Technical Paper

ISSN 1997-1400 Int. J. Pavement Res. Technol. 5(5):295-302

A Review and Perspective about Pavement Monitoring

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Abstract: Pavement monitoring is an essential part of pavement research and very important to the socialized transportation system. Since the middle of 20th century, various sensing technologies have been devoted to improve sensitivity, functionality, scale, survival rate and resistance to harsh environment. At the same time, other related monitoring system, such as bridge monitoring, Weigh-in-Motion (WIM), traffic classification systems are also developed vigorously, and can be integrated with pavement monitoring with more benefit.

In this paper, pavement monitoring is categorized based on the monitoring frequencies and sensing technologies, and each category is traced back with important development described. The history and current status of the related and integrated monitoring systems are reviewed according to different monitoring targets and sensing methodologies. Some new developments representing future trends are also discussed.

***Key words**: Bridge monitoring; Integrated monitoring system; Pavement monitoring; Sensing technology; Traffic classification; Transportation monitoring; Weigh-in-motion.*

Introduction

The importance of pavements for economy and society is self-evident. The concept “Smart Road” is being implemented with a variety of advanced technologies devoted to different intelligent responses, and one essential part of smart road is pavement monitoring.

In the recent years, Pavement Management System (PMS) has brought many benefits to the socialized transportation system. The strategies and decisions from PMS are based on various observations and measurements of the pavement or Pavement Monitoring. As an essential component of PMS, pavement assessment (low frequency monitoring, referred as pavement monitoring as well hereafter) and pavement monitoring have attracted much more attention and been improved via various advanced technologies and methodologies in the past decades.

Surface Condition and Pavement Deflection Assessment

The surface conditions of pavements, including the occurrence and severity of cracking, rutting, wear, deflection and other distresses present on pavement surface, are an important indicator of pavement performance. The Long-Term Pavement Performance (LTPP) program has collected pavement surface conditions and many other pavement performance measures on a variety of pavements, and most state transportation agencies have collected pavement distress data for pavement management in recent years [1].

Surface cracking is an obvious and important indicator of pavement performance. Conventional visual and manual pavement cracking analysis approaches can be used to monitor the surface conditions. However these traditional methods are very costly, time-consuming, dangerous to inspectors, labor-intensive, and subjective [2]. All the drawbacks lead people to explore more advanced, safer and more efficient methods for pavement surface condition assessments. Since 1990s, evaluation of pavements using digital images has become increasingly popular as a result of the significant leap in the sciences of computer vision and image processing [3]. In 1991, Mohajeri and Manning developed an approach to process segmented pavement distress images with directional filters [4]. In 1993, Koutsopoulos and Downey explored statistical algorithms for image enhancement, segmentation and distress classification [5]. Many sophisticated techniques have been studied to improve the accuracy of classification [6, 7], and among which the theory of Fuzzy sets is the most popular one [2, 8].

Surface deflection is a reliable pavement structural response indicator [9], and has been measured in many pavement monitoring projects. In 1971, the NAPTF (National Airport Pavement Test Facility) failure criterion was established through the US Army Corps of Engineers’ (US COE) Multi-Wheel Heavy Gear Load (MWHGL) test conducted at Vicksburg, Mississippi [10]. In 2000, the deformation of a pavement within the Newcastle University Rolling Load Facility (NUROLF) was measured by stereo-imagery using both analytical and digital photogrammetry [11]. In 2001, McQueen *et al*. [12] validated the linear load-deflection relationship of the NAPTF HWD test results. Gopalakrishnan [13] introduced a Heavy Weight Deflectometer (HWD) test to monitor the effect of simulated Boeing 777 and Boeing 747 aircraft on pavement condition.

The schedule for pavement monitoring, called monitoring frequency, has some impact on pavement performance prediction, and pavement decision making in the end [14]. To assess the conditions of pavements, most highway agencies collect the condition data annually, biannually and triannually [15]. According to the study of Haider *et al*. in 2011 [14], “monitoring interval may affect the short- and long-term network conditions for various preservation strategies”, “monitoring cracking (image based) at a

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Note: Submitted December 2, 2011; Revised April 6, 2012; Accepted April 18, 2012

1-year interval will be more appropriate, whereas for roughness (sensor based); a monitoring interval of 1 to 2 years could be suitable".

In-Situ Pavement Health Monitoring Sensors

As described in the previous sections, the monitoring of pavement condition can be conducted by visual investigation, and various testing methods. Most of these methods can be used on any pavement interested, having the advantages of spatial flexibility. In contrast, monitoring systems with sensing devices installed in pavement has also been heavily investigated to achieve real-time monitoring, which has frequency superiority of pavement monitoring.

Pavement health monitoring is essential in pavement management and critical to the socialized and integrated transportation system. The accurate measurement of the strain and stress distributions in pavement is critical for the understanding of pavement behavior and the modeling of pavement failure. Tremendous efforts have been devoted to in situ monitoring by governments and transportation agencies around the world. After several decades' research and application, a wide variety of sensors has been developed for in-situ pavement monitoring, and most of the sensors can be classified into two categories: electromagnetic sensor and optical fiber sensor.

Electromagnetic Sensors

The application of electromagnetic sensors in pavement monitoring can be traced back to the 1960s [16]. In 1991, Sebaaly *et al*. [17] tested various types of pavement instrumentation, including pressure cell, deflectometer, strain gauge, thermocouple, moisture sensor, and transverse vehicle location sensor, for field evaluation under actual truck loading. In 1995, Sebaaly *et al*. [18] measured the tensile strains in flexible pavement using the Hall Effect sensor in an H-gage configuration. In 2001, commercial diaphragm-type stress cells were embedded in subgrade to compare the performance of two instrumented pavement test sections under linear traffic simulator [19]. In 2005, Huff *et al*. [19] investigated piezoelectric axle sensors to obtain dynamic pavement deflection data. In 2011, Xue and Weaver [20] explored the effect of wide-base tire on pavement strain response based on the data collected from SPS-8 on Ohio-SHRP U.S. 23 Test Road in 1997. In the same year, a novel self-powered wireless sensor was developed based on the integration of piezoelectric transduction with floating-gate injection, which is also capable of detecting strain and temperature simultaneously [21].

Optical Fiber Sensors

Fiber optics sensors have attracted lots of efforts in civil engineering infrastructure monitoring because of several of its positive attributes, including distributed sensing capabilities, small diameter, light weight, immunity to electromagnetic interference, strong survival ability and high sensitivity [22, 23].

In 1994, Navarrete and Bernabeu [24] described an interferometry system, which can detect changes in pressure on fiber and measure another external stimulus and changes simultaneously. In 1995, Signore and Roesler [25] used fiber-optic sensors to study the lateral strain behavior of axially loaded emulsified asphalt specimen and obtained its Poisson ratio. In 1996, polymide multimode fiber was braided for increased sensitivity. In 2005, Wang and Tang [26] developed a new high-resolution fiber Bragg grating (FBG) sensor consisting of a referenced FBG and a pair of fiber gratings, and provided the potential of simultaneous measurement of strain and temperature within pavements. Due to the increasing interest of the response and performance in the whole structure, 3-dimensional monitoring has gained more and more attention. In 2012, Zhou *et al*. set up a 3D optical fiber grating based sensor assembly [27].

Pavement Monitoring System

For better understanding of pavement, various pavement research facilities (test roads) have become an integral of pavement research and engineering, and the foremost was the AASHO Road Test conducted in Ottowa, Illinois from 1958 to 1960 [28].As early as in 1989, Rollings and Pittman presented the result of instrumental model tests and full-scale traffic test on rigid pavement, which matched the Westergaard edge-loaded analytical model well on design stresses [29]. In 2004, eight sections were fully instrumented to measure in situ pavement responses under load at the NCAT test track [28]. Timm *et al*. [30] presented the data collection and processing procedures for the NCAT test track instrumentation. MnROAD in Minnesota was heavily instrumented with 40 test cells; based on the monitored data Lukanen developed mechanistically based load equivalency factors (LEF) in 2005 [31]. The Virginia Smart Road is another outdoor pavement research facility located in Blacksburg of Virginia, which has twelve instrumented sections [32]. In 2006, Loulizi *et al*. [33] used one section of the Virginia Smart Road to compare measured stress and strain, and obtained the difference between the stresses and strains measured in situ and calculated for a flexible pavement section.

Integrated Monitoring System

With the development of information technology and digitization, traditional pavement monitoring systems have been integrated with other monitoring systems, including bridge monitoring, Weigh-in-Motion (WIM), traffic classification and so on. Both electromagnetic and optical fiber optic sensors have been widely studied and used in various integrated pavement monitoring systems.

Bridge Monitoring

Many bridges worldwide are closely monitored because of their economic importance and vulnerability to extreme loading and harsh environmental conditions [34]. The monitoring of bridges is convenient to be integrated with pavement monitoring because of their similarity in structure and function. The monitoring system of Geumdang Bridge in Korea using high-resolution wireless sensors are combined together with the two-lane passing test road which employed 1897 sensors to evaluate three types of pavement constructed along the road length [35]. In Hong Kong, the integrated monitoring system with more than 800 sensors permanently installed on the three long-span cable-supported bridges- the suspension Tsing Ma Bridge, the cable-stayed Kap Shui Mun Bridge, and the Ting Kau Bridge [36]. In United States, the Commodore Barry Bridge is instrumented using 77 sensors and 115 channels to track the loading environment and structural responses, and expected to be integrated with a WIM system in the future [37]. In 2012, Kim and Lynch [38] installed wireless sensors on both the bridge and moving vehicle and record the dynamic interaction between the bridge and vehicle.

WIM System

Weigh-in-Motion (WIM) is to obtain the static weight of a vehicle while the vehicle is in motion. Since the concept was brought up sixty years ago [39], WIM technologies have been used increasingly around the world for weight control of heavy vehicles, the protection and management of pavement and other infrastructures [40]. For example, there are more than 100 Weigh-in-Motion stations throughout California by 2002 [41]. Today there are several major types of sensors used for WIM stations: piezoelectric sensors, capacitive mats, bending plate, load cell and optic fiber [40, 42]. The original highway WIM system [43] used weighing devices in one lane of the road. As early as 1989 [44], a high speed Weigh-in-Motion system which was manufactured and supplied by International Road Dynamics (IRD), was installed on Highway 1 near Regina of Canada.

During the past twenty years, each kind of WIM station has been widely studied and developed by worldwide scholars and transportation agencies. Due to the distributed sensing properties, high environment resistance, and other advantages, the studies and applications of optic fiber sensors in WIM systems increased significantly in the past 10 years [22, 45-48]. In 2007, Cheng *et al*. [49] presented the design of a new capacitive flexible weighing sensor for a vehicle WIM system. In the same year, Zhang *et al.* [50] investigated a novel WIM system based on multiple low cost, light weight, small volume and high accuracy embedded concrete strain sensors.

Traffic Classification

Vehicle classification is another important category of traffic data collection. The study of vehicle classification can be traced back to 1976 [51], and commercial detector equipment was used to measure some configuration parameters of a passing vehicle with rough estimation. As of today, lots of information and sensing technology have been devoted to improving the classification. Vehicle classification technologies in current use can be grouped into three major categories: axle based, vehicle length based, and machine vision (visual) based [52]. In recent years, the most popular sensing technologies used in vehicle detecting are piezoelectric sensor, inductive loops, and fiber optic sensors. Piezoelectric sensor is the most widely instrumented, and a lot of experience has been accumulated. In 1990s, cheaper inductive loops (usually single loop or dual loop detectors) were developed to replace the expensive piezoelectric sensors with high classification efficiency preserved [53-57]. Fiber grating sensor application in traffic classification increases because of its advantages and its wide application in pavement health monitoring and Weigh-in-Motion system. Efforts of scholars throughout the world are devoted to improving its performance in vehicle classification [58-61]. At the same time, some other researchers devoted efforts to making use of traditional sensors for health monitoring to detect and classify vehicles. In 2008, Zhang *et al*. [62] delivered a new vehicle classification method and developed a traffic monitoring detector with embedded concrete strain gauges.

Traffic Data Collection

WIM systems and vehicle classification system mentioned above, together with vehicle speed measurement, are all parts of traffic data collection. "Truck data collection and reporting is an important program that state departments of transportation (DOTs) must maintain to comply with FHWA requirements" [52]. For example, the Florida Department of Transportation (FDOT) has approximately 350 traffic classification and WIM sites located throughout the state, including thousands of piezoelectric sensors [63]. Due to the low survival rate of piezoelectric sensors, FDOT was committed to the development of optical fiber sensors in traffic classification and WIM system because of its flexibility, corrosion resistance and immunity to electromagnetic interference [64]; in this project, Cosentino and Grossma developed a fiber optic traffic sensor (FOTS) in 1996 [65]; they improved its sensitivity, validated its application in both flexible and rigid pavements, and exploreed its WIM accuracy in 1997 [66]; finally they deployed the designed fiber optic traffic sensor in monitoring system for traffic classification and WIM system in 2000 [67]. Since June 2008, an in situ measuring station has been used in Lenzburg, Switzerland [68]. This measuring station includes Weigh-in-Motion sensors, Stress-in-Motion sensors, temperature sensors and acceleration sensors, and serves as a useful tool for both the statistical assessment of traffic and the loading condition of the pavement.

Summarized Development of Monitoring System in Pavement

Pavement monitoring is very important to transportation management, and has been a hotspot of transportation research since the middle of 20th century. The broad concept of pavement monitoring includes pavement assessment (monitoring with low frequency) and in-situ pavement monitoring.

For pavement assessments, the surface conditions of pavement (cracking and deflection) are measured to evaluate its performance. Lots of sensing and measuring technologies have been developed to replace the traditional visual and manual methods.

In-situ pavement monitoring means obtaining the pavement responses via the sensing devices fixed in/around pavement, and realizes the timing flexibility of data collection. The sensing devices installed in pavement can be categorized into electromagnetic and fiber optic sensors according to their signal transferred, and both of them have been well studied on sensitivity, functionality, scale, survival rate and resistance to harsh environment. As a result, pavement monitoring system has been improved on accuracy, scale, lasting, comprehensiveness, and other factors.

Table 1. Summary of Recent Development in Monitoring Systems in/for Pavement.

Purpose of Monitoring System	Year	Authors/ Infrastructure	Measurement	Sensing Type	Sensors	Special Technology or Advantage
Pavement Health Status	1946 [29]	Rollings and Pittman	Strain	EM	Strain Gage	Full-scale, Accelerated Traffic Tests
	1991 [17]	Sebaaly *et al*.	Stress; Deflection; Strain; Temperature; Moisture; Vehicle Location	EM		
	1994 [31]	MnRoad, Minnesota	Stress, Strain, Applied Loading	EM	WIM Devices, Temperature, Moisture, Thermal Strain Sensors	Both Rigid and Flexible Pavements
	1995 [18]	Sebaaly *et al*.	Strain	EM	Strain Gage	Hall-effect Gage
	1995 [25]	Signore and Roesler	Strain	FO		Laboratory Test
	1997 [20]	US 23 Test Road, Ohio	Strain	EM	Strain Gage	
	1998 [32, 33]	The Virginia Smart Road, Virginia	Stress, Strain, Temperature, Moisture, Frost Penetration	EM	Pressure Cell, Strain Gauges, Thermocouple, Reflectometry and Resistivity Probes	
	2001 [69]	Goncalves *et al*.	Stress	EM	Diaphragm-type Stress Cell	Full-scale, Accelerated Traffic Tests
	2004 [28, 30]	NCAT	Strain, Stress, Moisture and Temperature	EM	Strain Gage, Pressure Cell, Moisture Probes and Thermistor	
	2005 [19]	Huff *et al*.	Digitized Current	EM	Piezoelectric Axle Sensor	
	2005 [26]	Wang and Tang	Strain and Temperature	FO	Fiber Bragg Grating Sensor	Measure Strain and Temperature Simultaneously
	2011 [21]	Lajnef *et al*.	Strain and Temperature	EM	Piezoelectric Transduction	Self-powered Piezo-floating-gate Array
	2012 [27]	Tailai Highway, China	Strain	FO	OFBG	3D Monitoring
Bridge Monitoring	2000 [70]	Tsing Ma Bridge, Kap Shui Mun Bridge and Ting Kau Bridge, Hong Kong	Strain/stress, Displacement, Acceleration, Temperature, wind, Axle load	EM		Wind and Structural Health Monitoring System (WASHMS)
	2000 [37]	Commodore Barry Bridge, New Jersey	Wind, Strain and Acceleration	EM	Strain Gages, Piezoelectric Accelerometers and Ultrasonic Anemometer	
	2006 [71, 72]	Alamosa Canyon Bridge, New Mexico	Acceleration	EM		
	2006 [35]	Geumdang Bridge, Korea	Acceleration	EM	Piezoelectric and Capacitive	Traditional Tethered and Wireless
	2012 [38]	Yeondae Bridge, Korea	Acceleration and Tactility	EM	Capacitive Accelerometer and Piezoelectric Tactile Sensor	Vehicle-bridge Interaction

Table 1. (Continued)

WIM	1986 [44]	Highway 1, Canada	Load, Speed	EM	IRD-WIM-5000 System and Radar	
	1994 [24]	Navarret and Bernabeu	Pressure	FO		Mach-Zehnder Interferometer
	2004 [45]	Yuan *et al*.	Pressure	FO		Michelson Interferometer
	2007 [42]	Cheng *et al*.	Strain	EM	Capacitive Sensor	Light Weight, Small Volume and Portability
	2008 [22]	Malla *et al*.	Load	FO		Two Concentric light Guiding Regions
Vehicle Classification	2001 [53]	Gajda *et al*.	Inductive Voltage	EM	Inductive Loop Detector	Cheap
	2002 [59-61]	Interstate 84 in Oregon	Amplitude of Optical Signal	FO		
	2003 [56]	Interstate 710 in California	Traffic Volume, Vehicle Length and Speed	Em	Single Inductive Loop Detector	
	2009 [54]	I-70 and I-71, OHIO	Inductive Voltage	EM	Single-loop, Dual-loop and Piezoelectric Detector	
Integrated Traffic Data Collection	2000 [64-67]	Cosentino and Grossman	WIM; Vehicle Classification	FO	Fiber Optic Traffic Sensor (FOTS)	Microbend Fiber-optic Sensing Technology
	1988 [63]	Florida	WIM and Vehicle Classification	EM	Piezoelectric Sensor, loop Detector, and Bending Plate	More than 300 Continuous Monitoring Sites
	2008 [68]	A1 motorway, Switzerland	Vehicle Weight, Traffic Classification, Temperature, Acceleration	EM	WIM, Stress-in-Motion, Temperature and Acceleration Sensor	Footprint Measuring Station
	2008 [50, 62]	Zhang *et al*.	WIM and Vehicle Classification	EM	Strip Strain Sensor	Simple and Efficient

Other related monitoring systems, such as bridge monitoring, Weigh-in-Motion (WIM), traffic classification systems, are also described and reviewed. They can be integrated with pavement monitoring conveniently because of their similar structure and function, and tremendous potential benefit can be expected.

As a summary of the review, the described developments of in situ pavement monitoring systems, and other monitoring systems which can be integrated with pavement monitoring system are tabulated into Table 1.

Future Trends

Currently, an integrated transportation monitoring system is under development in Virginia Tech Transportation Institute, which is funded by the collaborative project “Integrated Infrastructure Asset Monitoring Assessment and Management”. This project would investigate the feasibility and potential benefits of the integration of infrastructure monitoring systems into transportation management system.

This in situ monitoring system is located on Route 114 of Virginia in Christiansburg, Virginia. The instrumentation was devised to provide pavement responses of strain, stress, temperature and moisture in the asphalt concrete layer. The gauges selected include CTL horizontal and vertical strain gages, pressure gauge, thermocouple and moisture probe. The installation was assigned in the gap of an overlay project of VDOT. Wireless nodes, wired with installed sensors, are positioned by the side of the pavement to send the signal to the computer nearby.

Up to now, the design, installation, preliminary calibration of the monitoring system has been finished. Some experiments have been done to develop the back calculation methodology. The purpose of this transportation monitoring system is to monitor both traffic and pavement conditions. When finished, it will serve as a Weigh-in-Motion system and traffic classification system in addition to collecting the mechanical response and monitoring the health status of the pavement. A novel back calculation method based on a distribution model will be present for estimating a vehicle’s speed, wandering, number of axles, distance between axles, distance between wheels, and axle weights.

The VTTI research project represents future trends including the following:

1. Integrated pavement response and condition monitoring with traffic information monitoring;
2. Integration of multiple types of sensors for different variables;

3. Integrated advanced computational modeling for accurate parameter estimation;
4. Wireless and self-powered data transmissions.

In addition, the ruggedness of integrated sensor systems, improved installation procedures, and integrated data-collection and analysis packaging will continue to be the major focus of research and economic and feasible monitoring systems for large scope deployment will be become feasible in the next decade.

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