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PIEZOELECTRIC POLYMER AXLE SENSORS

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ABSTRACT

With the increased flow of traffic on our nation's roads, but with limitations placed on new construction due to cost, environmental concerns and land use, there is added pressure on the transportation engineers to allocate precious resources. These same engineers are looking for different methods to monitor the flow of traffic to determine how many vehicles are traveling a section of highway, and to determine the weight of those vehicles. One of the tools that has been used is a piezoelectric axle sensor. These sensors are used both on the surface of the road for short term applications, as well as emplaced into the road for longer term studies. Sensors developed in the past two years have addressed concerns from the field in terms of reliability, installation, and accuracy of the date. This paper will review the latest generations of piezo polymer axle sensors and explain their construction, installation, and advantages. Additionally, we will review the different applications for these sensors, including classification and counting, Weigh in Motion, Speed and Red Light Cameras, and Toll booth sensors.

INTRODUCTION

Over the past five years there has been a resurgence of interest in the use of piezoelectric polymers for vehicle and pedestrian sensors. The improvements that have been made during that time period in the manufacturing process and the different form factors that are available have opened new avenues for data collection and movement monitoring for the transportation professional.

Piezoelectric polymers are similar in configuration and function to that of ceramics, although the form factor and therefore certain attributes are different. "Piezo" is Creek for pressure. Thus piezoelectricity is really pressure electricity. When a piezo electric material is compressed or deformed, charge is produced. This charge is proportional to the stress that is applied to the sensor, thus allowing the sensor to be used for Weigh in Motion applications. The flexible nature of the polymer and its relatively low cost allow it to be used in applications where other sensor technologies cannot function.

Piezoelectricity was discovered more than 100 years ago by the Curie's. It was discovered that quartz generated a charge when subjected to mechanical strain, and conversely, changed its dimensions when an electrical field is applied. Later, it was discovered that other materials with a high net dipole moment could be synthetically fabricated by applying a high electrical field to make them into a piezoelectric material. An example of this material is Lead-Zirconate Titanate (PZT) An advantage of the PZT over the quartz is a higher piezoelectric coefficient and therefor a higher output. Unfortunately, PZT like other ceramics are relatively fragile and cannot be deformed. Both quartz and ceramics have many applications today, including sonar, accelerometers, buzzers, and pressure transducers, to name a few.

Piezoelectric polymers are relatively new in comparison, having been discovered in the late 1960's in Japan and elsewhere. It was known that organic materials have an inherent piezo effect. Bone, when compressed, will generate a small electrical charge. Polymers were investigated to see if any have a symmetrical molecular orientation and a high net dipole moment. Poly-vinylidene fluoride (PVDF) was investigated and techniques developed to fabricate it into a piezo electric material. Flat sheets of the PVDF piezo film were fabricated by first extruding the polymer, then orienting it in a 5:1 orientation process. Next, and intense electrical field was applied to the film (100 KV/mm). Finally, electrodes were applied to allow for the collection of the charge and the fabrication into transducers.

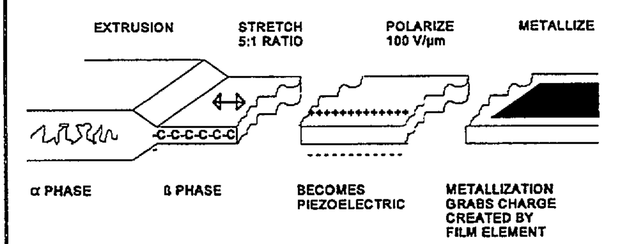

Figure 1: In the manufacturing of Piezo Film, PVDF is first extruded into sheet form and then stretched to a 5:1 orientation. Following polarization, it is metallized for charge collection.

CONSTRUCTION TECHNIQUES

Traffic sensors have in the past been made using piezo film. However, due to the linear nature of the sensors and the need to electrically screen the sensor from EMI, the fabrication techniques became prohibitively expensive, and susceptible to some problems. A different technology was needed to address these needs. Discoveries were made that by combining a small amount of trifluoroethylene with the PVDF during the polymerization process, a copolymer was made which did not require the orientation process in order reach the beta phase or the phase where polarization can occur. This copolymer can be polarized while the material is still in the melt, allowing it to be extruded directly onto wire and polarized in place.

This discovery has allowed for the manufacturing of piezoelectric coaxial cable. A form factor has a number of inherent advantages. First, it is already in a shielded configuration, so that it does not need any external shielding. Being a coaxial cable, lead attachment and splicing are comparable to standard coax applications. The linear format of the material is compatible with the format needed for installation into the road. Standard wire and cable technology can be used for a major portion of the manufacturing process, thereby decreasing the manufacturing cost. The piezo cable is manufactured on a continuous process. First the copolymer material is extruded onto the center wire, which is usually a stranded material for added flexibility. While the polymer is still in the melt, a corona electrical field is applied to the cable, orienting the dipoles and creating the crystalline formate and therefore the piezoelectric properties. Applying the electrical field in an extended corona process ensures a uniformity of the piezo effect,

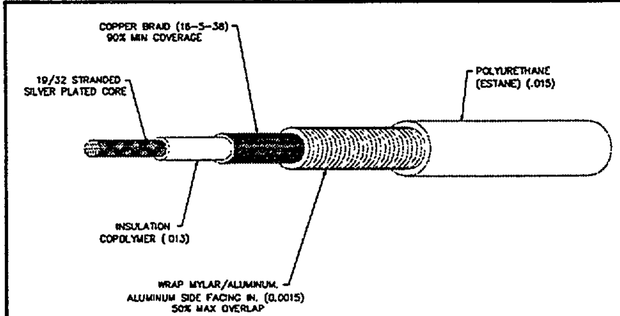

Figure 3: Piezo cable is the newest form factor of piezo polymer. The piezo material is extruded onto the center core, and then polarized.

making it independent of any variations in the thickness of the piezo material. Excellent process control is maintained on the thickness of the polymer jacket, ensuring that the core is centered in the material.

The outer shield or braid can be applied in two different manners. For piezo cable that will be used in flexible applications, the outer construction is applied in a format similar to a standard RG178 coax cable. An outer screen is braided onto the cable and then an outer jacket is extruded on. This outer jacket can be a polyurethane or a cross linked material, depending on the application. If the media is to be used in a non-compressible material, a stiff outer sheath is applied instead of the braid and the polymer. This is usually a brass or copper 'tubing' that is swaged onto the piezoelectric polymer and core. Process control must be used to ensure that there are no air gaps in the element, between the polymer and the sheath. This would lead to inconsistencies in the uniformity of the final product. A flat center core can be used, and the swaging process will produce a flat element. This product has been nicknamed the Brass Linguini.

SENSOR TYPES

Once the piezo cable is formed, it is the raw material for a number of sensors that are used for the monitoring of the intermodal transportation network. The simplest of the form factors is to install the sensor element directly into the road. This is done with the brass-covered element described above. The one end of the tube is welded shut and a passive coaxial cable is attached to the other end. Care must be taken in the selection of the outer jacket for this cable. Since it will be directly buried for at least part of its length, a material should be chosen that is rated for direct burial. Standard RG58 with a Polyvinyl chloride (PVC) jacket should not be used. A High Density Polyethylene (HDPE) or a Fluoro-polymer (such as Teflon) should be used. Although more expensive, these materials will help ensure a long life for the installed sensor. The sensor is put into a slot cut into the road.

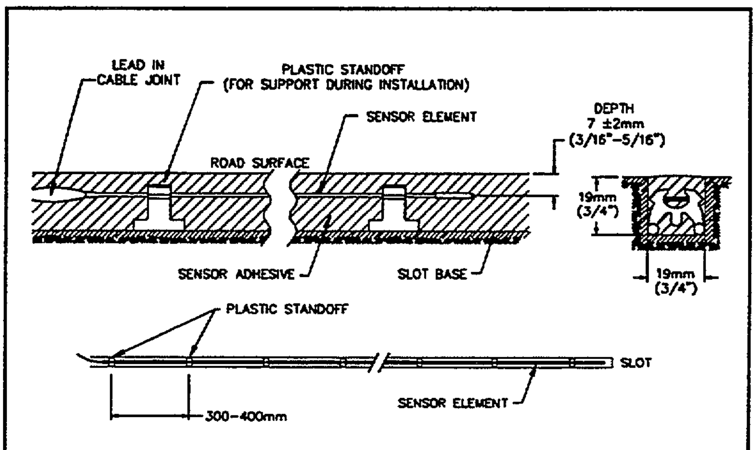

Figure 3: The sensor element is placed directly into a slot cut in the road and encapsulated with epoxy or acrylic.

This slot need only be ≈ 19 x 19mm (¾" x ¾"), since the element going into the slot is only ≈ 3 x 8 mm. It is necessary to suspend the sensor in the slot while the encapsulation material is poured. One technique that has been used is to cut rebar chairs, and drill a hole to hold the sensor. [1] Placing these every 250mm, they fit neatly into the slot and hold the sensor for the pouring of the encapsulation material. The properties of this encapsulation material are important, since this will form the boundary conditions for the sensor. The trend is away from the very hard epoxy and sand grout materials, and toward quicker curing, more flexible materials. These materials work well in a wide range of pavements, including portland cement, concrete asphalt, and chip seal found in other countries. The encapsulation material is poured into the slot with the sensor in place, leaving a small dome on top of the sensor. With an experienced two man crew, a 4-lane installation with two sensors and one inductive loop per lane can be completed in less than six hours, depending on traffic control.

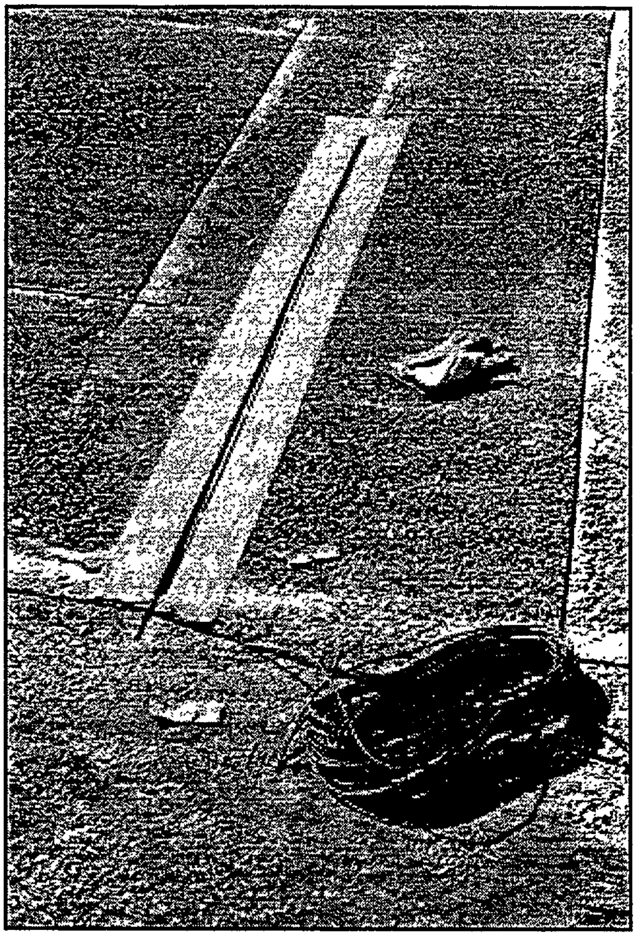

Figure 4: The in the slot cut in the road, ready to pour in the encapsulation material.

This installation has a number of advantages. The cut in the road is very small, and thus does less damage to the road. For flexible pavement, the more flexible encapsulation material is more compatible - flexing and expanding/contracting with the road. The time and therefore the cost of the installation is reduced, due to the smaller cut in the road and the fast curing of the adhesives. But, this installation technique has not been approved for Class I sensors and requires a more experienced installation crew.

In order to take advantage of some of the properties of the sensor installed directly in the road, but make it easier to install and give it better boundary conditions, the sensor element is fabricated into a completed sensor. In a manner similar to the techniques described above, the sensor element is suspended in an aluminum channel, and then filled with a high modulus encapsulation material. Since this is being done in a factory, the curing time is less critical, and the epoxy/sand grout encapsulation material can be used. Once the sensor is complete, it is tested for uniformity, and sorted into Class I and Class II sensors. The installation of the sensors is similar to the method described above. A slot is cut in the road ≈ 40 mm x 40 mm. The sensor is suspended in the slot, either from the top or on bottom supports. The top of

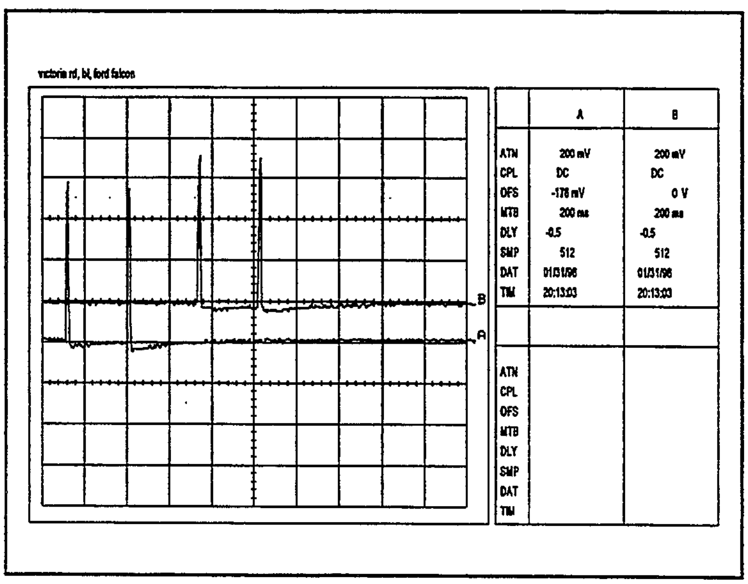

Figure 5: The output from two BL sensors installed into the road. The output is averaging 700-800 mV for a mid-sized car.

the sensor can be 4-5 mm below the road surface. The slot is then filled with an encapsulation material (epoxy filled with sand/grout), leaving a small dome over the top of the sensor.

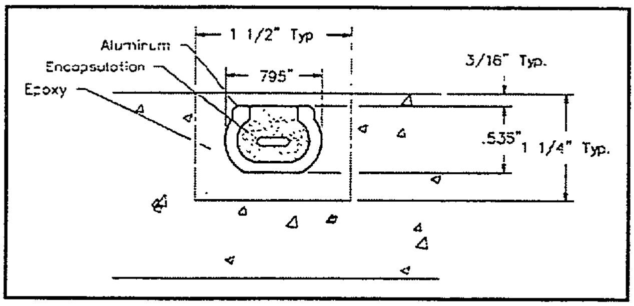

Figure 6: The sensor element is encapsulated in epoxy/grout in a "C" shaped aluminum channel. This is then embedded in the road up to 4 mm below the surface.

Compared to a piezoceramic sensor, both of these sensors have a number of advantages. The flat construction of the sensor element itself means that there is less susceptibility to the bending of the road and the "bow wave" horizontal deformation of the pavement. It is not necessary to place rubber strips on the sides of the sensors to attenuate the horizontal bending of the road. The sensor element itself is more rugged and flexible, making it less susceptible to damage. It can even be coiled into a ≈ 700 mm diameter coil - a real advantage compared to transporting a 2-3 meter straight element. When it is encapsulated, a "C" cross section element is used, with dimensions of ≈ 20 mm x 15 mm. This is a smaller cross section than the standard flanged element, and does not have any 90° angles which would be the catalyst for the propagation of cracks into the epoxy - leading to premature failure of the sensors. The sensor element itself is flexible enough to easily conform to the profile of the road. The completed sensor is also flexible enough to conform to most road profiles.

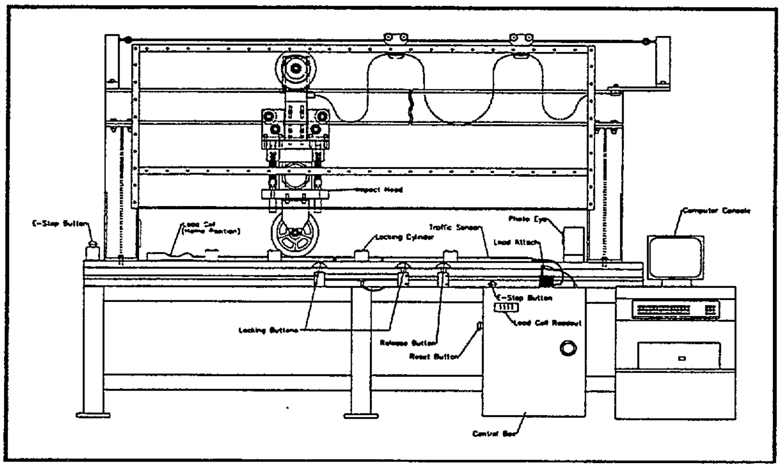
Figure 7: A vibrating head impacts the sensor at 256 points along the length of the sensor, determining its uniformity.

The testing that is done to the sensor to determine Class I and Class II is different from the testing developed by LCPC and currently in use.[2] The LCPC testing method applies a hydrostatic load to a length of the sensor. Unfortunately, this is not a direct representation of how the load is applied to the sensor in actual use. In order to adequately test the sensor for uniformity, it is necessary to apply a load to the sensor in the direction that the actual load is being applied. A vibrating head on a roller is transported over the length of the completed sensor. The output of the sensor is analyzed, taking into account any resonances in the system. A Fast Fourier Transform (FFT) is done of the signal and the uniformity of any point is compared to the average uniformity. This is done for 256 points over the length of the sensor. This test gives a better representation of how the sensor will function in the road.

The piezo cable in a flexible outer jacket offers a convenient form factor for a number of sensors. The most widely used in the United Kingdom is the UK Department of Transportation design. A permanent channel is put into the road, and then a replaceable sensor element is placed into the channel. This will allow for the replacement of the sensor if the need arises without having to recut a slot in the road. The sensor is in contact with the channel only at the ribs of the sensor element, eliminating any chance of a bow wave. Installations on heavy use motorways such as the M25 ring road around London indicate a very high level of reliability. The only disadvantage would be the large initial slot to be cut in the road for the installation of the channel. A newer design uses a small channel and sensor element, but this has not gained wide acceptance due to the high number of large channels already installed.

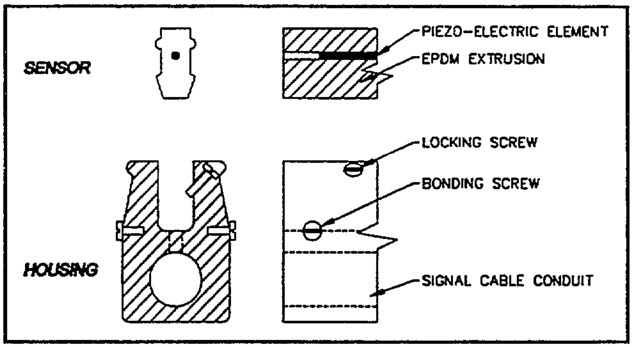

Figure 8: The bicycle sensor is a modification of the UK DoT design. The sensor is replaceable in the channel without having to recut the slot.

Variations of this sensor have also been used for bicycle sensors. A series of short sensors ≈ 500 mm long have been installed, with the signal cable going through the conduit in the bottom of the channel. Since the handlebars of the bicycles will not allow riders to simultaneously hit a sensor, an accurate count on a bicycle path is possible. The lower output from a bicycle due to their light weight may require an amplifier circuit to be used prior to conventional traffic data counters. Pedestrians do not trigger the electronics, since a sequential output is being looked for, and the frequency response of the footfall is very different from the wheel impact.

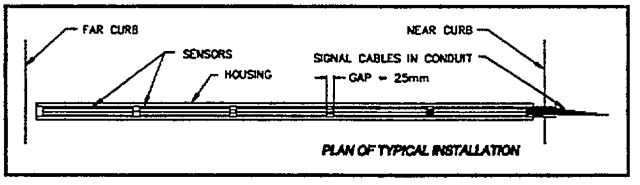

Figure 9: Short sections are used so that only one bicycle at a time can impact a sensor.

It is desirable to detect pedestrians at pedestrian crossings, to control the traffic lights. This allows for the faster response to the pedestrians for the traffic signals, yet prevent the turning of the lights when the pedestrians walk away from the area. A large ≈ 400 mm x 400 mm rubber tile is fitted with a piezo cable in a helical pattern. The cable is embedded into the rubber, and is positioned so that it is directly under the tactile bumps in the tile which allow blind people to feel the tiles. This positioning gives a higher output from the piezo cable, since more stress is being generated. Electronics have been developed with digital filtering to eliminate triggering on

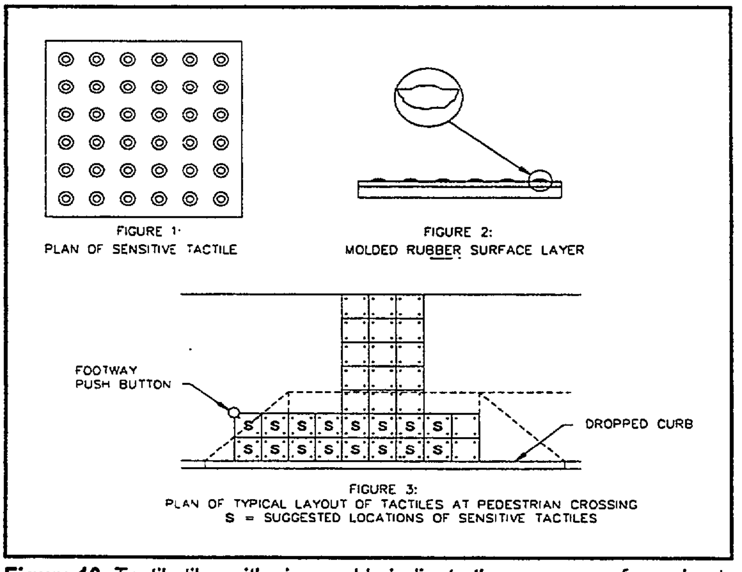

Figure 10: Tactile tiles with piezo cable indicate the presence of people at intelligent pedestrian crossings

road noise, yet still be able to detect the initial stepping onto the tiles and the low frequency motion associated even with the most determined effort to stand still.

This same electronics has been applied to sensors to be used for toll booths. Previously, piezo sensors have not been used for this application, since they were not able to detect a stationary vehicle. With the advanced electronics with filtering, a stationary vehicle can be detected by the transmission of the engine vibration to the sensor through the tires. Either a permanently mounted sensor can be installed, or a replaceable sensor such as the UK DoT model.

Much of the technology developed for traffic data collection can also be used for security purposes. The coaxial piezo cable has been directly buried in the ground and can detect people walking over it, as well as vehicles. Signal processing can be done to eliminate background noise, such as roads, waves on a beach, or animals in some cases. Long ≈ 30 meter sensors have been installed at airports on a technology demonstration project to monitor the movement of aircraft and other vehicles on taxiways. There are very distinctive signals for the different aircraft types, based on the tire configuration on each landing gear. A third sensor was used at a 30° angle to the other two sensors to detect the presence of a double tire. A flush installation technique was needed, since runways are scraped clean with snowplows, and any protrusion of the sensor would be torn off, creating the possibility of damage to the aircraft.

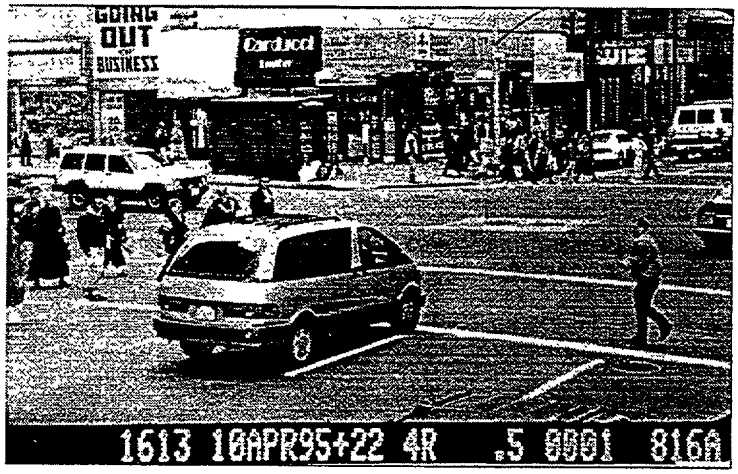

Figure 11: Picture A, before the vehicle enters the intersection. Note that the red light is 0.5 seconds into the cycle.

APPLICATIONS

The key application for these sensors in the US and other countries is still the gathering of data for LTPP and other statistical purposes. There is a growing trend though to use axle sensors for enforcement purposes in speed cameras, red light violation cameras, and automated toll booths.

Speed cameras have been used for a number of years in Europe as a way of effectively controlling the speed of vehicles. For these applications, either two or three sensors are used, all perpendicular to the flow of traffic.

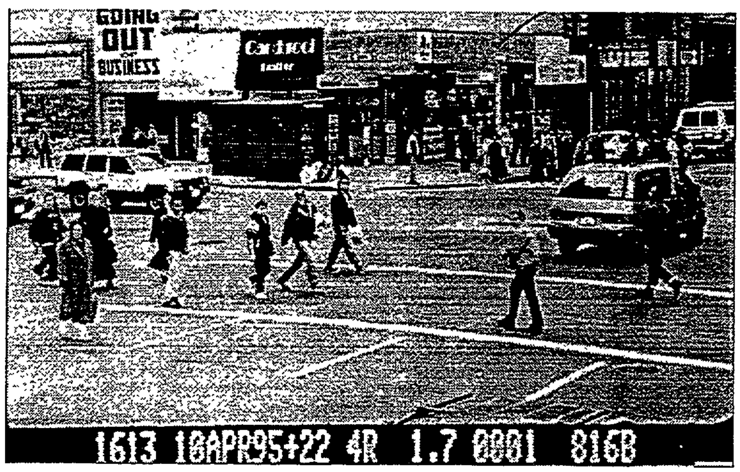

Figure 12: Picture B of the sequence, taken 1.2 seconds after the first shot. The license plate number is read from this photo.

The sensors are typically 3 meters long (ie full lane width) and are placed 1.5 to 6 meters apart, and are used in conjunction with an inductive loop. When the wheels impact one sensor, it starts the clock, and then turns it off when impacting the second sensor. A third sensor can be used as a verification of the first speed, depending on local laws and requirements. The camera will photograph the vehicle automatically if the speed is over a preset limit. These stationary cameras are often supplemented with mobile cameras which use radar or laser as the sensing media. In New Zealand, which implemented an aggressive speed control program, the ninety percentile of the vehicles (ie the speed at which 90% of the vehicles is below) is less than the speed limit. Public acceptance has been good, since it is viewed as an equitable enforcement system, where nobody has an unfair advantage.

Red light violations pose more safety issues than speeding, especially in major cities. New York City as well as many others have installed Red Light Cameras to monitor and enforce the violation of red light laws. Typically, two piezo axle sensors are installed per lane, just upstream of the stop line. When the light is red, and a vehicle crosses over the sensors at a predetermined speed, the first picture is taken. At a certain time, calculated based on the speed of the vehicle, after the first picture, a second picture is shot. On both of these frames of 35mm film, the vehicle, the red light and the sensors are all seen. In addition, information is printed on the film with the location, time/date, speed, time into the red light and the lane number. At the Red Light Camera Office, these photographs are all viewed, and either by an operator or with OCR, the license plate number is determined. These are all printed out and sent with the ticket.

A similar system can be employed with Automatic Vehicle Identification (AVI) for toll systems. The axle detectors are able to determine if a vehicle is a truck or a car. Since many of the AVI toll systems are vehicle type based, this information is needed to apportion out the correct toll. For vehicles that do not have the AVI tags or have an expired tag, the camera can photograph the vehicle and license plate for further action.

CONCLUSIONS

Piezoelectric polymer traffic sensors are being widely used for a variety of different applications. The construction techniques now available are producing lower cost sensors which are easy to install and produce reliable long term data.

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CERAMIC PIEZOELECTRIC TRAFFIC SENSORS

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VTBRACOAX CERAMIC PTEZOELECTRIC TRAFFIC SENSORS

1. INTRODUCTION

Vibracoax ceramic piezoelectric sensors were developed 25 years ago as vibration detectors. Since 1975, they have been tested and used for traffic management as axle sensors and Weigh-In-Motion sensors. The road environment is a very demanding one, and sensors should last as long as possible (at least as long as the pavement itself) and continue to perform accurately. Originally, the use of the Vibracoax ceramic piezoclectric sensors was restricted to almost "perfect" road sites. Nowadays, Agencies and operators want to be able to manage traffic on all roads, with as few restrictions on site selections as possible. This paper describes the manufacturing of Vibracoax ceramic piezoelectric sensors, how they can be used as traffic sensors to measure weights, and the latest developments of bare and encapsulated sensors.

2. MANUFACTURING OF VIBRACOAX CERAMIC PIEZOELECTRIC SENSORS

2.1 MANUFACTURING PROCESS

A Vibracoax ceramic piezoelectric sensor consists of two components:

-the active piezoelectric sensing cable, which generates the electrical signal,
-the extension cable, usually a SO ohm cable which transmits the signal to the electronic data processing devices.

These two components are connected together with a hermetic electrical and mechanical connection.

The active piezoelectric sensing element is derived from a "Mineral Insulated Cable" (MI cables). MI cables are produced with a very specific production process (see figure I). Usually the sheath and conductor(s) are made of stainless steel. nickel alloys or refractory metals. The insulating material is a metal oxide (Magnesium oxide for example). These MI cables are used to produce a variety of products including temperature sensors and heating devices that are able to work at temperatures as high as 2000°F. The same technology is used to produce ceramic piezoelectric sensors. utilizing different raw materials. and adapting the reduction process to these materials.

In Vibracoax, both the impervious outer sheath and the solid center conductor are made of copper and the insulator is a tightly packed piezoelcctric ceramic powder. The raw materials are assembled and then reduced in diameter by several swaging operations (see figure 2). The assembly is placed inside a set of three or four rotating hammers which compress the outer tube, the powder and the center conductor. When the powder density reaches approximately 85 to 90% of its theoretical density, the assembly is considered a "solid" wire. The outer diameter reduction process will then homothetically reduce ail MI cable components resulting in an increase in length. The exact reduction route (amount of diameter reduction per step and annealing temperatures) was developed to match the Vibracoax components mechanical and thermal properties. This technology allows production of ceramic piezoelectric cable of diameters ranging from 8 mm (.31") down to I mm (.04"). These cables are very strong and can withstand very harsh environments. They are at the same time very durable (they can survive very high mechanical stresses) and flexible (they can survive deformations without breaking any cable component).

2.2 POLARIZATION-SENSITIVITY- HOMOGENEITY

2.2.1 POLARIZATION

The completed assembly can be considered as a cylindrical condensator with the copper tube and conductor the electrodes, and the piezoelectrio powder the dielectric. The nature of piezoelectric material is to generate electrical charges when submitted to an external pressure. Every time the outer sheath is submitted to a pressure variation. it will transmit this variation to the piezoelectric powder. The powder generates electrical charges which are collected by the copper sheath and conductor.

As manufactured, Vi bracoax sensitivity (electrical charges created by external pressure variations) is very low. The individual piezoelectric particles are randomly oriented (see figure 3). In order for the individual particles to add their individual contributions they must be oriented in the same direction (radial direction in the case of a cylinder). This can be accomplished by an operation called "Polarization" (see figure 3). In this treatment, the temperature of the piezoelectric powder is elevated and at the same time a strong electric field is imposed. At the elevated temperature.. the individual piezoelectric dipoles can rotate to become aligned with the electric field, then this configuration is frozen to get the highest sensitivity. The polarization process is reversible which means a high increase of temperature could free the piezoelectric dipole allowing them to return to their original state. This is why it is not --- recommended to expose Vibracoax sensors to temperatures higher than 220F for long periods of time (i.e. several hours). Twenty four hours at 22OF can reduce the sensitivity by approximately 20% (ref. I).

Another way to reduce the sensitivity is bending the Vibracoax cable. Bending of the sensor, on a radius smaller than I foot. followed by straightening can also reduce the sensitivity. Handling in this manner forces some powder particles to slightly change their orientation and the generated electrical charges will not fully add. as in a fully polarized sensor.

Users of bare small diameter Vibracoax sensors (3 mm OD) are advised to use extreme care when installing them in road pavement. A small diameter sensor is not mechanically very stiff. It is difficult to handle long, small diameter sensors without bending them. This problem may be overcome by using larger diameter sensors (8 and 6 mm for example).

2.2.2 SENSITIVITY

When used as traffic sensors, Vibracoax ceramic piezoelectric sensors are buried into the road pavement. They are placed inside a small groove machined into the pavement, perpendicular to the direction of traffic, and held in place with an adequate grout. Depending upon the application, the sensor length can be either the full lane width or only half the lane width. When installed, sensors are almost invisible and can sense pressure variations induced by passing wheels. To help the installation sensors can be encapsulated. An encapsulated sensor is a Vibracoax piezoelectric sensor which is incorporated inside a stiff assembly to protect the bare sensor against any manipulation which can either alter ‘its homogeneity and sensitivity or reduce its expected life. In order to calibrate sensors before installation in the road, several methods were developed to simulate the pressure variations the sensors will experience in road pavements.

The conventional method to test the sensor sensitivity is to apply an external pressure (up to 10 bars, I SO psi) on the outside sensor sheath and to measure the generated voltage (isostatic method, see figure 4 and 5). This method was qualified by the French DOT I5 years ago (ref. 3). Several companies and government agencies use the same technology and results found on the same sensors are very similar from one lab to another. A precise evaluation of the accuracy of this method shows the measurement standard deviation to be about 3% (ref. 3). A similar method is used to test square or rectangular encapsulated sensors. Air pressure is applied to the external sensor surface through a flexible membrane.

An alternative method to test sensors is to apply a vertical unidirectional pressure on the surface of the sensor and measure the generated voltage (see figure 5). The advantage of this method is that it can be applied not only on bare and encapsulated sensors, but also on installed sensors in road pavement. But, it is difficult to test small diameter sensors and the method is not fully developed yet. On road applications, this method is also very time consuming.

The theoretical sensitivity of a 3 mm OD sensor is about 1 Volt generated for 1 bar (15 psi) pressure variation applied on the entire outside sensor surface (ref. 2). The typical sensor sensitivity is very close to the theoretical one. For larger diameter sensors, the sensitivity increases. The sensitivity of an 8 mm OD sensor is close lo 2 V/Bar.

2.2.3 HOMOGENEITY

A very important sensor property is the homogeneity of its sensitivity over its length. Variation of sensitivity can originate from several factors including: exact inner sheath and conductor sizes and shapes, position of conductor inside the insulator, insulator particle size, insulator porosity and polarization.

In the early 1980's, the French DOT created a classification for bare sensor accuracy :

Class 1	Sensitivity variations smaller than +/-7% when measured on 25 cm (10 in) every 25 cm, main application: WIM
Class 2	Sensitivity variations smaller than +/-20% when measured on 25 cm (10 in) every 25 cm, main applications: AVC, ATR

In 1994, the French DOT developed a new specification for bare and encapsulated sensors. The new specification for encapsulated sensors is (ref. 7):

Class 1	Sensitivity variations smaller than +/- 10% when measured on 25 cm (IO in) every 25 cm. main application : WIM
Class 2	Sensitivity variations smaller than +/-20% when measured on 25 cm (10 in) every 25 cm. main applications : AVC, ATR

In production, 100% of class I bare sensors are tested for homogeneity. It is difficult to test 100% of encapsulated sensors as their external shapes are different from one model to another. These sensors are stiffer than bare ones and any vibration induced in the sensor could produce a signal of the same order of magnitude as the one generated by the tested section. Our policy is to extensively test sensors in the development phase so that with the bare sensor testing and rigorous encapsulation work instructions will ensure that encapsulated sensors are manufactured according to specification.

2.3 CERAMIC PIEZOELECTRIC ROAD SENSORS

Since the beginning of the use of ceramic piezoelectric sensors several variations of road sensors have been developed. Figure 6 shows a selection of popular types. After initial tests made on bare 3 mm OD sensors, users came up with a simple encapsulation method. The ceramic piezoelectric sensor is placed at the neutral fiber of an aluminum channel in order to Iimit the influence of pavement and sensor bending. The channel filling is made of a sand epoxy mix, of which the mechanical sensitivity is almost insensitive to temperature. Many companies use this design. In figure 6, sensor #-I-is the most popular in France and #5 is the most popular in the USA. The US model is stiffer than the French one. Different colors of the epoxy fillings make it easier to identify Class 1 and Class 2 sensors. About encapsulation of sensors, it should be noted that many patents exist, in different countries. Our opinion is all patents describing sensors similar to theses two models have been preceded by a 1938 US patent granted to Warren Putman (ref. 14). The French DOT found this design too sensitive to pavement bending and vibrations, and came up with a special "LCPC" design (ref. 5. figure 6 model #2). The main differences with the previous versions are:

-the ceramic piezoelectric sensor is not on the channel neutral fiber, but over the channel,

-a vibration and deformation damping material is added to the channel sides.

This sensor has been used for many years in French roads for WIM with good success. The main disadvantage of the sensor is that it is brittle. The aluminum channel is not very stiff and if installed in flexible pavement, the sand epoxy can break and then the copper outer sheath of the sensor will snap. A special vehicle is used in France (Deflecto, ref. 15) to measure the pavement deflection under load. To be safe the "LCPC" sensors should be installed in road with a deflection smaller than .02 mm (.0008 in), under a Deflecto vehicle loaded with 13 metric tons on the back axle. This greatly Iimits the use of the LCPC sensor.

To open the use of ceramic piezoelectric sensors to almost all roads, the French DOT developed another encapsulation technique (ref. 6, figure 6 model 3). The 3 mm ceramic piezoelectric sensor is placed inside several layers of glass fiber mats and an epoxy resin is injected and cured to make a squared cross section sensor. This sensor is flexible, but very robust. The pavement installation technique, which is patented (ref. 6), is very important for long lasting and accurate WIM measurements. This sensor was developed in 1989, prototypes were installed in roads and survived more than 12 million truck axles without visible aging.

This sensor is the French DOT recommended model for WIM applications and the only one qualified, so far, for the "SIREDO" project. This project will incorporate 1200 stations for French traffic data collection (ref. 12). About 300 stations will classify the traffic in "silhouettes" and/or weights. The drawback of this "SIREDO" sensor is its **cost.** Each sensor has to be placed inside a mold with the glass fibers and the epoxy resin injected and cured. This is a time consuming process.

Thermocoax developed an alternative sensor type "FP" (figure 6, model #4). Instead of using an injection method to manufacture the sensor, a laminated epoxy channel is used with a groove precisely machined. The Vibracoax ceramic piezoelectric sensor is held in place with glue. Some prototypes are in the testing phase in a United Kingdom highway (A34 south of Oxford).

All the encapsulation methods were developed to improve the mechanical strength of the piezoelectric sensors. They all create another barrier between the sensor and the road: sand epoxy, or laminated epoxy, or polyurethane, the aluminum channel and the grout. An alternative to encapsulation methods is to increase the mechanical strength of Vibracoax ceramic piezoelectric sensors themselves. A simple method is to increase the outer diameter. A new Vibracoax mineral insulated cable manufacturing process was developed to produce larger size cable, while keeping the same piezoelectric properties and the cost down. Keeping costs down can be difficult because PXE materials are quite expensive and a larger sensor will incorporate more PXE ceramic powder.

We standardized two models (figure 6, model #6):

-6 mm OD for Class 2, 6 feet long sensors,
-8 mm OD for Class 1, 11.5 feet long sensors.

The sensor cross sections and lengths are matched to give enough strength to the sensors so that they will not bend when transported or handled. A number of sensors were tested in France and in Canada and they have given excellent results. The first advantage is the use of the bare Class 1 sensor specification (7% instead of 10% for encapsulated sensors). The second advantage is that the pavement installation groove can be smaller: 15 mm (3/4 in.) width by 15 to 20 mm (3/4 to 7/8 in) depth. The smaller groove allows the pavement to be less distressed and installations are quicker and less costly. Another advantage is the strength of the signal. Testing shows that signals generated by the 8 mm bare sensors are 2 to 3 times higher than the encapsulated sensors ones (ref. 8, 9, 13). Figure 9 shows a comparison made on adjacent encapsulated 3 mm and 8 mm bare sensors. From 40 trucks heavier than 5 metric tons, signals from the two sensors treated with different gains but by the same electronic equipment were found to be very similar. On 17 trucks, similar to “2S3”, the situation was the same.

All the previoiusly described sensors were permanently installed in the road pavement. There is also a demand for surface mounted sensors strong enough to survive truck traffic, but accurate and easy to install without having to work on the pavement. Thermocoax developed a “surface” sensor made of a I mm OD Vibracoax ceramic piezoelectric sensor placed inside two layers of thick adhesive road tape (figure 6, model #7). The 1mm OD cable is very small and brittle, but protected by the tapes it can survive the traffic. The main problem is to find a very smooth road pavement, with few variations which will create sharp bends in the sensor and break it. Experiments show (ref. 9) that on very smooth pavements, sensors can last as long as 3 weeks or 250,000 axles. On rough pavements, the life will he only a few days. This surface sensor’s output is twice as high as the conventional permanently installed 3 mm sensors. When used with a WIM electronic system, the accuracy on measured weights with the 1 mm surface sensor is slightly degraded compared to the 3 mm conventional sensors. Appendixes 1 to X describes several test sites used to develop and qualify these sensors.

3. THEORY OF OPERATION

3.1 ELECTRICAL CHARGES GENERATION

The physical property of piezoelectric materials is to generate electrical charges for any dimensional changes. In the elastic zone of material deformation, the elastic modulus is the ratio of the stress divided by the deformation. A ceramic piezoelectric material possesses a very high elastic modulus which results in high stress with very little deformation - it is a stress or pressure variation sensor. A plastic piezoelectric material possesses a low elastic modulus which results in high stress with a large deformation - it is more a deformation sensor.

When a piezoelectric sensor is submitted to a pressure variation, due to passing wheels for example, electrical charges are created (see figure 7. Q 1 and Q2). These charges are then spread over the sensor and extension cable inner surfaces. The sensor can be considered a cylindrical condensator and the voltage (V) applied between the electrodes can be related to the stored electrical charges (Q) and the capacitance (C) by the following relation:

$$Q = C + V$$

The capacitance of the piezoelectric material is rather high. A typical value of 10.000 pF/m (3,000 pF/ft) is found in Vibracoax cables. Extension cables are much less capacitive (100 pF/m, 30 pF/ft), but they are much longer! Figure 7 gives the relation which permits calculation of the generated voltage for a given sensor definition. In order to get a stronger signal, the capacitance must be kept at a minimum. This means that sensor and extension cable lengths should be designed as short as possible.

Often, users would like to install sensors with extremely long extension cables. This is easy to manufacture, but such a sensor could deliver a signal too small to be processed by the electronics. There is a way to estimate the signal decrease for a given increase of the extension cable. As an example, the sensor length is Lpxe and the extension cable length Ll . For a given stress, the signal will be VI. If, for the same sensor length and stress, we increase the extension length to L2, the signal would be V2. The voltage drop can be calculated as folollows:

$$(V2-Vl) / Vl = 30 (Ll-L2) / (3{,}000Lpxe+30L2)$$

For example, if the extension cable for an 11 ft. sensor is increased from 60 ft. to 300 ft.:

Lpxe= 11 ft, L1= GO ft, L2 = 300 ft,

$$(V2-VI) / VI = -15\%$$

Depending on the electronic device associated with the sensor, and also the kind of measurement to be performed, the extension length can be as long as 600 ft.

3.2 WEIGH IN MOTION WITH CERAMIC PIEZOELECTRIC SENSORS

In a cylindrical sensor the piezoelectric effect can be written as follows (see ref. 3):

$$E_r = -g_{31} T_\theta - g_{32} T_r$$

T_θ and T_r are the stresses induced in the piezoelectric material, g_{31} and g_{32} the piezoelectric constants. This electric field then creates charges and a voltage such as:

$$V = \int E_r \, dr$$

The generated electrical charges, or voltage, are proportional to the applied pressure variations. But what we want to measure is the "dynamic" weight of vehicles not the pressure they induce in the road pavement. Figure 8 will help us better understand how, from a pressure measurement, it is possible to calculate a weight. For example, a vehicle axle Weight generates a pavement Pressure on 2 tires footprint (each Cby L):

$$W = P \cdot 2\ell \cdot L$$

Electrical charges Q are created by the pressure variation ΔP on the sensors length 21 (width of 2 tires):

$$Q = k' \cdot \Delta P \bullet 2C$$

The total number of electrical charges created by the 2 tires are then proportional to the axle pressure:

$$P \cdot 2\,\ell = k \cdot \int Q$$

Now the problem is to estimate the tires footprint length L. From the electrical signal, V function of time, we know the length of time, τ, the tire touches the sensor. If we know the vehicle Speed we can calculate the tire footprint length:

$$L = S \cdot \tau$$

The weight can then be calculated as follows:

$$W = k \cdot \int Q \cdot S \cdot \tau$$

This method, which requires the use of two sensors for speed measurements, allows the calculation of axle weights even though the sensors are smaller than tire footprints and are measuring only pressure variations. The drawback of measuring pressure or stresses is that sensors are measuring all pavement stresses and deformations. Spurious signals have to be eliminated or reduced to a minimum.

Spurious signals may come from:

-vibrations: transmitted from the pavement. mainly concrete, to the piezoelectric sensor. They increase the background noise and can create problems with low weights. Their effects can be greatly reduced by proper sensor design and good choice of grout.

-pavement bending: created, mainly in asphalt pavements, by excessive vehicle weights. This occurs when the pavement is not strong enough to withstand the vehicle weight. Horizontal and/or vertical pavement defections generate low frequency signals which superpose with the axle weights signals. This generates a distortion of the signal base line and makes it more difficult to correctly assess the exact number of charges ($\int Q$) and time (τ). If the pavement deflection is too large not much can be done to get good measurements. For WIM, pavement deflection should be a criterion for site selection.

-pavement mechanical properties variation: as stresses are transmitted through the pavement, any fluctuation of the mechanical properties, mainly asphalt with temperature, will modify stress distributions and then signals. For low grade asphalt pavements, a temperature sensor should be added to the piezoelectric sensor to correct electronic measurements.

4. SENSORS ROAD INSTALLATION AND INITIAL CALIBRATION

4.1 ROAD INSTALLATION

It is well known that good site selection is crucial for correct WIM measurements with Vibracoax ceramic piezoelectric sensors. A partial list of recommendations will include:

- in concrete pavement stay away from slab joints, cracks, pot holes, repairs.
- in asphalt pavement stay away from flexible pavements, cracks, pot holes, repairs.
- stay away from curves, bumps. rough and/or non horizontal surfaces.
- stay away from speed variation zones. intersections, traffic lights.
- stay away from vibration generating devices such as railroad tracks, trees.
- stay away from electric signal generating devices such as high voltage power lines.

Every experienced company or contractor installing sensors will have its own installation practices and preferrences. Usually they have to cut a groove, as regular and perpendicular to the traffic as possible. Well controlled cutting dimensions help to achieve uniform and homogeneous grout filling. The selection of the right grout has to be made according to:

- type of pavement : concrete or asphalt.
- temperature level at the time of installation and in operation,
- the type of electronic device hooked up to the sensor.

The grout has to firmly hold the sensor in place and it is very important that the grout correctly adhere onto the sensor's outside surfaces and onto the road pavement. It should have mechanical properties similar to the road pavement. be soft enough to dampen the vibration noise existing in the pavement and produced by the traffic, and cure as fast as possible without getting too hot.

4.2 INITIAL CALIBRATION

Vibracoax ceramic piezoelectric sensors measure the pressure variations created by the vehicle passing wheels. This pressure distribution around the sensor depends on the sensor design and installation, but also in large part on the road pavement itself. Because of this, initial sensor calibrations are required for quality control, but they are not sufficient to calculate vehicle weights from the measured signals. An in situ calibration is then required. Several methods can be used (ref. 16):

-a follow weight deflectometer (FWD as the “Dynaplaque” for example): a know load is held at a given height over the sensor. It is allowed to free fall onto the sensor and the signal is recorded. Several tests, at different locations across sensors can give an idea of the local sensitivity of the couple “road + sensor”.

-the “Piezodyn” (ref. 8): a motorized piston applies a known pressure variation on the in-pavement sensor. The same system can also be used on sensors prior to installation. Again the output is recorded and can give local sensitivity indications.

Unfortunately, these methods are not very precise and reproducible. The surface of impact and/or contact between the test device and the sensor varies with location and repeated tests, and these methods are not very precise. Dispersions can be as high as 30 to 50% on the same sensor. The more conventional method is to run a known truck several times over the site to correlate outputs to axle and vehicle weights. The problem is we compare a static truck weight, measured onto a static weight platform. to a dynamic load which depends on the road itself but also on the truck suspension. The "DIVINE" OECD project (ref. 16) is studying the effect of dynamic loads on pavements and bridges. The "LCPC" (French DOT research lab) is studying the spatial repeatability of axle impact forces (ref. 16). Eighteen Vibracoax ceramic piezoelectric sensors were installed on a test site west of Paris. Their spacing are different, from .375 m (1.25 ft) to 2.25 m (7.4 ft). This site was initially calibrated with two known trucks. The sensor sensitivities were within a 10% standard deviation, total dispersion +/-22%. The site was then calibrated with an instrumented Canadian "3S2" truck. This truck. with a pneumatic suspension, is equipped with load cells which can measure the impact forces of the wheels onto the pavement, with a 3% accuracy.

Figure 1 1 shows how the measured sensitivity of the 18 sensors installed on the same site are scattered. Sensitivities measured with the instrumented truck are even more scattered than what is measured with conventional trucks. lt seems sensitivities can be split in 3 homogeneous groups. This scattering is coming from the road itself not from sensors.

A statistical analysis was performed on 64 Vibracoax sensitivities measured on bare 3 mm and then on the same sensors encapsulated with the SIREDO design. The sensors were manufactured in 5 different batches and delivered within 4 months (Oct. 94 to Jan. 95). On the bare 3 mm sensors the sensitivity dispersion was less than +/-8% and the homogeneities between 1.9 and 5.9%. On the same encapsulated sensors the sensitivity dispersion was less than +/- 1 0%, and the homogeneities between 1.6 and 8.3%. Only 2 encapsulated sensors, out of 64, showed a homogeneity dispersion larger than 7%.

Another influencing factor of sensitivity and calibration is temperature. Mechanical properties of materials are more or **less sensitive** to temperature. Plastic and rubber, asphalt and concrete as well, can be very sensitive to temperature. As the sensor is measuring the pressure variations induced by the passing wheels, it is important that mechanical properties do not change much **with** temperature, so that the system sensitivity does not change with the time of day or within a year. Components selected for the different encapsulation models are selected to be less sensitive to temperature: sand epoxy. laminated epoxy or polyurethane. The PXE material is not very sensitive to temperature. Figure 10 shows sensitivity variations measured on a 3 mm Vibracoax **ceramic piezoelectric** sensor between 80 and 1 56OF. The sensitivity increase is 0.1% per degree F or +/-4% within 80 to 150F. Concrete pavement does not change much with temperature, but asphalt pavement can change a lot. If the pavement is too sensitive to temperature, it is recommended that a temperature sensor be added during Vibracoax installation to correct outputs.

5. CONCLUSIONS

Vibracoax ceramic piezoelectric sensors have shoiwn their ability to perform well in traffic management and weigh in motion applications. Several sensor designs are available to give users flexibility in installation and **use.** Nevertheless. some care has to be taken in sensor selection, site selection, sensor installation and calibralion to get precise and long lasting systems. Several dozen of thousand of sensors arc installed worldwide, from very cold to very hot areas (Canada to Saudi Arabia). They have demonstrated excellent reliability at a low price.

An average good site will last up to five years and accuracy on total vehicle weight will be within 10% of the static weight. New sensors, based on this well known and proven technology, are under development to further improve and facilitate the use of ceramic piezoelectric sensors in areas or pavements that continue to be very difficult.

APPENDIX I

NEW SENSORS TEST SITES

Type of sensors

8 mm bare

Dimension of groove

15 x 15 mm (.6 x .6 in)

Sites

location: RN 10, France (4 lane highway, southwest of Paris) (ref. 8)
No. of installed sensors: 2
Installation date: April 1994
Traffic: as of January 96, more than 9 million vehicles of which 2 million are trucks heavier than 7500 Lb.
Application: WIM
Status as of Jan. 15, 1996: excellent signal (see figure I 1), working fine, almost no change in calibration

location: A l 1 and A8 1, France (divided highways, equivalent to Interstate) (ref. 8)
No. of installed sensors: 16 sensors
Installation date: early I994
Traffic: as of January 1996, more than 43 million vehicles of which I.5 million are trucks heavier than 7500 Lbs.
Application: WIM, pavement distress/management
Status as of Jan. 15, 1996: excellent signal. working fine, almost no change in calibration

location: Paris' Peripherique (equivalent to Interstate. 1 million vehicles/day) (ref. 8)
No. of installed sensors: 20 sensors
Installation date: early 1994
Traffic: as of January 1996, more than 2 million trucks heavier than 7500 Lbs.
Application: WIM
Status as of Jan. 15, 1996: excellent signal. working fine

location: CARROS, France (4 lane highway, southeast of France, close to Nice, Lacroix Tech test site) (ref. 13)
No. of installed sensors: I
Installation date: March 1994
Traffic: as of January 1996, about 200.000 trucks heavier than 7500 Lbs. (total accumulated weight 5,000,000 metric tons)
Application: WIM, testing
Status as of Jan. IS, 1996: excellent signal. twice encapsulated sensors working fine.

location: Saskatoon, Canada (IRD test site) (ref. 9)
No of installed sensors: 2
Installation date: Sept. 1995
Traffic: as of Jaunary 1996, 125,000 truck axles, l ,OOO,OOO car axles
Application: W IM, testing
Status as of Jan. 15, 1996: excellent signal. three to four times encapsulated sensors signals, working fine.

APPENDIX 2

NEW SENSORS TEST SITES

Type of sensors

Encapsulated type “FP” »

Dimension of groove

40 x 40 mm (1.6 x 1.6 in)

Sites

location: A34, the UK (divided highway equivalent to Interstate)
No of installed sensors: 3 sensors
Installation date: December 1995
Traffic:
Application: WIM, testing
Status as of Jan. IS, 1996: not connected to an instrument yet

APPENDIX 3

NEW SENSORS TEST SITES

Tvpe of sensors

Encapsulated type “SIREDO”

Dimension of groove

SO x SO mm (2 x 2 in)

Grout

laminated epoxy

Sites

Location: SIRED0 sites all over France
No. of installed sensors: 400 sensors
Installation date: prototypes in 1989, IS in 1993, 130 in 1994, 240 in I995
Traffic: on the oldest development models: 12 million truck axles, plus 22 millions car axles
Application: WIM, traffic management
Status as of Jan. 15, 1996: no defects

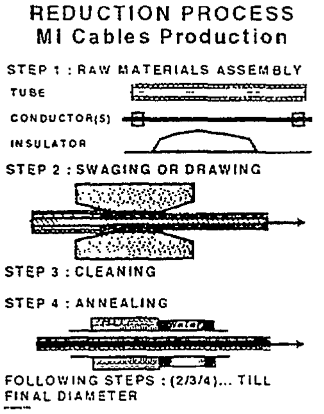

FIGURE 1

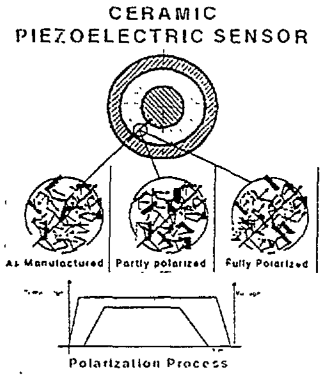

FIGURE 3

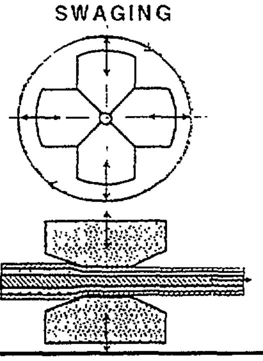

FIGURE 2

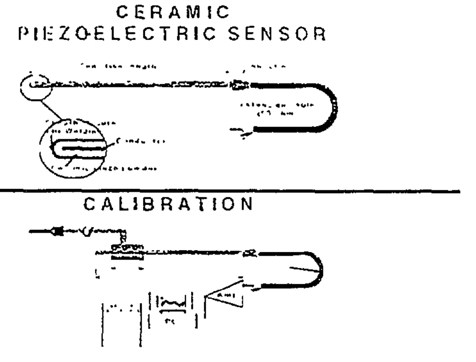

FIGURE 4

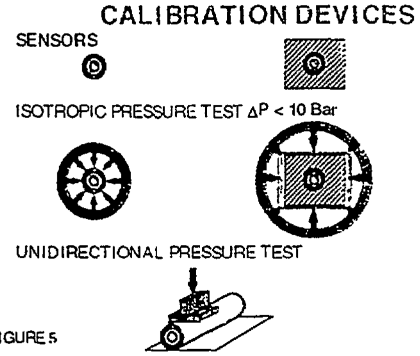

FIGURE 5

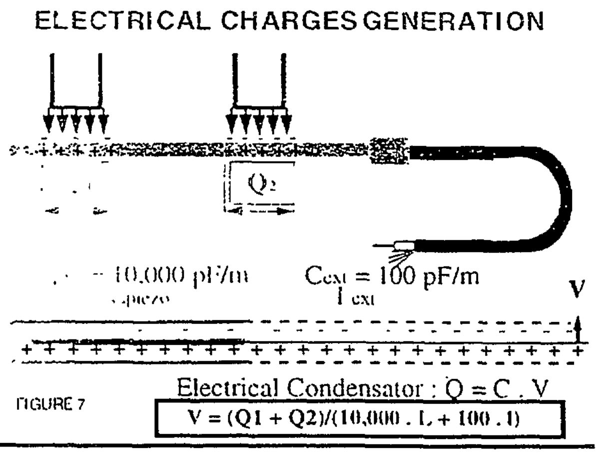

FIGURE 7

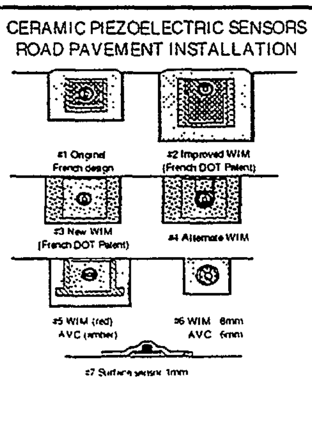

FIGURE 6

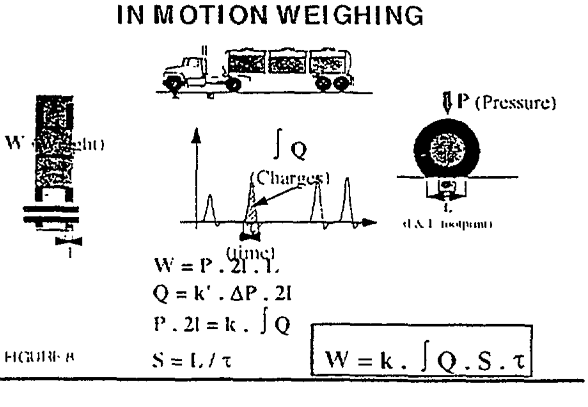

FIGURE 8

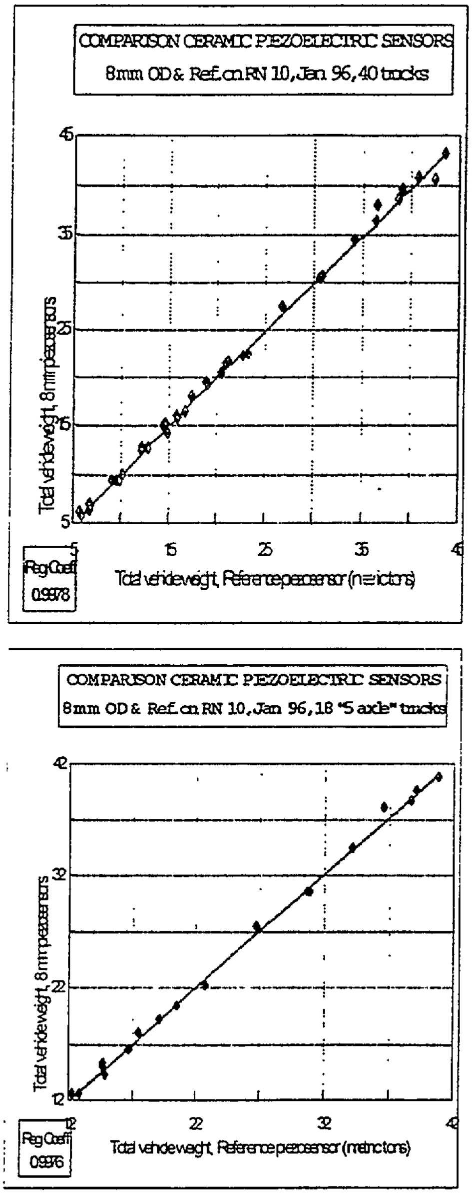

FIGURE 9

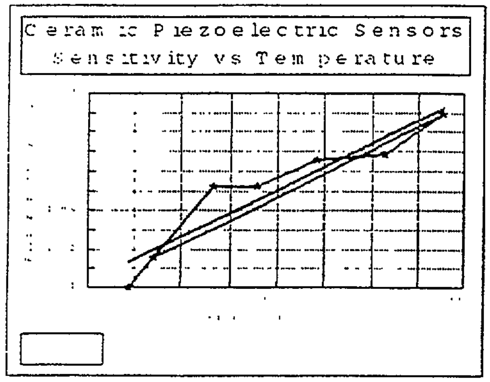

FIGURE 10

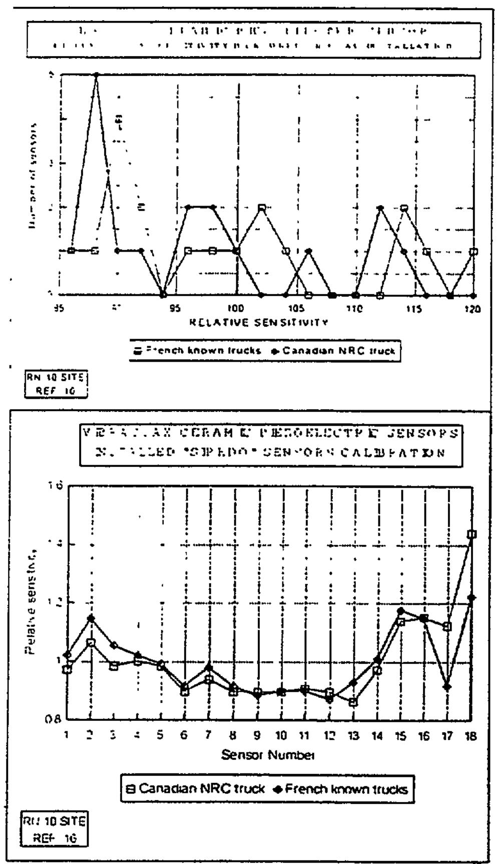

FIGURE 11

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LONG-TERM STABLE QUARTZ WIM SENSORS

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LONG-TERM STABLE QUARTZ WIM SENSORS

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Abstract

A novel sensor for the dynamic weighing of axles of road vehicles (WIM - Weigh-In-Motion) and a suitable road installation technology have been developed and tested with regard to the stability criteria for long-term performance.

The new sensor uses piezoelectric quartz crystals as force measuring elements. The sensors and their installation technology were tested in the laboratory, on a circular fatigue test circuit and on public roads.

The dependence of the sensor performance on speed, vehicle type, climatic conditions and its variation with time was examined.

Decoupling of the sensor from lateral forces in the road was found to be essential to obtain good signal pulse shapes and reproducible results.

The installation technology was investigated for different environmental conditions.

As optimized installation material a sand epoxy mixture was utilized.

The sensor performance was established in the context of the European WIM research project COST 323 by comparative dynamic weighings of some 1500 different vehicles on a public road in Switzerland.

Keywords:

Weigh-In-Motion, quartz sensor, load sensor, test track, gross weight mass, dynamic load.

1. Introduction

Weighing of road vehicles axles in motion (WIM) is getting more and more important for the record and analysis of traffic. For a more accurate classification of vehicles, also the axle and gross weights are needed.

Traffic weight data are mainly useful in the five following areas:

- Design of roads and bridges (bearing capacity)
- Traffic safety, overload warning thresholds
- Pavement management and repair costs
- Data base for traffic policy
- Preselection for law enforcement

In the last years increasing attention is paid not only to the gross weights of heavy vehicles, but specially to the individual axle loads. As the damage to road structures is roughly proportional to the fourth power of the wheel loads, the highway authorities show an increasing interest in detecting vehicles with overloaded axles with high impact factors, contributing significantly to the expensive consequences of fatigue in pavements and bridges.

There are a lot of different commercial WIM sensors available on the market, but some of them are still not very accurate or their installation in the road is rather awkward and their durability is not satisfactory.

Commercial WIM systems may be divided into two major groups according to their shaperelated functional principle:

- Weighplate systems

On a weighplate the full footprint of a tire is acting by its force onto the sensing elements. With strain gauges or other static sensor elements even vehicles at zero speed can be weighed. For measurements at high speeds the dynamic effects as wheelhop and suspension oscillations can affect the accuracy adversely. The wavelength of the oscillations generally exceeds the plate width, thus averaging by multiple systems would be desirable. In practice the high costs for plates and their installation with steel frames are an obstacle.

- Line sensor WIM systems

Load sensors with bar-shaped cross sections can be installed in narrow pavement grooves and are economic, thus multisensor arrangements for averaging dynamic effects are common practice. As bar widths are smaller than the tire latch, the force signal has to be integrated over the wheel contact length. Therefore the performance of line sensors depends extremely on the stability of their signal quality during the integration intervals, as well as of the longterm interactions between sensor and pavement.

The stability problems of conventional axle load sensors motivated the development of a novel WIM sensor based on quartz crystal elements. The sensor presented here provides high durability and accuracy and is easy to install.

2. Design Considerations

The mechanical and electrical stability of a WIM sensor is depending on a multitude of factors with influence time constants ranging from milliseconds to years. These influence factors vary in magnitude between piezoelectric, capacitive and other sensing systems. They shall be described in comparison with piezocable sensors as the most widely used WIM sensors.

2.1 Stability of Sensing Materials

Piezocables are copper sheath coaxial cables filled with a Perovskite-type piezoelectric powder. The exponential decay of sensitivity of piezoceramics, as well as their nonlinearity, hysteresis and relaxation effects are well known [1]. For dynamic high accuracy force measurement, quartz crystal sensors are clearly offering superior characteristics. The piezoelectric sensitivity coefficient of 2,3 pC/N of quartz is a natural constant of the material and therefore absolutely stable with regard to aging effects [2]. The absolute value of the sensitivity of a piezocable varies typically by ±7 % along the length because of the polarization tolerances of manufacturing. With quartz crystal sensing elements, by contrast, the length uniformity of sensitivity can easily be kept within ±2 %.

2.2 Signal Baseline Stability

For an accurate integration of the signals a stable pulse shape is important, especially for determining individual axle loads within tandem or tridem axle groups. Piezocables have inherent relaxation effects and relatively low insulation resistance causing signal undershooting and drift effects. Fig. 1 shows comparatively the baseline stabilities of piezocable and quartz WIM sensors. Because of the excellent insulation resistance of quartz, also quasistatic measurements can be done, giving the possibility of measuring very slow traffic and enabling deadweight calibration of quartz WIM sensors.

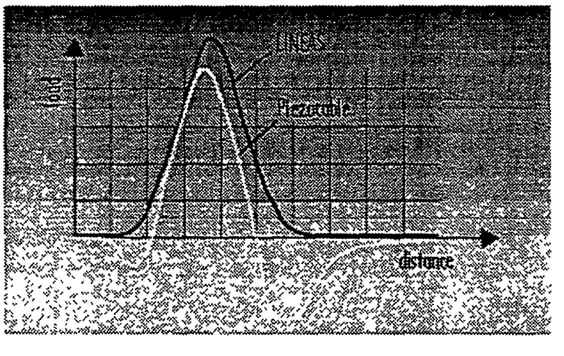

Fig. 1: Comparison of analog signals produced by piezocables and quartz WIM sensors

2.3 Thermal Stability

In contrast to piezocables, quartz crystals have no pyroelectric effect, thus even fast temperature changes do not cause any drift of the signals. Quartz also has the advantage of an almost negligible temperature coefficient of sensitivity (approx. -0,02 %/K), thus no special means for pavement temperature compensation are necessary.

2.4 Mechanical Stability

Capacitive strip sensors and - due to their omnidirectional sensitivity - also the piezocables, are generally embedded within plastic materials for transmitting the axle loads to the small cable diameter. The high rigidity of quartz crystals enables a Solid State design for WIM sensors with unidirectional sensitivity and pavement adapted stiffness.

3. Realisation of the Quartz LINEAS WIM Sensor

The design of the WIM sensor is based on a hollow profile in which the quartz crystal elements are mounted under elastic pretension, (fig. 2). By applying a lateral force the profile can be opened to insert the quartz elements. After releasing this lateral force, the piezoelements are pretensioned.

The extruded profile made of a high strength light metal alloy was FEM optimized for achieving a bending rigidity adapted to pavement deflections, in order to prevent fatigue or "squeezing-out" of sensors.

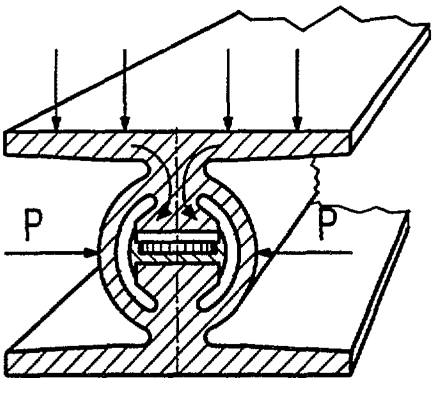

Fig. 2: Principle of the WM sensor

Fig. 3 shows the road implementation of the WIM sensor which is manufactured as modules of I m length with quartz elements every 5 cm. The 1 m modules may be fitted together to the desired length when the sensor is installed in the road. The cables may be passed through an integrated duct.

In order to achieve conformity to pavement wear characteristics, the sensor is equipped with a thick quartz sand-epoxy topcoat. This enables adaptation to road unevenness by grinding, which is necessary when sensors have to be installed in roads with track grooves. In the case of pavement repairs low compressibility of quartz sensors facilitates overcoating.

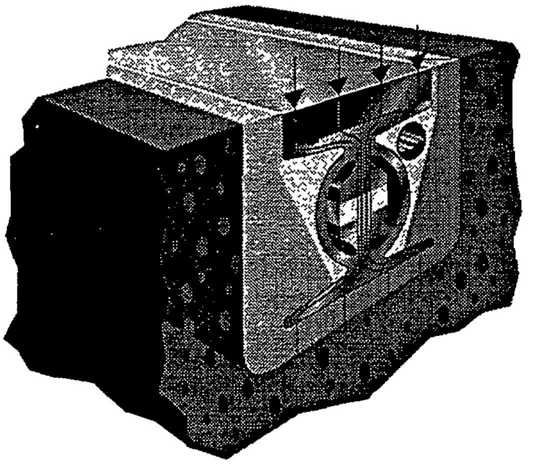

Fig. 3: Sensor installed in the road

A moving vehicle produces horizontal forces in the road, which can have the same magnitude than the vertical ones. Therefore, the sensor is decoupled from these lateral forces by soft materials as can be seen in fig. 3. This decoupling is essential to obtain good pulse shapes (fig. 4), without negative portions at the beginning and the. end of the pulse, and as a consequence, to get reproducible results.

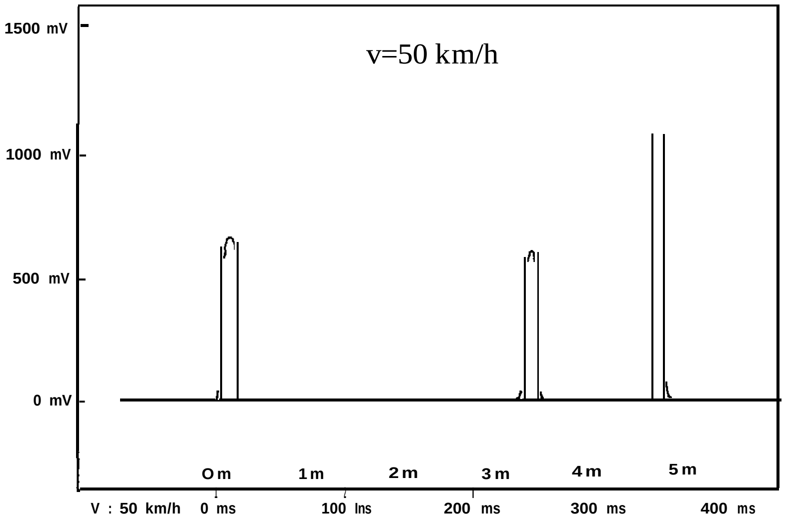

Fig. 4: Typical analog output signal of a 3 axle vehicle

Laboratory measurement showed a sensitivity which was better than ± 2 % along a 1 m module and constant to within ± 1 % between -20” C and 50” C.

4. Pavement Installation Tests

Laboratory investigations were done with the aim of finding the best suitable material for the installation of the sensors in the road and the determination of its physical properties.

The following measurements were carried out:
Water absorption, module of elasticity, hardening and freeze - thaw cycles.

Among the many different materials examined, the best material found was a mixture of 75 % quartz sand and 25 % epoxy resin. This mixture is hardening at temperatures down to 5” C, even under water. The water absorption of this optimized material is 0,2 % after 2 days and the static module of elasticity is 8000 MPa. The material withstood 12 freeze - thaw cycles without any deterioration.

At 20” C this quartz sand epoxy mixture is hardening within 2 hours, enabling thus the installation of the sensors in less than half a day. This material is suitable for installation in bituminous as well as in concrete pavements.

Practical road tests were done to determine the stability of the sensor-pavement interface in view of wear and deflection effects. The optimized sensor and installation material lifetime could not yet be determined, as no failures were detected during the 3 years of testing.

5. Measurements on a Circular Fatigue Test Facility

The test facility is a circular bituminous road with a 32 m diameter and a pavement width of 1.4 m as (fig. 5). Three twin wheels, each with a load of 50 kN; are mounted on arms rotating around a central column. Maximum speed is 82 km/h; during our measurements the speed was limited to 50 km/h however.

During the measuring period from July 91 to June 94 the sensors were exposed to more than 2 million loading cycles, corresponding to a heavily trafficked road during more than 10 years. After these tests the sensors and their signal did not show any deterioration.

For the measurements the speed varied from 5 to 50 km/h and the sensor temperature was always recorded.

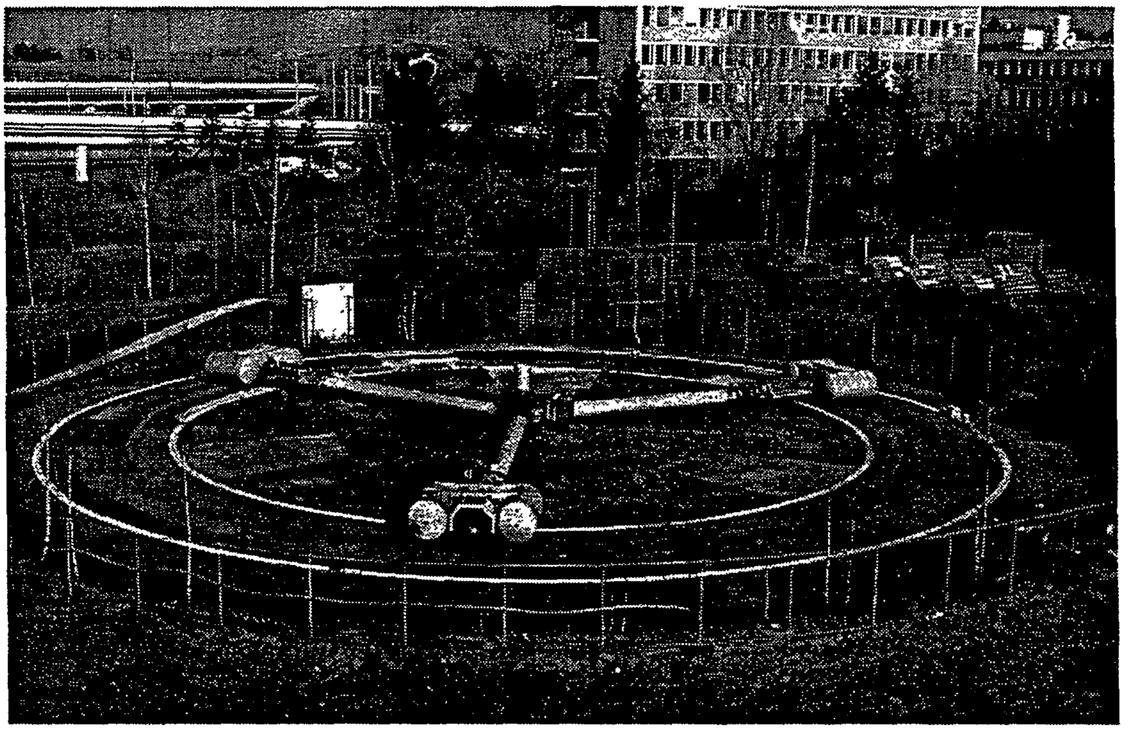

Fig. 5: Circular Endurance Test Track EMPA, Dubendorf

Fig. 6 shows that the speed dependence of the results is very good, it lies within the standard deviation of the measurements. The larger deviations for speeds over 35 km/h are due to dynamic effects. At these speeds the vertical acceleration of the wheels is getting larger, as it could be confirmed by acceleration measurements.

This good speed dependence is a consequence of the complete decoupling of the sensor from lateral forces, as shown in fig. 3. Without this decoupling the signal pulses would have large speed dependent negative portions at the beginning and the end of the pulses.

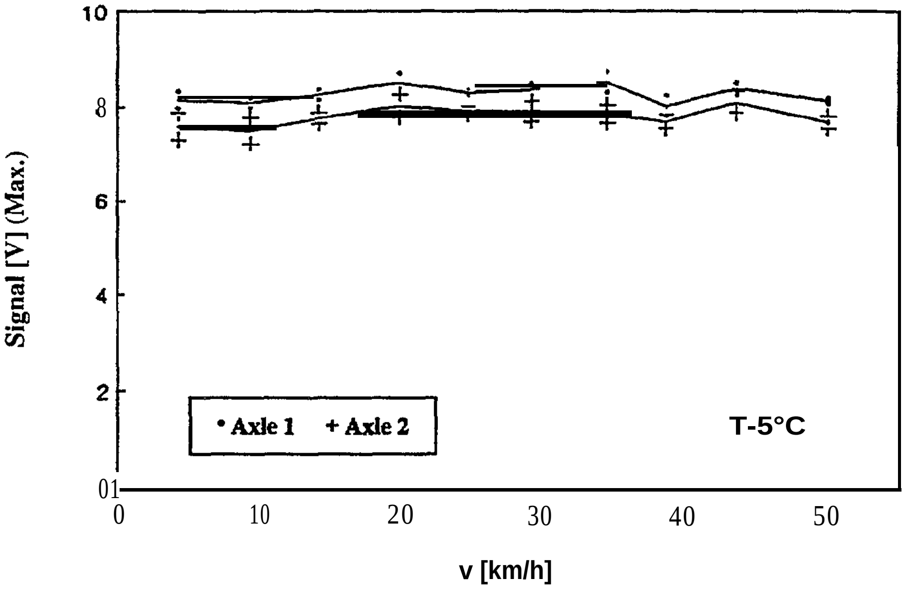

Fig. 6: Speed dependence

Fig. 7 shows the excellent temperature dependence of the sensitivity between 10" C and 25" C, measured at the circular fatigue test facility.

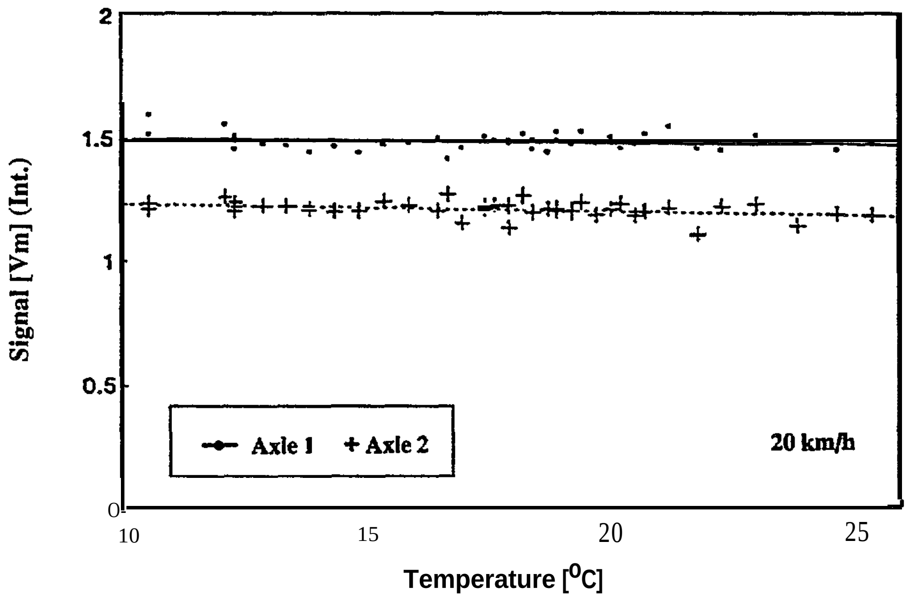

Fig. 7: Temperature dependence of sensitivity

6. Field Testing of Quartz WIM Sensors

Since July 1993 quartz sensors are road tested comparatively together with 8 commercial sensor types, in the European research program "COST 323 Weigh-in-motion of road vehicles" [3]. This test program was conceived neutrally to WIM system supplier's interests and carried out by the Swiss Federal Institute of Technology, Zurich. The results until 1994 have been published by E. Doupal and M. Caprez [4].

The objective of these measurements was to test the sensors on a real road with a maximum number of different vehicles. The road chosen is a wide town road (lane width 4 m) in Zurich with a flow of approximately 7000 vehicles per day in one direction, 10 % of which are trucks.

About 200 m after the measuring site there is a municipal waste incinerator, where all the trucks bringing waste are weighed on a static bridge balance (accuracy 20 kg).

In this way, about 150 different vehicles (100 waste trucks, the rest are vans and passenger cars) passing over the WIM sensors can be weighed (gross weight mass - GWM) statically every work day.

The main advantage of this site is, that a lot of different road vehicles can be measured in motion and be compared with their static weights, while in most of the other WIM experiments always the same few selected test vehicles were measured many times.
The above conditions are more realistic.

Until now more than 1500 vehicles have been measured and the data collection is being carried on.

The measured vehicles may be roughly classified as follows:

10 % of 2-axles with typical GWM of 1 - 8 metric tons

25 % of 2-axles with typical GWM of 8 - 15 metric tons

40 % of 3-axles with typical GWM of 13 - 25 metric tons

25 % of 4-axles with typical GWM of 16 - 28 metric tons

6.1 Measurement and Calibration Methods

The signals of the sensors were measured with a digital oscilloscope and stored on floppy disks. The stored data were then evaluated off-line on a computer. Beside the axle loads and the gross weight mass, also the speed, the axle distances, the track, and twin tires could be determined.

The sensor was calibrated once at the beginning of the measurements, afterwards the calibration factor was only checked but not corrected. For the calibration an unloaded 3-axle truck with a gross weight mass of 13'500 kg passed 10 times over the sensor with speeds of 20, 30 and 50 km/h.

As quartz WIM sensors are able to measure axle loads also at very low speeds (2 km/h), special calibration methods were tested in order to compare the slow traffic performance with the quasistatic quality check calibrations during manufacturing.The sensitivity distribution along road installed quartz WIM sensors was measured by quasistatic force loading with a hydraulic truck prop. (fig. 8).

Fig. 8: Force Calibration by quasi static method

The force of 0 . . . 5 kN was applied by a block of 50 x 50 x 150 mm shifted each 50 mm and measured by a Kistler type 9067 load washer as reference transducer. The measured sensitivities of 1,65 . . . 1,68 pC/N, equivalent to 0,808 . . . 0,823 pC·m/kg, are in good agreement to the dynamic calibrations at 20 . . . 50 km/h.

The quasistatic road sensitivities agree to -3 % with the laboratory calibrations. Good agreement was also found with roll-over measurements. The signal shape is impeccable also at speeds below 5 km/h (fig. 9).

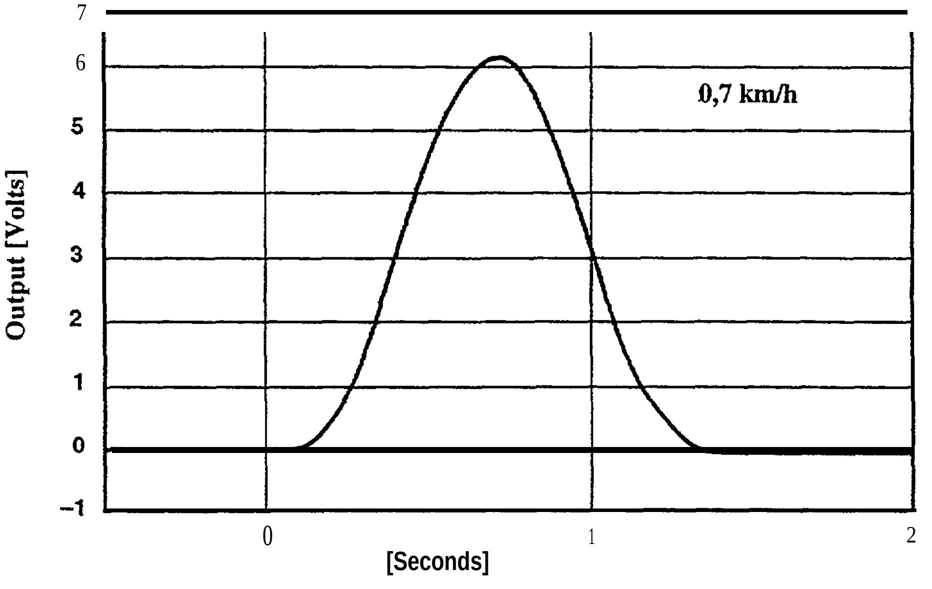

Fig. 9: Low speed signal of a I6 ton truck wheel

Because of the practically speed-independent quartz WlM sensitivity and as cordoning-off the traffic is expensive, quasistatic on-site calibrations generally are substitutable by normal speed calibrations.

6.2 Traffic Measurement Results

Results of about 1500 vehicle measurements are given in fig. 10 . *. 12.
In fig. 10 the dynamic weights are plotted versus the static weights.

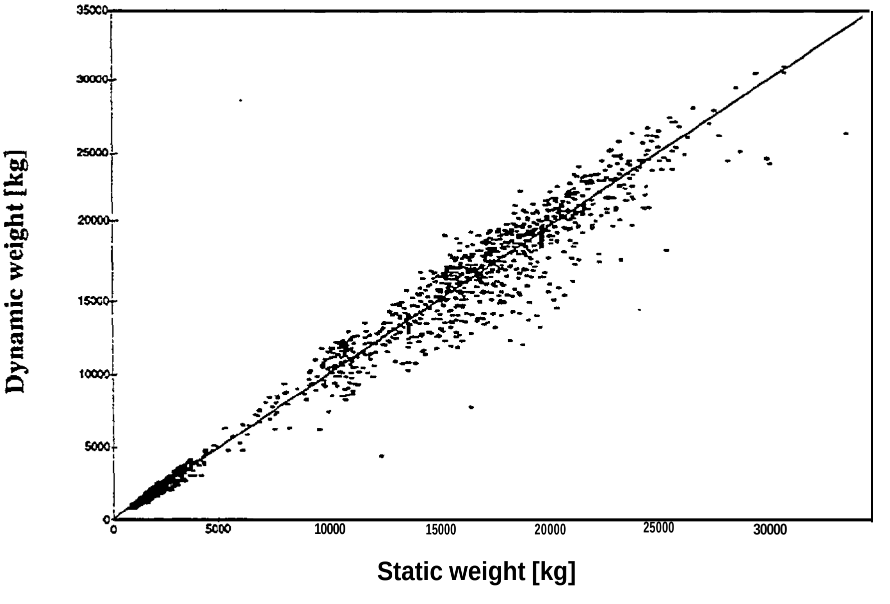

Fig. IO: Dynamic weight as a function of static weight [5]

Fig. 11 shows the dynamic weight divided by the static weight as a function of the static weight.

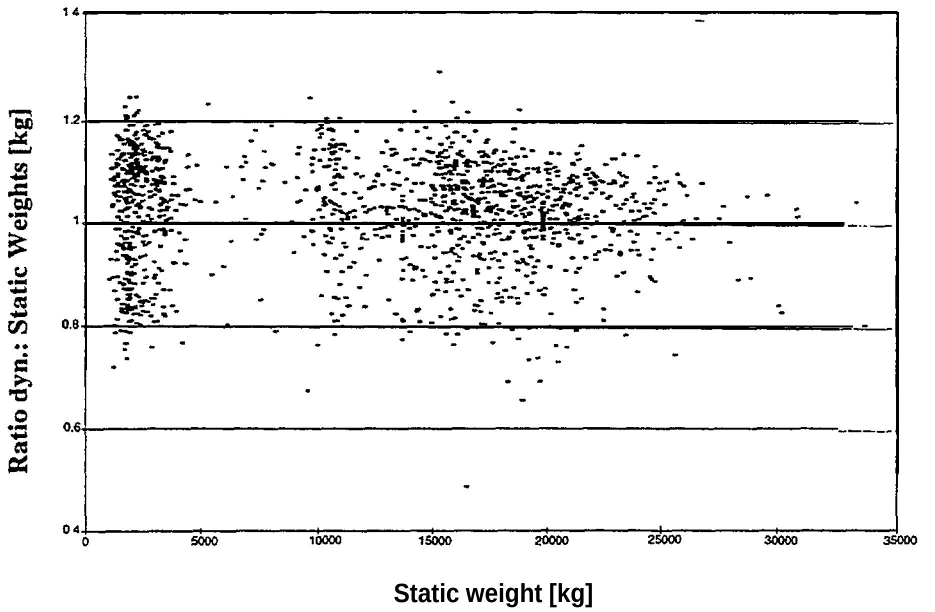

Fig. II: Ratio of dynamic to static weight as a function of static weight [5]

The results in fig. 11 show, that there is no systematic dependence of the measured ratio of dynamic to static weights and of the accuracy of the measurements on the static weights. Thus the linearity of the sensor is very good, thus it can measure small passenger cars with the same accuracy as large trucks.

Fig. 10 and 11 show, that ail the outliers originate from too small dynamic weights.

A more detailed analysis of the results revealed, that most of these low lying values are caused by vehicles, which drive slightly outside the lane and therefore did not pass complete-ly over the WIM sensor. This analysis could be done with the help of a position sensor installed at an angle of 2 1 ⁰ after the WIM sensor line.

The linearity over the full weight range is reflected by nearly constant mean value factors (corresponding to the calibration factor 1,0l determined after the installation in July 1993).

Weight class tons	Number of vehicles	Mean value factor	Standard deviation
0,5 . . . 3,5	410	1,02	0,12
3,s . . . 35	1061	1,02	0,lO
All vehicles	1471	1,O2	0.11

The accuracy is good, specially in view of the fact that all these measurements were done with only one sensor line [5]. If one takes into account only the vehicles which passed completely over the WIM sensor, this standard deviation is reduced to about 0,07.

The sensitivity and accuracy have not revealed any significant changes over the 2 1/2 years of operation.

Measurement period	Mean value factor	Standard deviation
Jul. 1993	1,0l	Initial calibrations
Aug. 1993 ... Dec. 1993	1,02	0,lO
Jan. 1994 ... Jun. 1994	1,03	0,ll
Jul. 1994 ... Dec. 1994	1,0l	0,lO
Jan. 1995 ... Dec. 1995	1,00	0,10

An analysis of the speed dependence was not carried out, as the observed speeds were all between 30 and 60 km/h (speed limit of 50 km/h). Measurements with higher speed with test vehicles are planned.

Fig. 12 shows the temperature dependence of the results. During the measurement period the temperature of the sensor varied form -2” C to 29” C. The temperature dependence is very good, the variation of the results with temperature lies within their uncertainty.

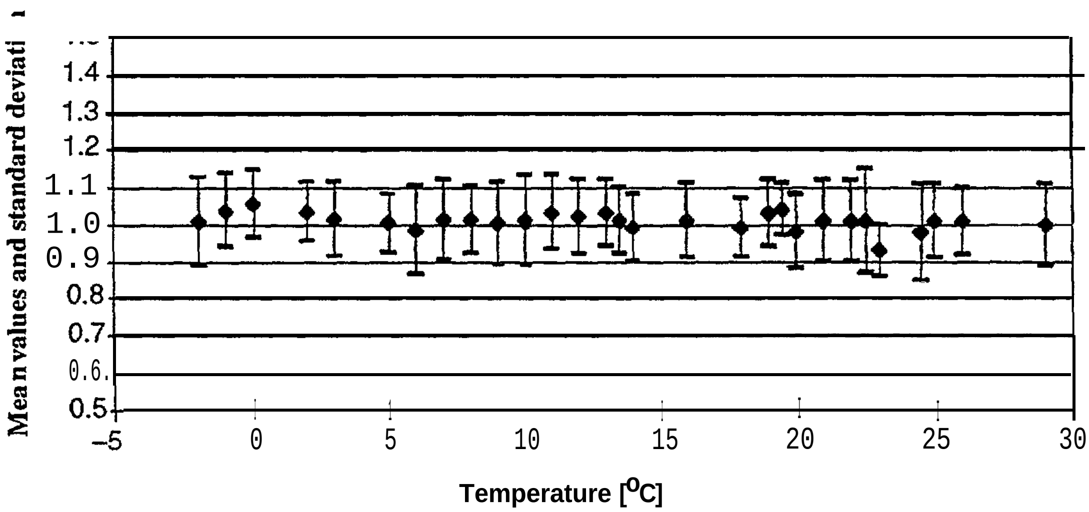

Fig. 12: Temperature dependence of traffic measurement data

The stability of the discussed measurement performance is not only due to the quartz sensor, but also to the pavement-adapted road installation technology. After the 2 1/2 years of traffic influence no damage to the sensor and its road interfacing could be detected. In this respect also, the quartz WIM sensor compares favorably with conventional WIM sensors [5].

An even higher accuracy of WIM measurements can be achieved by averaging the weight . data of multiple sensor arrangements [6]. Therefore additional quartz WIM sensors had been implemented later in the Zurich test field [3].

Measurements with two quartz sensor lines have given typical standard deviations in the order of 0,06 and better [5]. Further testing of single and multiple quartz WIM sensor arrangements is continued.

The excellent cooperation with Dr. M. Caprez and Dr. E. Doupal from the Swiss Federal Institute of Technology is gratefully acknowledged.

7. Conclusions

The novel quartz WIM sensor and its road installation technology presented here are characterized by:

- Longevity with excellent stability of metrological and mechanical performance.
- Large dynamic bandwidth from very slow traffic to highway speeds.
- High resolution and linearity thus small passenger cars can be weighed almost as accurately as heavy vehicles.
- Sensitivity constant within ≤ ±2 % over 30 months testing period.
- Uniformity of sensitivity along sensor length factory calibrated to ≤ ±2 %.
- Very low sensitivity dependence on temperature and speed.
- High insulation resistance of quartz crystals and inexistent pyroelectric effect enable almost driftless measurements.
- Good pulse shapes by decoupling from lateral forces in the road enhance the precision of integration and discrimination of individual axle loads.
- Typical standard deviations of the ratio of dynamic to static weights: 7 %, or lower by multisensor arrangements.
- A modular design enabling easy adaptation to any lane width and pavement surface.
- Easy and fast road installation even under severe climatic conditions.
- No deterioration after more than 10 years of heavy traffic simulated on a circular fatigue test facility.

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GEOPHONES FOR TRAFFIC MONITORING

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Sandia National Laboratories
Author: Don Schroeder
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Presented at
National Traffic Data Acquisition Conference
Albuquerque, New Mexico

May 5-9, 1996

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SMART PAVEMENT RESEARCH

DON SCHROEDER

SANDIA NATIONAL LABORATORIES

Sandia National Laboratories, the Alliance for Transportation Research, the New Mexico Engineering Research Institute, and the New Mexico State Highway and Transportation Department are working together to evaluate the use of acoustic signal receivers, coupled with advanced signal processing techniques, to achieve minimally envasive, lower cost weight-in-motion devices. We will also evaluate the use of these technologies to classify highway traffic, to detect traffic abnormalities, and, using active acoustic sources, determine the pavement state of health. This work is being funded by the Federal Highway Administration and is the nation's first **smart** pavement test bed.

Sandia's experience with acoustic signal processing in characterizing nuclear waste storage sites, enhanced oil recovery prospects, environmental restoration locations, and defense needs, combined with our research into, and application of, signal processing techniques for Synthetic Aperture Radar (SAR) imaging led us to believe that these technologies could be combined to provide low cost and effective smart highways.

This project began to collect data at a Special Pavement Study 1 (SPS 1) site in southern New Mexico in December, 1995. The results of the data **collection and** analysis work through mid April, 1996, will be discussed.

The concept is that vehicles rolling over the pavement will generate **acoustic signals** that can be received by accelerometers or geophones that are buried, invisibly, at the edge of the pavement. They are connected to a buried local processor via buried wiring and the processed data can either be transmitted, via phone lines or a radio transmitter, or stored for later retrieval. The receivers are in a linear array along the pavement, spaced about one vehicle length apart. We **believe** that the powerful data processing techniques developed for SAR images can extract considerable vehicle information from these acoustic signals.

The pavement state of health is expected to be achieved using the same array of acoustic receivers. However the signal source will be from a linear array of acoustic sources, on the opposite side of the highway, that are excited sequentially and swept over a range of frequencies. Each receiver will detect the generated signals and, by using the SAR image processing algorithms, we believe it may be possible to generate a 3D image of any pavement defects between the sources and receivers.

This work is in its very early stages and the progress to date will be reported.

FIBER OPTIC TRAFFIC SENSOR

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Florida Institute of Technology

Presented at
National Traffic Data Acquisition Conference
Albuquerque, New Mexico

May 5-9, 1996

Fiber Optic Traffic Sensor

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A rugged, reliable fiber optic sensor based traffic classification system has been developed and successfully deployed below the pavement surface at three field sites in Melbourne, Florida. The sensors developed are immune to electromagnetic interference and do not provide a metallic conductive path to the electronic interface. This property minimizes the likelihood of lightning damage to the electronic systems. This system incorporates fiber optic sensors that detect vehicle axles and provides an electronics interface to Peek's TrafiCOMP III Model 24 1. The sensors were housed in aluminum and had consistent light loss properties. These sensors were installed in pavement sections on the Florida Tech campus and on SR 507, Babcock Street, Melbourne, Florida. Data from all sites showed accurate counts of vehicle axles and vehicle classifications. Over l,000,000 axles were counted within four months after installation at the SR 507 site. The fiber optic sensors were compared to piezoelectric loop traffic classifiers installed in the same lane and gave comparable results. Additionally, the analog signal from the fiberoptic sensors can be directly correlated to axle weights, since both the magnitude and time duration of the output signal varies with load.

INTRODUCTION

The objective of this effort was to design, construct and demonstrate the feasibility of a fiber optic sensor capable of detecting the presence of and counting the number of vehicle axles in the desired traffic lane. The system design goals are: immunity to electromagnetic interference, expandablity to detect traffic in multiple lanes, be embedded at least 3.2 mm (l/8 in) below the pavement surface, be installed in both flexible and rigid pavements, be interfaced with existing Florida Department of Transportation (FDOT) traffic controls, be simple to install and have a long life.

Advantages of Fiber Optic Sensors

Fiber optic sensors have important advantages over present techniques. Their small size makes them ideal for in situ monitoring, they are immune to corrosion and electromagnetic interference, and multiple fiber optic sensors can be placed in series on one optical fiber (i.e., multiplexing) (Kim and Shaw, 1989) (0. S. Wolfbeis, 1989). They are flexible, moisture insensitive, reliable and rugged. Another unique advantage is the chemical stability of the plastics and glasses that make up the optical fibers. Because optical fibers inherently have low loss, the sensors can be separated from their electronic interface by hundreds of meters. These advantages along with the economics of fiber optic sensors have led to a significant research effort aimed at developing fiber optic sensors at Florida Tech's Photonics Laboratory and elsewhere(Ansari, 1993), (Cosentino et al., 1994), (Grossman et al., 1994).

Optical Fibers

A typical optical fiber consists of a glass core, a cladding layer that is either glass or sometimes plastic, and an outer buffer layer of acrylate or other material. These layers are in turn protected by cables similar to those used for wires. Fiber cables, such as the ones used in our field installations, can be purchased without any metal wires or strength members if desired. Optical fibers are typically 250 or 500 microns thick, including the buffer layer. When in a cable they are very robust. They are used extensively in telecommunications where' well over a hundred million kilometers of fiber has been installed.

The light from either lasers (ILD's) or light emitting diodes (LED's) are coupled into the fiber core. To make the fiber into a sensor some outside perturbation must cause changes in light intensity as portrayed in Figure 1. For example, a force that bends the fiber will cause light to couple out of the core through the sides of the fiber. The fiber then becomes a sensor when appropriate signal processing electronics or a calibration curve is developed correlating changes in light intensity to changes in the applied force.

During microbending (from loads, pressures, etc.) light travelling within the fiber core leaks out. A powermeter is used to measure the remaining light at the sensors output end and a calibration is developed between the load, pressure, etc., and the amount of output light.

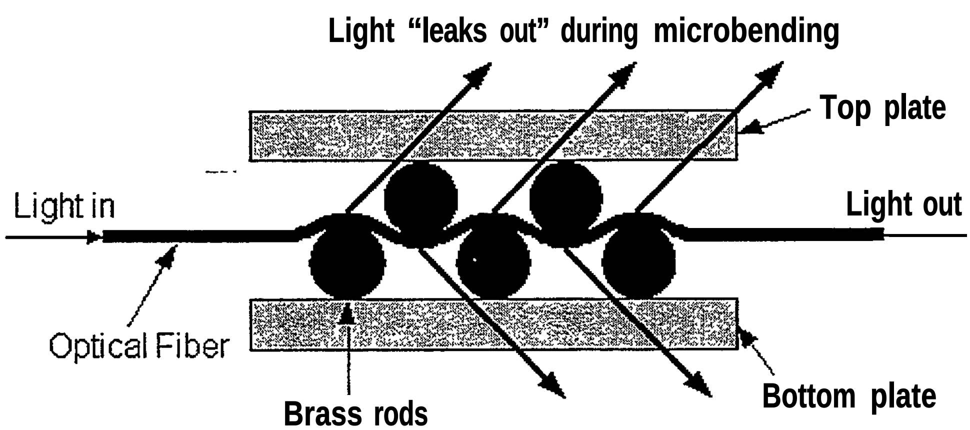


Figure 1: Microbend Sensor Technology (after Grossman et al, 1994)

SYSTEM DEVELOPMENT

Sensor

A number of different designs of sensors were developed during the course of the program. Initial designs were difficult to handle, not sensitive enough to detect vehicles when imbedded in the pavement, and were subject to water intrusion. These problems were overcome with a better combination of deformer structure and fiber as well as better packaging. The latest version sensor is packaged in a rigid aluminum channel which is impervious to moisture, protects the sensor before, during, and after installation, and provides a flat rigid lower sensor structure. The packaging resembles that of commonly used piezoelectric sensors.

Figure 2 shows a typical experimentally measured curve of sensor output light intensity vs. applied load for a sensor while Figure 3 shows a composite encapsulated sensor in a compression test machine.

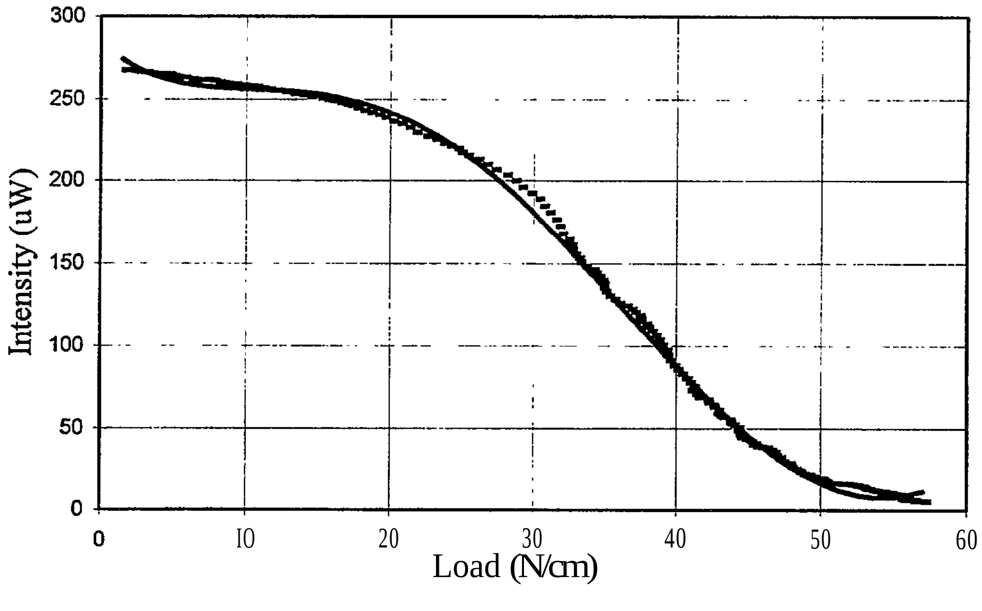


Figure 2: Typical Intensity vs. Load for a Microbend Sensor

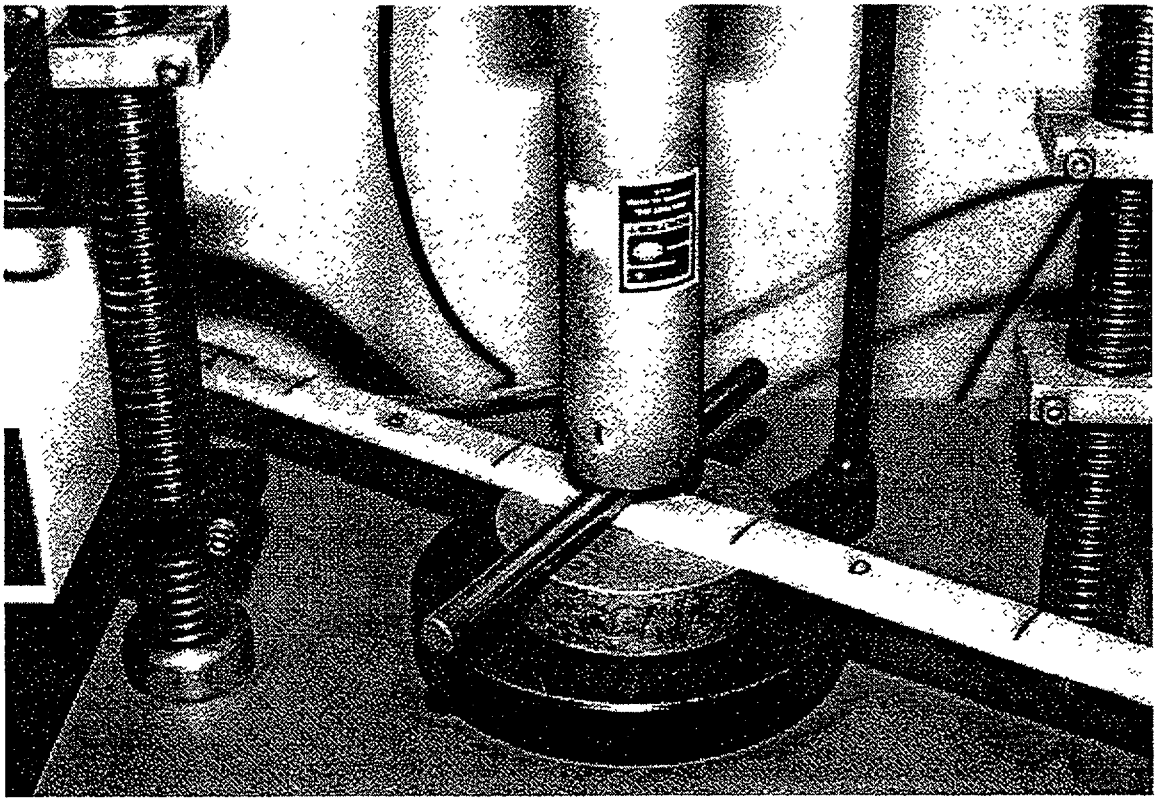


Figure 3: Microbend Sensor in a Compression Test Machine

Sensor Environmental Testing

To determine the effects of repeated extremes in temperature, a sensor was placed into an environmental chamber where it was totally submerged in water and cyclically subjected to extreme hot and cold temperatures. The output light was monitored continuously during these environmental variations to determine the effects on the sensor materials and performance. Over the temperature range of -23^{o}C(block of **ice)** to 66°C (-10°F to 150^{o}F), the output intensity **varied** by less than 2%. Additionally, no breakdown in materials or structure was observed even after 56 cyclic variations. Figure 4 below is the setup used for the environmental test.

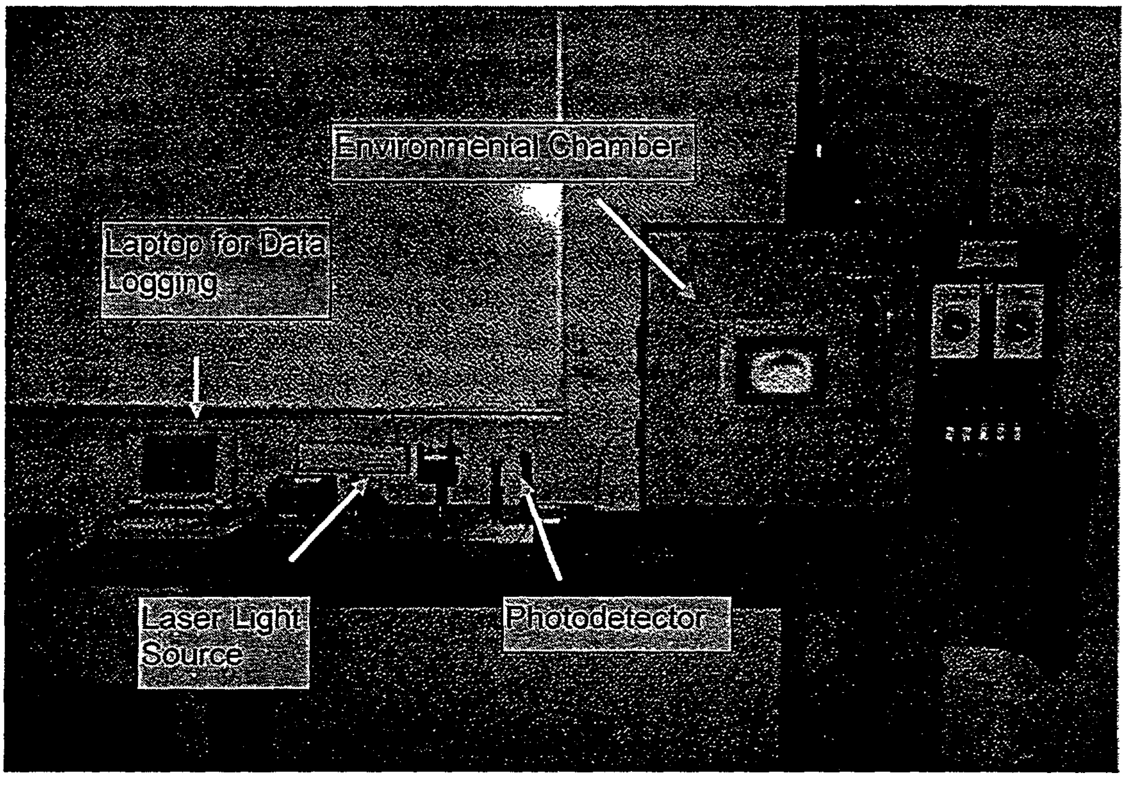


Figure 4: Environmental Testing Setup

Sensor Control Box Interface

The sensor control box is the interface between the fiber optic sensor and TrafiCOMP III. This subsystem provides the fiberoptic optical excitation and processes the light output from the sensors to generate the desired input to an off-the-shelf TrafiCOMP III.

TrafiCOMP III is basically a roadside computer that interprets the signals received from the road sensors, classifies the vehicles, determines their speeds, gap, etc., and stores this data in a 64K memory. The stored information can be retrieved via telephone or telemetry or manually downloaded via an RS-232 port to a laptop computer carried to the site location. A solar charging panel and batteries provide a constant power source for TrafiCOMP III and the fiber optic sensor control box.

Figure 5 shows the block diagram of the interface electronics. On the front panel are located ST connectors for two fiber optic sensors. A key feature of the signal processing system is an automatic power control (APC). This allows the output voltage of the receiver circuit to remain constant when the sensors are not activated by varying the output power of the LED to compensate for variations due to temperature conditions, cable loss, etc.

The basic technical description of the electronics is as follows. The transmitter, receiver and APC amplifier perform the closed loop control with a 5 second time constant. If a change in received light happens in less than 5 seconds, the APC will not change the output. This allows compensation for system variations which change slowly over time but will not affect the axle counting signal. The threshold circuit performs the level decision. If the received signal, which is caused by a vehicle passing over the sensor, falls below the threshold setting, the circuit will turn on the opto-isolator. The opto-isolator is the buffer which provides electronic isolation between the internal circuits and TrafiCOMP* III, but provides the necessary On/Off signal for axle counting. A sensor indicator LED on the front panel display shows whether the sensor is operating. If the fiber optic cable anywhere between the output and input connection on the sensor control box breaks (including in the sensor), the LED flashes indicating the failure. The entire circuitry operates over 6 to 12 volts and takes approximately 200 mA of current.

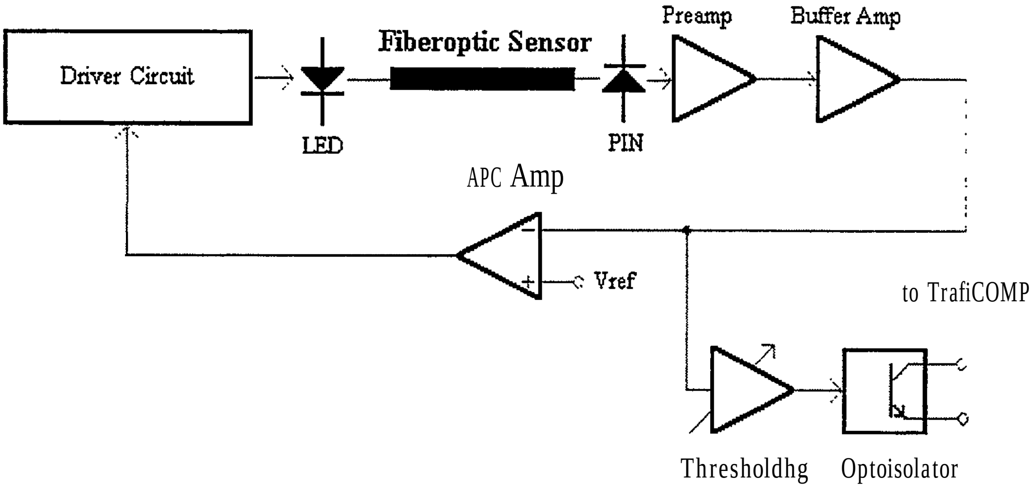


Figure 5. Block Diagram of Opto-electronics Interface

Installation Techniques

During field ‘testing an extensive effort was made to establish the methods for sensor installation. When installing a sensor in the pavement, several variables were considered. These variables are: (1) groove dimensions; (2) leveling and smoothness of the bottom of the groove; (3) use of the proper filler materials; (4) minimizing air voids in the filler material around the sensor; and (5) protecting the fiber optic cables. These variables, except for number 5, are valid for installing any type of traffic sensor, including piezoelectric sensors and inductive loops.

A walk behind street saw and a skill saw equipped with a masonry blade were used to cut and tailor a groove in the pavement to accept a fiber optic sensor. The grooves tried varied in depth and width between 6 mm to 25 mm (0.25 in to 1 in). Before putting the sensors in the pavement a thin layer of E-Bond G-100 epoxy was screeded level into the bottom of the groove. While the epoxy was curing, the sensor was placed such that no air voids were trapped in the epoxy around the sensor. It is important that the sensor rest on a solid, level surface because an uneven support can affect the load transfer in the groove. Once sensor placement was accomplished, hot roofing asphalt (steep) was poured over the sensor. It was poured in thin lifts that were allowed to settle for a few seconds until the entire groove was filled level with the road surface. The asphalt settled, cooled and hardened within a couple of minutes. A putty knife was then used to remove the excess asphalt from the groove to complete the installation. Although other types of materials could also have been used, the fact that the asphalt hardened quickly made it very attractive as a filler material.

FIELD DEPLOYMENT

Data Acquisition

The data acquisition system consisted of a laptop computer running National Instruments' LabVIEW in conjunction with a data aquisition card as well as TrafiCOMP III counter/classifier. Fiber optic cables from the sensors were connected to the sensor interface electronic box that contained 2 light emitting diodes and PIN type photodiodes. The light emitting diode produced the light and the PIN diode converted the light received into an electrical signal. The output signals from the electronic box were connected to the laptop system. Finally, a virtual interface was developed using LabVlEW. This soflware recorded and displayed the pulses from the sensors as vehicles drove over them.

Florida Tech Annex Smart Pavement Section

Once a field deployable Florida Tech fiber optic traffic classifier sensor was available, two loop-sensor-loop configurations (Figure 6) were deployed at the Florida Tech Annex smart pavement section. The first loop-sensor-loop configuration is a replica of FDOT's preferred traffic classifier system. It includes two inductive loops separated by a piezoelectric sensor. The second loop-sensor-loop configuration included two inductive loops separated by Florida Tech's fiber optic sensor. A TrafiCOMP III Model 241 was connected to both sensors to monitor traffic continuously at this site. TrafiCOMP III Model 241 was interfaced with the sensor control box and used to record data.

As discovered previously, the G-100 Epoxy was an excellent material for mounting the sensor in the groove. G-100 Epoxy provided a solid base which allowed the force generated by a moving tire to be transferred primarily to the top of the sensor and not to the surrounding materials. An additional parameter which affected the force on the top of the sensor was the depth from the pavement surface to the top of the sensor. At the Annex, a depth of 9.5 mm (0.375 in) was chosen based on tests performed at Florida Tech's Applied Research Laboratory (ARL). The ARL is the site of Florida Tech's first smart pavement section. As a final parameter, the asphalt application to fill the groove was observed. Leveling the asphalt with the surface could not be easily controlled due to many variations of the pavement height along the length and the quick cooling and hardening of the asphalt. The asphalt was kept just above (no more than 1.5 mm (0.0625 in)) the pavement level, which produced the most consistent outputs from the sensor.

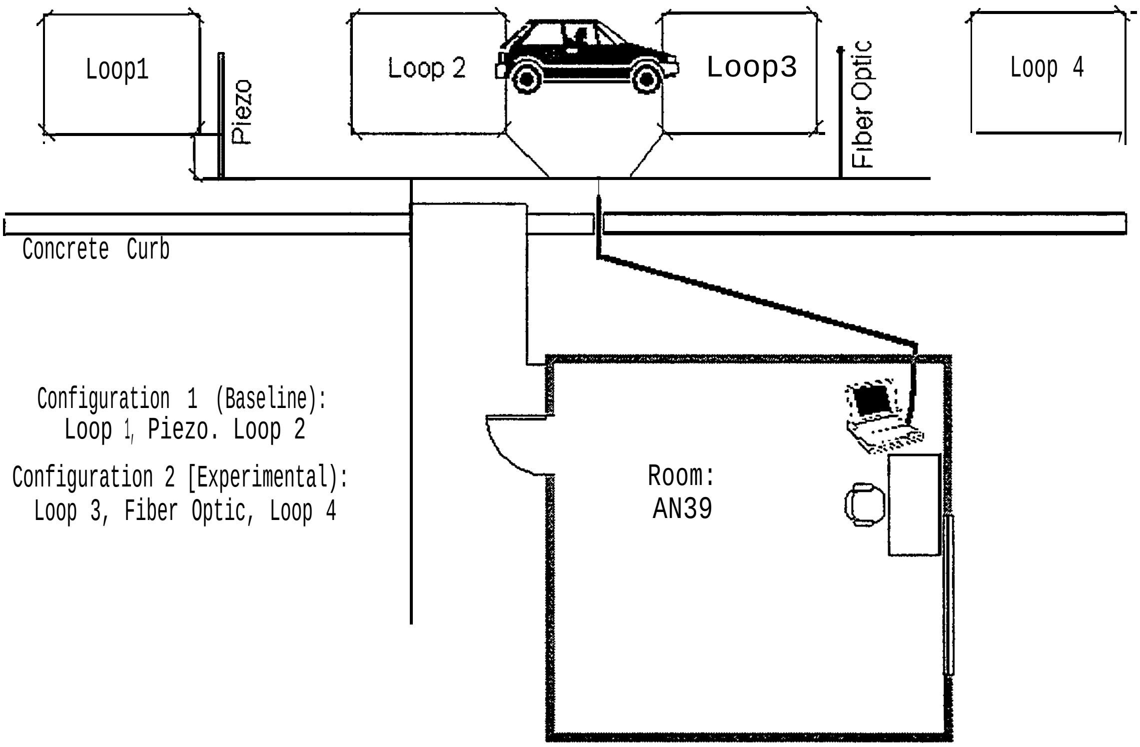


Figure 6: Layout of the Florida Tech Annex Smart Pavement Section

Florida Tech/FDOT Smart Pavement Section

Two fiber optic sensors were installed 4.8 m (16 fi) apart in the right southbound lane of SR 507, Babcock Street in 'Melbourne, Florida, on December 7, 1995 (Figure 7). Just to the north of the fiber optic sensors was FDOT's conventional traffic data acquisition site which included four piezoelectric sensors and eight inductive loops as illustrated (only shows southbound lane with FDOT and Florida Tech sensor systems). The conventional site was monitored by personnel working for the State of Florida.

The sensor grooves were cut with a walk-behind street saw to a depth of 25 mm (1 in). The first groove (hereafter termed sensor 1) was 3.5 cm (1.375 in) wide while the second groove (sensor 2) was 2.8 cm (1.125 in) wide. Each sensor was embedded in G-100 Epoxy at a depth of 9.5 mm (0.375 in) (Figure 8). The 9.5 mm was measured from the top of the sensor to the top of the pavement. Hot 149°C (300°F) Type III roofing asphalt was poured over the sensor and was allowed to cool. A putty knife was used to cut the asphalt flush with the top of the pavement.

Once the two grooves were cut into the pavement for each of the optical sensors, 3.5 cm (1.375 in) diameter holes were drilled through the concrete curb at these locations. The holes allowed the optical fiber to pass from the sensors into the underground conduit. The hole through the concrete curb was lined with flexible 25 mm (1 in) PVC conduit and sealed with traffic loop sealant. Additional 25 mm (1 in) diameter PVC and a junction box were routed underground from the sensors to the pull box. The fiberoptic cables, were then pulled through existing 50 mm (2 in) PVC conduit running from the pull box to the cabinet. The PVC conduit provided a competent, long lasting, waterproof installation.

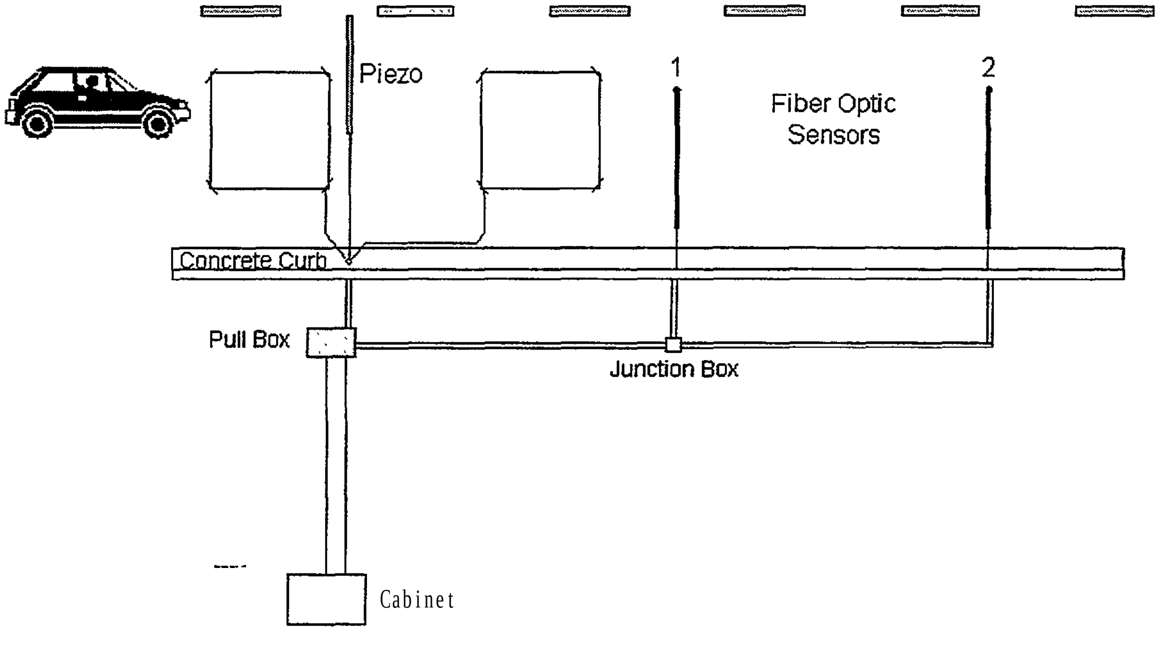


Figure 7: Layout of the Florida Tech/FDOT Smart Pavement Section

Florida Tech's TrafiCOMP III, the electronic interface box and a 12 volt deep cycle marine battery were housed inside the cabinet along with the TrafiCOMP III belonging to the State of Florida. Easy access to the two systems allowed for the data to be downloaded and compared often and in a simple way.

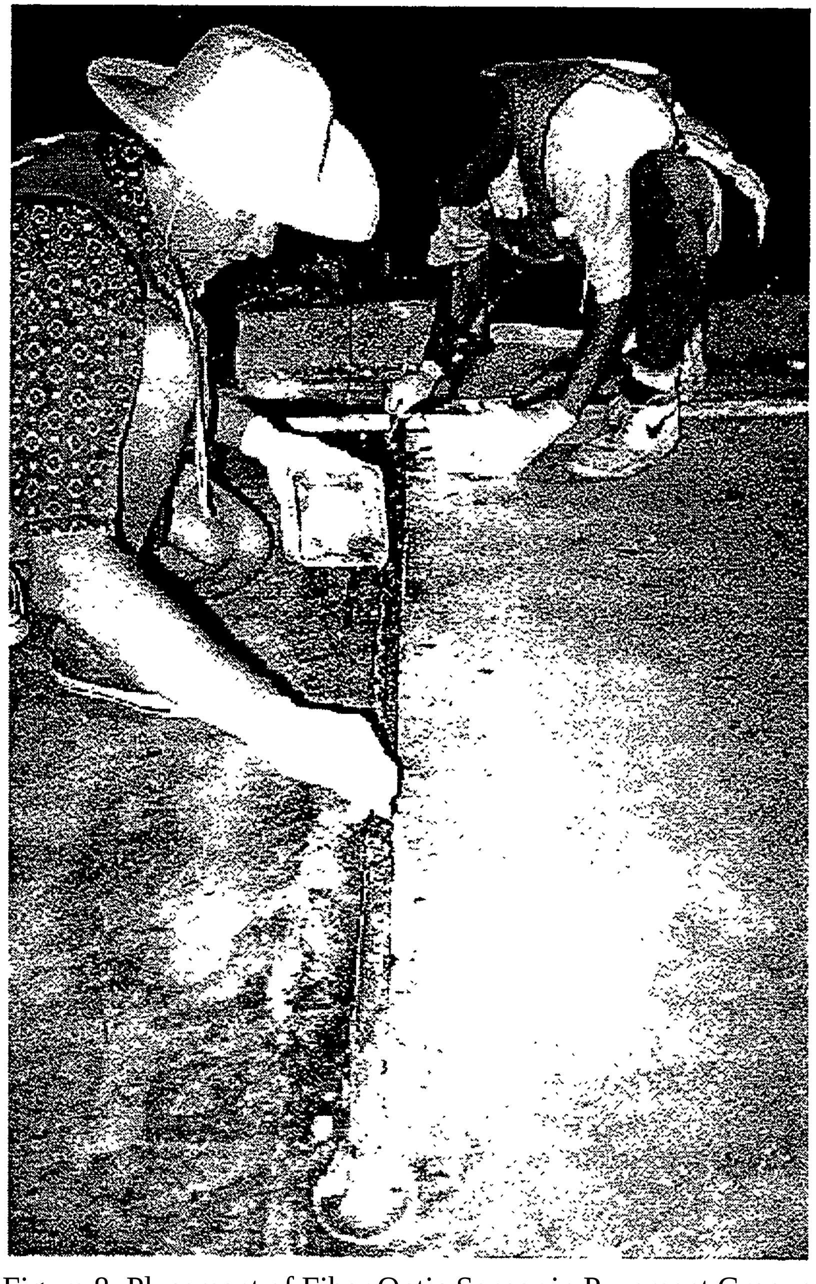


Figure 8: Placement of Fiber Optic Sensor in Pavement Groove

RESULTS

The second fiber optic sensor had a slightly lower sensitivity than the first. This caused the number of vehicles counted by sensor 2 to be about 10% lower than the number counted by sensor 1, The problem with sensor 2 was that the asphalt used as a filler material did not effectively transfer the load due to small cavities formed when leveling the asphalt. A field study over a 2 hour period indicated that the second fiber optic sensor recorded 3806 axles which was 9.5% less than the piezoelectric sensor and fiber optic sensor number 1 recorded 4204 axles which was 3.2% less than the piezoelectric sensor. The relatively small difference between the first fiber optic sensor and the piezoelectric sensor was believed to be caused in part by the difference in position of the sensors. The fiber optic sensors were installed from the curb seven feet out into the road whereas the piezoelectric sensor was installed from the middle of the lane (i.e. pavement stripe) six feet towards the curb.

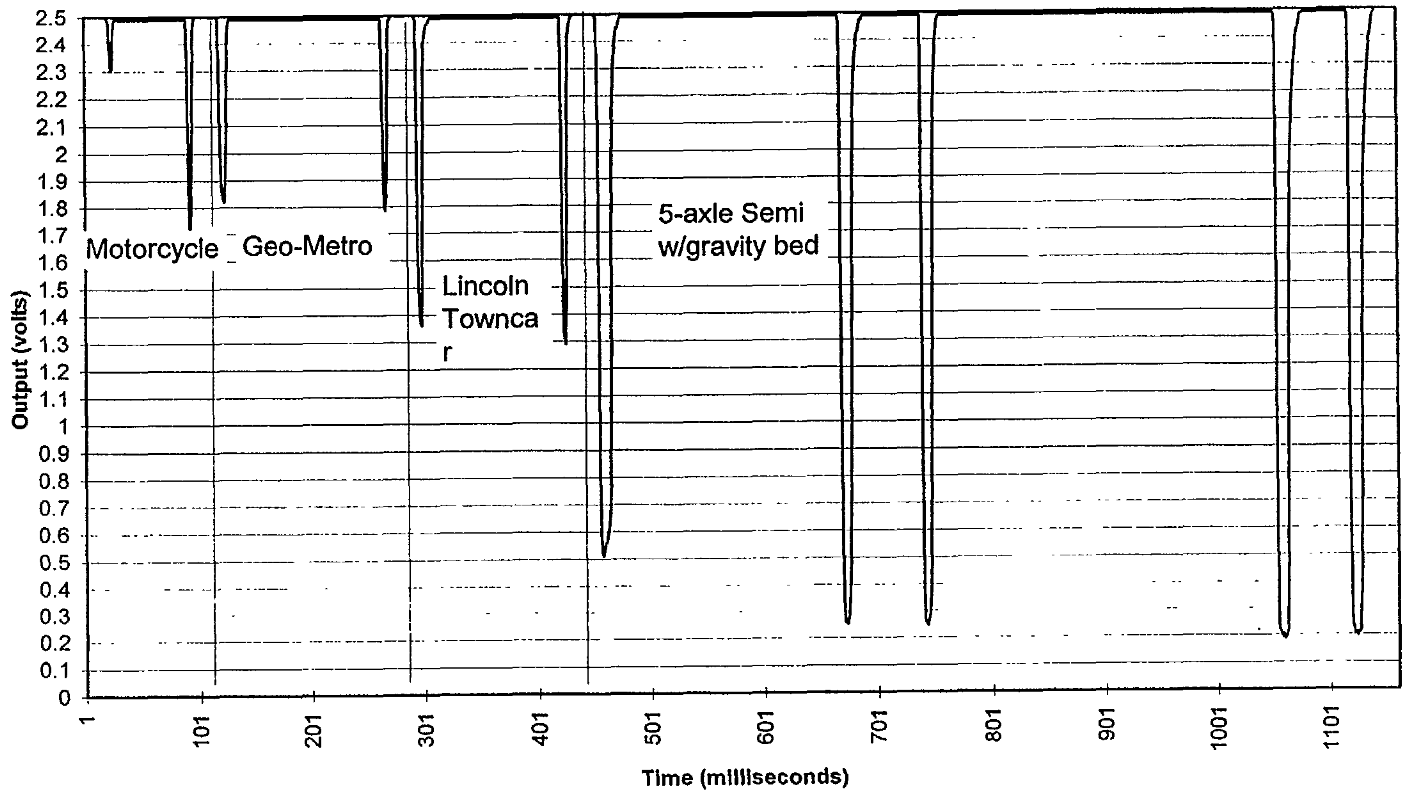
Figure 9 depicts a compilation of the wave form signatures from four vehicles as they passed over fiber optic sensor 1. As the weight of the vehicle increased so did the light attenuation of the sensor. Figure 9 depicts a motorcycle, Geo-Metro, Lincoln Towncar, and a 5-axle semi tractor trailer with gravity bed. The correlation between load and light loss can be visualized as the tractor trailer loses more than twice the light of the motorcycle. Additionally, the front axle of a motorcycle is known to be much lighter than the rear axle and the semi's front axle, a single axle, is also likely to be lighter than the dual-tandem axles. Also, the width of the pulse can be correlated to the vehicle weight. Two tires at the same pressure with different loads from the vehicle would give different width pulses, with the wider pulse belonging to the heavier tire. The last two impulses from the semi are wider than the others, therefore, these tires would logically be the heaviest.

CONCLUSIONS

The project objective of developing and demonstrating the feasibility of a rugged, reliable, fiber optic traffic classification sensor was accomplished. The successful vehicle axle counts and classifications at the SR 507 field site show that a reliable sensor design has been developed. Over 1,000,000 axles were counted within the first four months after installation (to the presesnt). The sensors can also be used to investigate axle weights as evidenced from the waveforms produced (Figure 9).

The sensor system was designed for ease of manufacturing and low system cost, both in materials and labor. The backfill materials used in the field installations (G-100 and Type III asphalt) were able to supply the properties necessary to properly house the sensors. Efficient methods were found to install the fiber optic sensors in various pavements. An interface was developed between the microbend sensors and TrafiCOMP III model 241, with an automatic gain control incorporated into the interface electronics.

Figure 9. Representative Waveform Signatures of Four Vehicles Demonstrates Weigh In-Motion Capabilities of Fiber Optic System



RECOMMENDATIONS

1) There is a need to develop and incorporate tests that will give classical engineering properties such as stress-strain response, elastic moduli, ultimate compressive and tensile strength.

2) A cyclic load test needs to be designed and performed to determine the life span of the fiber optic traffic sensor.

3) Long term and extreme environmental testing of a variety of sensors and sensor materials must be performed to determine the most suitable materials for a variety of climates.

4) The effects of varying groove widths and depths, and of varying filler materials needs to be studied to determine how to properly imbed the sensor in various pavements. Installation of sensors in a variety of roads would help identify problems associated with different pavements and climates.

5) The analytical relationships between axle weights and the sensor output waveforms need to be derived.

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