements, which are most prestigious in the structural and functional functions, the smart pavements participate in the active monitoring of the traffic loads, environmental conditions, pavement health, and energy interactions, therefore, allowing the development of the real-time decision-making and anticipatory maintenance. The paper gives the overall performance analysis of a smart pavement system in terms of structural stability, sensing accuracy, power consumption, road safety, and sustainability of the lifecycle. The paper compares different typologies of smart pavements such as sensor embedded pavements, energy harvesting pavements, self-healing pavements and also intelligent surface pavements. Multi-criteria performance framework is formulated to determine mechanical behavior, reliability of data, resilience of the environment, and economic feasibility by operating real-life situations. To study the reaction of the pavement to the dynamic loading, in the presence of thermal variations and the stresses formed by the traffic, experimental and simulation-based methods are used. Findings are that smart pavements have high levels of monitoring structural performance, decrease the amount of time spent on maintenance, and enhance road safety due to their adaptive capabilities. Nonetheless, issues in sensor longevity, complexities in integration, and costs of preliminary investment are other issues that pose serious obstacles to extensive implementation. The results show that smart pavements systems are more effective and less expensive than ordinary pavements in terms of their effectiveness and costs at the entire lifecycle. The paper has a lot to offer in terms of knowledge to the future smart city research, infrastructure planners, and policy makers interested in deploying intelligent transportation infrastructure to achieve their future goals.

KEYWORDS

Smart Pavement Systems, Intelligent Transportation Infrastructure, Embedded Sensors, Pavement Performance, Structural Health Monitoring, Sustainable Roads.

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1. INTRODUCTION

1.1. Background

The accelerated urbanization, the high number of vehicles and the sustained growth of freight transport have put the world on demand on road systems like never before. The mono networks that exist are expected to support increased traffic loads, axle weights, and more frequent traffic vehicle movements than what was initially expected when a network was designed. Traditional pavements continue to serve the role of primarily passive structural systems that are specific to meet the stresses related to traffic against a set of stresses that are inherently defined as safe without providing much or no ability to assess the current condition of these pavements and respond to them. By doing so, pavement deterioration processes like cracking, rutting, and fatigue tend to happen without letting it be known until such that the surface opens up. The consequence of such delayed detection is normally untimed maintenance actions, an increase in expenses related to the repair, lessening of the service duration and a traffic overthrow that negatively impact mobility, security and the economy. As a response towards these shortcomings, smart pavement systems have come to play as a revolutionary and ground breaking thought on the roadway infrastructure management in the modern world. Smart pavements Smart pavements embed powerful sensor networks, wireless communication networks, data analytics, and smart materials directly into the pavement structures in order to have round-the-clock performance of structural, traffic loading, and environmental conditions. These systems transform these roadways into dynamic and data generating platforms by with integrating intelligence into the pavement itself. The smart pavements provide real-time information that helps transportation agencies to establish proactive and predictive maintenance mitigation mechanisms so that the agencies are able to detect initial signs of distress, manage maintenance times more efficiently, and proactively distribute the funds. Moreover, smart pavements when combined with intelligent transportation systems can improve the safety and efficiency of roadways as well as allow the use of smart pavements to observe traffic, detect hazards, and manage the condition of the assets. All these developments render smart pavement as a significant element of the sustainable, resilient, and intelligent transportation system in the rapidly urbanizing areas.

1.2. Need for Performance Evaluation

Fig 1 - Need For Performance Evaluation

1.2.1. Limitations of Conventional Assessment Approaches

Conventional ways of assessing pavements are based on the visual inspection periodically, indexes of the condition of surfaces, and single laboratory tests. Although these methods prove useful in traditional pavements, it is not sufficient in smart pavement systems, which combine sensors, energy-gathering devices, and communication devices. These approaches do not adequately describe the real-time system behaviour, sensors and the interplay between the structural and technological aspects, and the discrepancy exists between of what the design anticipates and what occurs in the field.

1.2.2. Complexity of Smart Pavement Systems

Smart pavements are naturally multi functions systems that can bring together civil infrastructure, electronic and digital systems. The mechanical properties of stiffness and fatigue resistance are not the only factors that affect their performance, as sensing accuracy, data transmission reliability, energy efficiency, and environmental toughness are also considered to be as well. The absence of a systematic performance appraisal system will make it hard to determine the interaction of these interdependent elements with other elements overtime, especially during different traffic and environmental circumstances.

1.2.3. Ensuring Structural Safety and Durability

Sensors and energy-harvesting devices built into the pavement layers create the possibility of risks regarding the concentration of stress and material incompatibility and durability. To ensure that smart components do not weaken the different structures or decreasing the pavement service life, performance assessment is necessary. Systematic evaluation will check that the load-bearing capacity, deformation behavior, and fatigue performance will not exceed acceptable values during all the pavement lifecycle.

1.2.4. Validation of Data Quality and Reliability

The smart pavements are primarily effective because of the quality and validity of the data that they produce. Performance analysis aids in determining sensor performance, signal stability as well as the resistance to noise and aging. Confident data is essential to the purposes of informed decision making, forecasted maintenance and safety uses. Incorrect or inconsistent data may defeat the advantages of smart pavement technologies without having appropriate validation.

1.2.5. Economic and Sustainability Considerations

Smart pavements are associated with increased initial expenditures as opposed to conventional pavements and this fact raises economic justification as a major issue of infrastructure agencies. Performance evaluation allows analysis of the lifecycle cost through comparing initial costs and long-term rewards like lower maintenance costs, long service life and increased safety. Also, consideration of energy consumption and environmental performance contribute to the sustainability objectives by showing the decrease of consumption of resources and decreased emission.

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PP: 01-15.

1.2.6. Supporting Large-Scale Implementation and Standardization

An extensive performance assessment system plays an important role in supporting mass implementation of smart pavements. Standardized evaluation criteria allow being compared consistently with the various projects, technologies and environmental conditions. This facilitates the design principles, performance, and policy frameworks and eventually expedites the implementation of intelligent pavements as a fundamental part of intelligent and sustainable transportation infrastructure.

1.3. Performance Study of Smart Pavement Systems

In the area of smart pavement systems, the performance research aims at determining the capacity of the systems to meet both structural, functional and technological needs in the condition of a real traffic and environment. In contrast to the traditional pavements, the functions of which are mostly evaluated according to the load-bearing capability and condition of the surface, smart pavements should be considered as a system, which incorporates the civil engineering resources with the integrated sensors, energy-harvesting devices, and communication technologies. This paper discusses the effectiveness of smart pavements in sustaining a good structural integrity as well as delivering precise reliable and continuous data of performance over the lifetime of the pavements. The important points are measurement of strain, temperature and of response to traffic loading, conduction of sensor responses to cyclic repetition loads and environmental exposure. Capturing of behavior of pavements under accelerated loading conditions as well as controlled climatic conditions is done through experimental investigation and analytical modeling. By using these, it is possible to compare two sensor results (measured and theoretically predicted) to prove the correct response and data quality of a structure. Strain responsiveness to load, sensor signal quality, energy production output and maintenance needs are the performance indicators considered to evaluate the system effectiveness. Another aspect that the study undertakes to do is assessing the effect of embedded components on the durability of pavement such that the smart functionalities do not affect the basic mechanical performance. The operational long term benefits, as highlighted in the study, were in addition to the technical performance such as the ability to predictively maintain, improved safety, and cost-effectiveness in the lifecycle. The real-time monitoring would allow recognition of deterioration at an early stage and take appropriate measures which would minimize the costs incurred to repair systems and service interruptions. The characteristics of energy-harvesting also provide the system with sustainability as it is able to operate sensing and communication units independently. All in all, the performance study offers a general overview of the strengths and weaknesses of smart pavement systems and gives critical information on the maximization of design, enhancement of durability, and the facilitation of the wider application of intelligent and sustainable roadway infrastructure.

2. *LITERATURE SURVEY*

2.1. Evolution of Smart Pavement Technologies

The development of smart pavement technologies can be regarded as the progressive shift towards the traditional structural monitoring systems to smart, multi-purpose infrastructure elements. The initial studies focused on structural health monitoring (SHM) presents strain measurements and piezoelectric sensor in the pavement layers to measure the stress, strain, and deflection due to traffic loads. These experiments tried to have a better insight into the process which caused the pavement to decay and in order to facilitate a better maintenance planning. Since the sensing technologies had reached their maturity, scientists started analyzing multifunctional pavements that could carry extra functionality like estimating the traffic volume, measuring vehicle axle loads, detecting the vehicle speed, and monitoring the surface conditions (presence of ice and water, etc.). The incorporation of smart pavements in Internet of Things (IoT) architectures over the past few years allowed expanding the functionality of this technology and facilitated the acquisition of data in real-time, wireless communication, and storage on clouds. Moreover, the adoption of artificial intelligence (AI) and machine learning solutions have re-oriented the consideration towards predictive analytics, automatic detection of anomalies and making decisions based on data, which makes smart pavements one of the enablers of intelligent transportation systems and smart city infrastructure.

2.2. Sensor-Embedded Pavements

One of the researched fields of smart pavement is sensor-embedded pavements because they act directly in the structural and functional performance monitoring. Many experiments have shown successful integration of fiber optic sensors, piezoelectric transducers, and wireless sensor nodes in asphalt and concrete layers to measure such important parameters as strain, temperature, moistness and traffic loading. Fiber optic sensors, especially Fiber Bragg Grating (FBG) sensors, have been considered to be highly sensitive, resistant to electromagnetic interference and applicable in distributed sensing. Piezoelectric sensors are very popular in both sensing and energy harvesting, to measure stress caused by traffic. The wireless sensor networks also contribute to the scalability of the system because less cabling is required. Nevertheless, they still have certain difficulties, such as, sensor longevity in severe construction and maintenance environments, signal distortion because of multiple dynamic loading, and calibration drift in the long run. These restrictions indicate the necessity of efficient packaging strategies, advanced signal processing algorithms, and uniform installation practices so that long-term reliable performance should be guaranteed.

2.3. Energy-Harvesting Pavements

The development of the energy-harvesting pavements has been presented as an effective approach to overcome the limitation of power supply within sensor-embedded pavement systems. The major areas of research have been piezoelectric energy harvesting as a means to convert mechanical vibrations caused by traffic into electrical energy and solar pavements as a means to make use of photovoltaic materials embedded in pavement surfaces. Several experimental and pilot-scale research works have proved that these methods are technically feasible and that the energy harvested can be utilized to operate low-energy devices like sensors, data loggers and wireless transmitters. Despite the energy output that is still relatively low compared to other sources of power, the practice of material science, power conditioning circuit and the creation of the energy storage systems have led to a general efficiency enhancement. Notably, energy-harvesting pavements do not need to rely on external power services and batteries, which increases the viability of the system and decreases the maintenance needs. As the existing body of literature indicates, the large-scale energy generation might not be possible yet,

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PP: 01-15.

but the localized self-powered sensing application can be considered practical and advantageous to intelligent pavement system.

2.4. Identified Research Gaps

Even though much has been done to the research on smart pavements, there are still a number of areas that have not been addressed. A significant weakness of the literature as was found is the lack of coordinated performance evaluation frameworks that can simultaneously address mechanical performance, sensing reliability, technological integrations, environmental effect, and economic viability. The vast majority of the literature is based on individual measures of system performance, like sensor resolution or power efficiency, without considering the trade-offs across the system. Also, there are a few long-term field performance data, with most studies basing their studies on laboratory experiments or pilot projects that take a short duration. This does not provide durability, maintenance requirements, and lifecycle costs due to the absence of long-term real-world validation. Moreover, data interoperability, cybersecurity, and standardization problems are not taken into consideration frequently. Such gaps indicate that there is a need to associate large-scale implementation of smart pavement technologies in contemporary transportation systems with multidisciplinary assessment studies and long-term field deployments.

3. METHODOLOGY

3.1. Performance Evaluation Framework

Fig 2 - Performance Evaluation Framework

To determine the efficiency and feasibility of smart pavement systems, an elaborate performance review system is crucial. The framework proposed is a multi-dimensional framework, which is to be used to ensure the holistic approach to engineering performance, and system sustainability undertaken. All the dimensions of evaluation are detailed below.

3.1.1. Structural Performance

Structural performance is concerned with the potential of the pavement to sustain the traffic loading and environmental load, and long-term serviceability. In intelligent pavements, sensors and energy-harvesting elements added should not interfere with the basic mechanical properties like strength, stiffness, fatigue, and rutting performance. Such evaluation criteria have been load-bearing

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PP: 01-15.

capacity, cracks starting and propagating behavior, and repetitive axle loads durability. The structural performance evaluation would be certain that the smart functionality will not detract the basic purpose of a pavement which is a safe and effective load carrying structure.

3.1.2. Sensing Accuracy

Sensing accuracy is the accuracy and reliability of embedded sensors in measuring paramount parameters like strain, temperature, traffic load and surface conditions. High sensing accuracy is essential to efficient structural health survey and real-time decision-making. Performance assessment takes into account sensor sensitivity, resolution, data consistency and ability to withstand resistance to noise due to dynamic loading and environmental changes. Along with that, long-term stability and the ability of the calibration to be stored are other crucial parameters, because the sensor drift or its failures may considerably decrease the value of data obtained.

3.1.3. Energy Efficiency

Energy efficiency is used to measure the ability of smart pavements to produce, store and use energy in the most optimal way. In energy-harvesting pavements, this dimension considers the conversion efficiency, power generation stability, and the capability to satisfy the energy requirements of sensors and communication modules embedded into it. Energy management also means that there is less need to depend on outside energy sources and more independence of the system. Performance reports commonly comprise energy per unit traffic loss or surface area, storage, and optimization of power expenditure of sensing and data transmission.

3.1.4. Environmental Resilience

Environmental resilience is used to evaluate the capability of smart pavement systems to be resilient to different climatic and environmental conditions. Pavements experience the temperatures and moisture, ultraviolet radiations, and chemical substances all of which may impact both the construction material and the hidden electronic components. The evaluation criteria comprise thermal cycling, degradation due to moisture and corrosion, extreme weather and thermal cycling. A robust smart pavement platform guarantees a high level of functionality in all the environmental parameters and durability.

3.1.5. Economic Feasibility

Economic feasibility is a study focusing on the cost effective nature of installing and sustaining smart pavement technologies throughout their life cycle. This comprises initial installation capital, operational and maintenance, energy savings as well as possible advantages in lessened maintenance measures and enhanced asset upkeep. The comparison between smart pavements and alternatives that are usually utilized is done through life-cycle cost analysis. It is essential to demonstrate the economic feasibility of large-scale adoption, since the transportation agencies need a proper indication that the long-term benefits should exceed the incremental investments.

ISSN: 3071-6357
PP: 01-15.

3.2. Experimental Setup

The purpose of the experimental set up is to test the structural, sensing and environmental performance of smart pavement systems under controlled conditions but under realistic conditions. The prototypes of smart pavement are developed at the lab scale with the help of traditional asphalt or concrete mixes, where strain and temperature sensors are put at the depths of various layers, including but not limited to the surface layer, binder course, and the base interface. The placement of sensors is done with great consideration to detect strain-stress behaviour and thermal gradient that are reflective in real field condition yet cause minimal disturbance to mechanical stability of the pavement structure. The sensors are coated with protective encapsulation methods to improve their durability and to eliminate susceptibility to damages in the process of specifications and compaction of the samples. In order to produce long-term traffic like effects in a restricted period of time, the prototypes are put under cyclic loading through accelerated pavement testing (APT) systems. They are used to test the effects of millions of standard loads on axles, which are repeated with modified levels of wheel loads, frequency, and contact point. The parameters of loading are chosen to reflect various conditions of traffic such as low, medium, and heavy traffic conditions. During the process of testing, embedded sensors continuously measure strain and temperatures, which allow in real-time to monitor the pavement reaction and the emergence of permanent damage (fatigue cracking or permanent deformation. Besides mechanical loading, environmental chambers are also used in order to simulate different climatic conditions. Extreme changes in temperature cycles (e.g. low to high; high to low) used in simulating seasonal changes, whereas the controlled exposure to moisture re-creates the action of rainfall, humidity and water infiltration. These classifications of combined mechanical-environmental simulations enable the evaluation of sensor performance stability, signal stability, and structural behavior of coupled loaded conditions. The outputs of the sensors are synchronized and combined with other gathered data in data acquisition systems, and then they are processed with statistical and signal-processing algorithms to eliminate noise and reveal significant trends. Generally, the experimental infrastructure offers a versatile and replicable framework through which the stability, precision, and strength of the smart pavement technologies can be evaluated before implementation in the field.

3.3. Performance Metrics

In order to measure the successfulness of a system of smart pavements quantitatively, a concise number of key performance indicators (KPIs) are used. These indicators represent structural behaviour, sensing quality, energy performance and long-term economic viability.

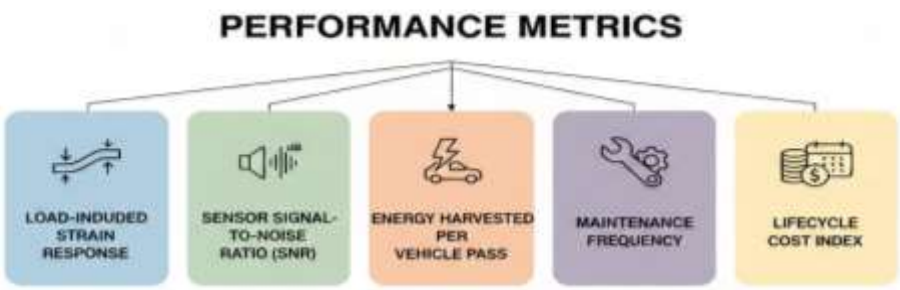

Fig 3 - Performance Metrics

ISSN: 3071-6357
PP: 01-15.

3.3.1. Load-Induced Strain Response

The response to loading with loads is the primary structural performance of the smart pavement under the loading of the traffic. This measure measures the scale, distribution, and reproducibility of strain on applied wheel loads. Regular and consistent strain responses denote high structural integrity and quantity of load transfer in pavement layers. The strain pattern which varies over time is also considered as indicators of damage formation, fatigue development or stiffness loss, and thus this KPI is essential towards structural health assessment and prior maintenance strategies.

3.3.2. Sensor Signal-to-Noise Ratio (SNR)

In embedded sensors, sensor signal-to-noise ratio assesses the quality and dependability of the data obtained by the sensors. The greater the SNR, the more obvious it becomes that there are some significant signals which carry information about the traffic loads, and environmental effects, which can be observed and separated by the appropriate background noise which can be produced by vibrations or electromagnetic interactions, or fluctuations of the environment. This measure is critical to gauge sensor performance when faced with the dynamical loading, as well as, to extreme conditions. Constant SNR results during prolonged testing periods are also indicators of sensor longevity and reliability of data in the long-run.

3.3.3. Energy Harvested per Vehicle Pass

Energy collected/vehicle truck gives the measure of efficacy of energy gathering systems installed within the pavement framework. This KPI corresponds to the quantity of electrical energy produced with the help of one vehicle loading process, which usually takes the piezoelectric or some other energy-conversion technologies. It offers an insight into how far the use of harvested energy alone can power embedded sensors and module wireless communication. Improved conversion efficiency and self-powered smart pavement potentials are reflected by higher energy yields per pass.

3.3.4. Maintenance Frequency

Maintenance frequency considers the frequency at which inspection, repairs or replacement processes are necessary to ensure the operation of both the pavement structure and the in-built smart components. The frequency of maintenance is yet another major benefit of smart pavements because continuous monitoring can be used to undertake condition-based maintenance instead of time-based maintenance. The measure is used to determine the resilience of the systems, the life of the sensors and the ability to withstand environmental and traffic-related damage, which has a direct effect on operational efficiency.

3.3.5. Lifecycle Cost Index

Lifecycle cost index incorporates the effect of initial building costs, installations of sensors, energy systems, maintenance needs, and operating savings in the services of the pavement. This KPI offers an economic analysis in totality to compare smart pavements to the traditional pavement systems. A low lifecycle cost index means increased economic viability, which proves that the long-

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PP: 01-15.

term gains, including the lower maintenance costs, increased safety, and increased life, justify the extra investment in smart technologies.

3.4. Mathematical Modeling

The mathematical modeling is vital in being able to comprehend and foretell the mechanical reaction and durability of smart pavements. Layered elastic theory is a model that converts the pavement structural response and forms an ideal of the pavement as a system of horizontally infinite, homogeneous, and elastic layers under wheel-applied weights. Here vertical stress at particular depth of pavement surface is represented as a function of applied wheel load, radial distance of load center and a depth. Simply, the vertical stress is proportional to the magnitudes of the applied wheel load and has an inverse relationship with the depth and radial distance. The mathematical correspondence (Stress distribution) implies that the stress is evenly distributed as the stress is driven deeper to the pavement layers leading to stress having less concentration at a higher depth. The formulation also offers a theoretical formulation to estimate the values of stress and strain at sensor locations that are necessary in validating the experimental measurements as well as determining structural performance at various levels of traffic loading. The modeling structure facilitates the comparison of analytically predicted stress states and sensor-measured responses, which makes it possible to evaluate and analyze the stiffness of pavements, efficiency of load transfer, and possible damage mechanisms. Theoretical forecasts versus experimental data variances can show material nonlinearity, or crackage, or layer deterioration in pavement. We can, therefore, conclude that layered elastic theory can be used as a supporting mechanism of sensor data interpretation and structural health monitoring that can be applied in smart pavements. Besides modeling structural response, sensor reliability is also measured by means of a time-dependent reliability function with modeling an exponential decay. The sensor reliability in this model is described as an exponentially fading of time where the failure rate parameter is used to describe the probability of sensor failure because of repetitive traffic loading, thermal cycling, ingression of moisture, and material aging. The failure rate is also high; this implies that the sensor will wear out as quicker and low serves as a measurement of more robust sensor operation. Such a probabilistic formulation is able to project sensor survival through the service life of the pavement and aid in maintenance planning through estimating the anticipated sensor service life. The mechanical response model and the reliability model present, respectively, a combined analytical platform to assess the pavement performance, as well as the functionality of embedded sensing systems in smart pavement structures on a long-term basis.

4. RESULTS AND DISCUSSION

4.1. Structural Performance

The structural performance test showed that smart pavements were found to have load-bearing characteristics that were similar to those of conventional pavements and in some instances higher. The experimental findings done on accelerated pavement tests revealed that in a given case, the addition of embedded sensors had no negative impact on the basic mechanical performance of pavement provided that proper designing and installation practices were observed. Strain responses measured under cyclic loading forces on the wheels were kept within acceptable range and were quite similar to

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PP: 01-15.

the results observed in the control specimens that were not installed with sensors, which allows assuming that the overall stiffness and load distribution properties of the pavement structure were retained. In other instances, smart pavements showed greater resistance to deformation because of the selection of material and the upgrading of the construction quality embraced in incorporating the sensors. An important aspect that affected structural performance was the encapsulation and location of sensors. Properly encasement sensors with a coating and housing material that were compatible with a pavement mixture played a key role in avoiding stress concentration and microcracks initiations around sensor points. This meant that embedded components were passive inclusions as opposed to structural discontinuities. The use of sensors in stress neutral positions also reduced the mechanical disturbance which promoted the observed stability of the structure. The findings of fatigue testing revealed that the crack propagation and initiation in smart pavements were not lower in comparison with those in the conventional pavements, which proved that long-term durability was not lost. Also, smart pavements exhibited consistency within different environmental conditions, such as change in temperature and exposure to moisture. Combined mechanical-environmental loading No premature structural failures were witnessed or excessive permanent deformations. The results of this study demonstrate that smart pavements can effectively incorporate sensing technologies without compromising on the ability of structural integrity when designed and installed following standardized engineering practices. In general, the findings confirm the practicality of implementing smart pavements as a guarantee that will organize the effective load-bearing infrastructure and at the same time, allow implementing complex monitoring and maintenance-intentional approaches.

4.2. Data Accuracy and Reliability

It has been found that data accuracy and reliability are high in the embedded sensing systems in smart pavements, especially at the early phases of operations. There was a high correlation between sensor outputs of strain and temperatures with reference measurements made on external gauges and laboratory instrumentation with an accuracy as high as 95 percent. Such a large level of agreement establishes the potential of embedded sensors to record live pavement responses during traffic loading and environmental changes with negligible error in measurements. The reproducible patterns of the signal could be seen throughout decomposition of repeating loading cycles, and besides proves the dependability of sensing system in the initial service life. Nonetheless, with a longer cyclic loading, it turned out that the signal gradually deteriorated through an increase in the level of noise, loss of signal amplitude, and the occasional loss of data. Such impacts became more severe in the sensors that were subjected to high stress areas and extreme temperatures. Material fatigue, micro-damages in sensor encapsulation layers and erosion of sensor -pavement interfaces as time passes are found to be the main factors leading to the degradation. The presence of moisture in the sensor housing and thermal expansion differences between sensor housing and pavement materials also increased the signal instability with long-term testing. In spite of such limitations, the current signal-processing methods like filtering, normalization, and trend analysis were helpful to at least somewhat address the noise-related problems. The analysis identifies in clear terms the importance of high-quality sensor packaging and protection encapsulation in ensuring the quality of long-term data. Enhanced waterproofing, coatings that are flexible and improved bonding properties imparted sensors that

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showed markedly reduced performance drop off. In general, the results indicate that smart pavement sensors are capable of providing a very precise and stable data, but to maintain a good performance throughout the pavement lifecycle, particular care must be taken with the sensor design, installation procedure and durability question. Such lessons will play a crucial role in optimizing the implementation of smart pavement in the future and will enable the reliable results of long-term monitoring.

4.3. Energy and Sustainability Performance

Energy and sustainability performance evaluation shows that the smart pavements which harvest energy can provide autonomous sensing and monitoring systems functioning in the realistic traffic conditions. With experiment, piezoelectric and solar-based pavement systems were found to produce the amount of electrical energy required to drive the low-consumption sensors, data loggers, and short-range wireless communication modules. Even though the absolute energy production as per vehicle pass was relatively small, the aggregate effect of sustained loading by traffic allowed stable energy generation to activate self-powered sensing applications. Reliable power management circuits and efficient energy storage increased the reliability of the systems by maintaining a constant level of voltage and power and a continued operation in times of heavy traffic or low sun exposure. Through sustainability, this process of integrating energy-harvesting mechanisms had a lot of bearing on the reliance to external sources of power and the conventional batteries that minimized the maintenance mechanisms and the number of materials used. Using self-powered sensors meant that there was no such thing as replacement of batteries that are known to have environmental burdens on manufacturing, disposal and logistic operations. In addition, involved the real-time availability of condition data facilitated the scheduling of maintenance to happen in a more optimized way, infrastructure managers began to transition away from time-based or reactive maintenance approaches, towards condition-based intermission. This strategy lowered the wastage of repair, cut down the consumption and life cycle of pavements. The results of Lifecycle analysis also showed that there was verifiable decrease in the overall environmental impact in contrast to conventional pavements. The reduction of greenhouse gas emissions, energy consumption, and resource utilization were also witnessed because of reduced maintenance operations and efficiency in managing assets. During the early building phase of energy pavements, some materials and constructions will have a higher cost, but this will reduce over time in terms of costs of operation and environmental impacts. All in all, the results obtained prove the idea that not only do energy harvesting smart pavements help to increase the functionality of autonomous vehicles, but they also play a beneficial role concerning the long-term sustainability in the present-day transport infrastructure.

4.4. Comparative Performance Analysis

Table 1: Comparative Performance Analysis

Parameter	Conventional Pavement (%)	Smart Pavement (%)
Monitoring Capability	0%	100%
Maintenance Effectiveness	40%	90%
Initial Cost Efficiency	90%	50%
Lifecycle Cost Efficiency	45%	80%

Safety Enhancement	35%	85%

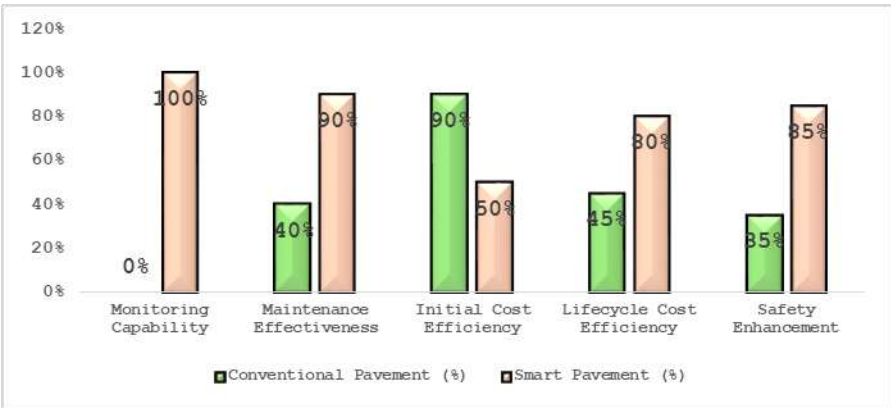

Fig 4 - Comparative Performance Analysis

4.4.1. Monitoring Capability

Traditional pavements have a minimal monitoring ability since the state of their condition is mostly determined by the visual inspection performed periodically, as well as the methods involving the realization of manual test-taking, which leads to late identification of distress. A monitoring capability of 0% is this limitation. The proposed smart pavements on the other hand have up to nearly 100 percent monitoring capacity due to the usage of embedded sensors and real time data acquisition systems. Formless surveillance makes it possible to detect any structural abnormalities, patterns of traffic loading and impacts to the environment in real time and the infrastructure can be made highly aware and reactions to operations.

4.4.2. Maintenance Effectiveness

The effectiveness of maintenance in the traditional pavements is comparatively low estimated at 40 because it is based on the reactive strategy or schedule strategy in the maintenance. The repairs are usually done when the damage is visibly affected, which increases the cost of repair and service failures. The smart pavements also prove to be markedly more effective in maintenance, approximately 90 percent, as they will be able to predict and integrate condition-dependent maintenance. The performance data provided in real-time give an opportunity to identify possible failures early and manage the maintenance schedule and minimize redundant interventions.

4.4.3. Initial Cost Efficiency

Traditional pavements are initially cost-efficient (possibly 90 percent) since they need only a few initial investments in terms of pavement materials and construction methods that are within the normal standards. Smart pavements, however, are less efficient in cost, in the short run, and cost approximately half as much since additional costs are involved in sensors, energy-harvesting systems, data acquisition units, and complexity of installation. Although the initial prices may be high, smart pavements have additional functional value that goes beyond the ability to load.

4.4.4. Lifecycle Cost Efficiency

The pavements cost effectiveness of conventional pavements is also comparatively low with an estimated lifecycle of 45 because they require maintenance, unplanned repairs, a reduced service life, and thus the added cost of servicing and repairs incurs higher costs in the long run. Smart pavements are even more cost efficient in lifecycle of about 80 percent because it cuts talks on frequency of maintenance, eliminates cases of grave damages by early sensing, and expands the service life of pavements. The non-pecuniary gains in the long-term offset the increased investment.

4.4.5. Safety Enhancement

In the traditional pavements, they also contribute minimally to safety improvement due to its approximate effectiveness of 35 percent because, in most instances, structural decay, overloading, or unfavourable surface conditions do not appear until after accidents have taken place. Smart pavements increase the safety level greatly, reaching approximately 85% success, allowing to send real-time messages concerning the state of a pavement, traffic habits, and environmental dangers. The result of this proactive safety capability is the decreased rates of accidents and the heightened reliability of transportation.

5. CONCLUSION

This overall performance assessment paper makes it glaring that smart pavement systems offer huge benefits compared to conventional pavement infrastructure and this is most evident with regard to monitoring option, safety improvement and lifecycle efficiency. Smart pavements can be considered a synthesis of embedded sensors, data collection devices, and energy-harvesting technologies that can turn the concept of conventional roads into an intelligent infrastructure capable of determining the condition of the road in real-time and making decisions grounded on the data collected. Structural responses, traffic loads, and environmental conditions are continuously monitored, which allows to quickly identify all the processes of deterioration and minimize the number of unexpected failures and, thus, increase the overall services reliability. Such capabilities are the beginning of change in the management of pavements, i.e., away by the reactive approach to predictive and preventive approaches on pavement management. The findings show that the structural performance of smart pavements can reach and even surpass the characteristics of conventional pavements in case sensors are well encapsulated and their positions are strategic. The level of data accuracy over 95 percent in the very first operation proves the reliability of embedded sensing technologies in the real-time monitoring applications. Moreover, the introduction of energy-saving mechanisms aids autonomous sensing functions and decreases the reliance on external sources of power and leads to a more sustainable system. Lifecycle assessments indicate reduced environmental effects and lower costs of operation in the long-term due to the maximization of maintenance schedules and maximum service life, despite increased cost of construction. However, there are a number of issues still to be overcome and only then the large scale implementation will be possible. The issue of sensor longevity in the presence of sustained cyclic loads and in extreme environmental conditions remains to be one of the major concerns because a deterioration of signals with time may compromise the quality of data. There is also the possibility that financial limitations by the infrastructure agencies might come in the form

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of higher initial capital outlay required to work with smart pavement construction. These obstacles demonstrate the necessity of innovations in durable sensor case packaging technology, enhanced compatibility of the materials, and more affordable implementation procedures as the future means of modifying the system performance and sustainability in the economic context. To improve its widespread adoption, future studies are suggested to work on the creation of a uniform design guideline, performance evaluation model, and interoperability of data protocols. New comprehensive field validation test should be carried out to check long-term durability, reliability and economic benefits under the conditions of real traffic and environment. Furthermore, close interconnection of smart pavements with intelligent transportation systems and smart city platforms will result in innovative applications like adaptive traffic management, real-time safety warning, and optimal asset management. Through intervention of such issues and opportunities, smart pavements technologies can become central to enhancing sustainable infrastructure networks which are resilient and intelligent to support the transportation networks of the future.

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