Piezoelectric cable sensors in traffic monitoring

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Abstract – **Velocity and the load of vehicles are factors important not only from the point of road transport safety view but also the ones that strongly affect road quality and durability. Other factors influencing the safety are related to observing some important traffic regulations like red-light-no-entry or ban on continuous white line crossing. Therefore, easy to install and low-priced means of control are urgently needed for monitoring of those quantities and objectively monitor violation of the Highway Code. Applicable devices should conform to a concept of decentralised automated system auditing the traffic and documenting violation of its regulations.**

This paper presents an approach to a remote measurement of load and speed of moving cars using piezoelectric cable strain sensors. The sensors are also applicable in monitoring of crossroad traffic - the idea of a computerised monitoring system incorporating a network of the sensors is presented.

1. Introduction

Road motor transport – passenger, goods as well as municipal – has been booming for last few decades propelled by an intense economic growth. The number of transport means as well as the traffic flow intensity rises in rates every year. Unfortunately the increase is much more rapid than any development of the road and traffic infrastructure. But even more dangerous is a lack of necessary imaginativeness of drivers, passengers and pedestrians as well as the level of due care, attention and reasonable consideration to other road users, which may be called "a dangerous driving" manifesting in permanent violation of the most important Highway Code rules.

The soaring rate of road accidents is the main and the most fatal effect of the traffic boom. One may enumerate a lot of reasons for the car crashes that occur in Poland: bad condition of the roads, poor road marking and traffic signalling, fatal technical condition of a considerable number of the vehicles being in use. But the main reason still stays to be a lack of the imaginative and anticipative thinking, faults and transgressions of the Highway Code for which a human factor directly involved in the traffic is responsible. The police services alert - the main cause for majority of the road accidents is overspeeding, lack of driving adaptation to the appropriate type and condition of road and traffic as well as violation of "right of way" principle, even at crossroads with traffic lights. To paint an illustrative but catastrophic picture one may quote the most current statistics from south-west region of Poland – Dolny Slask (Lower Silesia): 392 persons killed and 3974 injured in 3241 accidents and 31547 collisions in 2002 year [1]. 392 persons is a small village population...

The EU Commission's policy as expressed in its White Paper is to halve the number of road fatalities by 2010 by promotion, development and deployment of new traffic monitoring technologies [2]. The "dangerous driving" need to be thus monitored and controlled by any affordable and available means – e.g. tightening up controls and objective penalisation. The passive traffic calming measures: reduced speed limits, traffic "calmed" areas, road humps, chicanes and narrowings intended to slow the traffic are satisfactory but not efficient enough. The promotion of new, active systems aims at speed limiting devices, global vehicle-speed management and monitoring of heavy goods vehicle travelling. Among the new projects, targeting at improved road safety one may mention: Intelligent Integrated Road Safety Systems (eSystem initiative) aiming at technologies for intelligent vehicles [3]; "Vision Zero" - the safe road infrastructure idea exploiting intelligent transportation technologies [4] or automatic route guidance system for road safety and mobility using GALILEO satellite positioning, dead reckoning and radar and video data [5].

In April 2000, a cost recovery system for speed and red-light enforcement cameras was introduced in eight pilot areas in England, Wales and Scotland. It brought, after 2-year period, almost a total elimination of an excessive speeding, a drop in mean vehicle speed by approx. 13 % and a reduction in heavy casualties by 35 % [6]. The video speed monitoring systems have also been officially identified as being very successful and are considered to be made mandatory by the UK government [7].

From the other hand the traffic safety depends strongly on the quality and durability of road's pavement, which is primarily affected by overloaded heavy lorries devastating roads in urban areas and producing hazardous wheel tracks. In Poland "Ustawa o drogach publicznych" (the Highway Act) defines the maximal axle load and authorises e.g. Custom Offices to control this parameter in trucks crossing the border.

Therefore, it is obvious that easy to install, durable and low-priced devices enabling automatic and objective control of the velocity and axle load in moving vehicles are urgently needed to be installed into the roads as well as used as portable devices. An unbiased remote supervision of the traffic movement, especially in congested road conditions at crossroads (breaking the contiguous white lines, entering the crossing when the red light is showing) becomes also needful. This paper presents a trial approach aiming at implementing piezoelectric cable strain sensors in traffic monitoring to satisfy the stated requirements.

2. Measuring equipment

The piezoelectric cable strain sensor (PCSS), designed and manufactured by the Electrotechnical Institute Wroclaw (Poland), is an all-plastic component completed of a semiconducting inner electrode, polyvinilidene difluoride (PVDF) sensing cladding, semiconducting outer electrode and external protective coating as shown in fig. 1a. The sensor operates on the piezoelectric properties of PVDF by converting the mechanical stress (compression, tension, torsion as well as hydrostatic pressure) into a change of the electric charge manifesting as the voltage signal at its electrodes. More detailed and comprehensive information regarding PVDF and its sensing applications may be found elsewhere [8]. The PCSS is manufactured as a flexible cable with the outer diameter of approx. 5 mm. It is durable, resistant to severe weather conditions and highly sensitive; may also be manufactured in lengths up to 500 m (100 m standard length). The linear sensor may be also easily and firmly implanted into the road pavement by cutting a narrow and little-in-depth slot in its surface and fixing the cable by means of a durable but elastic adhesive compound (e.g. Tartan®) as shown by a draft sketch in fig. 1b.

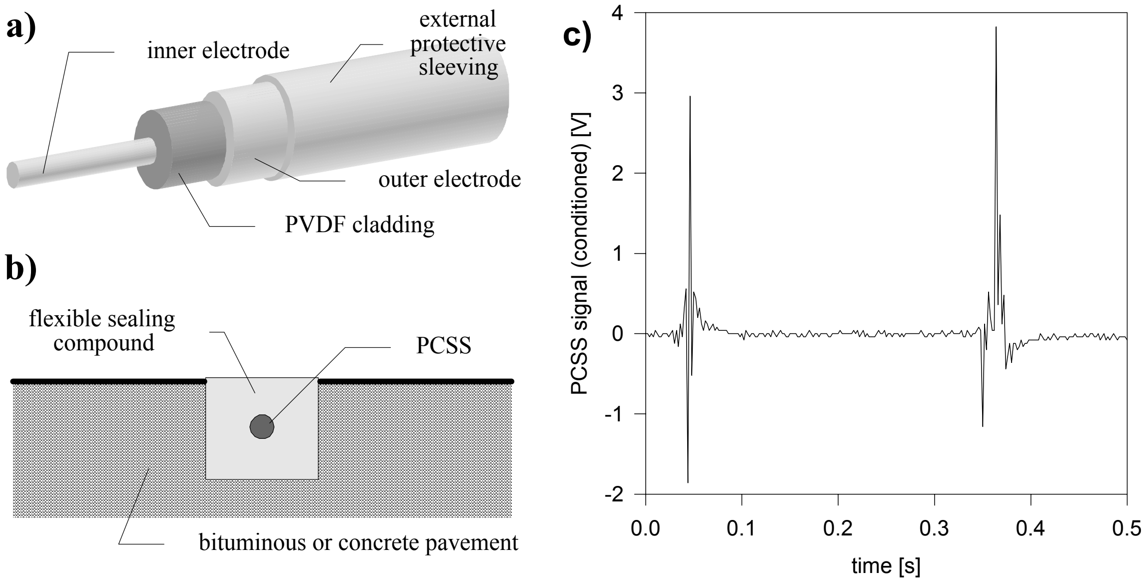

Fig. 1. Piezoelectric cable strain sensor: a) schematic configuration, b) incorporation into the road pavement, c) exemplary signal record when stimulated by vehicle's tyres.

The exemplary voltage signals shown in fig. 1c are generated by the PCSS stimulated by a vehicle's tyre passing over it. When appropriately conditioned they may be used to monitor all the traffic events related to unapproved crossing of the white continuous line and "Stop" sign line or entering the crossroad when the red light is showing.

3. Results and discussion

3.1 Velocity measurement

The principle of a vehicle's velocity measurement by means of a PCSS sensor is based on registering the time interval *Δt* expiring between a consecutive excitation of two parallel linear strain sensors (PCSS 1 and PCSS 2) placed perpendicular to the direction of the vehicle movement at a known and constant distance *d* between them. The velocity *V* is then calculated from a simple relationship $V=d/\Delta t$. The measurement methodology and the denotations are illustrated by fig. 2a.

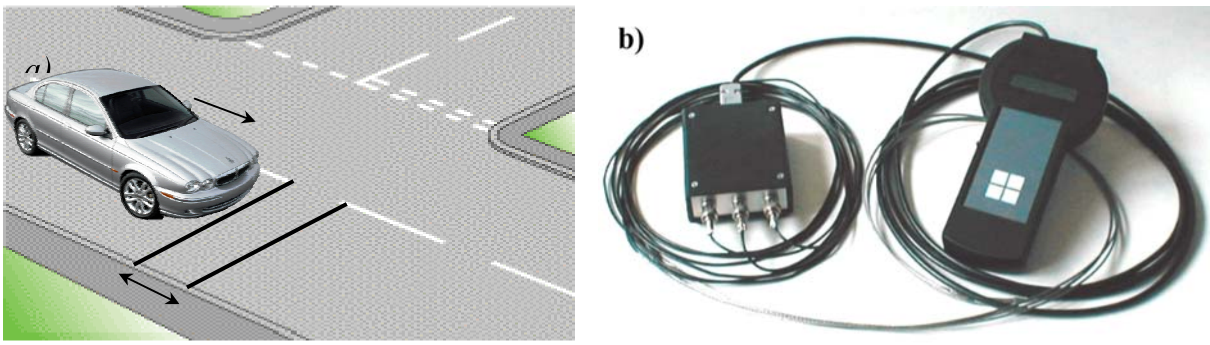

Fig. 2. PCSS velocity measurement system: a) principle of operation, b) portable velocity meter.

Fig. 2b presents a portable battery supplied design of the PCSS vehicle velocity meter. It consists of a PCSS signal conditioning unit (the box on the left) and a microprocessor controller (the handheld housing on the right). It makes use of 2 or 3 (for increased accuracy) linear strain sensors to be fixed to the road pavement by a rugged adhesive tape or mechanical clamping and is able to control a remote velocity display (LED or electromechanical) or transfer the velocity data to a remote computerised system. In case of the device meant for a permanent installation the signal conditioning circuitry and the controller are housed together in a rugged containment to be buried in the road shoulder; this version needs a mains power supply.

Fig. 3a displays the graph illustrating the PCSS velocity meter scaling curve i.e. the velocity measured by means of the device related to a velocity reference value. The reference velocity was calculated basing on the time delay measured by a digital storage oscilloscope for signals from a single PCSS device (PCSS 1) excited by the frontal and the rear test car tyre. Almost perfect agreement observed speaks well for the established model of the measuring system and the meter performance. The upper speed limit open for the meter depends mainly on the performance of the electronic control circuitry and the ripples (increasing in amplitude with the rise of the velocity) always present in the PCSS signal and spans to well over 150 km/h. The lower limit is mainly dependant on the sensitivity of the PCSS and the mass of the vehicle and ranges from 2 to 5 km/h.

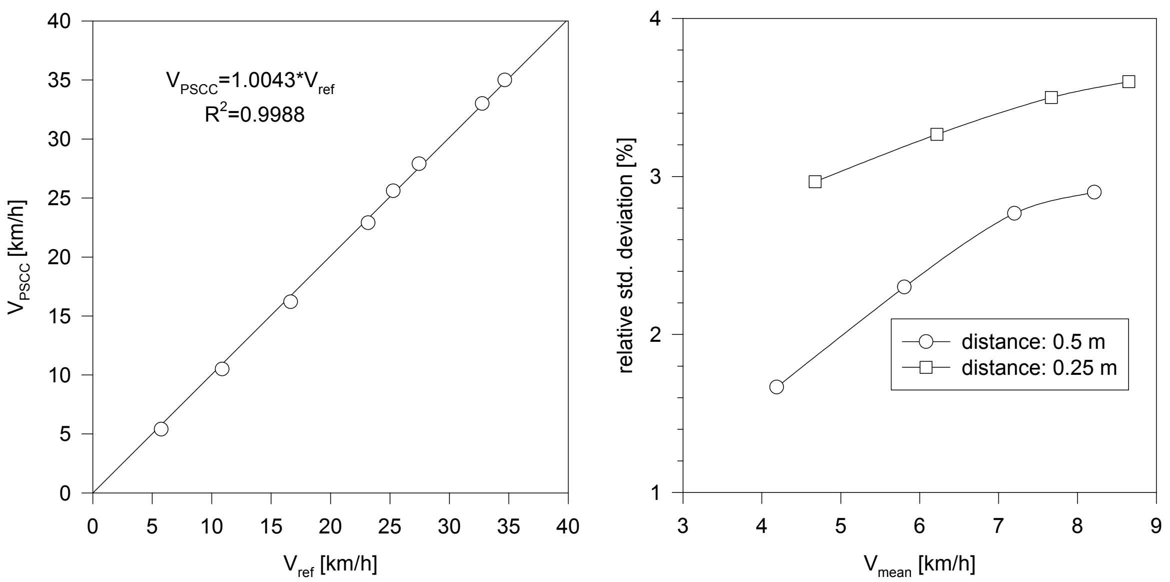

Fig. 3. PCSS velocity measurement: a) scaling curve, b) accuracy of the measurement.

In a real application the spacing of the PCSS sensors is constrained by the smallest distance between vehicle axles. In practice the distance of 25-50 cm is suitable in most of the road situations. The proper choice of this value is also important because it directly affects the overall accuracy of the method – a relative error of the velocity measurement increases as the sensor spacing is reduced. In a real application the uncertainty of the spacing distance results mainly from a nonparallel sensors alignment and errors in measuring the separation and in a careful work it is of a magnitude of 2-5 mm giving theoretical accuracy of 1-2 %. When a quartz-stabilised digital time delay-measuring device is used its relative error is negligible and may be not taken into account. Fig. 3b presents the relative standard deviation determined from a population of 25 successive measurements done for selected speed values. The estimation was performed in a laboratory scale set-up with an inclined plane and a heavy iron ball to simulate the movement of an object in a repeatable way with a strictly given speed. Therefore, the results are strongly influenced by the scatter of the test object velocity itself, but they give a brief overview of the statistics involved in PCSS velocity metering. It should be thus stated that even in this case the scatter of the test results is acceptably low and the true value characterising the meter itself is lower than the overall ones shown in fig. 3b.

3.2 Weight and axle load measurement

As the PCSS reacts to a force producing its deformation it is an obvious intention to employ this effect to measure the force exerted by a moving vehicle on the road and thus its axle load or total weight. But as it has already been experimentally verified a voltage signal generated by a PCSS is a function of not only the moving object weight but also of its velocity thus complicating the direct dynamic load measurement [9]. When this approach is used in a real set-up installed into the roadway it turns out that a PCSS mass measurement concept equivalent to that presented in fig. 1b results in very noisy signals. The signal component standing for a direct interaction of the mobile mass with the sensor is rather weak and difficult to extract from the background ripples, as it is shown in fig. 4a. The strong signal peaks are related to vibrations produced in the sensor elastic mount by the tyre when it approaches and leaves the sensing area. It is therefore justified to state that the application of PCSS equipment operating in so-called direct mode is troublesome although possible.

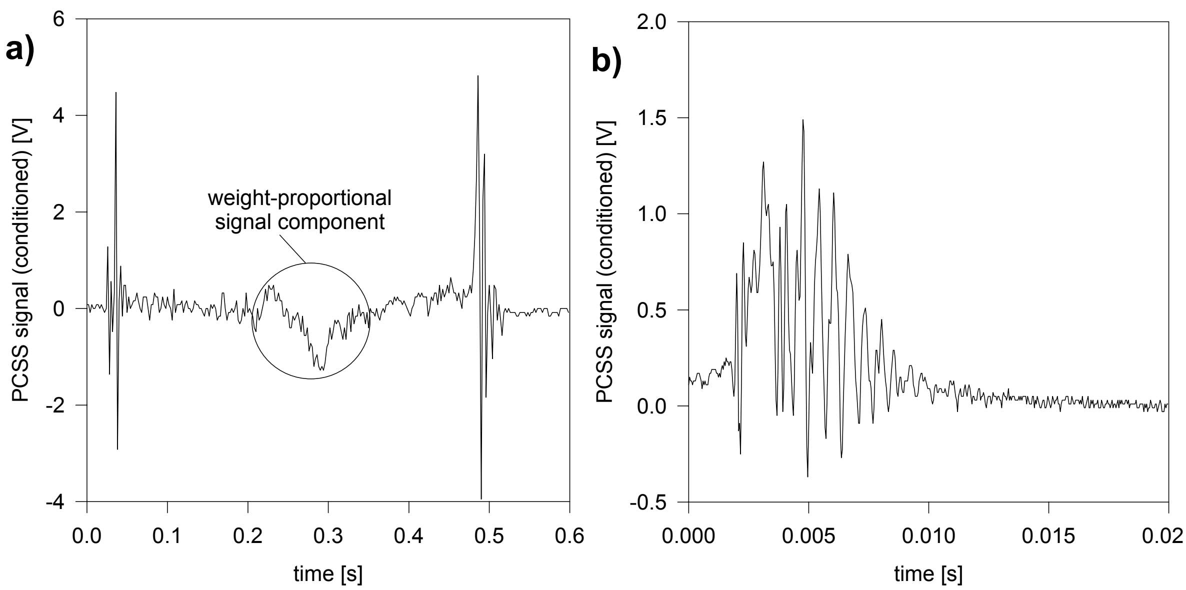

Fig. 3. PCSS load measurement a) signal recorded in a direct mode, b) signal recorded in indirect pressure conversion mode.

As PCSS produces, although with lower sensitivity, a voltage response to any variation of the hydrostatic pressure in its surrounding one may also try to adopt this phenomenon in the load measurement. Such an approach should, in theory, result in stronger dumping of the oscillatory signal component. In order to test this the PCSS was inserted into a flexible plastic tube filled with an inert fluid transmitting the pressure. As the fluid is incompressible, it prevents the sensor from being directly excited by any mechanical action. A signal train generated by a single tyre pass recorded for that configuration is shown in fig. 3b. Unfortunately it is still noisy and the signal descriptors proportional to the axle load are not easy to identify. The oscillatory constituent seems to originate from vibrations passed from the car's body and the sensor mechanical vibrations induced by the pressure waves travelling inside the tube.

The third tested variation of a vehicle weight measuring device was also based on recording changes of the pressure in fluid-filled tube compressed by a moving tyre. But this time a commercial piezoresistive pressure transducer (0-1 MPa range translated onto 0-10 V output signal span) was applied. Fig. 4a shows the sensor output signals recorded when a car (950 kg vehicle weight + 80 kg driver) drives over the pressure sensing tube incorporated into the pavement. In the tested design the signal-load conversion factor was approx. 180 kg/V when calculated for the lowest chosen velocity. As it may be deduced from the record, the car's rear axle was slightly more loaded than the frontal one: 480 kg and 550 kg accordingly, which fits well with the car's datasheet.

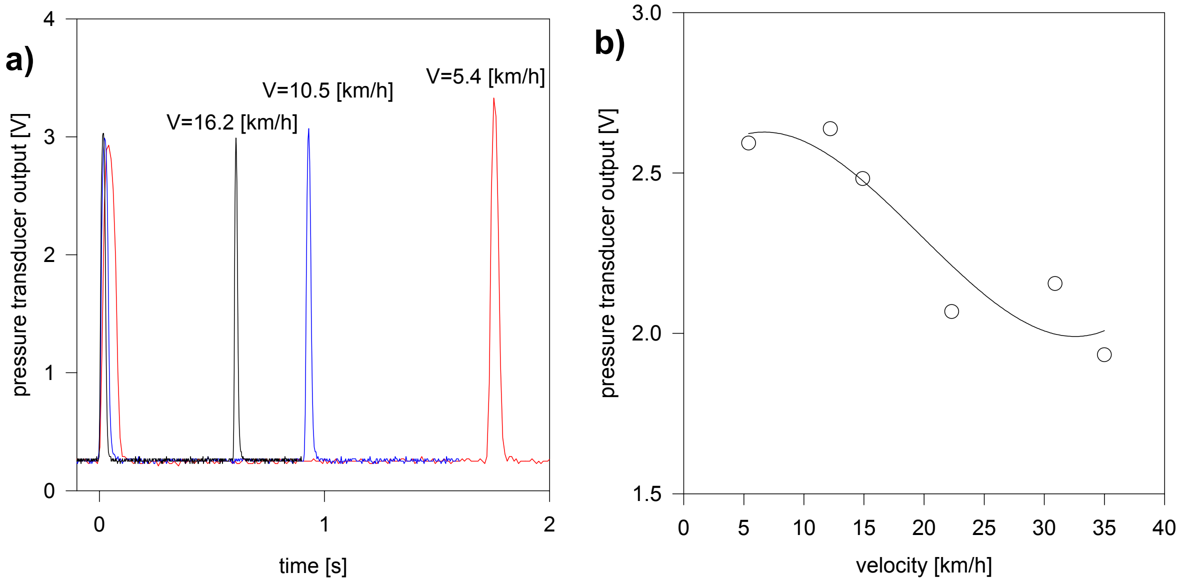

Fig. 4. Vehicle weight measurement by means of a pressure transducer: a) signals recorded for different velocities, b) velocity-signal dependence.

The pressure transducer output signal is dependent on the vehicle velocity, as it is shown in fig. 4b. The relationship is caused mainly by too slow response of the pressure transducer to a sudden pressure increase and decrease at higher velocities – it does not follow up the true pressure build-up because of its too long response time. Therefore for a reliable assessment of the load it is necessary to simultaneously measure the velocity, e.g. by means of a PCSS located just before the weighting device or to apply a faster transducer.

4. Summary

A concept of metering the velocity and weight of vehicles by means of piezelectric devices mounted permanently into the road pavement creates a foundation for a road intersection unmanned traffic monitoring system. A basic building block of the system for a single roadway, as shown in fig. 5, includes a weighting sensor and a single strain sensor (PCSS 1). The couple is used for a combined velocity, weight and axle load assessment as well as monitoring of any disapproved access to the crossing when the red light is showing. The second PCSS (PCSS 2) is mounted along a continuous line to supervise any attempts to trespass it. A set of these 3 sensors is controlled by a micro-controller.

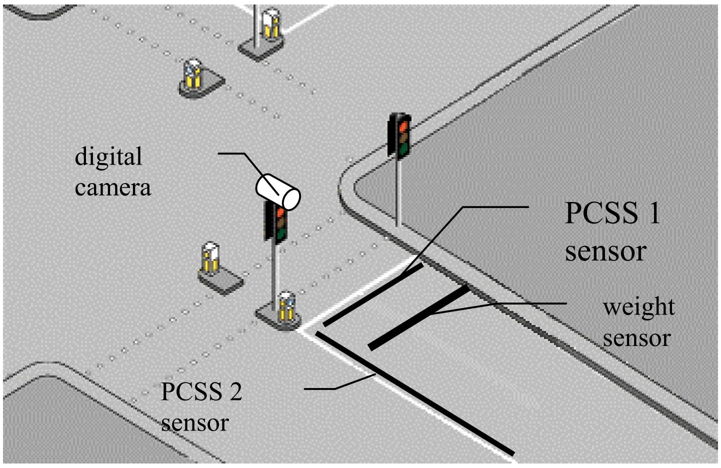

Fig. 5. Crossroad traffic monitoring system (one single direction line shown for clarity; explanation in the text).

A local industrial-type PC is linked to all the sets mounted at the crossroad by low-speed serial digital data links. It videorecords the situation at the crossing all the time but buffers only a few last seconds of the video record. It also listens for and analyses the transmission from the sensor sets and in case of any attempt to violate the Highway Code stores the buffered videorecording of the offender in its non-volatile memory. The crossroads PCs are linked to a central database system, which periodically checks for any recorded events and downloads the evidence. The local PCs in such a decentralised system work independently and do not need much computing power. Modern image compression algorithms allow to interconnect the PCs with even slow data links since every case is documented by a few tens of frames only. Just connecting new local PC terminals and registering them by the central database may also flexibly expand the network of monitored crossings.

5. References

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