Energy Efficiency studies for the Folgoso Tunnel. Introducing the new TUNELEC, a portable device for electrical measurements and tests in tunnels

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1. Introduction

Tunnels have a series of facilities to provide security and comfort to users, such as lighting, ventilation, video surveillance, etc.

Geocontrol, S.A. is a consulting and engineering company founded in 1982 developing an intense consultancy activity in performing projects and monitoring the construction of civil works; particularly with regards to tunnels and other underground works.

During the development of these works, it has been observed that occasionally oversized or underperforming facilities appear due to on/off protocols that are not adjusted to actual needs. These circumstances for the most part have been unknown to the exploiters and have reverted to greater energy expenditure.

The Folgoso road Tunnel is in the North-West of Spain, connecting the central plateau with southern Galicia.

It is a twin tube, unidirectional, 2551 m long, tunnel. It has been operating since 1998. It has an average daily traffic of 15.000 veh/day and a 17,2% of Heavy Vehicles. Traffic of Heavy Good Vehicles inside the tunnel is allowed.

In 2006, the Spanish Ministry of Public Works undertook the tunnel's refurbishment design project, in accordance with national standards in tunnel safety. As a result, in 2009 the refurbishment works began, with the tunnel still in operation.

During these works an interesting study on energy consumption was conducted, which aimed to monitor multiple circuits and verify their performance in a long-term period.

In order to monitor the consumption a portable monitoring devise was built, TUNELEC, for electrical measurement and tests in tunnels. This device can monitor the electrical parameters of the system and supervise the activation of up to sixteen circuits in a nonintrusive manner. The data is stored locally and can be send by GSMR or Internet to a remote database.

In the following section, the design and installation of the device in the Folgoso Tunnel is described, so as the process of data analysis which results in a number of proposals to improve the energy efficiency of the tunnel.

2. Device design

In this section the requirements imposed to the supervision devices are determined and different alternatives are evaluated, to finish manufacturing and testing a system that combines commercial elements with equipment of own design.

2.1 Design requirements

The registering unit has been designed to respect the following requirements:

- Easy installation without modifying the electrical installation aimed to be analysed.
- Easy transport with no need of auxiliary equipment.
- Capacity of measuring both intensities and voltages and to obtain the energy consumption based on those values. The commercial units able to perform this kind of work are the network analysers.
- Capacity of detecting the activation of every single circuit. In order to do this task with commercial equipment, it should be required modules with digital inputs and a wide set of adaptation units, in order to adapt the circuits' working voltages to the voltage of the modules with digital entries.
- Capacity of increase to integrate other equipment's measures, such as anemometers, thermometers, cinemometers, photocells, and other environmental and traffic sensors. This requirement is easy to meet if the system has a standard communication bus.
- It has to provide registering capacity for several months and/or have the remote transmission systems such as a GSM modem. Commercial units with these functions are denominated dataloggers, but the automated logic controllers could also perform this work.
- The system must maintain the registered data face power outages. Most of the commercial dataloggers verify this requirement, while the automated logic controllers don't.

2.2 Commercial alternatives

Once the design criteria have been established, it has been needed to contact the technical assistance departments of several manufacturers to make a request about the possible combination of different units to meet the requirements. The following table presents a summary of the proposed alternative solutions:

Table 1 *Proposed alternative solutions*

Manufacturer	Equipment	Network Quality	Intensity probes	Circuit Activation	Extension	Memory Registrations	Modem	Cost
ABB	It hasn't sent any proposal							
CIRCUTOR	EDS-3G CVM-V10	Analyser Qualty	Transfor	I/O Digital	Modbus	SRAM 250MB	3G	Medium
CIRCUTOR	EDS-3G CVMNET4	x4 A Quality	Transfor	I/O Digital	Modbus	SRAM 250MB	3G	High
CIRCUTOR	AR6	A Quality & Trigger	Flexible	NO	NO	SD Card Years	NO	High
IAC	S203-D	Analyser Qualty	Flexible	NO	NO	NO	NO	Econom-ic
Microcom	Hermes-200	NO	NO	I/O Digital	Modbus	SRAM 40000Reg	3G	Econom-ic
Schneider	It hasn't sent any proposal							
Socomet	Diris A-40 Datalogger	Analyser Quality	Transfor	I/O Digital	Modbus	Unknown	3G	High

None of the alternatives verify all the desired requirements, highlighting:

- Only the analysers AR6 of CIRCUTOR and S203-D of IAC can be easily installed without the need of modifying the installation, due to the fact that they are the only alternatives that use flexible intensity probes.
- None of the alternatives allows circuit activation detection easy to install without previous knowledge of the electric switchboards' operation and without the need of introducing small modifications.

2.3 Development of a system for activation detection

When it comes to determining which installations are responsible of the global energy consumption of the tunnel, there are two options:

- Monitoring the expenditure of every single circuit. This option requires a network analyser in every circuit, what means a high cost and a high complexity of the installation.
- Monitoring the global expenditure of the installation and registering the state of activation or not of every circuit. This way, only a single network analyser and a single circuit activation detection system are required. Although less data are collected, the same information can be obtained with respect to the first option provided the consumption of the monitored circuits is constant through the time.

In most cases, the energy expenditure of the installed circuits in the tunnels presents little variations throughout the time for activation in such a manner that often, the second option is chosen.

With respect to monitoring the circuit activation, some commercial alternatives are available, based on cards with digital inputs that have to be electrically connected to the monitored circuits, through voltage conversion modules. However, this system needs to be electrically connected to the installation, which means being forced to introduce small modifications in this installation and also to provide a high quantity of electrical cables working in the same level of the voltage supply.

Since the activation detection systems are considered rather complicated to install, a new one was due to be created, so that it would be possible to detect a single circuit's activation by measuring the magnetic field produced by the intensity circulating through the chosen circuit. This way, the installation would consist in placing this sensor on one of the electrical conductors of the circuit aimed to be monitored, without the need of electrical connexion.

If we establish a lower limit for detection of electrical charges of 1000 W (with 220V power supply) and under the assumption that the sensor isn't further than 3,75 mm of the conductor's centre, the magnetic field reaches values of 0,2 µTesla or 2,3 mGaus.

These values are very low to be detected directly with conventional Hall Effect sensors. However, there are currently available intensity transformers with its core split that, although they offer low precision, they are quite easy to install and have a competitive price, being ideal for our objective, since it's not required to quantify the intensity with much accuracy.

The signal sent by this sensor has to be filtered, compared with a reference value and monitored continuously; for this reason, an electronic circuit, able to process the signal from 16 sensors was designed.

Another additional electronic circuit based on a microcontroller Atmel was designed, in order to show the monitoring of the sensors to the users thanks to the lighting of some LED pilot light and also to communicate the state of activation to the equipment in charge of the registering, with a bus Modbus.

Both circuits were implemented in both plaques of printed circuit, integrated inside a box for its assembly over DIN rails (see Fig. 1).

Fig. 1 *Parts of system for activation detection*

2.4 Multi-manufacturer solution

Given that there is no manufacturer that provides equipment with the desired characteristics, it's chosen to undertake a multi-manufacturer solution based on network analyser S203-D with data-logger EDS-3G. It includes web server in the datalogger itself, great capacity of storage and permits changing the configuration remotely.

Some of the above equipment work with direct current, thus it is required having a power source to convert the voltage supply (230 V AC) into a common voltage for the analyser and the detector.

Fig. 2 *Supervision unit*

In order to facilitate the transport of the equipment, a light plastic suitcase is due to gather all the elements that integrate the equipment, in which some DIN rails will be installed (see Fig. 2).

The elements inside the suitcase must be connected to the exterior probes and to the power supply.

Also, the following connection elements between the equipment probes and the suitcase have to be provided:

- A C14 connector is chosen for power supply, widely used in Europe.
- Connectors of 4mm and large safety alligator clips are chosen for the connection of the voltage probes, commonly used in measuring units since they permit the connection without any electric risk.
- Gold – plated RCA connectors with low voltage losses are employed for the connection of the intensity probes.

- 3,5mm Jack connectors are employed for the connection of the activation probes, which are provided by their manufacturer. This sort of connection has the advantage that it's easy to find extension cables which are compatible with audio equipment suppliers.

2.5 Additional elements

When the different electrical feeding typologies for tunnels are analysed it is stated that in long tunnels there may be up to 3 different transformation centres. More specifically, the Folgoso Tunnel has 3 TCs, one per entrance and another inside the tunnel, in a gallery that connects both tubes.

This situation forces to having an additional equipment unit for consumption supervision, so the third equipment is manufactured.

It is also foreseen that in tunnels with transformation centres placed in the inside of the tunnel, the phone coverage may be poor and, therefore, it is mandatory to seek an alternative way of communication with the exterior, using for purpose the communication capacity through Ethernet Modbus of the EDS of Circutor.

The device also includes a TCP1RS+ of Circutor, which is communication gateway that converts the Ethernet physical environment to RS-485 serial communications.

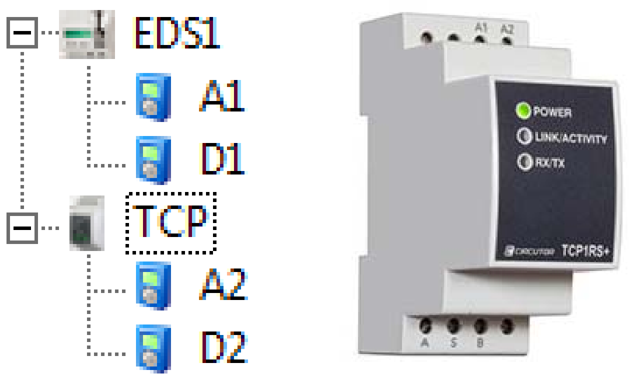

***Fig. 3** Connection Diagram of TCP1RS+*

In the case of road tunnels with an Ethernet Internal network, the TCP1Rs can be used to replace the datalogger of one of the consumption supervision device. The gateway would be connected to a second equipment unit employing the internal tunnel's network in such a manner that a single EDS would be in charge of two consumption supervision units, as shown in Fig. 3.

Finally, since the EDS of Circutor do not have analogic inputs, a Z-8AI module, from Seneca manufacturer is equipped, which can be connected to the EDS transmitting up to 8 analogic signals through Modbus protocol.

3. Installation of the units

The Folgoso Tunnel has three transformation centres: two external centres and one internal centre. The Transformation Centres are listed from 1 to 3, according to the criteria of the increase of the kilometric points of the road.

A supervision device for the energy consumption is installed in each Transformation Centre, taking advantage of the free space in the electrical switchboards.

In the Fig. 4 it can be appreciated that the installation of the intensity transformers (blue) of the activation detectors are hardly noticed and they don't interfere or modify any characteristic of the electrical switchboards.

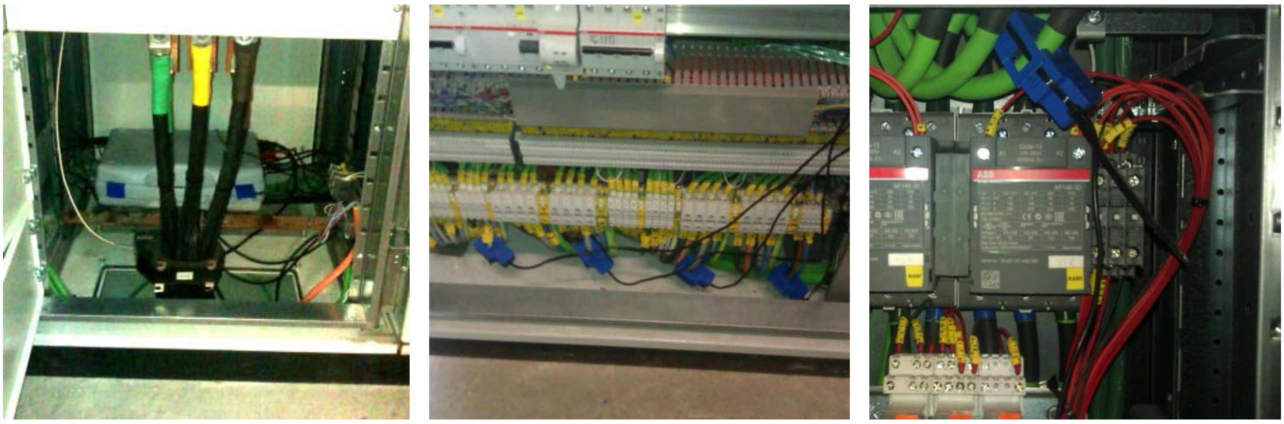

Fig. 4 *Details of the installation of the units*

The EDS-3G of the TC3 is configured to collect the energy consumption and the activation that take place in the TC3 and additionally registers the signal emitted by the luminancimeter for the lighting control of the tunnel, which is collected through the installation of the module Z-8AI.

The equipment units are installed for two months and the acquired data are exported to two Excel files, one for the TC1 and TC2, and the other one for the TC3.

The amount of collected data is considerable, which allows knowing with much detail which installations have been in operation at any moment and their consumption.

4. Processing and analysis of the acquired data

The volume of the collected data is so large that for its correct processing it is necessary to perform a filter through which to extract the most relevant information using the following steps:

- Average consumptions are obtained along periods of one hour. In this manner the high peaks of consumption due to the startup process of certain equipment such as fans are removed and the volume of information to take into account in the study of the installations energy efficiency is reduced. The results obtained for the first 31 days of the study are shown in Fig 5.

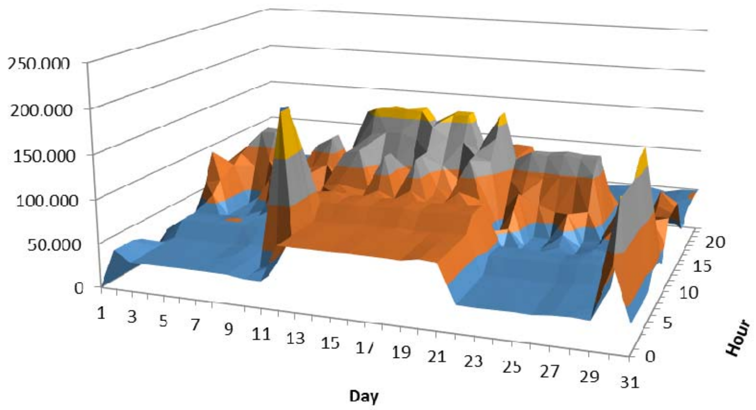

Fig. 5 *Hourly Energy Consumption (Wh)*

- The extraordinary circumstances that could occur during the interval time of data capture are identified with the operator of the tunnel and are removed from the study, such as testing equipment for preventive maintenance.

- Activation times are obtained throughout each day for each monitored circuit. In this manner, the amount of information is reduced to take into account in the study of the efficiency of algorithms for automatic activation of the facilities. . The results obtained for the first 31 days of the study are shown in Fig 6.

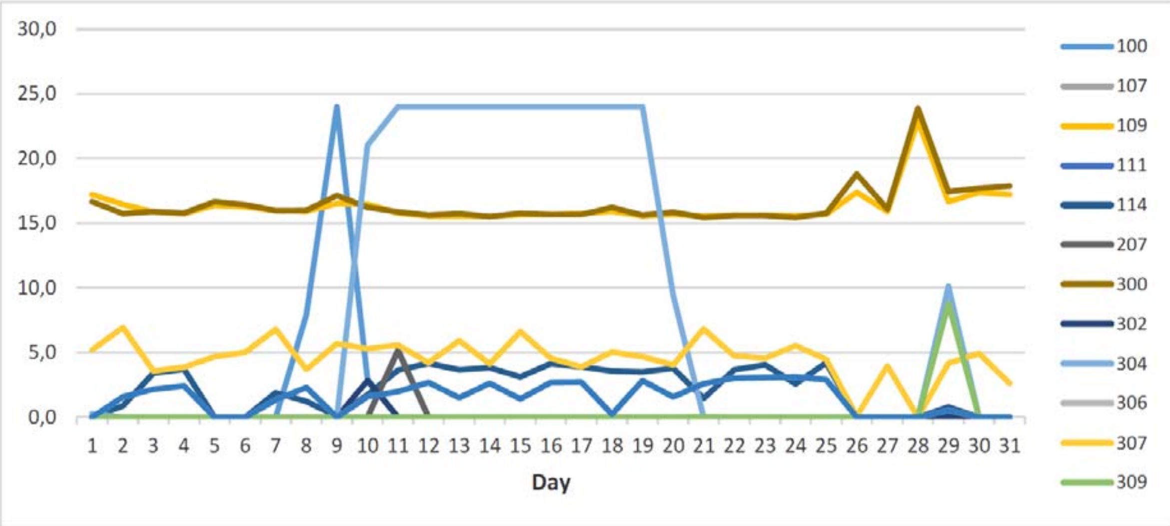

Fig. 6 *Daily Operating hours (h)*

The data collection provided by the luminance meter of the tunnel provides support for analyzing the activation times of the corresponding electrical circuits to the lighting system. Being able to verify how:

- The activation times of the outdoor lighting circuits (300 and 109) are slightly reduced along the passage of time because the number of hours of daily sunshine increased during the study period.
- The appearance of fog or clouds lengthens the activation of exterior lighting.
- The activation times of the interior lighting circuits (114 and 311) increase on sunny days.

The sharp peaks of consumption of days 9 and 29 are highlighted, due to the use of ventilation (100, 304 and 309) to prevent entry of fog into the tunnel.

It also highlighted in Fig. 6 the activation of circuit 304 (corresponding to a fan) continuously between days 10 and 20, reflecting in Fig. 5 as a rise in consumption compared to other days represented.

After analyzing with the operator this strange circumstance, it is found that due to a fault in the control system there was no signal confirmation received from this particular fan activation. The absence of confirmation the activation caused that the tunnel operators were unaware that a fan was kept on in manual mode and therefore did not order to shutdown the fan.

Finally Fig. 5 shows that every day there is an abrupt change in consumption at 06:00. This change is due to the lighting inside the tunnel which is scheduled to reduce its intensity fixed between 00:00 and 06:00 each day.

5. Improvements proposed

The fault in the confirmation mechanism of the fan activation 304 had a direct consequence to an unnecessary consumption and wear, which are easily avoided by implementing absence confirmation alarms of the control system, which are generated when a preset time flows out without receiving signal activation confirmation from equipment.

The implementation of absence confirmation alarms is simple and inexpensive and protects cases like the one studied, although they have a low probability of occurrence, they can lead to consumption or indirect damage of equipment with a high economic cost. Moreover it increases the installation reliability.

To use the ventilation system to prevent the entry of fog into the tunnel leads to a significant power consumption. Additionally, it is expected that the performance of the fans used as a method of fighting against the fog is very small, since they are note designed for that purpose.

Since the Folgoso Tunnel is not the only one who uses this strategy to fight against the fog, it would be interesting to look for other alternatives which present higher performance, although that work is beyond the scope of this article.

Currently the Folgoso Tunnel lighting algorithm activates the reduced indoor lighting for 6 hours a day in a fix schedule throughout the year, which allows a significant reduction in energy consumption. However, during the winter months it the number of hours of reduced lighting could be extended since nights are longer.

An astronomical clock is a device that calculates the time at which twilight and sunset occurs for each day of the year. The implementation of an astronomical clock in the tunnel control system has a very low cost.

The activation of the reduced interior lighting by using an astronomical would increase the annual operating time of the consumption reduction system by 50% resulting in a very significant energy saving.

To get an accurate estimate of the energy and economic savings associated with the above proposals it is necessary to keep the devices installed in the tunnel for at least a period of one year, since the facilities such as lighting have consumptions dependent of the season.

Through the installation of more monitoring devices in other tunnels a comparison between the performances of different tunnels could be carried out.

The comparison could be independent for each system integrated in the tunnels, since the developed devices are able to discern the origin of the consumption.

6. Conclusions

A portable system for monitoring electricity consumption has been developed adapted to the equipment's characteristics of those usually available in tunnels, allowing nonintrusive installation and has high storage capacity, complemented with the ability to transmit the data collected in real-time to an external server.

The device can be easily adapted to different topologies of power supply that can be found in tunnels since it is fully configurable and uses for its internal communication standard MODBUS RTU and TCP/IP, which facilitate the expansion of its capabilities with additional commercial modules.

Although the equipment is prepared for long duration supervision, it was enough with the installation for a couple of months in the Folgoso Tunnel to detect improvements in the control algorithms with a low cost of deployment and without compromising the safety of users the power consumption of the tunnel would be reduced, increasing clearly its energy efficiency.

Subsequently, the analysis of the data obtained in longer term in the Folgoso Tunnel compared with the data obtained from other tunnels will serve for possible improvements in the efficiency of each particular facilities.