Wireless monitoring of highways

Richard Bennett *[a], Barrie Hayes-Gill [b], John Crowe [b], Robert Armitage [a], Dale Rodgers [b], Adrian Hendroff [b]

[a] Scott Wilson Pavement Engineering, Nottingham, NG7 2QP, UK
[b] School of Electrical and Electronic Engineering, University of Nottingham, UK

ABSTRACT

Electronic hardware has been developed to telemetrically transmit temperature and strain measurements from within a public highway in the UK. These measurements provide an important health check for monitoring fatigue damage in pavements. Previous attempts at measuring strain and temperature have required lengths of cable to be installed in the highway. The installation of these cables is both expensive and damaging to the pavement and provides potentially unreliable electrical connections.

The new system consists of a retrofitted instrumented asphalt core which is bonded into the pavement structure. The core contains all the electronics necessary to record two temperatures (surface and roadbase) and two strains (longitudinal and transverse). An analogue front end provides signal conditioning which is digitized and passed to microcontroller for encoding. From here the data is transmitted via a low power radio link to a receiver and data logger positioned by the side of the road. The system has an in-situ operating life of 6 months on AA alkaline batteries. Results are presented of power management and fault tolerant radio protocol techniques, long term temperature variations, dynamic strain measurements within the highway, and RF transmission capabilities through a layer of asphalt.

Keywords: Highways, Temperature, Strain, Telemetry, Health monitoring

1. INTRODUCTION

The principal function of the asphalt layer of a flexible pavement is to spread wheel loads over the granular layer (sub-base) and foundation (subgrade) of the pavement. This capacity to spread loads is a function of asphalt layer stiffness, which can degrade through cracking and shorten pavement life. For thinner pavements in the UK, fatigue cracks usually initiate at the bottom of the asphalt layer, where the tensile strains are highest. Most UK pavement design methods [1,2,3] have been based on analytical predictions of strain at the bottom of the asphalt road-base layer to determine the fatigue life of the pavement. These strains are not routinely monitored in-situ, however, and there is a clear need for a method to measure these strains in trafficked pavements, in order to give a 'health check' on pavement life. This information can be used to plan cost effective preventative maintenance.

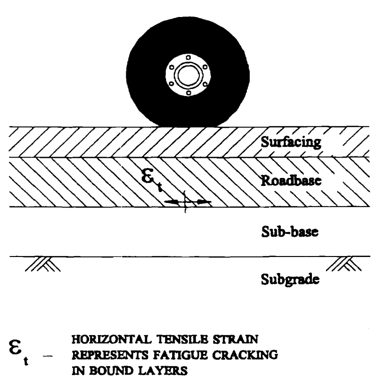


Figure 1, Section through a thinner asphalt pavement showing mechanism of fatigue cracking

* Correspondence: Email: rab@swpe.co.uk; Website: www.swpe.co.uk; Phone: +44 115 9229098; Fax: +44 115 9431302

The approach adopted in this work, funded as part of the UK Highways Agency research programme, was to measure the strains at the bottom of the asphalt road-base layer using resistive strain gauges. As the stiffness of asphalt is dependant upon temperature, thermistors are also installed in the asphalt to record the thermal variations. This approach has been used in previous work [4], where the transducers were connected to a data logger placed by the side of the highway. This required cabling to cross the highway, which generated high installation costs, and pavement damage, and suffered from unreliable electrical connections. The development of a wireless telemetry system is therefore necessary for effective measurement of strain and temperature, and has implications in many other areas of pavement instrumentation.

2. OVERVIEW OF THE SYSTEM

The system takes the form of an instrumented cylindrical core of asphalt, which is retrofitted in the highway (see Figure 2). Two strain gauges (S1 and S2) are located at the base of the core and are orientated parallel and perpendicular to the direction of traffic. The core is of variable length so that the strain gauges are positioned at the bottom of the roadbase layer. Temperature is measured at 25mm and 125mm depths (T1 and T2) on the sides of the core, to monitor daily and seasonal temperature variations. The core contains a void which houses the electronics. The system records temperature once every 30 minutes and strain for 10 minutes once a day. An RF wireless link is used to transmit the data from the core to a roadside receiver and logging unit.

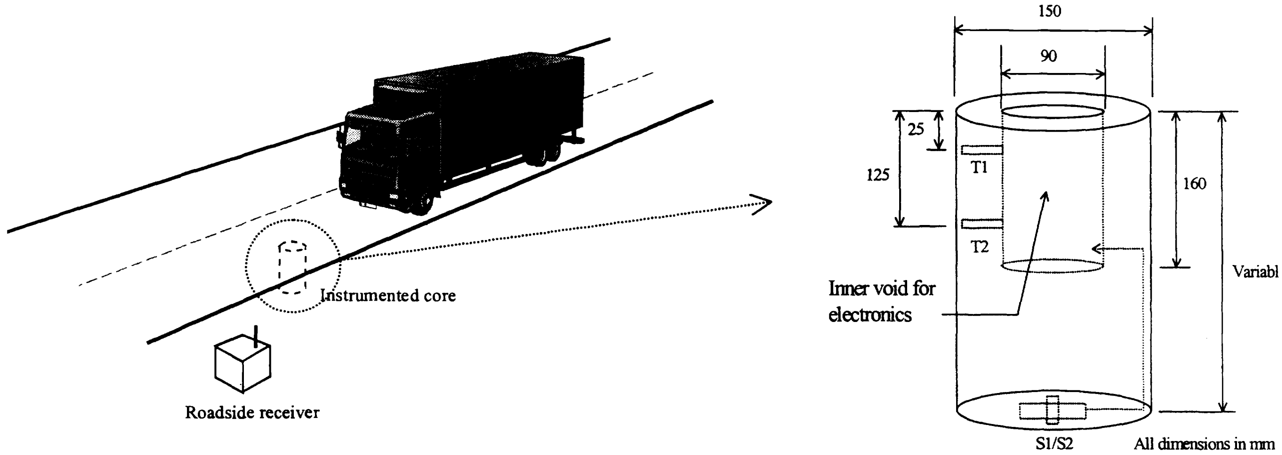


Figure 2, Overview of the instrumented core and wireless system

3. OVERVIEW OF THE ELECTRONICS

A block diagram of the electronic hardware is shown in Figure 3 and consists of three printed circuit boards. These are: an analogue board; a processor board; and an RF transmitter board. The processor board consists of a microcontroller (H8) which is kept powered down via the combination of a low power calendar chip, a power control circuit and a regulator (REG1) that has a 'SHDN' pin which disables the power supply. At every half-hour interval the calendar chip powers up REG1 which switches on the H8 which runs through a sequence of events. These events consist of the H8 powering up the regulators REG2 and REG3 on the analogue and transmitter board respectively. Once the whole system is powered up, the four analogue values of two temperatures (T1 and T2) and two strains (S1 and S2) are individually sampled by a multiplexed (MUX) 16 bit Analogue to Digital converter (ADC). This data is collected by the microcontroller, formatted into a serial data string and passed to the radio transmitter (TXD). In order for the receiver not to receive a DC bias the data must have an even number of 1's and 0's and hence is encoded into a form called 'Manchester encoding'. The Manchester encoded data is then arranged into RS232 format prior to passing to the radio transmitter. Using RS232 format allows the received data from the receiver to be fed directly into a serial port of a lap-top PC without any further processing.

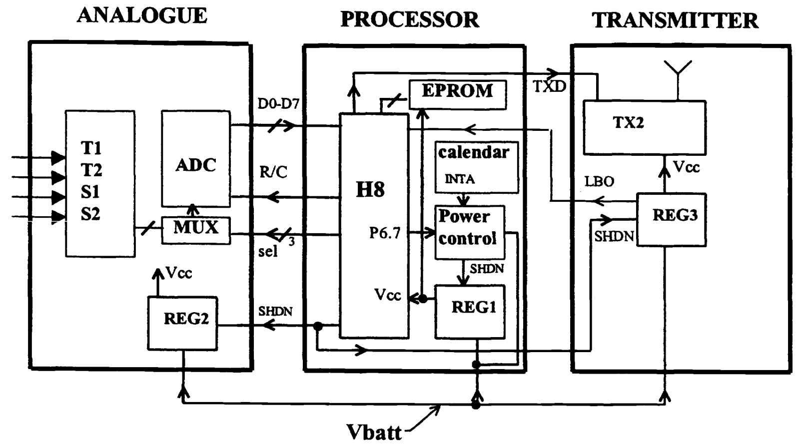


Figure 3: Block Diagram of the Electronics

3.1 Analogue Board

A block diagram of the analogue board is shown in Figure 4 and consists of: signal conditioning; multiplexer/buffering; and signal conversion. Both the strain gauge and thermistors require a voltage reference whose accuracy and stability determines the corresponding accuracy and stability of the measured temperature and strain. However, the analogue to digital converter also requires a voltage reference and the combination of the two produces a stabilising effect thus elegantly removing the dependence of the strain and temperature on this reference source.

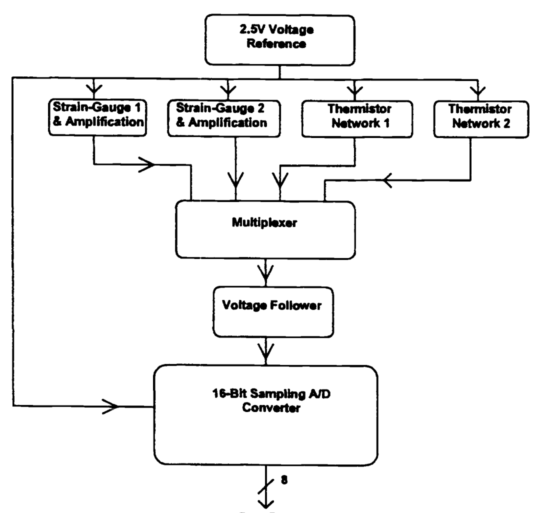


Fig 4: Analogue Front End

3.1.1 Signal Conditioning

The measurement of temperature and strain requires two different circuits:

Temperature

The temperature is measured with 44203 linear thermistors. These are arranged into a potential divider which produces an output voltage linearly dependent upon the temperature of the thermistor probe and proportional to a reference voltage supplied by a 2.5V voltage reference. These thermistors have a specified accuracy of +/- 0.1 ^{0}C over the range of -30 to +50 ^{0}C. The voltage developed across the thermistor (V_t) as a function of temperature (T) and the voltage reference (V_{ref}) is:

$$V_t = (-0.0068V_{ref})T + 0.651V_{ref} \quad (1$$

Strain
The strain transducer is a 120Ω resistive strain gauge configured as part of a Wheatstone bridge. The resulting offset balance is passed to a high gain (5,000 - 10,000) instrumentation amplifier and the output voltage produces a voltage signal linearly related to strain. The output voltage (V_{out}) of the Wheatstone bridge is given as:-

$$V_{out} = V_{ref}.GF.\varepsilon/8 \quad (2$$

Where 'ε' is the strain ($\Delta L/L$) in the strain gauge and 'GF' is the gauge factor – typically 2.1. Hence with a gain setting of 10,000, for every 10 microstrains (ε) a voltage of approximately 65mV would be outputted from the high gain amplifier.

Finally, all four analogue signals (T1, T2, S1 and S2) are fed into an 8 channel analogue multiplexor and then into a 16 bit analogue to digital converter, ready for processing in real time by the microcontroller.

3.1.2 Analogue Power supply

Four AA +1.5V Alkaline batteries with a capacity of 2700mAh are used as the battery supply. A MAX667 voltage regulator regulates the voltage to produce a 5V output. This regulated voltage supplies power to the instrumentation amplifiers, the 2.5V reference, the 8-channel multiplexer and the 16-bit ADC.

3.2 Processor Board

A block schematic of the processor board is shown in Figure 5. This board is centred around a Hitachi H8/329 microcontroller which, once initiated, controls all aspects of the system. This 8 bit microcontroller is clocked by a 9.8304MHz crystal and runs internally at 4.9152MHz. This clock speed divides down to the exact baud rates for the serial data transmission and also provides the sampling frequency required for the ADC. The microcontroller functionality is programmed via a C-compiler and the resulting program is stored in an EPROM on the processor board. This EPROM is used to store program code and the Manchester coding look-up table required for encoding the data for the radio transmitter.

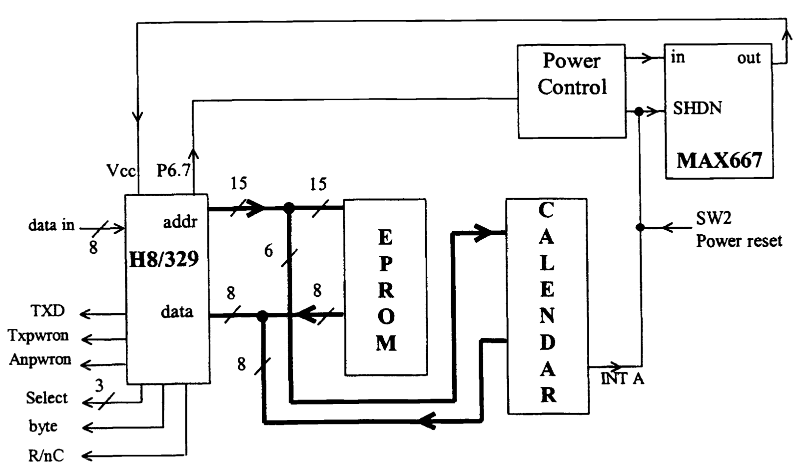


Figure 5: Processor Board

A key component of the processor board is the Dallas Semiconductor, calendar chip which maintains time and date when system main power is turned off. This is achieved through a lithium battery moulded into the case of the device which has a life of 10 years. The unit has two independent open drain alarms (only 'INTA' is shown in Figure 5) which can be programmed for time match alarms. Time, date and alarm settings are stored in 16 bytes of non-volatile RAM such that when the main system power turns off, the alarms continue to function and when a time match occurs 'INTA' is brought low to turn on the main system power.

The processor board has two main modes of operation: normal or continuous mode. In normal mode the temperature is recorded once every 30 minutes and the strain is recorded for 10 minutes in one day. Continuous mode is used for test purposes. In this case the complete system is permanently powered up and temperature and strain are continually being transmitted to the receiver. Two switches were added to the processor board: SW1; (not shown in Figure 5) is used to control the system into one of the two modes of operation; whilst SW2 is used to reset the system by forcing the regulator to power-up the H8.

3.3 Transmitter Board

Once a sequence of data has been collected and encoded the data is passed from the microcontroller in a serial form to the transmitter board. This board contains a radio transmitter and a voltage regulator.

3.3.1 Power Regulation

The transmitter board obtains its power from the same AA alkaline batteries used for both the analogue and processor board. To regulate the voltage another MAX667 voltage regulator was used along with its low power shutdown facility. The only difference from the analogue board power supply is that the regulator is wired in its 'low battery detection' mode. In this mode the regulator detects if the batteries are low thus enabling a bit in the serially transmitted data stream.

3.3.2 Transmitter Circuit

The radio transmitter used is a 418MHz Radiometrix data link module capable of data rates up to 40kbits/s at distances up to 75m in-building and 300m open ground. The module is fully screened and nominally delivers 0.25mW of RF power at 5V consuming typically 6mA.

The module is mounted horizontally on the area of ground plane close to the helical stub antenna to minimize feed length. The antenna type and position directly controls the system range and must be kept away from other metal and ground planes in the system. The unit is type approved in the UK by the Radiocommunications Agency to specification MPT1340 for use in telemetry, telecommand and in-building alarm applications. Such a device has shown to be of use for medical telemetry applications.[5,6,7]

3.4 Receiver Unit

The receiver unit has been designed to interface directly to the serial port of a standard lap-top personal computer such that data can be logged and displayed when on site. It consists of a regulated battery power source, an RF receiver and a serial interface. The receiver is a compatible radio receiver module supplied by Radiometrix and is designed to work with the chosen transmitter. The output of the receiver is then converted into RS232 logic voltage levels so that the data can be read into a PC's serial port.

A Borland C++ program was written for the PC to graphically display all 4 analogue values. The software is an interrupt driven program, which for reliable data collection a 16550 UART on the PC must be used. The data is time-stamped once every 256/8 samples and stored in a binary file with optional 'under-sampling' capability for reducing file size.

3.5 Data Format

In order to provide a reliable RF data link the design of the data protocol format is crucial. The format of a single data packet was designed as: Preamble (16 bytes); synchronisation bytes (2 bytes); data (16 bytes); packet number (2 bytes); and checksum (2 bytes). The preamble which consists of a series of '101010...' bits is necessary to bias the receiver to prepare it for the oncoming data. The synchronisation bytes allow the receiving PC to lock into the data packet. The data consists of one longitudinal strain (S1), one lateral strain (S2), one surface temperature (T1) and one roadbase temperature (T2). Next is sent the packet number. This is an 8-bit count value (i.e. from 0-255) such that the receiver can determine how many packets have been lost during bad transmissions. The data packet is completed by sending a 'checksum'. This is the binary addition of the whole data packet (except the preamble) and is used for error checking. Hence if a checksum is recalculated at the receiving end and if it does not agree with that transmitted then that packet is discarded.

The data packets can be transmitted in two modes. The first mode is called continuous mode and here each data packet is transmitted back to back continuously. This mode is for test purposes. The second mode is called normal mode where eight packets of data are transmitted back to back once every 30 minutes. Also once every 24 hours the strain is logged and transmitted for 10 minutes. In both cases the serial data rate was 38.4kbps with both temperature and data sampled at 100 Hz per channel.

The strain measurements use the full 16 bit resolution of the ADC. However, this is not necessary for the accuracy required for temperature (0.5 ^{0}C) and hence only 12 bits are used. The spare 4 bits in both T1 and T2 have therefore been used for battery low, ID tag and operating mode (normal or continuous).

3.6 Mechanical

Even though the aim of this work was to build a prototype, the physical size of the final system was important since the electronics had to fit inside a cylindrical bituminous asphalt core typically 150mm diameter and 300mm deep (see Figure 2). In order to maintain the strength of the core the walls had to be approximately 30mm in thickness which left an enclosure of diameter 90mm and depth 150mm to house the three PCB's. This was easily achieved (even without using surface mount devices) and all three boards were enclosed in a water-tight PTFE cylinder inside the asphalt core. The two strain gauges (S1 and S2) are mounted orthogonally on the base of the core and the wires are passed up a slot in the side of the core to the inner enclosure. The thermistors (T1 and T2) are placed in blind holes at two depths of 25mm and 125mm. Finally the whole asphalt core is sealed with a toughened plastic lid.

4. TESTING

The testing was divided into basic tests prior to installation and in-situ highway testing.

4.1 Testing Prior To Highway Installation

4.1.1 RF Transmission Through Bitumen

In order to test the ability for the chosen RF frequency to pass from underground a simple RF test unit was built. This unit consisted of a digital sequencer and a 418MHz transmitter. The receiver was connected to the serial port of a lap-top PC and the percentage of valid bytes received were recorded. It was found that when the receiver was positioned 10 metres from the transmitter a 100% success rate for valid data packets was obtained.

With a view to future rapid collection of data the receiver was positioned in a vehicle moving at 30km/h. Approximately 1,500 bytes of continuous data were successfully collected by the receiver as the vehicle passed overhead. This is potentially equivalent to over 160 analogue values with this RF telemetry frequency.

4.1.2 Strain Testing in Laboratory

In order to test the strain in the laboratory the instrumented core was switched to continuous mode and the strain gauges were positioned vertically on the outside of the core. Once the system was balanced the noise in the system referred back to the Wheatstone bridge input represented a maximum of 2 microstrain. A 6Kg weight was placed on the top of the core and the resulting strain gauge compression was recorded on the lap-top via the wireless link. The deflection is equivalent to a compression in the strain gauge of approximately 20 microns which is consistent with theory.

4.1.4 Temperature Testing under soil

In this case the instrumented core was buried under-soil for 70hours. The receiver was situated inside a brick building 10 metres away from the core. The system was switched to normal mode and the resulting temperature variation is shown in Figure 6. As expected, due to the position of thermistor T2, situated 125mm below the surface it permanently lagged behind thermistor T1 positioned at 25mm.

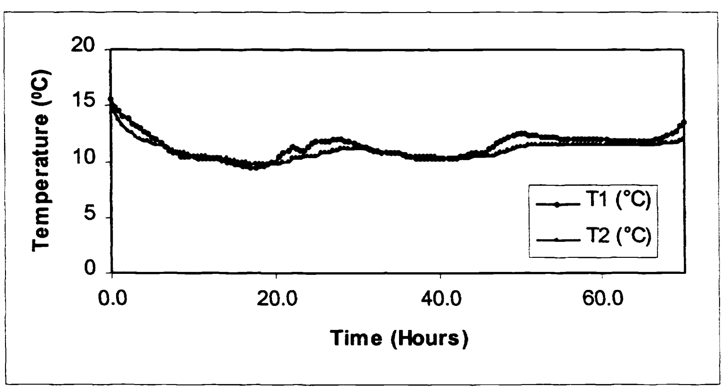


Figure 6: Plot of temperature under-soil over a 70 hour period

4.1.4 Power consumption tests

The power consumption for the two modes of operation were measured by recording the average current in continuous mode and then dividing by the duty cycle for normal mode. In continuous mode the battery life was found to be 47 hours whilst in normal mode a battery life of 4700 hours is expected i.e. nearly 7 months.

4.2 In-Situ Highway Testing

4.2.1 Highway Installation Procedure and Location

The final tests consisted of installing the core in a trafficked pavement during March 1998. The site chosen was in the wheel-path of a four lane section of highway at a point where lane changing occurs prior to an intersection (Figure 7). A core was removed from the pavement and the instrumented core bonded in its place using epoxy resin. The thickness of the pavement required the instrumented core to be 340mm in length, in order for the strain gauges to be positioned at the base of bottom of the roadbase. Clearance of the instrumented core in the hole was 2mm in order to produce a tight sliding fit, as an effective bond is essential to allow the transfer of tensile strain from the pavement to the instrumented core. Various recordings were taken with the system operating in continuous mode and the receiver and data logger positioned approximately 4 metres from the instrumented core.

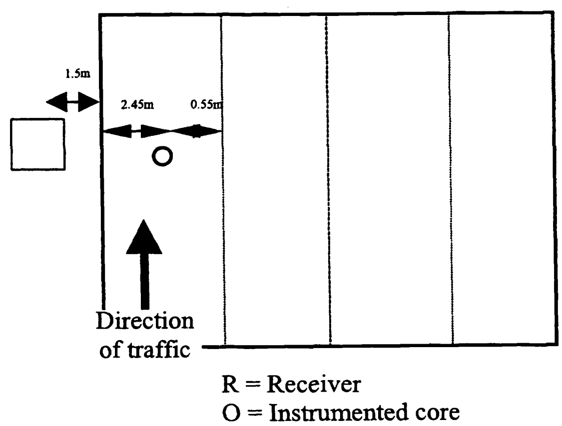


Figure 7: Location of highway test

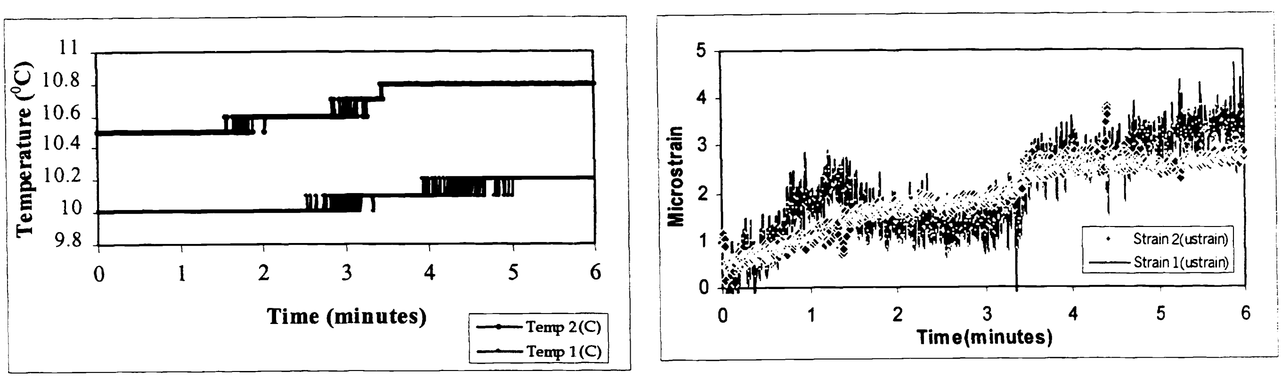


Figure 8(a) and 8(b): Plot of Strain and Temperature In-Situ with no Traffic

4.2.2 In- Situ Testing - Untrafficked

Figures 8(a) and 8(b) shows the data obtained with no vehicle passing overhead; a steady temperature reading of 10 ^{0}C in Figure 8(b); and the balance drift for the strain gauges in Figure 8(a) over approximately 6 minutes.

The maximum input referred noise in terms of microstrain for Strain 2 is +2 microstrains. Strain 1 has a maximum noise of + 0.7 microstrains, the difference being due to the differing conductive paths between S1 and S2 on the analogue PCB.

It is important to appreciate the significance of the packet number byte in the data packet. Figure 10 shows a plot of the packet number transmitted in 21seconds. With 100% successful transmission then 256 packets should be received at which point the count should return to zero and start to count back up to 256 again. Hence a perfect sawtooth waveform is expected and this is shown in Figure 9.

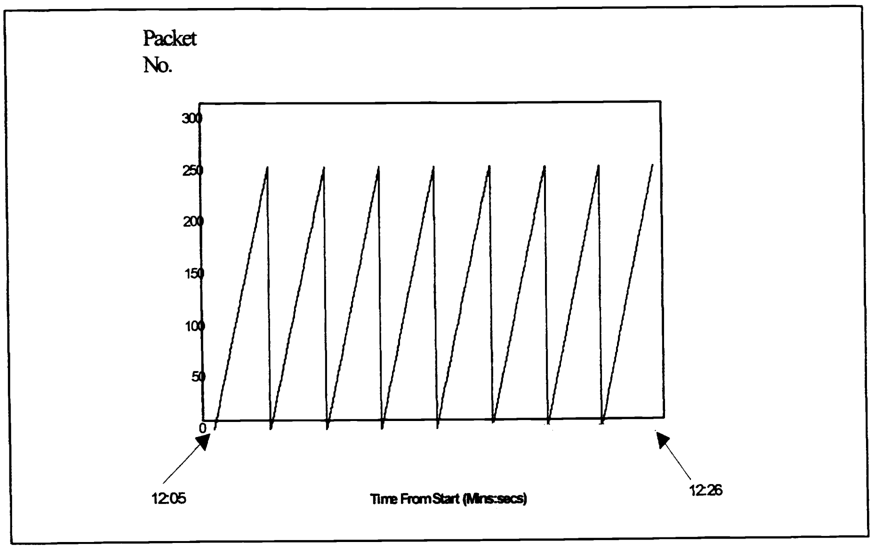
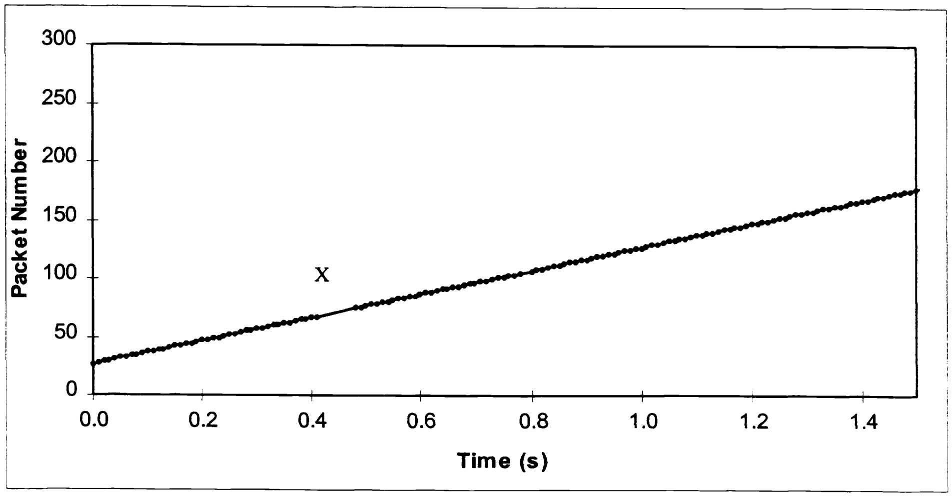
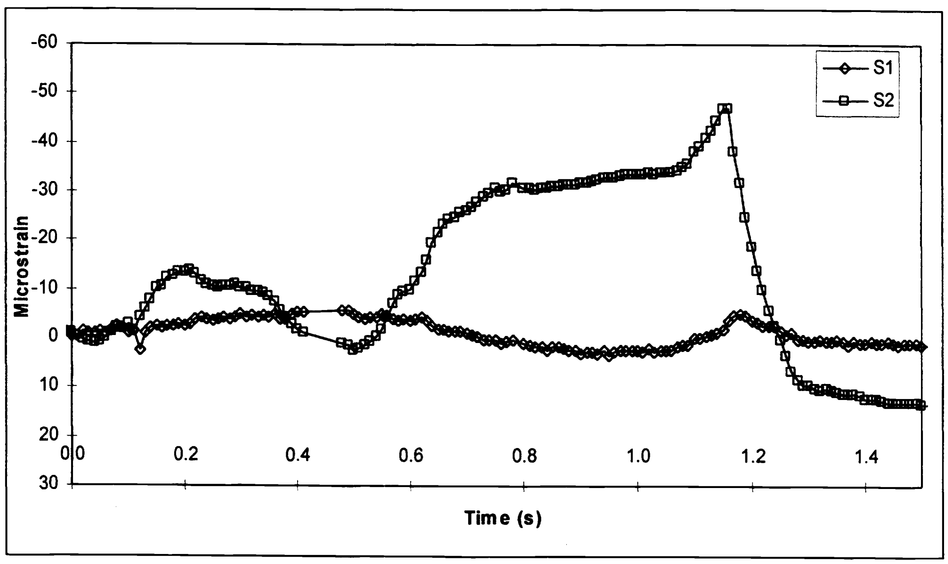


Figure 9: Graph of Packet Number versus Time - taken from Figure 8 with no Traffic

4.2.3 In-Situ Testing - Trafficked

Strain measurements and signal transmission tests were conducted under trafficked conditions. When data is lost during transmission, (indicated by an invalid checksum) the data is ignored and the packet number is no longer consecutive, and a gap in the packet waveform will be observed. This typically occurs for a very short time when a vehicle passes overhead. Figures 10(a) and (b) shows the data collected when a loaded truck (three axle rigid) passed over the instrumented core at 65km/h. The lost packet is labeled as 'X' in figure 10(a). The corresponding strain data, extracted from Figure 10(a) is shown in Figure 10(b). This plot shows the strain results for the truck, where wheel loads would be expected to be approximately 40kN. (S1 represents longitudinal strain and S2 transverse). The longitudinal tensile strains recorded are in the region of 50 microstrain, which is in the range expected for this load and pavement configuration.





Figures 10(a) and 10(b): Graphs of Packet Number and Strain under a loaded truck (40kN wheelload) travelling at 65km/h

5 CONCLUSIONS

5.1 Conclusions

This work has successfully demonstrated the feasibility of telemetrically transmitting temperature and strain data, from within a pavement to a roadside receiver. The temperature is measured to an accuracy better than 0.2 ^{0}C over a temperature range of -10^{0}C to +50^{0}C . The system has also demonstrated its potential to measure strain with a maximum error of 0.7 microstrain in-situ. Hence it is feasible to detect strains induced by heavy vehicles of at least 5-10 microstrain.

This system records four analogue values sampled at 100Hz and can either continuously transmit all data or will pulse the data once every 30 minutes with a 10 minute period for all data collection once a day. In continuous mode the battery life is approximately 47 hours however, in the pulsed, normal mode the system is expected to continue operating for nearly 7 months.

5.2 Further Work

System improvements are currently being made and include the addition of networking capabilities via roadside mobile telephones for remote dial up, plus the inclusion of a low power transceiver system to implement tele-command. Further work will include a substantial long term testing programme of the system. Instrumented cores will be installed at a number of sites in the UK and monitored for a period of three years. The test programme will produce long term pavement fatigue data and will include exhaustive testing of the wireless telemetry system.

5.3 Acknowledgements

This work was funded by the UK Highways Agency as part of the SMART Roads programme. The authors wish to thank Barry Brodrick for his technical help in constructing the asphalt cores and Kevin Last for his construction of the sealed PTFE cylinders.

References

1. Volume 7, Pavement Design and Maintenance, *Design Manual for Roads and Bridges*, UK Highway Agency et al., IID, February 1998

2. Brown, S.F, Brunton, J.M. and Stock, A.F, The analytical design of bituminous pavements, *Proceedings of the Institution of Civil Engineers*, Paper 8834, Vol. 79, Part 2, pp1-31, March 1985

3. Powell, W.D, Potter, J.F, Mayhew, H.C and Nunn, M.E, *The structural design of bituminous roads*, Transport and Road Research Laboratory, LR1132, 1984

4. Elliot, R.C and Brodrick, B.V, *SMART Roads - Monitoring Using New Technology*, Report to the UK Highways Agency by Scott Wilson Pavement Engineering, Vol. I and II, December 1997

5. Taylor J, Hayes-Gill BR, Crowe JA and Paull CJ, "Multi-patient leadless cardiotocography via RF telemetry" *Medical Engineering & Physics*, 1998, In Press

6 Hendroff A. A., Hayes-Gill B R and Crowe, J A, "A Multi-Site Telemetry System For Temperature Measurement" *Biological and Medical Telemetry Workshop*, University of St Andrews, Scotland, August 6th-8th, 1998

7. B.R.Hayes-Gill, J.A.Crowe, C.J.Paull, J.Taylor, A.Hendroff and J..Ashley, "Hardware Considerations in Telemetric Monitoring of Physiological Variables" *XIV International Symposium on Biotelemetry*, April 6-11, 1997,Marburg, Germany, 1998