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Proceeding Paper

A Framework for Smart Pavements in Canada †

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Abstract: Maintaining an acceptable durability and satisfactory in-service condition for pavements is a crucial and relatively complex task, which otherwise can have considerable economic, environmental, and social consequences. Design and management of pavements have traditionally relied mainly on empirical models. However, pavements have been undergoing drastic changes, especially during the new millennium, which can compromise the reliability of the empirical models which were developed based on relatively stagnant historical data. Climate change, traffic loading growth and advancements in pavement materials are some of the main drivers of moving towards more mechanistic-empirical methods which would allow for a better understanding of pavement performance evolution in the future. To this end, this paper discusses the opportunities and challenges of a proposed framework for developing smart pavements in Canada, as well as a summary of the efforts that so far have been made in this regard. The goal of the study is to enable autonomous monitoring and data collection from the instrumented pavement sections in a suitable manner to allow for training Artificial Intelligence models, improving interpretation of the pavement responses and, ultimately, future pavement performance predictions.

Keywords: smart pavements; instrumentation; performance prediction; artificial intelligence; machine learning; mechanistic responses; autonomous monitoring

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1. Introduction

Pavement networks play a key role in our modern societies by accommodating the economical, efficient, and safe movement of goods and people [1]. In addition to their significant economic and societal impacts, pavement construction and maintenance activities demand an enormous amount of natural, and mainly non-renewable, resources annually, and, hence, can result in a significant environmental footprint if not managed properly [2]. Therefore, maintaining the long-term performance and durability of pavements is a common goal at different levels including the planning, designing, construction, and management of transportation infrastructure [3,4]. Pavements are typically designed to last for several decades. Traditionally, we have mainly relied on empirical design based on limited experimental studies that were conducted between 1956 and 1961 in the U.S. [4]. Despite the relatively good success rate of these approaches in the past, the appearance of premature distresses and unexpected shortening of pavements' service life during the past two decades have motivated pavement engineers and researchers to further investigate the contributing mechanisms behind these phenomena. To this end, a paradigm shift in terms of pavement design and material characterization has been happening over the course of the past two decades which requires moving away from purely empirical approaches toward linking the empirical and mechanistic characteristics to develop better distress prediction models. Development of the Pavement Mechanistic-Empirical Design (PMED) [5] can be named as one of the well-known examples in this area. Although a robust mechanistic platform for modelling pavement performance is a positive step forward in achieving a better accuracy when designing pavement structures, it is also crucial to calibrate and verify pavement structural responses and performance trends in the eye of the changing climate and introduction of unconventional paving materials [6]. This requires systematic management of the transportation infrastructure, performing regular pavement condition assessments, intervening for maintenance and rehabilitation activities in a timely manner, and improving the practice of design and construction to accommodate for the desired resilience level against climate change effects and the dynamic nature of the exerted traffic loading. The development of autonomous pavement monitoring systems would, therefore, yield several advantages in terms of informing decision making about the timing of maintenance and rehabilitation (M&R) activities based on more realistic performance prediction models [7]. As a result, developing smart pavements has recently become the focus of some research groups across the world.

On the other hand, the application of Machine Learning to predict pavement's performance measures has also been gaining momentum during the past two decades [8,9]. Most of the work conducted to date has been focused on the prediction of the functional indexes such as the International Roughness Index (IRI) [10–12] or general pavement condition metrics such as the Pavement Condition Index (PCI) [13–15]. Predicting the structural response of pavements and distress modes such as rutting and cracking have seen relatively limited attention. Nevertheless, measuring pavement responses in a semi-continuous manner using smart pavement sections also provides an opportunity for utilizing the artificial-intelligence-based methods to improve the pavements' performance prediction as well as locally calibrating the PMED.

This paper provides a summary of the proposed smart pavement framework and the activities undertaken to date in this regard through the instrumented pilot section in Ontario, Canada.

2. Proposed Smart Pavement Framework

The proposed conceptual framework for smart pavements in Canada is composed of five major components. Figure 1 presents a schematic overview of this framework, including: (i) instrumented pavement sections and a Data Acquisition (DAQ) triggering system; (ii) an autonomous and semi-continuous data logging platform with remote data collection/storage capability; (iii) a preliminary (raw data) postprocessing unit; (iv) a secondary data aggregation and metrics computation unit; and (v) a cumulative structured database to store the data pertinent to long-term performance and key structural responses, through the use of both the dynamic and static data types.

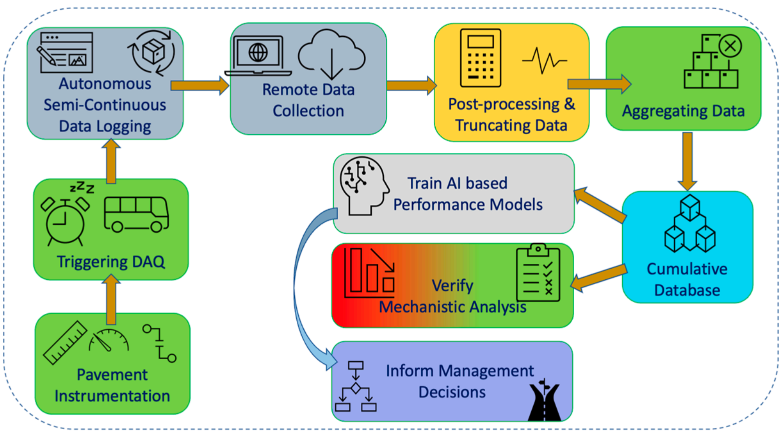

Figure 1. Proposed framework to deploy smart pavements in Canada.

A maximum traffic speed of 70 km/hr would be expected for the pilot section built to implement the proposed framework in Ontario, Canada. This required using dynamic asphalt strain gauges and pressure cells (PC) with a minimum data logging rate of 1000 Hz per channel to capture the full spectrum of the dynamic pulses induced by moving vehicular loads. The selected gauges provided a rate of 1 kHz per channel (not shared). Furthermore, temperature and moisture trees were instrumented to record the temperature and moisture variation at nine different levels within the pavement structure (see Figure 2). The temperature gradient would especially provide valuable information that could help better model the structural response of the pavement at different times of the day and year. Temperature probes (identified by red crosses in Figure 2) recording every 15 min can capture the daily fluctuation and gradient within the pavement structure.

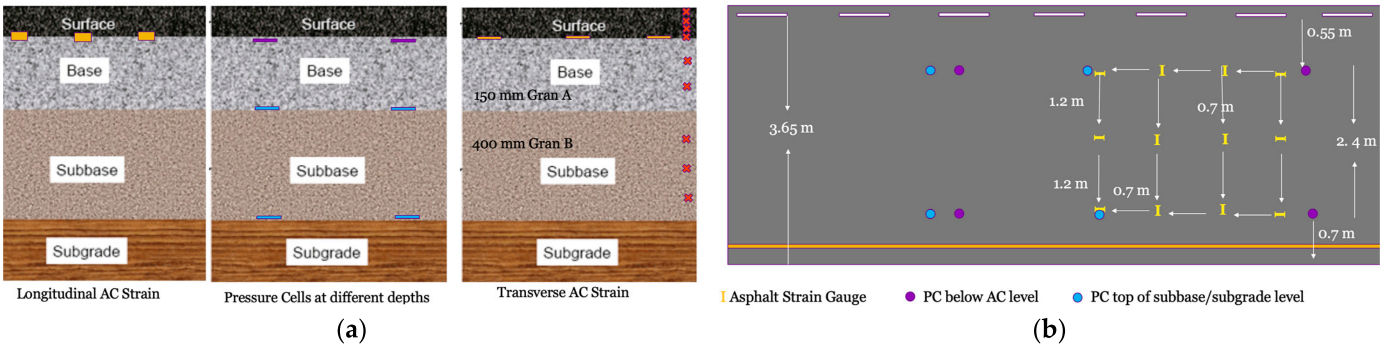

Figure 2. Schematic of the pilot section in this study: (**a**) cross section and (**b**) plane view.

Given the dynamic and semi-continuous nature of the collected data, a triggering system to activate the data collection can help avoid the collection of unnecessary data. This can be achieved through one of the pressure cells embedded underneath the asphalt concrete layer and at a distance from the main cluster of the sensors array, which was used to awaken the DAQ and collect the data until 120 s after the last sensed pulse. Using laser reflectometers or traffic cameras were also identified as viable options, which are not investigated in this study.

The DAQ system is equipped with a wireless modem that allows for remotely accessing the system and periodic downloading of the data. The raw data need to be routinely post-processed for noise removal and to truncate the signals with their corresponding time stamps. These data are then aggregated in terms of engineering metrics to describe the peak magnitudes and frequencies of strain/stress pulses at different depths of the pavement structure, as well as the incremental temperature and moisture changes.

3. Challenges and Opportunities

3.1. Barriers for a Fully Functional System

One of the major hurdles for the dynamic and semi-continuous collection of pavement responses is handling humongous amounts of generated data, which is different than the traditional static data collection. This poses multiple problems, e.g., the need for timely raw data processing and the required data storage logistics. The aggregated processed data in this project will be ultimately transferred to the National Logistics Database in Canada, as a part of the Artificial Intelligence for Logistics (AI4Logistics) program. Another issue preventing the widespread use of such a system remains the high cost for the existing pavement instrumentation. Furthermore, a comprehensive array typically requires a considerable power supply, buried wired connections, and interruptions to the conventional paving operations. Developing a wireless sensor that can eliminate the need for wired connections has been the focus of several research groups, including the authors' research. However, technical barriers such as the need for substantial power and limited operation life on battery power remains a gap in the existing work, along with the short life span of embedded sensors under sever climate conditions, which suggest the need for research on the ruggedness of the sensors. Promising progress has been made during the past few years in terms of wireless temperature measurements. However, this remains a challenge for stress/strain measurements without wired connections and power.

With respect to pavement data analysis and interpretation, most of the existing work on AI applications has focused on the use of supervised learning algorithms to predict functional metrics, such as the International Roughness Index (IRI), or overall pavement condition measures such as PCI, based on the existing databases such as Long-Term Pavement Performance (LTPP). The application of Machine Learning (ML) algorithms to obtain performance-related measures from the structural responses of pavements has seen limited attention. This also requires utilizing a database of a certain size to develop meaningful models.

Finally, unlike the controlled sections and accelerated testing facilities, monitoring live traffic typically becomes more complex due to the wandering of traffic loads, which ultimately affects the measured responses' amplitudes relative to the axles' vertical alignment on top of the sensors array. On the other hand, the axles' load and configuration will be highly variable as compared with the controlled tracks. In the case of live traffic loading, having a Weigh-In-Motion (WIM) station can significantly help with better interpretation of the structural responses to different axles. However, a WIM is not always available, creating one may not be practical for an in-service pavement section, and one-to-one synchronization of detailed traffic data with millions of recorded responses will require a lot of effort. The latter requires a considerable budget and would require further approval from the owner agency.

3.2. Applications of Smart Pavement Data and Future Steps

The ability to measure actual pavement responses under live traffic loading and in-service conditions allows for improving the current state of pavement design and management practices. Three major areas that can especially benefit from such a system are: (i) the quantification of climate change implications for pavements, (ii) validating the pavement analysis results with in situ measured data as well as calibration of the MEPDG transfer functions and distress models, and (iii) developing enhanced pavement performance prediction models using suitable ML algorithms. Furthermore, smart pavements can facilitate the implementation of innovative and high-performance paving materials, for which very limited data currently exist in terms of their in-situ responses/performance. This is especially a barrier in reflecting the added value for using such materials in the existing design methods, hence their implementation.

Moving forward, data collection from the proposed instrumented section in Ontario will be continued and once the required data size is available, pertinent ML models will be trained and tested by the research team. In the meantime, the research team has been working on the application of a Random Forest (RF) algorithm using the existing LTPP pavement performance database to predict the IRI and Rutting performance of flexible pavements in North America. In terms of structural response verification, samples of the paving materials have been collected for each layer and mechanical testing in the lab will be performed to correlate the engineering properties of the materials measured at the laboratory scale to their corresponding in-service response under varying temperatures and loading frequencies. In addition to the live-traffic data, verifications will continue to be performed using a truck with a known axle load driving on the instrumented section at different passing speeds, at least once every season, and ideally for several years.

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