# WIRELESS MAGNETIC BASED SENSOR SYSTEM FOR ROAD TRAFFIC DATA COLLECTION

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## ABSTRACT

A complete pre-industrial prototype implementation of an innovative system capable to detect, classify and describe passing vehicles, is presented. This work studies the architecture of a autonomous road sensor network to help reducing the impact of conventional magnetic wired systems in roads. The power supply is supported by no rechargeable batteries, for communications the IEEE 802.15.4 with ZigBee on top are used to transmit digitalized vehicle's magnetic signatures up to classification server. This information is acquired using a magnetometer translating in voltage the variation of the Earth's natural magnetic field caused by ferromagnetic components, induced by vehicles. Results show a clear and distinguish magnetic signatures among different vehicles.

## INTRODUCTION

With the increasing number of vehicles travelling, the need of road traffic control and monitoring also increases. The available technologies includes inductive loops, video image processing, weight-inmotion, pneumatic tube, infrared and magnetic sensors. Inductive loops presents high installation and operation costs. Camera image processing requires expensive specialized processor unit per equipment and is sensible to weather conditions. Other remaining techniques have a smaller range of application when compared with magnetic sensors (Leduc, 2008).

The sensor technology used in this study is the Anisotropic Magnetic Resistance (AMR) with a magnetic resolution of one part in ten thousand of the Earth magnetic field (Honeywell, 2011a). With such a good precision, it has been clear during the development that the quality of the electronic design plays an important role to retain this level of precision. For this application the Earth magnetic field has an important advantage its presence anywhere on Earth. Inductive loop requires the production of an artificial magnetic field with significant energy consumption and the need for external power supply. The natural magnetic field may vary from 0.2 to 0.7 Gauss and its lines of forces are not horizontal but oblique, changing place to place in strength and inclination. The intensity of this field can vary with the weather and the season. Therefore, do not offer stability or accuracy like artificial inductive loop (Honeywell, 2011b). This variability is a challenge that must solved in the developed device.

This prototype transmits data using a low bit rate wireless communications with low energy consumption. The installation and operation cost of the proposed road sensor are expected to be much lower compared with the inductive loop systems solutions. The control centre that processes the vehicles magnetic signatures is a fundamental subsystem in road management to identify traffic load per vehicles behaviour/profiles/classes. The study of magnetic sensor is a natural development of this strategy. Works of other research centres have been studied in order to gain knowhow. (Cheung, 2008) (Brunelli et al., 2008) (Hajimohammadi, 2009). To describe the work in more detail, this paper is structured as follows: in Section 2, the system architecture and implementation overview is provided, in Section 3 results of the performed tests are presented, while in Section 4 conclusions and future work are summarised.

## 2. ARCHITECTURE

The proposed system architecture, Fig. 1, for vehicle count and classification considers the installation of sensors in the centre of motorway lanes. On the road side, the access point collects data from the sensors and relays them to the motorway network via 2G/3G or fixed network. The control centre receives the sensor signature and processes it in real time. Then the information system computes and displays the traffic load for each installed road sensor and gives access to a statistical distribution of the detected vehicle's class.

The low cost of each detection point allows a higher density of these road sensors and a much better visualization of the traffic load.

The installation of the access point close to sensors decreases the wireless transmission power to the lowest possible value, extending the sensor battery life time.

### 2.1 MAGNETOMETER

The selection criteria for the magnetic sensors for this work were based on a set of principles: sensitivity to the Earth magnetic field variation caused by a ferromagnetic objects, the energy consumption and the financial sensor cost.

Fig. 1. *System Architecture Overview.*

TABLE 1: COMPARISON BETWEEN SENSORS.

| Reference | A | B | C | D |
|---|---|---|---|---|
| Supply [V] | 5-12 | 5-25 | 1.8-25 | 1.8-25 |
| Current [mA] | 10 | 5 | 1 | 10 |
| Set/Reset Current [A] | 3 | 0.5 | 0.5 | 0.5 |
| Sensibility [mV/V/Gauss] | 3.2 | 1 | 1 | 1 |
| Ground Resolution [μGauss] | 27 | 85 | 120 | 120 |

Another important selection criterion was the ability to restore the sensibility of the sensor via included coils and a Set/Reset operation that only one supplier offers. We chose the B component in Table 1 (Honeywell, 2011a).

The family of Anisotropic Magneto-Resistances (AMR), allows to measure the Earth magnetic field with a precision below 0.5%. This background field is quite permanent, suffering only small and slow changes. Thus, the sensor includes an auto -calibration algorithm that adapts the measures so that this reference can be considered stable during a period of time well suited to vehicle detection.

Vehicles metallic characteristics produces typically a flux variation around 50% of the Earth magnetic field, but the variation can be many times this value with vehicles built with reinforced iron parts. In those rare cases, the magnetic signature will be partially saturated but still distinctive and usable for classification.

The project also wanted to determine the overall parameters offered by the technology and two orthogonal magneto sensitive axes where important to study the relation between the orientation of magnetic field and the vehicle's movement 2011a).

Modern vehicles include many ferromagnetic components as show into the representation in Fig. 2 for example the wheels axels, motor components, transmission, gas escape are made of steel or iron. Electric motors and alternator creates a magnetic field. All those components concentrate or disperse the Earth magnetic field and thus, create detectable variations at the output of the AMR sensor.

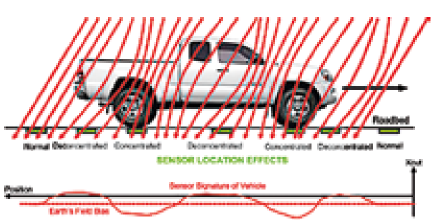


Fig. 2. *Vehicle magnetic signature (Honeywell, 2011b).*

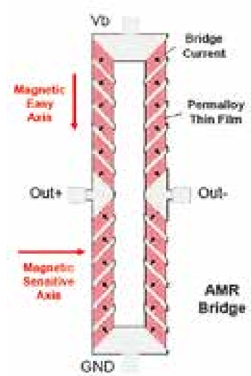


Fig. 3. *Structure of the sensor (Honeywell, 2011b).*

The resistive elements of the sensor are placed in a Wheatstone Bridge shown in Fig. 3 that allow the comparison between two tensions that come from two resistive dividers. Each resistive divider is made of two branches which are composed of 6 Permalloy magneto-resistive elements oriented at 45º. Each branch elements are positioned at 90º of their companion branch elements. When a branch has low magnetic resistance, its companion branch will have a high value. Both dividers are in a mirrored conformation and respond in an opposite way allowing a maximum tension difference between them.

Where Vb is the applied tension, in our case, 3.3V, Out+ and Out-, the tension of the two dividers values *Vb*/2 when the magneto-resistance are equal, therefore when there is no external magnetic field applied. The output differential tension (*Out*+, *Out*-) is equal to the ratio of the variation of the resistance of one branch on the resistance of it, times the applied tension *Vb*. It is a small voltage value of few mV. On the influence of the Earth magnetic field, a value of 0.5 Gauss creates a 2.5mV of differential tension.

The magnetometer requires a correction of the bias created by the local value of the magnetic field of the Earth and an amplification of the differential tension which gain should be between 500 and 2000.

Those values changes at each installation location because the orientation of the main magnetic sensor direction must be parallel to the road traffic direction and therefore, the strength of the Earth magnetic field is always different. To solve this issue a set of digital potentiometers was implemented in order to perform the sensor auto-calibration.

## 2.2 ELECTRONIC COMPONENTS

The AMR sensor that provides a small tension variation between two outputs must be followed by a stage of operation amplifiers (OpAmps) that provides a bias correction, a difference and an amplification operation.

The 3 operations can be done in one circuit or via many OpAmp in cascade, depending of pretended level of precision. The signal is conditioned to remain into the range of [0, VCC] Volts, where VCC is the power supply voltage.

Those two tensions values are then redirect to a microprocessor that can digitalize them, store the data signature and send it to the wireless radio subcomponent after capturing the magnetic signature.

The prospection of electronics components to build a Low Rate Wireless Personal Area Network (LRWPAN) was limited essentially to the wireless solution available for the Industrial Security and Medical (ISM) band without licensing procedure. The IEEE 802.15.4 compliant components offer the better choice and a market research was made in order to select a good and reliable solution. The selected component accept the digitalization of up to 8 analogue inputs, offers 8 kB of RAM, one transceiver for 2.4 GHz IEEE 802.15.4 compliant, one OpAmp and two power outputs (Texas Instruments, 2011).

### 2.3 ZIGBEE

To transmit wirelessly the collected information, the IEEE 802.15.4 standard with ZigBee on top is adopted because it was developed to operate in short range communications and low power consumption systems, supporting also high level networking features. In this work, we have not found a specific ZigBee profile for sensors data capture through the implementation of duty cycles; so, we have developed a proprietary ZigBee profile and use only the ZigBee Network layer. Our communication features includes a transport layer with data fragmentation, packet resend, packet acknowledge if well received by the ZigBee coordinator in the access point. The coordinator firmware had also to be developed.

The energy effort associated to the signature transfer is maintained to the minimum with maximum speed.

The road sensor activates communications only when it has data to send or after some seconds of inaction. Data from the server and the access point are accessed only at these moments.

The ZigBee stack is well suited for fast development project and has parameters that are available to tune it to specific applications. The main features that are offered are the automatic association and reassociation to the network knowing that the coordinator chooses a channel that is not known by the terminal equipment.

The ZigBee features used by the project are limited and the use of the ZigBee stack is not mandatory. Another Stack simpler and power saving, maybe proprietary could also fit in all the needs, without license costs.

### 2.4 ORIENTATION AND ATTENUATION

The maximum radiate power generated by sensor's antenna orientation should be in a quarter of hemisphere in the direction of the road side as the sensor is always oriented toward the vehicles direction. Presently, it is plan to use an isotropic ceramic antenna embedded into the cover of the road sensor, allowing the coordinator installation anywhere around. To increase radio link performance it is recommended to use directional antennas to support adverse weather like rain and snow.

The coordinator must be oriented with a vertical angle of a least 30° and must use a directive antenna. For sharp angles the link attenuation rises quickly because there is no line of sight between antennas. In fact, the road sensor in located into a hole that is a kind of wave guide and the isotropic radiation of the ceramic antenna is affected and the majority of the radiation goes vertically. As higher is the angle of the coordinator, better is the reception. The attenuation caused by the cover material has being taken into account and some tests were made using acrylic, glass and asphalt materials and 1 dB/cm of attenuation was obtained. This is surprising but asphalt is made of very long aliphatic chains and is hydrophobic so the result is coherent with other similar material like plastics. Modified asphalt with the substitution of the gravel with adequate low attenuation material can constitute a good cement to embed the device into the road.

### 2.5 POWER MANAGEMENT

The sensor was designed to extend the battery live time to the maximum, thus the device architecture is modular, being each part only active when strictly necessary. The CPU remains always the master and not depended of any external interrupt to wake-up. It is the most convenient architecture and also the more efficient. The CPU uses one output signal to suspend the magnetometer and manage all internal functions. An alternative architecture use an external interrupt to CPU wake-up process avoiding the appearance of an indeterminate state in which the sensor would never wake-up, in this case a more complex electronic circuit is needed which increases the power consumption, therefore, this approach was not implemented.

The power management developed is based on the electronic architecture and on developed firmware strategies.

ZigBee is turned off when no communications are needed. The road sensor wakes up periodically to check for incoming data or to detect vehicles, then digitalise and send the magnetic signature and check again for incoming data. This optimisation cut 75% of the energy requirements: from 32mA the consumption falls to 8mA.

The ZigBee Stack provides elements to implement a closed loop TX Power control but ZigBee do not implements it. Each received packet of 802.15.4 comes with a Line Quality Indicator (LQI) computed based on the energy detection a signal to noise parameter. The received LQI coming from the coordinator is used by the road sensor to manage dynamically the TX Power. This power control is important to ensure the auto adaptation of the road sensor to changing weather conditions because heavy rains attenuate the radio signal and require more TX power, when weather conditions turns better, the priority must be to diminish TX power in order to minimize transmission energy power. The link budget between the road sensor and the coordinator must have an important power reserve. ZigBee chip have a sensibility around -95 dBm. The design of the antennas is essential to make a road sensor system adaptable to any weather conditions: traffic jam and accident happens during those situations and the road sensor mission is to guaranty full functioning state and information dispatch without failures at that moment.

As the road sensor should only send data to the right side of the motorway in right hand traffic countries, the gain of its antenna can be better than 6 dBi which correspond to a quarter of hemisphere of the isotropic antenna of 0 dBi. On the coordinator side, it is very important to use an antenna with a gain higher than 14 dBi, which is about a 60° Beam Wide (BW) at 3 dB. This combination offers more than 20 dB total antennas gain that can constitute part of the necessary power budget. The space diversity that some manufactures propose is important if the application is sensible to multipath but, for this open air application, few installations may suffer from short distance attenuation due to the lack of reflection of the transmitted signal.

In order to improve power savings, the firmware has been compiled to activate the sleeping mode provided by the ZigBee stack. In Fig. 4, the Normal firmware shows a power saving starting only with a low frequency sampling. After an optimisation of the firmware, we compiled a version that processes much better this switching and can achieve about 90% of saving, switching from 8 mA without duty cycle to 0.7 mA.

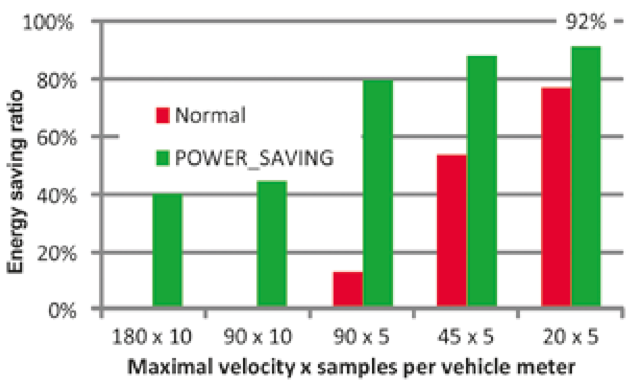


*Fig. 4. Energy consumption with both firmwares.*

### 2.6 POWER SOURCES

In a power saving energy mode spending 0.7 mA, this sensor represents a very low drain voltage equipment enabling the use of none rechargeable batteries. A Professional Long Duration Alcaline Battery offers a capacity of 17000 mAh at 2.2-3.3 V. The discharge per year is about 3% (Energiser, 2008), this means about 4,94 years of useful life. A lithium battery offers more than a 1.5 times the capacity of an Alkaline and very low discharge current. Lithium batteries are not stable when exposed to temperatures higher than 60° C and therefore should not be a first choice for a road sensor in Portugal (Energiser, 2009).

### 2.7 FIRMWARE DEVELOPMENT

The selected component is a SoC, executing our firmware and the full ZigBee stack. The firmware had to achieve a set of goals:

- scan the magnetometer axis in the direction of the traffic in order to detect passing vehicles;
- start the scanning of the magnetic signature at a rate that is adapted to an estimated speed in order to minimise data size;
- detects the end of the vehicle;
- insert the start of curve data store in a circular buffer;
- adapts the sampling rate from start to the first vehicle's axis;
- send the data via ZigBee;
- set/reset the magnetometer in order to maintain its high anisotropy and magneto-resistance sensitivity.

Maintenance processing of the road sensor includes:

- the TX power management,
- power control of the magnetometer and operational amplifiers;
- auto calibrations;
- Earth magnetic field detection.

The speed estimation (1) is made by the firmware and based on the average distance between the start of digitalisation and the first wheel of the car. Since each car model is different, this estimation will be different among cars and trucks however, it is expected to be always similar for the same vehicle. This allows a reasonable and fixed amount of samples per vehicles model, independent of the sampling rate.

$$V_{es} = \frac{d}{\Delta t} \tag{1}$$

Where:

- $V_{es}$ is the speed estimation;
- $d$ the distance between start and first axe;
- $\Delta t$ the duration between both.

The coordinator has been also a matter of attention because packets reception depends of its availability. Using an input circular buffer list for the transmission on the serial gateway was decisive for the coordinator radio reception efficiency.

*Fig. 5. Developed sensor prototype.*

## 3. RESULTS

The first issue to be solved is the sensor orientation. The reproducible effect on a magnetic axis is achieved when the vehicle motion is in its direction. This means that we do not orient the main magnetic axis in the direction of the north magnetic pole that would provide the best sensing amplitude, but always in the traffic direction.

The parallel sensing direction, the $2^{nd}$ axis, has a quite different measure of the Earth magnetic field and its amplitude is different from the main axis. The bias can be corrected via a supplementary OpAmp for its calibration. If the magnetic axis' input signals are amplified with different gains, it can be demonstrated that the vector norm of the two orthogonal axis change if we turn the sensor horizontally, for the same vehicle. Thus, applying different gains into both magnetic axis it can produce different magnetic signatures for the same vehicle when road sensors are installed in different locations. This must be avoided in order to guarantee information coherence. The 1- axis magnetometer, oriented in the traffic direction it can provide relevant information, completely coherent, with a much lower cost in processing and energy.

The current prototype version is show by Fig. 5.

Vehicle's signatures are shown by Fig. 6 and Fig. 7, they represent the forward and parallel BMW signature, respectively.

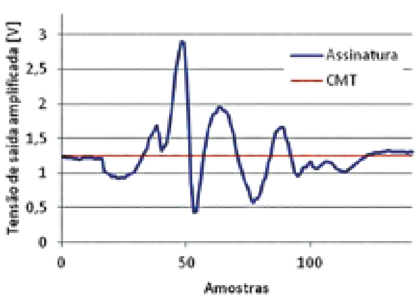


Fig. 6 *Forward axis scanning.*

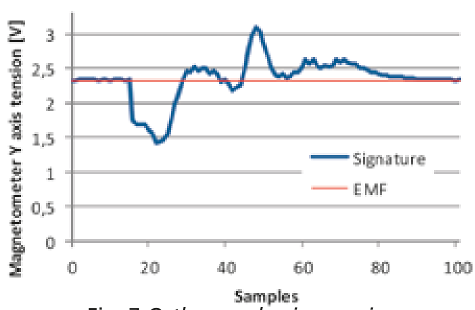


Fig. 7 *Orthogonal axis scanning.*

Results show a correct EMF estimation for both axis. Vehicles' magnetic signature detection and scanning is completed and well captured. Thus, one concludes that vehicles count is therefore correct.

Fig. 8 shows the DC-DC converter stability when input power variations are applied. This test is important since the sensor will be capable to extract the full battery power, while keeping power supply stable.

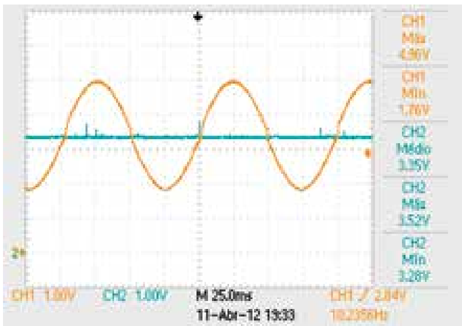


*Fig. 8. DC-DC Converter stability to input variations.*

We verify that for a specific vehicle model and for speeds from 20 km/h (Fig. 9) up to 60 km/h (Fig. 10), we receive about the same amount of fixed samples validating the speed detection algorithm. With other vehicle model, we had the same result but with a different number of samples.

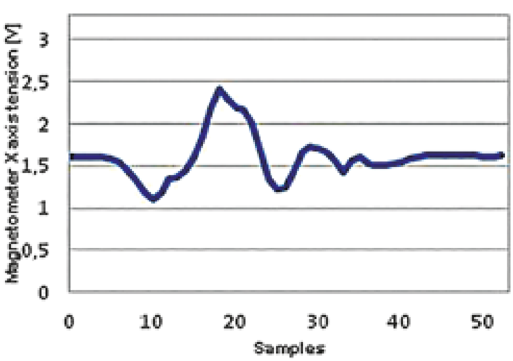


Fig. 9 *Main axis vehicle at 20 km/h*

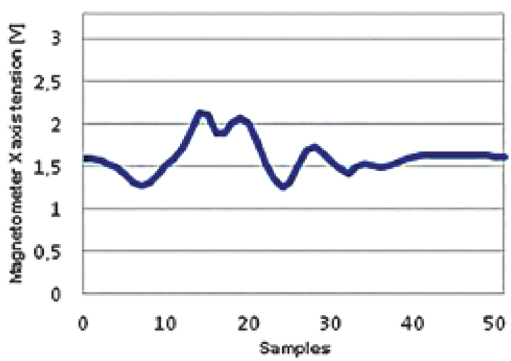


Fig. 10 *Main axis, vehicle at 60 km/h*

## 4. CONCLUSIONS

The firmware that has been developed processes successfully the magnetic signature captured and allows confirming that for each tested vehicle, there was a very distinctive signature with significant variation between successive tests for the same car, although it depends on vehicles' positions in the road (sensor location).

The developed speed detection algorithm performs well and provides a discrimination factor for the classification engine.

According to the results, two sensors devices types are possible as follows: a small sensor expect to measure 30 x 80 mm that would only use one magnetometer axis and would be powered by battery, having a low cost production as advantage. It is expect, from the consumption model and the test with POWER_SAVING firmware, to achieve at least 5 years of permanent operation. The use of a special asphalt cement to embed the sensor into the road is also an option that is considered in order to turn very simple, quick and cheap the insertion of the sensor into the road. Another sensor architecture proposed uses 3-axes magnetometers and high precision digitalisation. It is expected to measure 125 x 80 mm. A solar cell would power the sensor with a super capacitor to maintain the operation during the worst winter days in terms of solar radiation power. Rechargeable batteries last only some years, for this, reason super capacitors can be used at 80% of the maximum charge voltage which provide about 10 years of live spanning. This sensor type should be inserted into a permanent chamber embed into the road and be easily maintained, providing the best precision available with this technology.

To optimize the current solution and decrease production and maintenance costs, some changes have been introduced, such as one axis detection and battery support.

## ACKNOWLEDGEMENTS

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