

# PAVEMENT SENSING SYSTEMS : LITERATURE REVIEW

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## Abstract

In situ monitoring of pavement health has been getting much attention due to the efficiency, reliability and accuracy of data. This review consists of various embedded as well as nondestructive sensing options that have been used to perform analysis on pavement health either by simply calculating horizontal and vertical strains under pavement layers or by crack detection models inside pavement structures by supplementing information from moisture, temperature and traffic related sensors. With optimum integration of such combination sensors, engineers can predict the optimum rehabilitation time of the pavements and reduce a huge amount of budget spent on infrastructure reconstruction.

## Keywords:

Sensing technologies;  
Pavement health monitoring;  
Embedded sensors;  
Pavement rehabilitation;  
Sensors.

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## 1 Approach and organization of literature review

Literature review has been conducted on a semi systematic approach. Entire review is based on published studies in English language consisting of handbooks, original research articles from journals, conference papers and scientific reports. Documents were searched using search strings on various journal web pages and by citation chasing. Each identified literature was read in full and useful information from each source was gathered and compiled. Keywords were identified based on the type of literature required. Since this literature review deals with introduction of sensors and their applications in road infrastructure, the keywords specifically related to types of sensors such as electromagnetic sensors, optical fiber sensors etc were used for the classification part.

Although the sensing technologies mentioned in this literature are not limited to their application in road infrastructure, most of these technologies are being used in the fields of medicine, electronics, structural engineering and mechanical engineering. Therefore, search filters were used to only get information about the sensing technologies that are related to road pavements. Keywords were used to get the information about the sensors based on their nature of use such as for deflection measurement, temperature measurement etc for the classification part. For performing a review on practical application on these sensors, keywords were selected based on nature of use of these sensors such as damage detection, stress and strain analysis, temperature detection etc. It was important in this review to obtain the latest bibliography for each of the mentioned sensing technology. Moreover, bibliography was compiled by selecting the most cited original research papers mentioned in the literature. The entire bibliography has been compiled based on the usage of each type of sensing technology in a chronological order and then a whole summary of literature related to sensing technologies is provided in the Summary section. The organizational chart for classification and practical application of sensors is shown in Fig. 1.

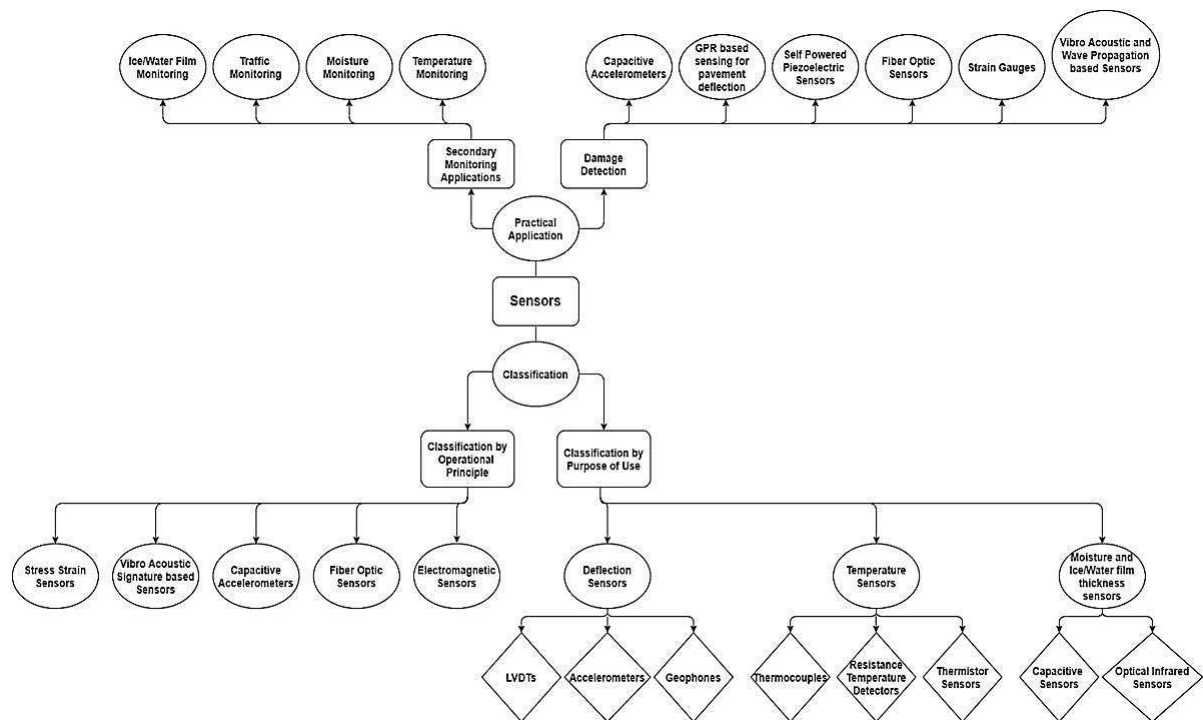


Fig.1: Organization of classification of sensors.

**2 Introduction**

The life expectancy of asphalt pavement is governed by two factors: construction design and material stability [1]. Since the asphalt mixture contains some volatile compounds that weather by time, it is essential to monitor the condition and health of an asphalt pavement before it gets too costly to rehabilitate the pavement structure. Early repair and maintenance scheduling can increase the in-service performance of the pavement [2]. Usually, sensors are employed on behalf of the, Pavement Management System (PMS) which aids in predicting the remaining service life of the pavement under traffic loading and climatic conditions. Monitoring the pavement condition using sensors is considered a proactive approach unlike the reactive approach that usually consists of manual distress surveys or automated monitoring using specially equipped vehicles [3].

Repeated tensile and compressive strains can lead to development of fatigue cracking and rutting respectively. The most common method used to evaluate pavement response is through strain measurements. Measurements can be obtained through different layers of the pavement structure. Prediction of fatigue cracking or rutting can be performed by collected the strain measurements in pavement overtime [4].

Sensors embedded in the pavement structure measure the pavement response such as stress, strain, deflection and temperature. Roads embedded with sensors and intelligent communication systems are also termed as Smart Roads [5]. In such case, a smart road consisting of in situ sensors can improve service life, quality and performance of the pavement by continuously measuring pavement response. The options for different available sensors are pressure cell, deflectometer, strain gauge, thermocouple, moisture sensor and fiber-optic sensors.

The sensor system consisting of three main elements: sensing devices integrated with data acquisition system, post treatment of sensor output data, and reproduction of obtained data in understandable pavement response terminologies depicting the remaining pavement life and excess of repair needed for rehabilitation procedures [6].

Development of a sensor monitoring system can be challenging especially when selecting the type, layout and quantity of sensors to be used since they vary based on type of measurement required [7]. The recommended size of the sensor or the sensitive element should be 2 - 3 times the size of the surrounding pavement material and the tensile and compressive strength of strain gauges should be lower than that of surrounding pavement material for sufficient deformation of the gauge [8].

### 3 Sensors

A sensor is a device that responds to an input physical property and converts it into an electrical signal. The output of signal of the sensor can be in form of voltage, current or charge [9]. The sensors can be of two types, passive or active. A passive sensor doesn't any external energy source and operates under the input activity thereby generating a signal. Examples of passive sensors are thermocouples, photodiodes and piezoelectric sensors. An active sensor requires an external power source for operation called excitation signal. The sensors give response to the excitation signal thereby converting it into an output signal. Example is a resistive strain gauge, in which electrical resistance is used to calculate the strain and in order to measure resistance of the sensor, an electrical current from external power source is applied.

### 4 Classification by operational principle

Working principle of sensors changes with the application they are used for. With the development of various sensing technologies, sensors are selected based on their operational principle. Sensing technologies take time to evolve, thus this section mentions different sensing technologies that have progressed through time. For instance, earlier sensing technologies started with the use of electromagnetic and vibroacoustic sensors. For higher speed and accuracy in data collection, optical fiber sensors have been introduced specifically for rutting progression in pavements. Nowadays, the self-powered piezoelectric sensors are being coupled with stress strain gauges and accelerometers for independent and continuous data collection for extended period of time in the pavement structure.

#### 4.1 Electromagnetic sensors

These sensors are being used in pavement monitoring since the 90's. Pavement monitoring using thermocouple, strain gauge, pressure cell, deflectometer and transverse vehicle location sensor have been used by Seebaly et al. [10]. Later a hall effect sensor in a famous H-gage configuration has been used by Seebaly et al. [11]. SPS-8 type electromagnetic sensors have been used by Xue and Weaver [12], in determining the pavement response by using a wide base tire in Ohio SHRP U.S 23 test road. Self-powered piezoelectric sensors developed for measuring strain and temperature values have been used successfully by Lajnef et al. [3].

#### 4.2 Optical fiber sensors

Optical fiber sensors usually consist of a sensing element composed of a lighting source to which the optical fiber is connected. Fiber optic sensor can provide in detail pavement response due to their small size, flexibility, immunity and high sensitivity to electromagnetic interference as well as high precision strain measurement of upto  $\pm 1\mu\epsilon$  [13]. Fiber optic sensors can be used as discrete, quasidistributed and distributed sensors. Ferby Peot interferometer usually performs the discrete measurements and there are low semi reflecting parallel mirrors placed at a distance in FP sensor [14].

For quasi distributed measurements, Fiber Bragg grating (FB) is used. Usually, the variations in reflective index of small portions of an optical fiber through an intense ultraviolet source are given, forming an interference pattern, thereby producing the FB interference pattern [15]. FBG is a small portion of an optical fiber several millimeters long in which a diffraction grating is written by ultraviolet (UV) exposure [16]. This pattern is an induction of reflection of a particular wavelength called Bragg wavelength. FBG sensors have been used strain and temperature and strain sensors, rutting performance, response of flexible pavement and weight in motion types. Two principles are used for strain sensing measurements: the Rayleigh scattering effect and Brillouin scattering effect. Usually, the relationship between measured strain and optical properties are different for both cases; however the Brillouin is strain and temperature dependent, hence strain measurement must be modified for correction to temperature values [17].

#### 4.3 Capacitive accelerometers

Capacitive accelerometers are the sensing devices that come under the category of accelerometers that operate on a force to mass relationship. Capacitive accelerometers consist of capacitive sensing materials that change an induced acceleration into electrical capacitance [18]. A

capacitive accelerometer determines the acceleration experienced by the sensor by measuring displacement of proof mass with respect to accelerometer housing [19]. These accelerometers can not only measure constant but also a slow gradual increase in acceleration. Two basic components of capacitive accelerometer include a primary or a stationary plate that is connected to housing and a secondary plate that is attached to inertial mass and is connected to the housing. Hence a capacitor is formed by these plates and its value is a function of distance  $d$  between the plates as shown in Fig. 2.

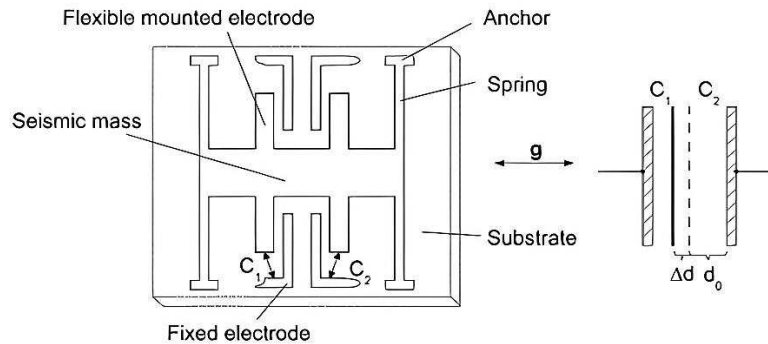


Fig. 2: Principle of capacitive accelerometers. Taken from Busching et al. [21].

The sensing material used can be a nickel plate or an electronic chip. As the acceleration takes place the signal is proportionally measured to the occurring displacement as a result of uniform acceleration. Maximum displacement for a capacitive accelerometer is 20  $\mu\text{m}$ . Capacitive accelerometers are used for large structures, consumer electronics and automobiles due to their ability to measure around wide frequency range and with better stability, sensitivity, resolution, temperature performance and low fabrication costs [20].

#### 4.4 Self-powered piezoelectric sensors

With recent developments in sensing technologies self-powered piezoelectric sensors are getting further improvements regarding their stability and sensitivity characteristics. Piezometric sensors work on a principle of converting the oscillating mechanical energy into electrical energy [21]. They usually consist of nanogenerators that upon excitation would produce an output voltage that can easily be recorded by a specific receiver. In the sensing system, one of the major components used is a piezoelectric transducer which consists of commercial lead zirconate titanate. Piezoelectric transducer is responsible for inducing the sensing signal that is responsible for generating the electrical energy. Other than the use of piezoelectric transducers, other forms of energy harvesting for piezoelectric sensors include heal strike system that consist of a heals strike generator and a power electronics circuit developed by Howells [21]. Moreover, the self-powered piezoelectric sensors are also composed of pressure sensors based on piezoelectric nanogenerators (PENGs) and polyvinylidene fluoride (PVDF) that consists of the use of single electrode used for mitigating the short circuit problems as developed by Liu et al. [22].

Most of the self-powered piezoelectric sensors have been designed to be used as embedded sensors in pavements in order to monitor pavement health. As the vehicle passes over the pavement, mechanical energy is induced, that energy can be used by a piezoelectric transducer to convert it into electric energy. Hence the basic purpose of piezoelectric transducers is to harvest electrical energy as a result of piezoelectric effect [23] applied as shown in Fig. 3. In this case, the electrical energy inside the material changes with the amount of stress applied.

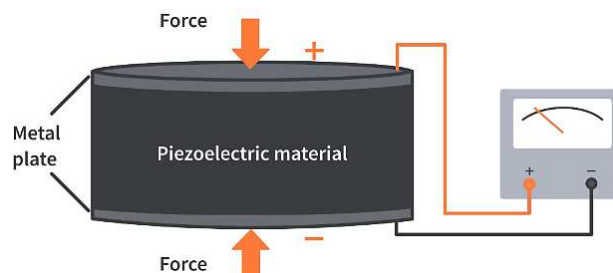


Fig. 3: A schematic of piezoelectric system. Source: Xiao et al. [23]

The positive piezoelectric effect excites the charge on the surface of the piezoelectric material by mechanical external forces, and the charge could be stored and utilized by the energy storage device. Piezoelectric signal crystals, polycrystals and polymers are some of the conventional piezoelectric materials having a piezoelectric effect. When the piezoelectric transducer is deformed by external force, the electric dipole moment inside the material becomes shorter due to compression.

In order to harvest energy in a controlled fashion, a charge storage unit is used that is usually an aluminum electrolytic capacitor (E-CAP) or a super capacitor (SC) with large capacity. The sensor is embedded in the asphalt concrete to measure the data, the use of piezoelectric transducers to the system power supply, wireless sensing module to send sensor data to the host computer, to detect the asphalt temperature and humidity or other information, in order to carry out data collection as shown in Fig. 4.

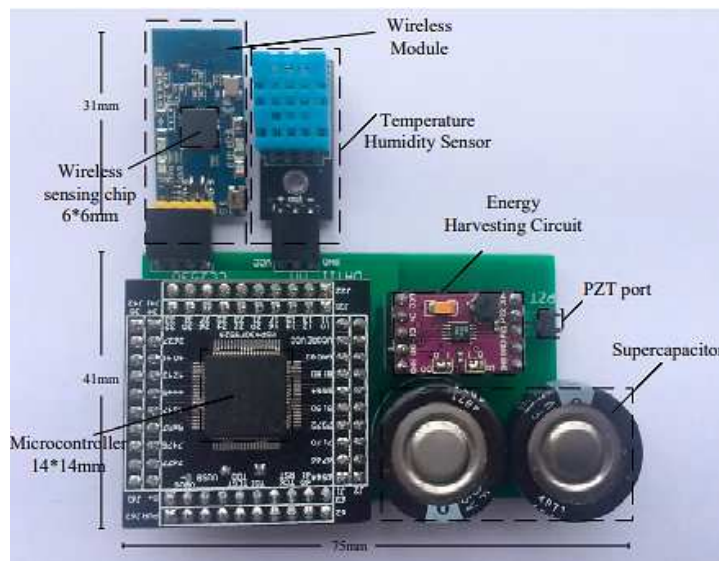


Fig. 4: Typical self-powered piezoelectric sensor setup. Taken from Xiao et al. [23]

**4.5 Vibroacoustic signature sensors**

Acoustic signature sensors provide a nondestructive methodology for monitoring pavement health. These sensors work on the principle of measuring the modulation of an ultrasonic wave by low-frequency vibration by a method know as nonlinear wave modulation spectroscopy (NWMS) [24]. These sensors are ideal for located and determine the severity of cracks in the structures. As shown in the Fig. 5, when the structure is excited with a low-frequency vibration, a sinusoidal signal changes the width of the crack depending on the phase of the vibration.

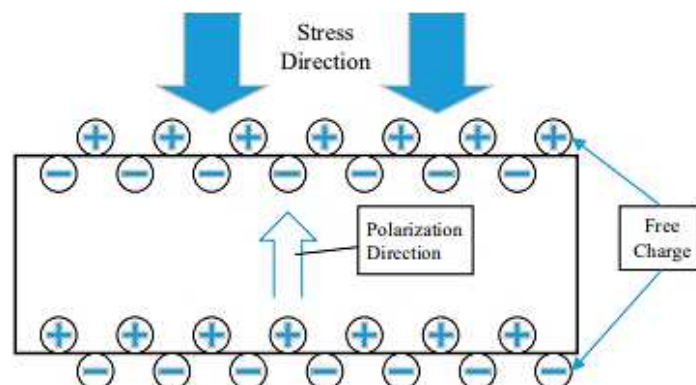


Fig. 5: a) Material with a crack closed and open under vibration and b) amplitude modulation of probe signal: i) vibration and ii) ultrasonic signal. Taken from Meo [25].

Vibroacoustic signal methodology is related to measurement of non-linearity defects in the structures. Vibroacoustic signature is a terminology related to measure the acoustic response of pavements to loading. In this case a road pavement is considered as a filter of acoustic waves. A

mechanical source is used to generate these waves by using the vehicular traffic and a microphone that is isolated from the airborne noise can be used to receive the signals [25]. The collected data consisting of acoustic responses of road pavements to the vehicular loads is shown in Fig. 6. The propagation of these acoustic signals justifies the structural health of pavement to be better or worse.

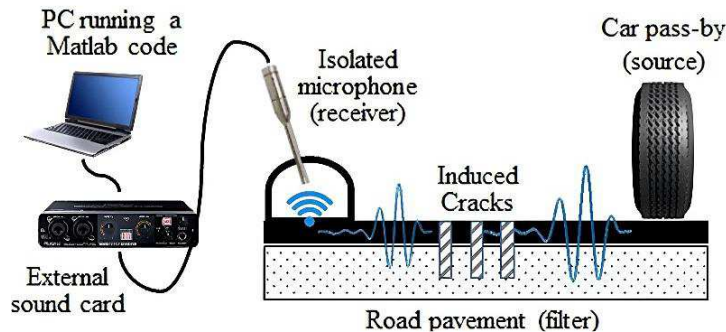


Fig. 6: Acoustic system setup. Taken from Pratico et al. [26].

Wave propagation depends on different parameters, such as the elastic modulus that in turns is affected by the temperature, the distance source – receiver (geometric damping), the material damping (related to the properties of the material and the vibration amplitude), the boundary conditions, and the occurrence of concealed distresses [26].

Hence this method can be used to classify the structural health of pavement by detecting the cracks generated by traffic as well as thermal cracks hidden inside the pavement structure [27]. Moreover, the power spectrum of acoustic signal depends on factors such as experimental setup and sampling used [28]. In case of experimental setup used, the distance between the impulse generator and acoustic receiver can highly affect the magnitude of power spectrum. Vibroacoustic signatures can be induced by two different mechanical sources:

- 1) controlled mechanical source that usually consist of a falling weight deflectometer,
- 2) uncontrolled source which consist of random vehicular traffic.

#### 4.6 Stress/strain sensors

Strain gauges and piezoelectric sensors come under the category of force sensors and transducers [29]. Force sensors can be divided into two classes: qualitative and quantitative. Force is measured in quantitative sensors and output is presented in the form of electrical signals. Examples are strain gauges and load cells. Qualitative sensors are threshold devices that indicate whether a sufficiently strong force is applied or not. The output signal usually indicates a force magnitude exceeding a predetermined threshold level. These sensors are used for detection of motion and position.

Strain gauges measure the deformation of elastic body under applied force. Hence strain gauge is a resistive elastic sensor and the resistance here is the function of applied strain. In this case, resistance can be related to applied force, and such relationship is termed as piezoresistive effect. Equation (1) shows the relationship that is expressed through the gauge factor  $S_e$  of the conductor and  $e$  as a resulting strain.

$$\frac{dR}{R} = S_e e . \quad (1)$$

For small variations in resistance not exceeding 2 % (which is usually the case), the resistance of the metallic wire can be approximated by a linear equation (2).

$$R = R_0(1 + x), \quad (2)$$

where  $R_0$  is the resistance with no stress applied,  $x = S_e e$ ,  $S_e$  is the measured strain,  $e$  is the constant.

Resistance decreases with compression and increases with tension Strain gauge acts like a resistive sensor having a fine wire and a semiconductor element bonded to an insulating base. When the sensor is strained, the wire or a semiconductor element would experience change in resistance proportional to the strain applied. In order to measure the resistance change, a bridge circuit is used. An individual strain gauge can measure up to 0.1 mm of displacement however when modified using

extensometers with a case of clip gauges, the bending beam mechanism is introduced hence the displacement measured capacity exceeds up to  $250\ \mu\text{m}$  [9]. Most commonly used sensors are strain gauge-based load cells with their primary applications in weighing industry. It consists of a metal foil strain gauge which is bonded to beam and would deform under force. Accuracy of these sensors is around 0.03 % to 1 % [30].

Strain gauges as horizontal asphalt strain gauges or vertical asphalt strain gauges. H-gauges measure the horizontal strain under the pavement layers as a result of dynamic loading. This shape of sensor housing allows the sensor to be embedded within the aggregates providing enough stability against vibration. Sensor itself is located in the middle part of the strain gauge as shown in Fig. 7.

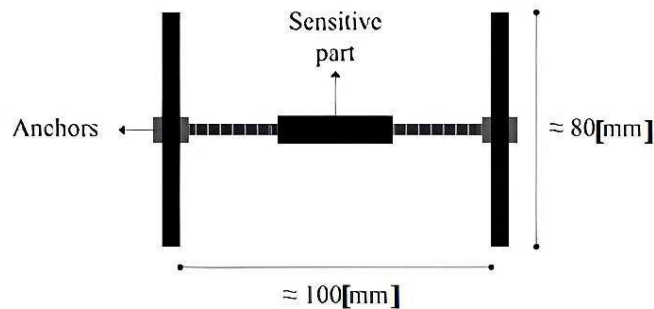


Fig. 7: Schematics of an H-Gauge. Taken from Naverrete et al. [32].

These strain gauges are usually placed under the asphalt layers where high tensile strains are measured for fatigue analysis. Commercially available strain gauges are often covered by protective layers to withstand high temperature, compaction loads and water penetration. Measurements with sensitivity up to  $\pm 1\ \mu\epsilon$  can be obtained with these strain gauges.

Vertical strain gauges have a vertical part that is secured by two circular plates. The sensor is kept in position by the bottom plate while the top plate uniformly transfers the load to central bar. A positioning needle or stake is also included at the bottom of gauge for insertion and fixation in the bottom layer as shown in Fig. 8.

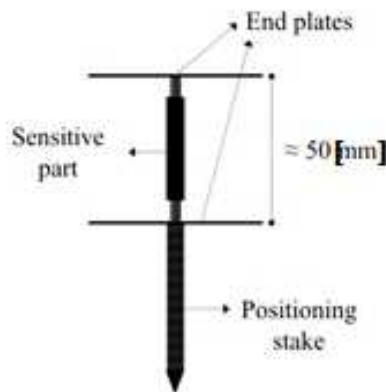


Fig. 8: Schematics of a vertical strain gauge. Taken from Naverrete et al. [32].

Installation of this sensor is accomplished by drilling a hole for the positioning stake and later filling up the hole with sand binder filler. The strain gauge is then pressed into the layer until the bottom plate is flush to the surface. Later on, the end plate is installed after asphalt has been placed in between the two plates. It has been found that vertical strain gauges have a lower survival rate than that of H-gauges.

#### 4.7 Pressure cells

Pressure cells can be used for compressive stress evaluation of the pavement. Most commonly used pressure cells are Hydraulic and Diaphragm pressure cells. Hydraulic pressure cells consist of two steel plates having a cavity in between them which is filled with liquid. The induced pressure on the liquid is measured by strain gauges and is related to the applied load in diaphragm cells a strain gauge is used to measure deflection of the diaphragm that is supported by a stiff ring.

## 5 Classification by purpose of use

### 5.1 Deflection sensors

Deflection measurements can be used to calculate pavement layer stiffness and subgrade resilient modulus. Although the most common practice to evaluate deflection properties is by using a Falling Weight Deflectometer (FWD), sensing devices such as Linear Variable Displacement Transducer (LVDTs), accelerometers and Geophones can be used to measure such variables.

#### 5.1.1 LVDTs

LVDTs can measure the vertical deflection of the pavement. LVDTs convert the mechanical displacements into output voltage. Deflectometers can be single layered (SLD) that can measure deflection at one layer of the pavement structure or Multi-Layer Deflectometers (MDD) that can measure deflection at various points of the pavement structure. Installation is done by drilling a hole, placing the sensor and sealing the hole, laying and compacting the asphalt before fixing the upper plate [31]. The accuracy of measurement using LVDTs is high since they have an infinite resolution.

#### 5.1.2 Accelerometers

Accelerometers convert acceleration into force by using the mass of an element. It basically measures the velocity change. Accelerometers consist of a force/displacement sensing element, inertial mass and a damping element. Whenever the acceleration is applied, there will be an increase in displacement of the inertial mass, when the acceleration is applied to a force sensing element, the amount of force applied will increase with respect to the acceleration applied [31].

Accelerometers can be piezoelectric also since they consist of a piezoelectric crystal (e.g. like quartz), which sets in between the seismic mass and the sensor housing. The effect is direct conversion of mechanical energy into electrical energy [9]. When the inertial mass is accelerated, it would generate a force on the crystal inducing a charge which can be detected by a charge amplifier as shown in Fig. 9.

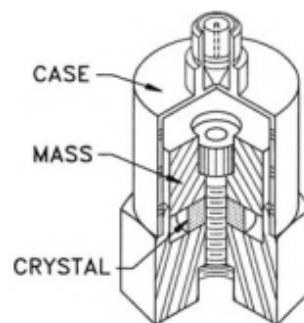


Fig. 9: A basic schematic representation of a compression mode piezoelectric accelerometer. Acceleration of the case moves it relative to the mass, which exerts a force on the crystal. The output is directly proportional to the acceleration or vibration level.

Piezoelectric accelerometers operate within a frequency range of 0.1 Hz to 20 kHz. Piezoelectric sensors basically use the piezoelectric of sensing elements to predict an output charge which means that the charge generated from piezoelectric crystal is amplified into output voltage signal. Naturally occurring substances such as barium titanate, single-crystal quartz, and lead zirconatetitanate (PZT) and synthetic piezoelectric substances such as ceramics are used in piezoelectric sensors since they generate an electrical charge when subjected to mechanical stress or strain. Such piezoelectric effect can be found in touch screens of computer monitors and the piezoelectric sensors are considered self-generating since they do not require any external power to operate [6, 32].

#### 5.1.3 Geophones

Geophones just like accelerometers perform by measuring the displacement velocity of pavement under loading. Whenever the signal is integrated, the deflection response can be obtained.

Whenever the geophone is moved it creates a relative movement between coil and a magnet as shown in Fig. 10, hence the voltage is induced in the coil that is related to the displacement velocity of the spring [32].

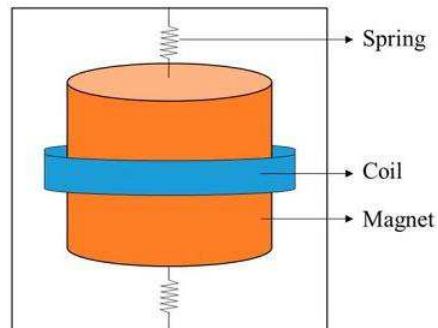


Fig. 10: Schematic of a Geophone. Taken from Liu et al. [34].

Both geophones and accelerometers do not need any reference point, hence they can be installed at any depth in the pavement.

## 5.2 Temperature sensors

Whenever the pavement is loaded the response usually depends on time and temperature [33]. Therefore, in most cases strain and displacement measurement are combined with temperature measurement for accurate understanding of pavement behavior under various traffic loading and climatic conditions. Therefore, there is a need to use temperature sensing devices for temperature detection of the pavement.

### 5.2.1 Thermocouples

Thermocouples are the most commonly used temperature sensors in the pavement. Thermocouples work on a principle of Seebeck effect in which a small voltage is generated due to the junction of two dissimilar metals; the voltage usually varies with temperature. Different types of thermocouples such as K, E or T can be used for various temperature ranges as shown in Fig. 11. Accuracy of thermocouples ranges from 0.5 to 5 °C.



Fig. 11: AK probe thermocouple. Taken from Benedetto et al. [35].

### 5.2.2 Resistance temperature detectors

Temperature sensitive resistors consist of a fine wire (platinum, copper or nickel) wrapped around a ceramic core. Various temperature ranges can be covered depending on the type of wire used. RTDs are more accurate than Thermocouples having accuracy of 0.1 to 1°C.

### 5.2.3 Thermistor sensors

Thermistor sensors have resistance that is temperature dependent. The operating temperature is small but measurements are accurate than previously mentioned temperature sensors from 0.05 to 1.5 °C [34].

## 5.3 Moisture/water film/Ice film sensors

### 5.3.1 Capacitive sensors

Capacitive sensors have been used to measure the moisture content as well as depth of water/ice film thickness in pavement [35, 36]. Capacitive sensors consist of two electrodes and a

dielectric. A high frequency electromagnetic pulse (50 MHz to 150 MHz) is applied to the electrodes which provide resonant frequency. Thereby a capacitance field is generated to between two electrodes of each sensor. With proper calibration, capacitance sensors can measure moisture content with higher accuracy [37]. Capacitive sensors calculate value of the electrode assembly based on geometric configuration and dimension of surface of electrodes [35]. The sensor developed for determining ice film thickness is shown in Fig. 12, which consists of pair of conductive electrodes, a frequency generator and a charge generator.



Fig. 12: A typical ice sensor. Taken from Troiano et al. [37].

### 5.3.2 Optical infrared sensors

Optical infrared spectroscopy-based sensors have also been used to detect water/ice film thickness. An example of such technology is a Luft MARWIS mobile sensor. That can measure road surface temperature, water film height, dew point temperature, road conditions (including dry, moist, wet, chemically wet, snow, or ice), ice percentage, friction, and relative humidity above the road surface. As shown in Fig. 13, the four emitting and two receiving diodes capture the reflecting behavior of the road surface at varying wavelengths.



Fig. 13: MARWIS components. Taken from Fay et al. [40].



Fig. 14: Mounted RCM411 sensor. Taken from Fay et al. [40].

These sensors are mounted on moving vehicles. The collated information be viewed by a smart mobile phone device using the built-in application. Optical remote sensing technique based on sensing the optical reflection signal from pavement's surface has also been employed using the Teconer RCM411 sensor. It can provide real-time information on road surface conditions such as dry, moist, wet, slushy, snowy, or icy road surfaces and water thickness of friction. This sensor is usually mounted on the rear side of the vehicle having a measurement height of 56 cm as shown in Fig. 14. This sensor can be connected via Bluetooth with smart phones using the built-in application for accessing recorded information.

### 5.4 Sensor arrangements

Wireless Sensor Network is composed of a large number of sensor nodes embedded in an extended area of the pavement. Currently most research effort is subjected to designing of the sensors rather optimizing the network for better sensing capability [38]. WSNs should be able to produce maximum amount of information with minimum loss of accuracy. The idea is to install the sensor closer to the area prone to damaging rather than embedded too many sensors that make the collected data render unreliable results.

Whenever a series of various sensors are embedded in the pavement, it is important to improve energy consumption and combine the processed data efficiently whenever a large-scale sensor

network is used. Ye et al. [39] has proposed a novel communication setup termed as strip clustering scheme, (SCS) for data collection. The networks can be divided into several strip shaped regions having a cluster head node in each region and data is transferred from a non-head node to a head node simultaneously. The data fusion takes place towards a higher-level cluster head node thereby increasing the monitored area which is ideal for network expansion.

For optimum deployment of sensors and optimization of sensor nodes, Khamlichi et al. [40] has proposed an optimization method to achieve a larger coverage area with minimum amount of sensors. Optimization is developed by combining the gradient method and simulated annealing algorithm. If the information from nearby sensors is missing, then a solution termed as Group Effect has been introduced by Alavi et al. [41]. Rhimi et al. [42] has used a probabilistic approach to gather information from the missing sensor location by using a Kriging estimation technique which works by estimating the attribute value of unobserved position by interpolating the known values.

## 6 Practical usage of sensing technologies

Practical usage of sensors has been divided into two categories:

- 1) damage detection,
- 2) secondary applications.

The damage detection part is further divided by nature of sensing technologies used since the majority of research performed is based on evaluation of pavement structural health.

### 6.1 Damage detection

Damage detection component deals with the research performed for evaluating permanent deformation, stress accumulation, pavement response to loading and crack propagation in pavements using sensing technologies.

#### 6.1.1 Capacitive accelerometers

Arraigada et al. [43] has employed the use of high-resolution capacitive accelerometers to determine pavement deflection using numerical double integration in a full scale Circular Pavement Test Track (CPTT). Under normal traffic, pavement and environmental conditions, road deflections are very small [44]. Frequency contents range from zero Hz for permanent deformations up to a few tenths of Hz. The combination of small and low frequency deflections results in a very low acceleration.

In this research improved correction algorithm has been developed to correct the baseline drift for accurate measurements. The CPTT consists of three arms with loaded tires and then accelerometers PCB Piezoelectronics series 3700 are installed in an asphalt pavement having a thickness of 290 mm. The sensors are placed at a depth of 40 mm in a 50 mm deep hole as shown in Fig. 15. The sampling rate in this test is 200 Hz. Each acceleration record is composed of 10000 samples.

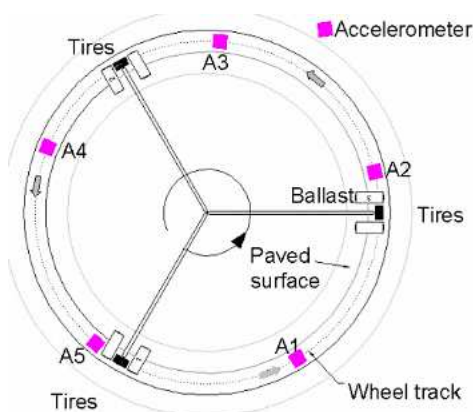


Fig. 15: Schematic of the CPTT showing the 3 arms with their tires and pavement sections from A1 to A5. Taken from Arraigada et al. [46]

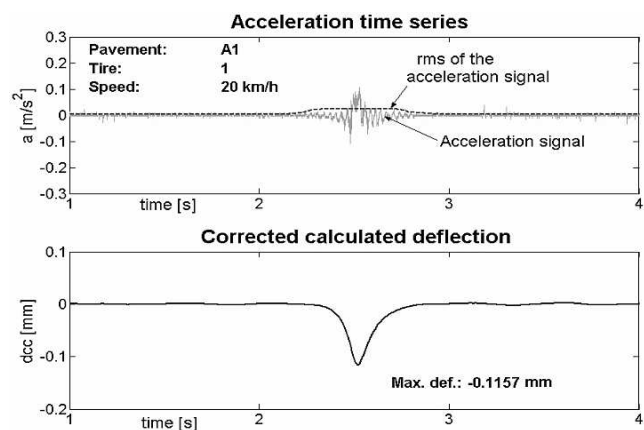


Fig. 116: Acceleration time graph. Taken from Arraigada et al. [46].

**Chyba! Nenašiel sa žiaden zdroj odkazov.** Fig. 16 shows the acceleration time series graph and the corrected calculated reflection using improved baseline correction method. The amplitude and size of the calculated deflection time history indicate a relation to the speed of the tire; when the speed is higher the deflection lasts less and the maximum deformation is smaller.

Lee et al. [45] incorporated the use of accelerometers and smartphone camera to detect the surface anomalies on pavement surface by mounting it on a moving vehicle. The acceleration data was collected in 3 axis mode and the vertical acceleration data was used to compile the histograms that showed the trends in road surface anomalies with variation in magnitude of vertical acceleration values on the moving vehicle. Using vertical or three axis accelerometers that have been correlated to vibration-based detection method where the accelerometers measure the variation in vibrations on the mounted vehicle rather than embedding them in the pavement. Data acquisition was made possible by using an image recognition software in the smart phone that used a convolutional neural network (FCN). Images were collected at a frequency of 3 Hz and the data from accelerometer was obtained in 3s intervals at 100 Hz. A total of 1959 images were used in this study. The FCN was further trained using adaptive moment estimation (ADAM). Fig. 17 shows the detected anomaly as in case of a manhole.

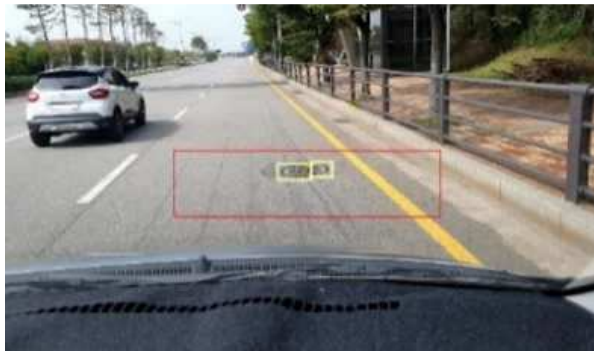


Fig. 17: Detected anomaly by the smartphone. Taken from Lee et al. [48].

Results showed that the variations in vertical accelerations were less than  $2 \text{ m/s}^2$  in the absence of surface anomalies while in the presence of surface anomalies the variations in vertical accelerations were greater than  $2 \text{ m/s}^2$ . Potholes and repaired road surface showed the maximum variations in vertical accelerations; hence this method could be used as a cost-effective alternative for detecting road surface anomalies.

### 6.1.2 Self-powered piezoelectric sensors

Piezoelectric axle sensors have been used by Huff et al. [2] to determine the dynamic pavement deflection data under commercial truck loads. It has been mentioned that data from certain piezoelectric sensors and configurations could potentially predict deflection characteristics of a typical flexible pavement system. Piezoelectric sensor output responses were superimposed on the Benkelman Beam deflection profiles. This research verifies the usage of piezoelectric sensors to determine the in situ primary mechanistic response of pavements [1]. The maximum error was calculated to be 29.7 % and the minimum error was 8.7 %.

Ji et al. [46] has developed a self-powered piezoelectric aggregate based on attenuation principle. Whenever the piezoelectric aggregate is excited by external voltage it starts vibrating according to the inverse piezoelectric effect. The vibration energy is transmitted as sound waves to other pavement particles and other piezoelectric sensors. The other sensors transform the sound waves into varying sinusoidal waveform which can be detected by a signal receiver. The material properties of the pavement, climatic conditions and presence of cracks can affect the sound wave attenuation through the pavement.

Piezoelectric transducer has been used by Lajnef et al. [3] to monitor the strain levels in the pavement. The stored data of the self-powered sensor nodes were subsequently transmitted to the data collector vehicle by radio frequency protocol [31] as shown in Fig. 16.

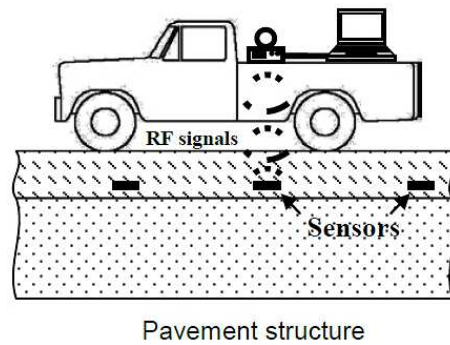


Fig. 18: Array of self-powered sensors capable of monitoring cumulative strain history of the host pavement structure. Taken from Lajnef et al. [3].

Type of piezoelectric transducer is ceramic transducers (CEB-35D26). The elastic modulus of the sensor is  $10.4 \times 10^6$  Pa having an electrical permittivity of  $3500 \epsilon_0$ , length, width and thickness of 1.57, 0.4 and 0.02 mm respectively. Cyclic loading frequency of 1 Hz has been applied with total 2000 to 3000 loading cycles in the field. The piezoelectric transducer in this research has been protected with Araldite® GY-6010 epoxy resin, having an elastic modulus of 300,000 psi as shown in Fig. 19.

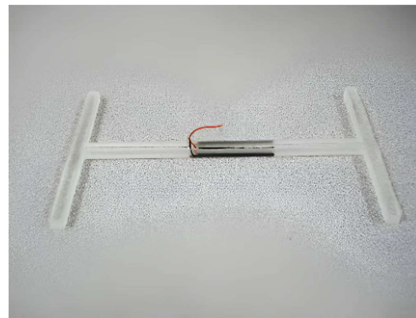


Fig. 19: Piezoelectric transducer embedded in Araldite® GY-6010 epoxy. Taken from Lajnef et al. [3].

Paredes et al. [47] used combination of strain gauges and newly built piezoelectric floating gate (PFG) sensors for determining the environmental friendliness of maintenance activities and to develop optimized maintenance plans. A type KM-100HAS strain gauge was used that was designed to be waterproof and could withstand high temperature and loading. The strain is converted into electric signals that results from the variation in positioning of the flanges and the passage of displacements to the spring. The data can be read out by the data acquisition. In this study a modified piezoelectric sensor termed as piezoelectric floating gate sensor (PFG) was used. The sensor employed the same self-power generation principle using a piezoelectric transducer that consists of a rectangular polyvinyl fluoride film (PVDF) for converting strain into electrical signal. PFG sensor differs from the conventional sensor in such a way that it uses memory cells used for storing successive duration of strain events. An antenna was also attached to the sensor for wireless data communication as shown in Fig. 20.

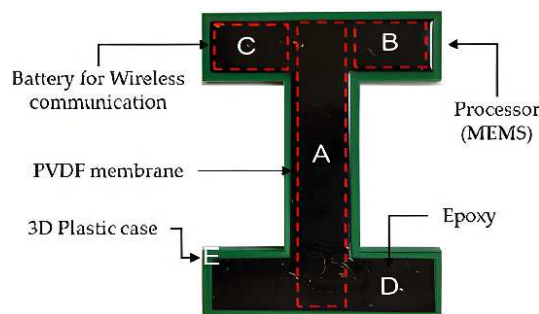


Fig. 20: Piezoelectric floating gate sensor composition with PVDF. Taken from Paredes et al. [50].

The data communication was possible up to maximum vehicle speed of 70 Km/h. the number of load repetitions used were 999,200 and data was recorded by strain gauges and PFG sensors for

every 20,000 load repetitions, at mean vehicle speed of 76 km/h. Results showed that sensors could monitor loadings and detect the weakening of pavement structure for a duration of three months. It was discovered that the drastic increase in pavement distress happened after 600,000 load repetitions. In regards to selection of optimum maintenance strategies, it was found that FBG sensors were able to provide a reliable data stream with better understanding of weakness in pavement's health overtime.

### 6.1.3 Fiber optic sensors

Fiber optic sensors have been used as early as in 1994 by Navarrete et al. [48], in which an interferometry system capable of detecting changes in pressure on fiber has been developed. Signore et al. [49] has used fiber optic sensors to evaluate the lateral strain behavior of an axially loaded emulsified asphalt specimen. Wang et al. [50] has developed a new high resolution fiber Bragg grating sensor consisting of referenced FBG and a pair of fiber gratings capable of measuring strain and temperature values in the pavement structure. The detailed literature of most prominent work in the field of fiber optic sensors has been provided below.

Optical sensors are also used for sensing dynamic strain based on Brillouin Scattering. Brillouin scattering-based distributed sensors can measure strain and temperature distribution over a larger length of the pavement with high resolution. Brillouin Frequency Shift (BFS) is a phenomenon that happens when the frequency of the scattered light is downshifted from that of the incident light, by a quantity equal to the frequency of the acoustic wave, whenever a pump light is injected into an optical fiber.

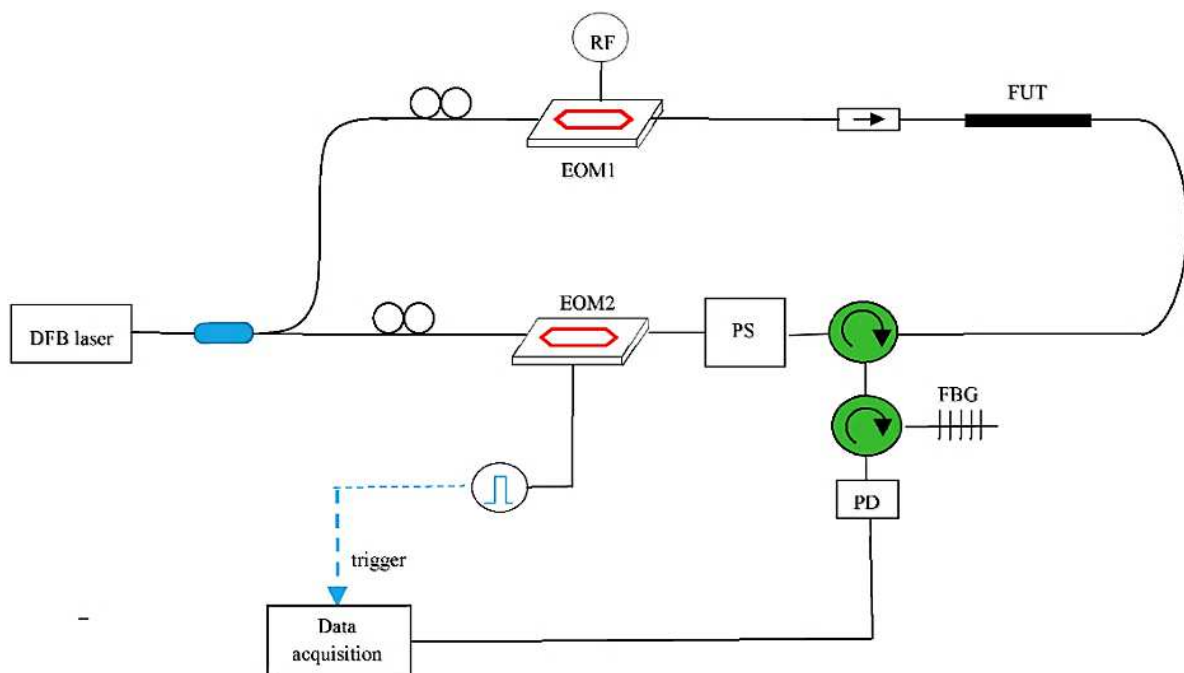


Fig. 212: A typical BOTDA configuration: PS - polarization scrambler, FBG - fiber Bragg grating. Taken from Grellet et al. [53].

Brillouin Optical Time Domain Analysis works on the principle of two counter propagating light waves exchanging energy along the optical fiber and the magnitude of exchanged energy depends on their frequency offset as shown in Fig. 21. The interaction between incident light waves and acoustic phonons in optical fibers generates Brillouin scattered light as backscattered light, which propagates in the opposite direction of the incident light waves [51]. A single laser source (typically, a distributed feedback diode laser), is employed for pump and probe beam generation. The frequency-shifted probe is generated through an electro-optic modulator (EOM1) biased near zero transmission point, driven by a radiofrequency signal to realize a dual sideband modulation.

Mao et al. [51] introduced a monitoring method in which BOTDA has been coupled with and Fiber Bragg grating have been used to monitor concrete expansion and development of cracks as a result of reinforcement corrosion. Expansion of concrete and crack width is measured by BOTDA while

time and position of cracking is measured by FBG [51]. The measured accuracy using BOTDA technique was  $\pm 20 \mu\epsilon$  and the average cracking strain of concrete was around  $\pm 132 \mu\epsilon$ .

Fiber optic strain gauge developed by Rajibul et al. [14] measured the horizontal strain at the bottom of surfacing layers of the pavement. The gauge can be placed into existing pavement layers by drilling a small diameter hole. These sensors have been protected by placing them in a polymeric proof body. Fiber optic sensors in this study have proven to be insensitive against moisture and frost action as well as electromagnetic effects. The diagram of OpSens interferometric fiber optic strain transducer can be seen in Fig. 22. In order to get detailed information of about distribution of BFS along the fiber, modulation of pump light can be performed using BOTDA.

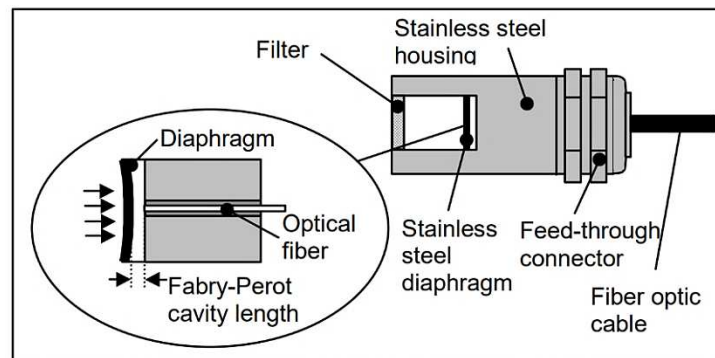


Fig. 22: Strain sensor based on the Fabry-Perot (FP) interferometer. Source: Taken from Rajibul et al. [14]

The sensor is made of two optical fibers that are precisely aligned inside a microcapillary tube to form an optical FP sensing interferometer. This makes the strain gauge completely immune to any electromagnetic interference and completely insensitive to transverse strains and temperature, as opposed to fiber optic Bragg gratings sensors.

Chapeleau et al. [52] employed the Telecom fiber optic cable as a distributed sensor for developing a nondestructive method for crack detection in asphalt pavements at full scale testing facility of French Institute of Science and Technology for Transport, Development and Networks (IFSTTAR), which has a length of 120 m and a width of 6 m. An optical interrogator based on the Rayleigh scattering was used to measure strain profiles. This fiber optic sensor however has some limitations such as maximum sampling frequency of few Hertz. This technique is only useful for measuring the long-term static effects of loading on pavement temperature, not for measurement of dynamic testing on the pavement.

Grellet et al. [53] employed the use of fiber optic strain plate using a polymeric plate technology for measuring strain response as shown in Fig. 23. A total of four tests sections were used and in each test section the plate has been placed perpendicularly to the traffic direction. The system consists of a polyphenylene sulphide (PPS) thin body in which 24 fiber optic strain gauges were embedded and bonded with epoxy. White Light Polarization Interferometry (WLPI) technology has been used for fiber optic strain gauges in which a signal conditioner is used to sense the path length difference inside a FP interferometer of a known cavity length and delimited by two dielectric mirrors.



Fig. 23: Instrumented plate installation at the Federal Aviation Administration (FAA) National Airport Pavement Test Facility (NAPTF) in Atlantic City, New Jersey, USA. Source: Grellet et al. [57].

The determined path length difference can be used to check engineering values such as displacement, stress and strain. To accomplish this task, three signal conditioners equipped with 8 channels were used to collect the data of the 24 gauges on one plate. The signal conditioner sends

and receives the light and the software interprets and transforms the received signal into physical quantitative values.

Zhou et al. [54] used Optical Fiber Bragg Grating (OFBG) sensors to monitor the 3D strain of asphalt layer. The proposed 3D configuration consists of one inset hole for a vertical sensor and spiral components for installation of two transverse sensors. The short gauge sensor measures the vertical strain and a long gauge sensor measures the horizontal strain of the pavement structure. Optical Signal Analyzer (OSA) was used to monitor the reflective optical fiber grating signals.

During the FBG sensors installation all cables were bound to avoid loss of signal for being pulled up. Static compaction (without any vibration applied for first two times) was applied to protect sensors from a heavy-duty loading.

The FBG monitoring system prototype was installed by University of Antwerp in 2017, consisting of a three-layered pavement test track, a bicycle path (CyPaTs). It is used for in-situ strain and temperature monitoring under real heavy loaded traffic (e.g. truck, paver, roller) in the asphalt pavement [55] Van den Bergh et al.[56] introduced two new approaches for embedding FBG sensors in asphalt layers: installation of FBG sensors in prefabricated asphalt specimens with dimensions 50 × 15 × 500 mm with a 2 mm deep groove at the bottom of the specimen in the base layer, directly towards the base and (ii) the installation of FBG sensors at the surface of the previously constructed asphalt layer in 2 mm deep grooves. Sensors used are commercially available and are embedded in a glass fiber reinforced plastic having a 1 mm diameter and an additional high-density polyethylene (HDPE) layer having a diameter of 0.5 mm for operational protection. The sensor itself has been ceramic coated using Draw Tower Gratings (DTG). The monitoring system consisted of: 2 fibers with 30 DTG (spacing between sensors 10 cm) and 4 fibers with 5 DTG (spacing between sensors 80 cm) and two temperature sensors. The strain and temperature data were obtained using an interrogator FBG-SCAN 808D with 8 channels (1507 – 1593 nm wavelength range, 250 Hz measurement frequency for all channels). Sensing fibers are connected to a single mode multifiber (SMF) backbone cable to enable continuous monitoring from inside the building. Such system is ideal for installation during construction of heavy-duty roads.

#### 6.1.4 Application of strain gauges

Rabe [8] has developed a full scale pavement test track as per German pavement design guideline RStO which comprises a combination of sensors such as strain gauges, pressure cells and thermocouples. Federal Highway Research Institute of Germany (BAST) has developed their in-house asphalt strain gauge and the material is comprised of fiber reinforced epoxy resin that acts as a carrier for strain gauge patterns. Aluminum anchors are used to transfer tensile and compressive forces from the surrounding asphalt material to carrier strip hence the strain gauge pattern is used to measure tensile and compressive strains. In order to protect the gauge from mechanical impact and heat during placement and compaction, an aluminum cover is provided. Gauge dimensions are 150 x 75 x 15 mm as shown in Fig. 24. **Chyba! Nenašiel sa žiaden zdroj odkazov.**

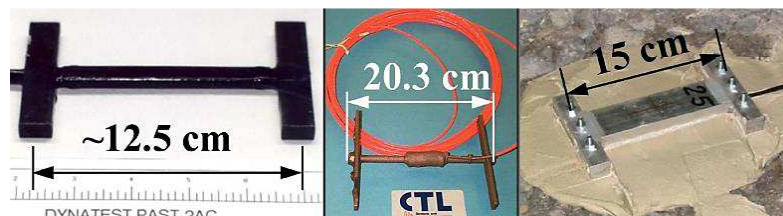


Fig. 24: Dynatest PAST-2AC (left), CTL (center) and BAST1st generation (right) asphalt. Picture taken from Rabe [8].

The stress on strain gauges is usually applied in terms of a moving vehicle or by using FWD. Fig. 25 shows the types of strain patterns in XY directions measured by the strain gauges.

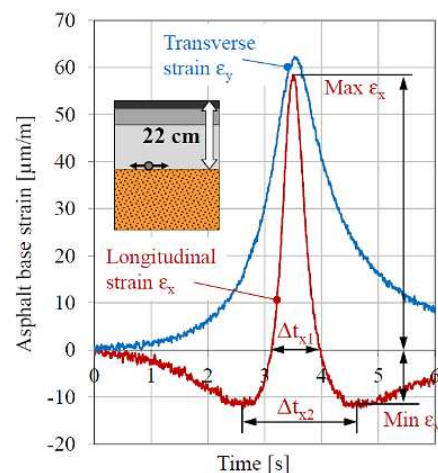


Fig. 25: Dynatest PAST-2AC (left), CTL (center) and BAST1st generation (right) asphalt. Picture taken from Rabe [8].

Tensile strains occur at the bottom in transverse direction; moreover the duration of transverse tensile strain is higher than in longitudinal direction.

One of the first full scale testing of embedded pavement sensors was conducted during the Virginia Smart Road project [57], in which an in situ pavement monitoring system was developed. There were 12 pieces of 100 m long sections in which sensors were embedded at various depths in the pavement. The types of sensors used are strain gauges (H-shaped and vibrating wiretype), pressure cells, thermocouples, TDR probes, and resistivity probes. Moreover, a monitoring system, Data Acquisition System (DAS) and software were also developed. The data acquisition system was composed of two Analog-to-Digital units, the DaqBook 200 unit for the acquisition of static data and the WaveBook 200 unit for the acquisition of dynamic data under moving loads. Three softwares were developed: SmartAcq for data acquisition, Smart Organizer for the management of raw data, and Smart Wave for post processing and displaying.

Horizontal strains in longitudinal and transverse arrangement have been calculated and the magnitude of the strains was higher when the vibrations were used. The pavement was loaded by a moving truck by performing several passages with three different tire pressures 724 kPa, 655 kPa, and 552 kPa; three different loading configurations; and four different speeds 8 km/h, 24 km/h, 40 km/h, and 72 km/h. Results showed that the variation in speed and temperature had a considerable effect on the magnitude of resulting strains. Experimental and numerical results were then compared in a finite element model which suggested the use of viscoelastic calculations for accurate predictions of pavement response.

In 2012, sensors were installed in French highway A41N [58]. A total of two sections were installed with 47 strain gauges (horizontal and vertical asphalt strain gauges), 12 temperature probes, and 2 FBGs sensors were located at different depths in the road structure so as to gain information about the wearing and the underlying base, and subbase course. The MGCplus data acquisition system provided by HBM was used with 5 acquisition modules. Measurements were acquired at 600 Hz. The loading passes were conducted at 3 different speeds (10 km/h, 50 km/h, and 90 km/h) and along 3 different trajectories (called "delta D") to evaluate pavement behavior. Results showed that the variation in speeds had high impact on measured strain values.

In 2016, Eurovia Research Center performed in situ pavement monitoring by sensor installation for understanding the impact of trenches on new roads [59]. The test section has a total of 98 sensors including temperature sensors (PT100), strain gauges (H-gauges), moisture probes, and FBGs sensors. The data acquisition system has been developed by using three data acquisition controllers. For tracking the truck passes, a digital camera operating at a frequency of 1 kHz was used.

In 2017, Ai [60] performed in-situ monitoring of asphalt pavement under different axle configurations, axle loads and traffic speeds and pavement temperature on a 900 m long pavement section. Moreover, three different pavement structures (semi rigid, converted and compound asphalt pavement) were constructed each having a length of 300 m. Each section has been equipped with 4 different asphalt strain gauges in two different orientations to the direction of moving traffic. Results showed that variations in speed, temperature and axle loads had considerable effects on measured strain values from the sensors. Increase in temperature, decrease in speed and increase in axle

r=loads resulted in increase in measured strains. A multi regression model was developed depicting a good match between numerical and experimental results.

In 2018, continuous strain monitoring on slow lane of the French motorway has been conducted by integrating Asphalt Strain Gauges ASGs with geophones and temperature probes [61]. Real traffic was used to collect the data from sensors. Data was collected only from heavy vehicles passing above the strains sensors to minimize the sensitivity of strain caused by various vehicle types. The signal was recorded by geophones placed at various locations. Softwares ALIZE and Viscoroute© were used to understand the viscoelastic behavior of asphalt through Huet-Sayegh model [62]. Results showed that the viscoelastic behavior of asphalt must be considered under loading at high temperatures for better understanding of pavement behavior.

### 6.1.5 Vibroacoustic signature and wave propagation

Pratico et al. [25] employed the use of vibroacoustic sensing technology for detection and monitoring of cracks in road pavements and later developed a machine learning approach for better classification of pavement's structural health condition. The acoustic sensor basically consisted of a receiver microphone that had been isolated to remove any airborne noise. The data is fed to the computer and represented using MATLAB. Test section consisted of newly constructed dense graded friction course (DGFC) having two asphalt layers and the drive paths of the vehicles were predetermined for ease in data analysis. The vehicle speed used for a mechanical source was 20 km/h. Authors later performed data size optimization using augmented procedures. Different machine learning classifiers for structural health classification of pavement used are multilayer perceptron (MLP), Convolutional Neural Network (CNN), Random Forest Classifier (RFC), and Support Vector Classifier (SVC). Results showed that the highest accuracy of presenting a specific vibroacoustic signature to a cracked road was produced using SVC.

Cafiso et al. [27] estimated the elastic moduli of different pavement sections using vibroacoustic sensing approach. A combination of controlled and uncontrolled mechanical sources was used for determining the acoustic response of pavement. The sensing unit consisted of an insulated microphone. The variation in air pressure inside in each sensing unit would give a specific acoustic signature. The test setup consisted of an omnidirectional pre-polarized microphone "Audix TM1" (frequency response: 20 - 25 kHz  $\pm$  2 dB, sensitivity: 6 mV/Pa at 1 kHz, dynamic range: 112 dB), sound card and computing system consisting of MATLAB codes. The sampling frequency was kept at 19 kHz.

Variability in elastic modulus of payment at different cross-section was calculated using controlled mechanical sources such as the data obtained from FWD. Results showed that sections with no surface damages exhibited higher elastic moduli values than the sections with hidden damage or cracks inside the pavement structure.

Fedele et al. [28] presented a novel approach for using vibroacoustic sensors in determining pavement health in the form of pavement moduli using a light weight deflectometer (LWD) and vehicular traffic as mechanical loading sources. The test setup incorporated the use of a receiver microphone for detecting acoustic response of pavement under impact loading generated by LWD on predetermined cracked and uncracked sections. Audio recordings were then converted into time series and Power Spectral Density (PSD) with a sampling rate of 192 kHz. Time, frequency and time-domain frequency data was obtained for signal analysis. The data was later analyzed and differences between each of the domain's amplitudes were evaluated. The algorithm was used to perform hierarchical clustering of vibroacoustic signals. Results showed a probable correlation between the collected spectral response and measured elastic moduli at different cracked and uncracked section of the pavement holes inside the pavement structures impeded the passage of waves with shorter wavelengths.

Iodice et al. [63] introduced a novel crack detection approach in asphalt pavements using the propagation of Rayleigh wave components in a wave decomposition method. In the wave decomposition method, the frequency-wavenumber ( $f - k$ ) was used. The cracks are detected in such a way that the amplitude of positive and negative going Rayleigh components is calculated and finally the resonant peak frequencies of the reflection coefficient and the cut-off frequencies of the transmission coefficient provide information about the depth of cracks. The wave decomposition setup consisted of geophones to be used as receivers and an algorithm was developed to detect and analyze the discontinuities in the asphalt pavement. The impact hammer was used as a source of vibrations induced in the pavement. Furthermore, numerical simulation model ABAQUS was used for

investigation of wave decomposition and detection of discontinuities with accuracy. The detection of depth of cracks was done using reflection and transmission coefficients. It was discovered that the reflection coefficient would only decrease and rapidly approach to zero in the absence of cracks. Results showed that the deeper the crack is the lower the resonant and cutoff frequencies are. Fig. 26 shows the obtained reflection coefficients.

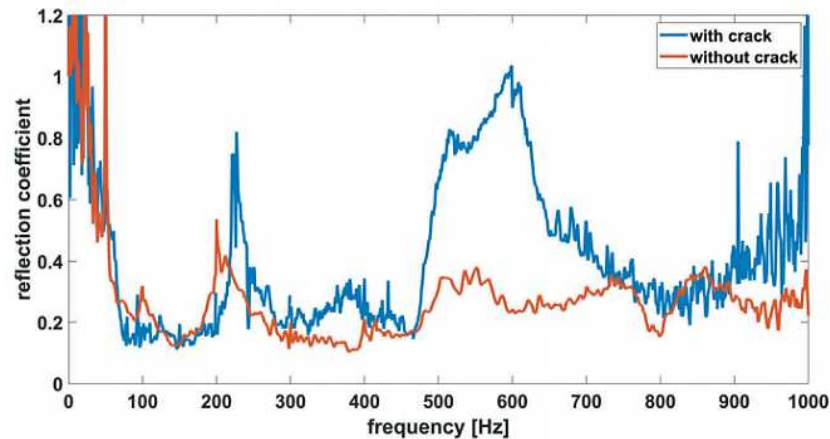


Fig. 26: Vibroacoustic signature of pavement for one car pass in three different domains: a) time, b) frequency and c) time frequency. Taken from Fedele et al. [29].

The figure above shows major resonant peak at the frequency of approximately 620 Hz, when the coefficient is approximately equal to 1, and a second minor peak at approximately 220 Hz. Authors found that influence of the distance of the deployment of sensors from the relevant crack affects the accuracy of the depth estimation. This method can successfully analyze the bottom-up cracks in the pavement by measuring the resonance of transmission and reflection coefficients. Hence this method can be used for crack detection, depth estimation and location of discontinuities.

## 6.2 Secondary monitoring applications

Majority of previous research is conducted on damage detection and evaluation by sensors mentioned in the previous section. The primary idea behind the development of majority of aforementioned sensors was to monitor pavement structural health. Therefore, sensors were used to measure propagation of strain and deflection in the pavement upon loading. However, in some of aforementioned studies secondary sensors used for temperature monitoring, moisture measurement, ice/water film and traffic detection have also been used to supplement the measurements obtained from damage detection sensors. Since secondary sensors play an important role in supplementing and further refining the research, such as analyzing the relationship of pavement damage with temperature and moisture variations or the analyzing the effect of magnitude of traffic loading, duration of loading on pavement damage. Hence a review of notable research work in this regard is mentioned in the following section.

### 6.2.1 Temperature monitoring

Geernaert et al. [64] has developed a novel temperature sensing method for using microstructure optical fiber Bragg grating based sensors for temperature monitoring in concrete buffer which can later be used in concrete pavements. The double reflection spectrum of these sensors is used to monitor temperature with the help of attached thermocouples and vibrating wire sensors installed nearby. Readings were checked and confirmed with the values of temperature obtained by thermocouples and it was found that the prediction of temperature in concrete buffer by FBG based sensors was in close correspondence with the conventional thermocouples.

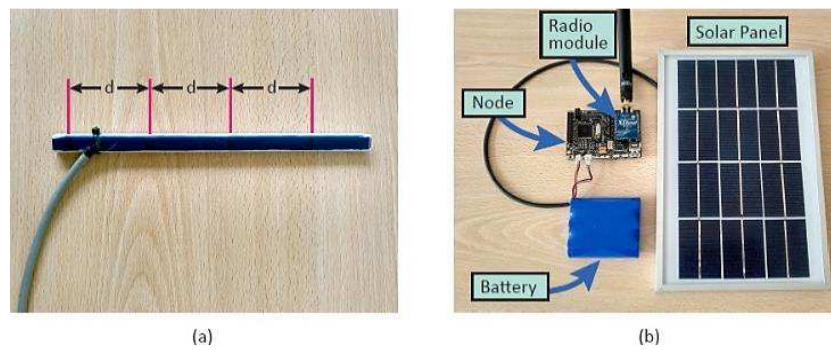


Fig. 27: WSN setup. Taken from Godoy et al. [65].

Godoy et al. [65] employed the use of low-cost conventional temperature probes for pavement temperature monitoring using Vehicle to Infrastructure (V2I) communication protocol in which an auscultation vehicle can collect the data from embedded temperature sensors in the form of WSNs in the pavement. Moreover, a neural network-based model BELLS3, has been calibrated for prediction of pavement temperature. The sensors used have an input range of  $-55\text{ }^{\circ}\text{C}$  to  $125\text{ }^{\circ}\text{C}$  having an accuracy of  $0.5\text{ }^{\circ}\text{C}$ . the used temperature probe and WSN node power supply is shown in Fig. 27.

The sensors in WSN are placed at 5cm apart and the depth of measurement is up to 15cm. the auscultation platform consisted of a WSN Gateway so that the onboard computer can communicate with on ground WSN. The communication distance of this system was 330 m with the normal speed of the vehicle at 20 km/h. Results showed that auscultation vehicles could measure the temperature at several depths with great accuracy and the calibrated BELLS3 model could be used for pavement temperature prediction on annual basis with good precision.

Bergh et al. [56] has used the FBG sensors for pavement temperature monitoring by embedding them in a saw cut joint inside the asphalt pavement. In order to verify the credibility of collected data, an infrared thermography measuring technique using a thermographic line scanner was used. Moreover, to further verify the data collection process, an infrared hand-held camera was also used for taking pictures every 2 meters. The study concluded with the development of temperature contours in real-time basis and authors recommended the use of FBG and IR temperature measuring methods to be integrating in pavement management system (PMS).

Rabe [8], Gaborit et al. [58], Pouteau et al. [59] used conventional electricals sensors such as thermocouples for supplementing the data collected by asphalt strain gauges. The thermocouples used have 4 - 20 mA standard industry interface. The strain measurements collected were highly dependent on the temperature data collected by thermocouples.

### 6.2.2 Moisture monitoring

Ziliute et al. [66] employed the use of moisture and temperature sensors for evaluating the effect of varying climatic conditions on the bearing capacity of the pavement. The research was conducted on 4 different sections on the highway with depth range of temperature and moisture sensors from 100 to 150 cm. Data was collected for a period of 3 years and the variations in temperature and moisture inside the pavement were analyzed. The moisture sensors were able to measure correct data based on the annual precipitation patterns. Later on, the bearing capacity at designated pavement sections was conducted and results showed that nature materials used in pavement structure and traffic volume had high impacts on bearing capacity of the pavement structure.

Yang [67] used radio frequency identification (RFID) temperature tag for temperature monitoring and a digital humidity sensor for moisture detection in the concrete pavement. Actic wireless RFID tag is capable of providing real time data collection and processing. The RFID system consists of a RFID transponder as shown in Fig. 28. The tag is powered by batteries and it contains internal temperature logger to capture temperature at various intervals and there is an antenna mounted inside the transponder which can communicate with the receiver to read and extract data.

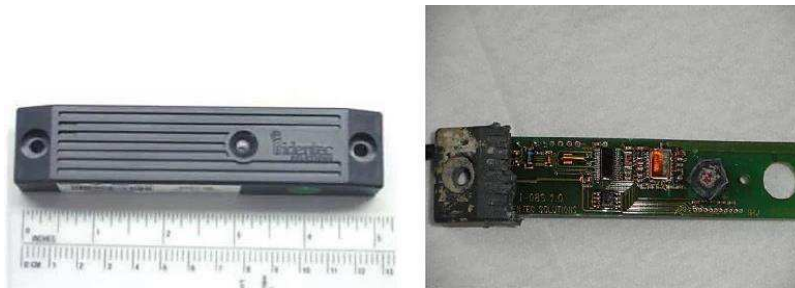


Fig. 28: HardTrack portable handheld transceiver Pro. Taken from Yang [71].

The moisture sensor used was the commercial off the shelf Micro Electro Mechanical Systems (MEMS) sensor capable of measuring both relative humidity and temperature. The sensor consisted of both sensing elements and signal processing circuits on a silicon chip. A capacitive sensing element used paired conductors for measuring relative humidity as shown in Fig. 29.

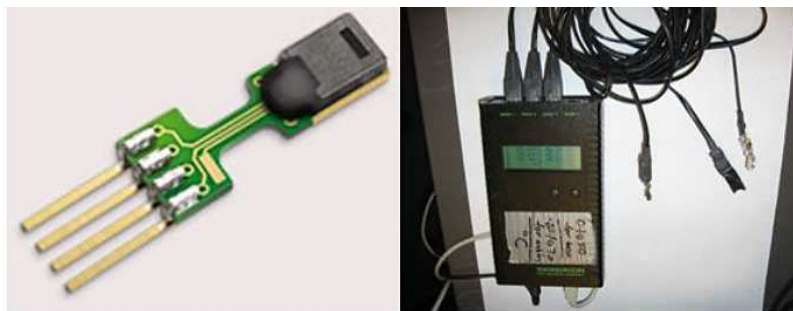


Fig. 29: Sensirion SHT71 sensor (left) with complete evaluation kit (right). Taken from Yang [71].

Both the moisture and temperature sensors were used for a total monitoring period of 10 months. The depth of the sensors ranged from 5 cm to 25 cm at various predetermined sections on the concrete pavement. It was found that the sensors closer to the pavement surface were highly affected by temperature variations. However, both these sensors provided a reliable stream of data for the designated testing period.

### 6.2.3 Traffic monitoring

Xue et al. [68] performed temporal analysis by collecting and analyzing the data collected from the group of sensors embedded in a longitudinal pattern in the pavement. The idea was to perform traffic monitoring in terms of traffic volume, speed and weight classification of each passing vehicle. The sensor used was the conventional H gauge strain sensors. In the developed temporal analysis method two parameters:  $\Delta t_{sensor}$  and  $\Delta t_{axle}$  were measured and deemed crucial. Hence, speed of the moving vehicle was calculated by measuring  $\Delta t_{sensor}$ , which is a time interval between fluctuations collected by sensors in a group.  $\Delta t_{axle}$  gives information about time interval related to moving axles when the fluctuations in strain values are collected by sensors. Hence the traffic volume was calculated with this approach. Results showed that the proposed temporal analysis approach provided valuable information for determining traffic properties such as volume, speed and loading for supplementing the data used to perform pavement distress prediction and overall pavement health monitoring.

Lan et al. [69] proposed an approach by developing a system that can measure and process magnetic signal using a MEMS sensor. This method was used to detect and classify vehicles based on the magnetic response collected by the sensor. The sensor works in a way that the magnetic field disturbance produced by a moving vehicle can be measured by a single axis magnetic sensor, since the distortion in magnetic field happens near the wheels and engine. The detection setup consisted of battery power, a magnetic sensor and a containing circuit, a data acquisition card and a computer. During the data collection process, different magnetic signals were generated by different weight categories of vehicles. Vehicle classification and recognition was achieved using an Improved Support Vector Machine (ISVM) which is a statistical learning method for one-against-all algorithm. The total of 93 vehicles consisting of heavy and light tracked vehicles were selected for detection and classification approach. The data sampling frequency was 2000 Hz on a 2 km long testing section.

Results showed that ISVM classifier performed with successful recognition rates of 90 % due to its robustness and small sample rates.

Kunzler et al. [70] successfully used the fiber Bragg grating (FBG) sensors in vehicle detection, classification and speed measurement. Sensors were embedded on an asphalt concrete pavement at a depth of 8 cm along the vehicular wheel path. Results showed that fiber optic sensors were highly capable to monitoring traffic related information and could further be used as Weight in Motion (WIM) devices, since the fiber optic sensors have higher bandwidth. Moreover, authors found advantages of using fiber optic sensors such as their resistance against electrical interference, small size, accuracy in measurement and robustness.

Cosentino et al. [71] incorporated the use of fiber optic sensors for traffic classification. The operating speed of test traffic was kept at 8 km/h. Sensors were embedded in 18 m long vertical grooves along the wheel path. A total of 50 sensors were used out of which 30 sensors were used vertical and 20 sensors were placed in a horizontal pattern. Furthermore, Fiber optic leads from the sensor were connected to an interface electronics device that converts light intensity to voltage. The principle of obtaining the measurements was kept simple as the vehicle passed over the sensors, the loading from the tires would deform the sensor and the light intensity would decrease which could be detected by the roadside computer system with specially developed algorithms that could perform traffic classification and measure weight of the vehicles. Results showed that sensors would produce accurate results when installed in a vertical groove pattern by placing the sensor about 5 mm below the pavement surface.

Loukili et al. [72] have developed a wave current interaction method that uses the Numerical Wave Tank flow to carry out the predictions of computer flow. Such concept is being used in detection of vibroacoustic signatures if any damage along the pavement structure exists.

#### 6.2.4 Ice/water film monitoring

Troiano et al. [35] proposed a novel approach for detecting water and ice film on pavement surface using capacitance-based ice sensors. Study was conducted on an idea to bring cost effective solutions for improving safety of highway traffic. Two capacitive measurements at frequencies of 200 Hz and 20 MHz were conducted using the ice sensors at low and high frequency ranges to distinguish between presence of water, ice and air on pavement surface. Reliability of the measured data was further verified using laboratory tests where measurements were collected based on similar field conditions in a climate test from -40 °C to +180 °C. Algorithm was used during signal processing form to distinguish between ice, water and air on the sensor surface. A first order derivate of capacitance values was obtained to in order to specify the jumps that occur due to change in state of the sensor. Furthermore, low pass filter to raw data was also applied to reduce high frequency variations. Fig. 33 shows different states of capacitance values obtained after application of algorithm. Results showed that using the applied algorithm, sensors were clearly able to distinguish their state from liquid to icy condition on the pavement surface. It was found that during dry state, the values of capacitance were close to zero and during the wet state the value of frequencies were at higher limits.

Fay et al. [73] employed the use of Luft MARWIS and Teconer RCM411 sensors in detecting depth of ice/water film on pavement surface at temperature range of -2 °C to -28 °C. Furthermore, sensor's sensitivity to varying chloride content was also determined. The concept behind this research was to compare the performance of these two sensors in terms of readability and reliability in data measurements. Tests were conducted in laboratory where the field conditions were simulated using trafficked snow and plowed off samples having salt spread on both asphalt and PCC samples. Later on, friction variations for compacted snow and plowed off snow for each pavement sample were calculated. Results showed that MARWIS was able to detect water/ice depth with higher sensitivity regardless of effect of temperature with a response time of 0 seconds to 4 seconds. RCM411 was also able to calculate the process of water freezing over time however it could not detect first freezing of water at very cold temperatures. It was found that water/ice depth data calculated using MARWIS was much precise and accurate. Moreover, MARWIS was able to measure loss in friction with traffic compaction of snow with high consistency and variation in chloride content for plowed off snow conditions.

### 7 Research work summary

The research work summary is shown in Table 1.

Table 1: Summary of previous research work on adaptation of sensing technologies.

Monitoring year	Authors	Measurements	Sensors	Remarks
1991	Sebaaly et al. [10]	Stress; deflection, strain, temperature, moisture, vehicle location.	Pressure cell, strain gauge	Laboratory tests
1995	Sebaaly et al. [11]	Strain	Strain gauge	Hall effect gauge development for flexible pavements
1995	Signore and Roesler [49]	Strain	Strain gauge	Laboratory tests
1997	Sargand et al. [74]	Strain	Strain gauge	Development protocol
2001	Goncalves et al. [75]	Stress	Diaphragm type stress cell	Accelerated traffic tests
2002	Al Qadi et al. [57]	Stress, strain, moisture, temperature, frost penetration	Pressure cell, strain gauge, thermocouples, reflectometry and resistivity probes	Development protocol
2003	Kunzler et al. [70]	Traffic classification, weight in motion	Fiber Bragg grating (FBG) sensors	Traffic monitoring protocol
2003	Cosentino et al. [71]	Traffic classification	Fiber optic sensors	Traffic classification and optimum placement of embedded sensors
2004	NCAT	Stress, strain, moisture and temperature	Strain gauge, pressure cell, moisture probes	Prototype testing
2005	Huff et al. [2]	Digitized current	Piezoelectric axle sensor	Prototype testing
2005	Wang et al. [50]	Strain and temperature	Fiber Bragg Rating sensor	Laboratory testing
2007	Arrigada et al. [43]	Deflection, strain	Accelerometers	CPTT testing
2010	Grellet et al. [53]	Stress, strain, displacement	Fiber optic strain plate	Integration of White Light Polarization Interferometry WLPI for full scale testing
2010	Troiano et al. [35]	Water film thickness, ice film thickness	Capacitive sensor	Prototype testing under laboratory conditions
2011	Rhimi et al.[42]	Strain and temperature	Piezoelectric transduction	Development of self-powered piezo floating gate array
2011	Lan et al. [69]	Traffic classification, traffic detection	MEMS sensor	Traffic detection and classification using distortion in magnetic field
2012	Zhou et al. [54]	Strain	OFBG optical fiber Bragg Grating sensor	3D monitoring of pavement response
2012	Gaborit et al. [58]	Strain, temperature	Strain gauge, Temperature probes, FBG sensors	Testing on French highway A41N using MGC data acquisition system
2013	Lajnef et al. [3]	Strain	Self-Powered Piezoelectric transducer CEB-35D26	Wireless sensor data acquisition using RF reader mounted on a moving vehicle
2013	Rabe [8]	Vertical strain	Strain gauge, thermocouples, pressure cells	Pavement response testing by BAST Germany
2015	Xue et al. [68]	Strain, traffic volume, traffic speed, weight classification	Strain gauge, MEMS sensor	Traffic monitoring and its impact on pavement health
2016	Pouteau et al. [59]	Strain, temperature, moisture	Strain gauge, moisture sensor, temperature probe, FBG sensors	Full scale testing
2017	Chapeleau et al. [52]	Vertical strain, displacement	Telecommunication fiber optic cable used as strain measurement	Full scale prototype testing at IFSTTAR
2017	Ai et al. [60]	Strain	Strain gauge	Full scale testing on a 900 m long section
2018	Van den Bergh et al. [56]	Temperature, strain	FBG sensor	Full scale testing sections for strain detection
2018	Duong et al. [61]	Strain	Geophones, Asphalt Strain Gauge	Full scale pavement testing
2018	Fay et al. [73]	Water film thickness, ice film thickness, pavement surface condition	Optical infrared spectroscopy	Performance comparison of MARWIS and RCM411 sensors in laboratory conditions
2019	Ji et al. [46]	Crack detection using acoustic attenuation	Piezoelectric vibrators encapsulated by PZT and polyvinylidene fluoride (PVDF)	Crack detection in lab prepared asphalt concrete beams
2019	Paredes et al. [47]	Strain	Strain gauge, piezo floating gate (PFG) sensor	Pavement maintenance optimization using PFG sensors
2020	Liu et al. [22]	Strain	Single electrode piezoelectric sensor with polyvinyl fluoride (PVDF) film and piezoelectric nanogenerators (PENG)	Movement detection in civil engineering applications

2020	Pratico et al. [25]	Vibroacoustic signature, strain	Isolated microphone receiver	Acoustic response of pavement for pavement structural health monitoring
2020	Cafiso et al. [27]	Acoustic signature, strain	Isolated microphone receiver	Elastic moduli estimation of pavement structure using the AR data
2020	Fedele et al. [28]	Acoustic signature, strain	Isolated microphone receiver	Crack detection in asphalt pavements using AR
2020	Iodice et al. [63]	Reflection coefficient, transmission coefficient	Geophones	Detection of cracks and estimation of crack depth in asphalt pavement
2021	Lee et al. [45]	Vertical acceleration, vibration induced by moving vehicle	Accelerometer	Road surface anomaly detection using accelerometers and image recognition software

## 8 Conclusions and recommendations

Realtime monitoring of road performance using embedded sensors is a powerful tool for assessing pavement deterioration with time. With the help of remote sensing solutions, huge database can be recorded throughout the lifetime of pavement, which can be useful for efficient maintenance planning of pavements. As described in the literature, various sensing technologies are available to evaluate pavement health. Embedded as well as nondestructive sensors can be used without traffic disruption thereby saving lots of time. However, data acquisitions and post data processing systems need to be refined with ability to store mass data and transfer such data in a short amount of time.

The aforementioned sensing technologies can measure stress, strain, deflection, moisture, traffic characteristics, temperature and ice/water film thickness that directly affect the pavement response under stress caused by vehicles and environment. It has been found that duration of loading and temperature of the pavement can strongly influence the magnitude of the resulting strains in the pavement layers. The most common strain sensors used are asphalt strain gauges that can be used in horizontal H-gauge configuration or in a vertical configuration. Other available options such as FBG provide similar results however their size is much smaller than the ASGs, making them ideal to be used in large quantities. Moreover, accelerometers and geophones have also been used to evaluate pavement deflection that led to calculation of resilient modulus of layers based on back calculation procedures. These devices differ from conventional LVDTs as they are smaller in size and provide same output measurements however data collection process is usually time consuming since the drift in the data has to be adjusted to minimize the error due to high sensitivity of accelerometers. Newer technologies developed by [3, 8] employed the use of self-powered piezoelectric sensors capable of measuring strains in the asphalt pavement with high accuracy and less time, however the data acquisition system needs further refinement and the provision of protective coating can lead to loss of recorded strain values can be up to 30 % [8]. Lebental et al. [76], has proposed RFID-enabled carbon nanotube strain sensor in concrete and a nanoparticle-asphalt sandwich for weigh in motion applications. Sensors used in asphalt are the force sensors based on piezoresistive nanocomposites which consist of thin piezoresistive layer of carbon-clay nanoparticles deposited between two preheated asphalt slabs. These sensors are low cost and have high survivability with better signal processing capabilities. Based on the literature following are the recommendations related to design, installation and data acquisition of sensors. In case of supplementary sensors, the use of optical infrared spectroscopy-based sensors has yielded promising results in determining ice film thickness thereby providing an option for improving safety of road users. Traffic based sensors can accurately measure traffic speed, classify the traffic based on loading and unloading time. Such data can be easily integrated with damage related sensors for optimizing the weight control of heavy vehicles.

- 1) A minimum sampling rate of 4 kHz is required to obtain better quality of response signals under a traffic speed of 90 km/h [60].
- 2) Sensors should have long longitudinal and short transverse segments having a longitudinal to transverse dimension ratio of 4:1 for better sensitivity [13].
- 3) Data acquisition and post data processing system should be robust for continuous data processing for long term applications with capability of processing higher frequency triggered events [58].
- 4) Optimized WSNs should be used whenever embedded sensors in large quantity with wireless communications are used [38].
- 5) Sensors should be less intrusive and have ability to withstand high placement temperatures and vibrations [19].

- 6) The modulus of elasticity of protecting coating of ASGs consisting of piezoelectric sensors should be less than that of the asphalt mixture it is embedded in [8].
- 7) Ideal sensors yielding less complicated and lengthy post processing times are piezoelectric sensors, FBG sensors and ASGs [46, 56, 61].
- 8) For strain measurements the accuracy of strain gauges should be closer to  $\pm 1 \mu\epsilon$  [48].
- 9) Airborne noise in case of acoustic response should be mitigated by using isolated microphone receivers (68).
- 10) Inaccuracy in obtained data and fluctuations in measured coefficients can be reduced by calculating an optimum distance between the mechanical vibration source and a geophone receiver [63].

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