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# Energieffektive tunneler - ENERTUN - D1.1

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**Sammendrag**
Denne rapporten er den første av totalt seks rapporter fra et to-årige FoU-samarbeid Varige konstruksjoner har med det spanske engineering-selskapet Geocontrol. Samarbeidet er rettet mot utvikling av energieffektive tunneler gjennom prosjektet ENERTUN som Geocontrol leder. ENERTUN gjennomføres i regi av EEA GRANTS, en samarbeidsorganisasjon der EØS-landene Norge, Island og Lichtenstein gir midler og tilskudd (via Innovasjon Norge) til 16 EU-land i Sentral- og Sør-Europa.

Rapporten gir en beskrivelse av innholdet i ENERTUN-prosjektet med hovedvekt på status for dagens teknologi og målsetting for energieffektive tiltak i tunnelene.

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**Summary**
This report is the first of a total of six reports from a two-year R&D collaboration Durable structures have with the Spanish engineering company Geocontrol. The partnership is aimed at developing energy efficient tunnels through the project ENERTUN as Geocontrol leads. ENERTUN is pursued by the EEA GRANTS, a cooperative organization where the EEA countries Norway, Iceland and Lichtenstein provides funds and grants (via Innovation Norway) for 16 EU countries in Central and Southern Europe.

The report provides a description of the contents of the ENERTUN project with emphasis on the state of today's technology and objectives for energy efficiency measures in the tunnels.

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# Forord

Denne rapporten inngår i en serie rapporter fra **etatsprogrammet Varige konstruksjoner**. Programmet hører til under Trafikksikkerhet-, miljø- og teknologiavdelingen i Statens vegvesen, Vegdirektoratet, og foregår i perioden 2012-2015. Hensikten med programmet er å legge til rette for at riktige materialer og produkter brukes på riktig måte i Statens vegvesen sine konstruksjoner, med hovedvekt på bruer og tunneler.

Formålet med programmet er å bidra til mer forutsigbarhet i drift- og vedlikeholdsfasen for konstruksjonene. Dette vil igjen føre til lavere kostnader. Programmet vil også bidra til å øke bevisstheten og kunnskapen om materialer og løsninger, både i Statens vegvesen og i bransjen for øvrig.

For å realisere dette formålet skal programmet bidra til at aktuelle håndbøker i Statens vegvesen oppdateres med tanke på riktig bruk av materialer, sørge for økt kunnskap om miljøpåkjenninger og nedbrytningsmekanismer for bruer og tunneler, og gi konkrete forslag til valg av materialer og løsninger for bruer og tunneler.

Varige konstruksjoner består, i tillegg til et overordnet implementeringsprosjekt, av fire prosjekter:

Prosjekt 1: Tilstandsutvikling bruer
Prosjekt 2: Tilstandsutvikling tunneler
Prosjekt 3: Fremtidens bruer
Prosjekt 4: Fremtidens tunneler

Varige konstruksjoner ledes av Synnøve A. Myren. Mer informasjon om prosjektet finnes på vegvesen.no/varigekonstruksjoner

Denne rapporten tilhører **Prosjekt 4: Fremtidens tunneler** som ledes av Harald Buvik. Prosjektet skal bidra til at fremtidige tunneler bygges med materialer, utførelse og kontroll bedre tilpasset det miljøet konstruksjonene er utsatt for. Prosjektet skal bygge videre på arbeidet i Moderne Vegtunneler, samt innspill fra Prosjekt 2: Tilstandsutvikling tunneler, med hovedfokus på tunnelkonstruksjonen i et levetidsperspektiv. Prosjektet skal resultere i at installasjoner i fremtidige tunneler oppnår tiltenkt levetid med reduserte og mer forutsigbare drift- og vedlikeholdskostnader.

Rapporten er utarbeidet av *Daniel Octavio de Toledo, Geocontrol*.

| EFICIENCIA ENERGÉTICA EN TÚNELES<br>ENERTUN<br>ENERGY EFFICIENCY IN TUNNELS | Statens vegvesen · GEOCONTROL |
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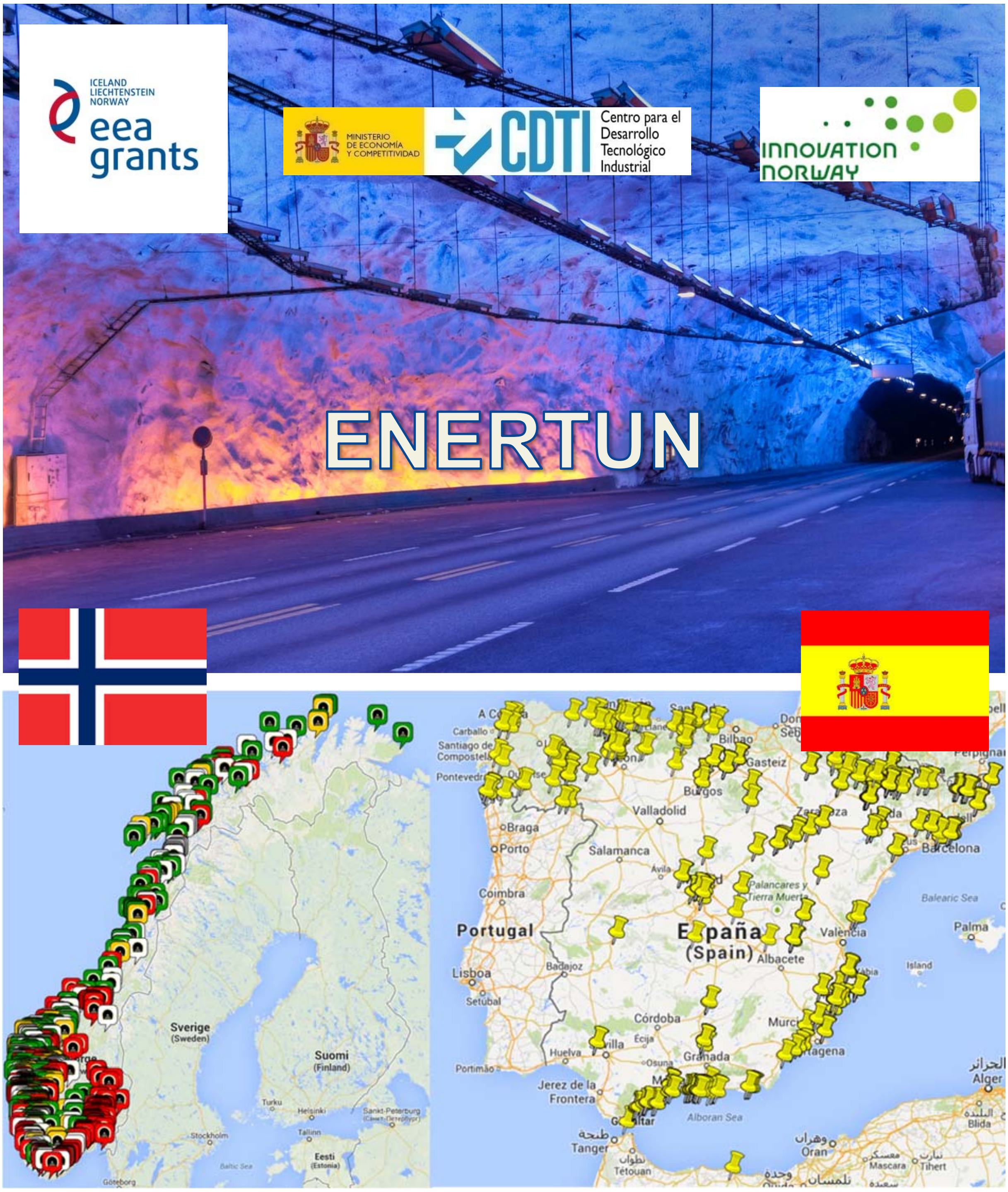


# DELIVERABLE D1.1.- BENCHMARKING ON TECHNOLOGY AND ENERGY EFFICIENCY FOR ROAD TUNNELS

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# ENERTUN
# DELIVERABLE D1.1.- BENCHMARKING ON TECHNOLOGY AND ENERGY EFFICIENCY FOR ROAD TUNNELS

## INDEX

# ENERTUN
# DELIVERABLE D1.1.- BENCHMARKING ON TECHNOLOGY AND ENERGY EFFICIENCY FOR ROAD TUNNELS

## 1. INTRODUCTION

This report is written as the first document to deliver in the framework of the EnerTun project.

The deliveries in the framework of the Enertun project are divided into four phases or packages of work:

- Work Package 1:

This phase is oriented on investigating existing technologies for achieving energy efficiency in the industry sector and evaluating the possibility of integrating them in a tunnel.

- Work Package 2:

This phase consists on the study of the energy consumption in real cases of tunnels in Norway and Spain.

The electricity bills will be studied in order to set a pattern of consumption, which allows making proposals of improvements.

- Work Package 3:

This phase consists on the evaluation of measures to undertake in order to accomplish three objectives:

Reduction of the energy consumption.

Reduction of the time of consumption.

Increasing of the power generation.

This phase has to be done with the feedback of phase 2.

- Work Package 4:

The aim of this phase is a study of economic viability for the development of prototypes with the cutting-edge of technology.

The content of this first delivery completes the benchmarking phase, which means an investigation of the technology existing at present dealing with energy efficiency.

The investigation has had as objectives:

- Seek different ways of obtaining higher energy efficiency in the performance on a system.

- Analyze how to apply those principles to the case of a tunnel.

In the next sections of the document, further information is given about all the collected information.

## 2. BENCHMARKING OF NEW TECHNOLOGIES AS FAR AS ENERGY EFFICIENCY IS REFERRED

The phase of benchmarking is the first one in the framework of the Enertun project.

The aim of this phase is collecting all the possible energy efficiency measures that can be applied to the particular case of road tunnels; besides, it has to be investigated which ones have been deployed in real cases of road tunnels.

Therefore, there are several sub-phases within this phase:

- Sub-phase 1: collection of measures of increasing the energy efficiency in general.

- Sub-phase 2: evaluation of the possibility of integrating them in the particular case of a road tunnel.

- Sub-phase 3: collection of real cases of tunnels where those measures have been deployed.

In the following sections further information is given about the sub-phases 1, 2 and 3.

According to the planning of the deliveries for every work package, the duration and objectives of every work package is:

- Work package 1: around 70 days.

The aim is to do a research of possible measures to improve the energy efficiency that are applicable to road tunnels.

- Work package 2: around 260 days.

The aim is to analyze and study the electricity bills of real cases of road tunnels. It will be verified if the consumption follows a regular pattern and a mathematical model will be created to estimate energy consumption in road tunnels. Equipment for measure of consumption will be installed in road tunnels both in Spain and Norway to collect more accurate data.

- Work package 3: around 110 days.

At the same time as the tasks of WP2, a study of possible measures for increasing energy efficiency in road tunnels will be carried out.

- Work package 4: around 200 days.

It will be evaluated the economic viability of implementing the measures found in WP1, recommended in WP3 and eventually others that may be interesting for this purpose.

## 2.1. METHODOLOGY FOR COLLECTION OF INFORMATION.

An exhaustive work of research has been completed in order to obtain as much information as possible related to the following concepts:

- Lighting.
- Ventilation.
- Building sector.
- Other sectors.

The majority of the information has been obtained through online platforms. The online pages that have been consulted are outlined in the following lines:

- **Research websites:**

Research websites have been consulted in order to know which advances have been achieved by researches all over the world concerning energy efficiency.

The main websites consulted are:

- Generic pages:

- Science direct.

- Web of knowledge.
- International Journey of Scientific and Engineering Research.
- IOP Science.
- Website of the Department of Building Services Engineering of the Hong Kong Polytechnic University.
- Scientific research.
- International Journey of Engineering, Science and Innovative Technology.

- Pages related to tunnels:

- Totalrail: investment and development in rail of operators, developers and investors.
- Trentino Research and Innovation for Tunnel Monitoring.
- Tecnocarreteras.

- **Events information:**

A research has also been done in order to find all information available about Forums, Summits and other events related to energy efficiency.

The most remarkable events that have been treated are the following ones:

- International Conference of renewable energies and power quality in Córdoba, Spain.
- Congreso Nacional de Geotermia y Eficiencia Energética, 12-13 de June 2014 in Pontevedra, Spain.
- Tunnels and ITS 2013 – Traffic and Incident Management, 18-20 September 2013 in Bergen, Norway.

- **Websites of manufacturers:**

Websites of manufacturers have been consulted in order to know which improvements have been integrated in their technology. The websites are especially those related to lighting, ventilation and building materials manufacturers.

The main pages consulted are presented in the following lines:

- Thorn lighting.
- Schréder.
- Lead Lighting.
- Environmental lights.
- Straits Design.
- Transurban.
- IBS.
- Swareflex.
- Piezo Systems.

- **Websites of administrators:**

The websites of administrators from all over the world have been investigated, since they contain in some cases information about measures undertaken to reduce the energy expenditure of several systems.

The most relevant pages that have been consulted are outlined in the following lines:

- TEKNA.
- Oregon Government.
- NSW Government.
- The port authority of New York and New Jersey.
- Chinese Taipei Tunneling Association.
- Metro de Madrid.

- **Newspapers:**

A research has also been carried out through several newspapers, mainly from Spain, which inform about news concerning the energy efficiency.

The most relevant newspapers consulted are the following ones:

- El País.
- El Mundo.
- Europapress.
- El Confidencial.
- La Razón.
- BBC.
- Cleantechnica.

- **Other pages:**

As well as the pages mentioned above, other pages containing useful information about energy efficiency have been consulted. The most relevant ones are the following ones:

- Plataforma Tecnológica de la Carretera española.
- Instalaciones y eficiencia energética.
- Ian Visits.
- Alliance to save energy.
- COB.

A special mention has to be done to the Congress ACLUXEGA and to the International Conference on renewable energies and power quality. The first has taken place in Pontevedra, Spain, the 12-13 June 2014 and the second one has taken place in Cordoba, the 8-10 April 2014.

Geocontrol has attended both events, which were focused on matters of interest in the aim of increasing the energy efficiency of systems. People who attended both Forums were researchers, manufacturers and people from the public administrations.

## 2.2. INVESTIGATION ABOUT WAYS FOR INCREASING ENERGY EFFICIENCY

A reduction in the electricity bill can be achieved either with more efficient facilities, either by having a contribution from an external source of energy.

This concept can be applied to the different systems mentioned before: lighting system, ventilation system and other systems.

In the following sections, further information is given about every system and how to make a road tunnel more sustainable.

### 2.2.1. Lighting system:

The research work effectuated to seek ways for increasing efficiency of the lighting system has revealed the aspects described in the following lines.

The individual performance of every luminaire is not the same. In the market, there are different sort of luminaires:

- Incandescent lamps:

This type of lamp produces light thanks to the Joule effect.

An appreciable part of the energy (around 85%) consumed is transformed into heat. So, its energy efficiency is low.

- High Sodium Pressure (HSP) luminaires:

It’s the most commonly used luminary for public lighting. Its lamp uses Sodium Vapour to produce light and the individual efficiency is around 100 lum/W.

The time required for its complete switching on is around 9-10 minutes and the life time varies, but it may be around 25.000 hours.

- High Mercury Pressure luminaires:

This sort of luminaires has also been employed for public lighting, but not as much as the HSP luminaires.

Their lifetime is also around 25.000h, but the quality of the light emitted decreases as time goes by.

- LED luminaires:

This kind of luminaire is becoming more known lately and its uses are overall for public lighting needs.

The power demand of this luminaires are lower than in other types, but the light emitted is lower as well. Some positive characteristics of these lamps are: elevated life time, regulation possible without harming the quality of the light and quicker adjustment between 0-100% of its maximum performance than other lamps.

Taking into account all the aspects involved in each type of lamp, it's possible to obtain higher energy efficiency in the lighting system by choosing the lamps which best fit to the specific demands.

An analysis about boundary and geometrical conditions of the work space to illuminate can be carried out: modifying the reflectivity of walls or other factors may drive to a less power demanding situation.

In addition, it has been verified that in most of the cases of public lighting, the lighting system is working the whole time, even if nobody is taking advantage of it. Therefore, there is a way of reducing the working hours of the lighting system by restricting it only for the periods when it is mandatory its use, which will have as a consequence a reduction in the electricity bill.

### 2.2.2. Ventilation system

The benchmarking phase realized for the ventilation system has revealed different ways of increasing the energy efficiency in ventilation.

Geometrical aspects can be taken into account in ventilation operation, because they may introduce located losses of energy. The wall friction of the air flow from a jet fan in the work area is a cause of decreasing of energy efficiency. Therefore, a way of increasing the performance of the ventilation system with the same power supply is by minimizing the friction effect of the air with the walls of the space.

Also, as far as the ventilator itself is concerned, there are other geometrical aspects related to its fabrication that can be evaluated to verify its optimization.

Furthermore, another way of increasing the energy efficiency of this system is by restricting its operation only to when it's mandatory. In some cases, the protocols of ventilation are over extended in time in order to make easier its operation; however, this is closely related to wasting energy for periods when ventilation is not required.

The price of the energy according to time periods is related to the energy bill. This is not exactly the same concept as energy efficiency, but it may lead to making economic savings, which is one of the worries of administrators.

### 2.2.3. Other sources of energy.

The research done in the benchmarking phase has revealed the existence of other sources of energy. The renewable energies field has been of wide application in the building sector up to now, what has permitted getting high reductions in the electricity bill.

In this section, these ways are explained with further details.

**Energy from the sun:**

The energy from the sun can be useful in order to obtain savings in energy consumption. This way of energy is free and respectful with the environment. The methods involving this source of energy can be divided into two categories: large scale and small scale. Big scale infrastructures are rather thought to produce big amounts of energy for its distribution, while small scale equipment are thought to cover small consumptions, like the ones of a building.

Large scale infrastructures are being implanted all over the world: either they accumulate heat from the sun in a fluid and release it in a power steam process, either they transform directly the sun's energy into electricity with photovoltaic panels. Given that the amount of energy generated is elevated, the electrical energy generated is sent to the grid.

One of the most common infrastructures employed for this purpose is the cylindrical parabolic collector, which is shown in **Photography 2.2.3.I**:

**Photography 2.2.3.I**. – Cylindrical parabolic collector

Photovoltaic parks have also been built in order to collect energy from the sun.

For small scale purposes, the equipment that has been employed recently is principally:

- Solar cells: they convert sunlight into electricity, thanks to the PV effect, the process of converting light (protons) into electricity.
- Solar hot water: most of the solar water heating systems for building consist on two parts, the solar collector and the storage tank. The solar collector consists on a thin, flat, rectangular box with a transparent cover that faces the sun; small tubes run through the box and carries the fluid to be heated.

The **Photography 2.2.3.II** shows equipment for solar hot water installed in the roof of a building:

**Photography 2.2.3.II.** – Solar hot water equipment for a building.

In addition, it is possible to capture the sunlight and then deviate it to the place we want to illuminate. It is also possible to use the sun's light to charge photo luminescent panels.

**Wind energy:**

As in the case of energy from the sun, in the case of wind energy, there are two possibilities: large scale infrastructures and small scale equipment.

When it comes to producing large amounts of energy, large infrastructures must be employed, such as aero generators. In the **Photography 2.2.3.III** it is shown an aero generator of 3MW power:

**Photography 2.2.3.III**. – Aero generators of 3MW power

The wind energy in small scale has been of application in order to reduce energy consumption in buildings. The equipment used for this purpose consists on small urban aero generators, which are usually placed on the top of the buildings and collect wind energy.

An example of application is the installation of eight small 1,75 kW power aero generators on the top of the commercial Centre AMOREIRAS, in the center of Lisbon. The expected electricity produced by this installation is 38.000 kWh per year.

The **Photography 2.2.3.IV** shows an example of small scale aero generator for the urban environment:

**Photography 2.2.3.IV**. – Small aero generator for urban environment.

## Geothermal energy:

The geothermal energy is an alternative source of energy that has been integrated over the last years in the use of buildings. There are two possibilities of geothermal extraction from deep foundations: large scale and small scale.

Large scale: geothermal energy extraction.

In this case, the aim is to take advantage of the fact that the deeper in the earth, the more elevated the temperature it is.

The way of extracting energy consists in introducing a fluid through a pipe, which arrives up to a very deep place. In this place, because of being at a certain depth with respect to the surface, the temperature is higher.

The fluid can elevate his temperature and, therefore, its enthalpy, which represents the thermal energy accumulated in a fluid. When the fluid is extracted to the surface, it's possible to carry out a steam cycle in order to release the energy from the heat stored in the fluid.

The constraints are quite particular in this case, as it fits best for high productions of energy, and it's required to build very deep prospections, like the ones realized in the petroleum sector. Thus, this source of energy doesn't seem very appropriate for the consumption of a tunnel, unless a big investment is done to build a geothermal central.

Small scale: geothermal air conditioning or heating.

The more evident difference between this source of energy and the previous one is the amount of energy obtained. Geothermal energy for air conditioning or heating has significantly different uses than geothermal energy as described above.

The base of this source of energy is based on a thermal storage of energy, which is the earth at a certain depth, which plays the role of thermal reservoir. The thermodynamic inertia of the soil is used with the seasonal operation in order to store energy in the ground.

The advantage of having the earth as a reservoir is that beyond a certain depth, estimated in 10-15m, the temperature of the ground is constant and doesn't vary. This allows taking advantage of the fact that there is a thermal gradient between the reservoir's temperature and the environment temperature. This difference of temperature is a synonym of source of energy.

In fact, the basic condition for a geothermal installation is that the temperature of the underground started from a certain depth is virtually constant. In most climates zones of Europe, this temperature has been measured to be around 10-15ºC.

Therefore, depending on the season, the use can be different as far as this source of energy is referred:

During the summer, let's suppose that the environment's temperature is more elevated than the reservoir's temperature. Then, the difference of temperature between the room and the underground can be used to cool the room. With a geothermal cooling system, the heat is extracted from the room via an air cooling system or a water-based cooling integrated into the walls.

During the winter, let's suppose that the environment's temperature is lower than the temperature of the underground. Then, the difference of temperature between the room and the reservoir in the underground can be employed to heat a room. The way of heating is similar to the case of the cooling: a pipe passes through the space of the room releasing heat in the room. A pump is needed to make the water flow go along the pipe.

**Heat extraction:**

In many work places in the industry, large amounts of heat are generated and then rejected to the environment.

This involves a source of energy that is wasted, because the thermal energy accumulated in the fluid that has been rejected, can be stored or used somehow. The heat rejected to the environment depends on every case but, the more heat rejected, the more use it can provide.

**Conversion from mechanical into electrical energy:**

A new source of energy has recently been integrated in buildings, which is based on the transformation of mechanical energy into electrical energy.

The equipment employed for this purpose are the piezo transducers. Piezo actuators convert electrical energy to mechanical energy, while piezo sensors convert mechanical energy into electrical energy.

The equipment installed in buildings has permitted to take advantage of the passage of people by public places, which involves a mechanical effort applied on the floor. This mechanical effort can be transformed into electrical energy and be stored.

Also, some studies are taking place to know in which measure an electromagnetic induction may be a source of generation of energy. Moreover, other studies focused on generating kinetic energy by the circulation of vehicles on the roads are currently being carried out.

## 2.3. EVALUATION OF THE POSSIBILITY OF APPLICATION FOR ROAD TUNNELS.

Throughout this section it will be outlined the real cases of tunnels where the ways of increasing energy efficiency explained previously have been put in practice.

The systems involved in increasing the energy efficiency are:

- The lighting system.
- The ventilation system.
- Other systems involving renewable energies.

### 2.3.1. Lighting system.

The objective of the lighting system in a road tunnel is allowing the traffic passing through it with the same degree of safety and comfort as if it were the outside road. The difficulties that involves approaching to a tunnel and passing through it are influenced especially by the speed of the vehicle, the density and type of traffic and the straightness of the road.

Normally, the lighting system of a tunnel is divided in two regions:

- The entrance region, where the daylight luminaires are due to permit the users' eye adapt from the external to the internal conditions.

- The interior region, where the users' eye have adapted themselves to the inside conditions.

Therefore, it's possible to discriminate the energy consumption of the lighting system into two contributions:

- The consumption of the daily lighting, which takes place during the day.

- The consumption of the base lighting, which takes place during the whole day.

The main factors involved in the phase design of the lighting system are the following ones:

- The safety distance: it is directly related to the velocity of the user. The bigger the velocity is, the longer the safety distance is.

- The maximum velocity authorized in the tunnel.

- Type of lighting system: it can be symmetric (luminaires in both sides) or asymmetric (luminaires only in one side).

- Configuration of the tunnel: unidirectional or bidirectional.

- Rate of traffic: it can be discriminated in several levels, according to the amount of vehicles.

- Length of the tunnel.

- The cross sectional area of the tunnel.

- Type of road: asphalt, concrete, etc.

The safety standards require an acceptable degree of lighting in the inside of a road tunnel, which permits the tunnel user to adapt from the external to the internal conditions in a safe manner.

The requirements of the standards as far as lighting is referred, focused mainly on two aspects:

- The luminance is the reflected lighting on the road, which is what the user is able to see. Minimum levels are established for every case of tunnel.

- The uniformity of the lighting.

The method employed to calculate both the lighting levels required for the inside of the tunnel and the uniformity as well depends directly on the external conditions. The aim is to adapt progressively the user's eye from the external to the internal lighting conditions. Therefore, the higher the luminance on the external road is, the higher the luminance on the internal road is and also, the higher the energy consumption will be. The L20 factor (cd/m2) is the parameter employed to take the external luminance conditions as input for the calculation of the internal requirements.

The **Figure 2.3.1** shows the requirements for the lighting system in a unidirectional tunnel:

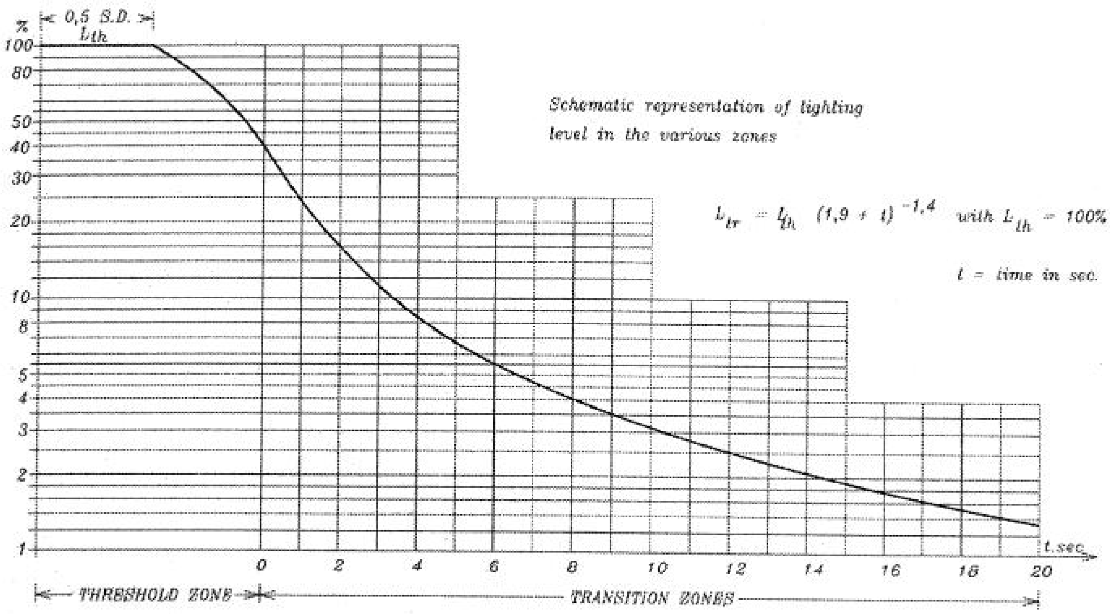


**Figure 2.3.1**. – Example of lighting levels required for a unidirectional tunnel

Where:

$L_{20}$ (cd/m$^2$) is the luminance in the access zone of the tunnel.

$L_{th}$ (cd/m$^2$) is the luminance in the threshold zone of the tunnel.

$L_{tr}$ (cd/m$^2$) is the luminance in the transition zone of the tunnel.

To sum up, the method used to design an internal lighting system in a tunnel has several characteristics that allow decreasing the levels required for the lighting, while meeting the standards.

As stated previously, the lighting system of a tunnel can be optimized and, therefore, be more sustainable, through three measures:

- By employing more efficient equipment.
- By modifying the boundary or geometrical conditions.
- By integrating algorithms that allow an intelligent use of this system.

In the following sections, it will be explained the different ways found after the research phase in order to improve the energy efficiency of the lighting system.

**More efficient equipment: LEDs**

As far as the technology employed is referred, many tunnels all over the world are being refurbished with newer and more efficient luminaires than the conventional high pressure sodium lamps. The refurbishment is being carried out in most of the cases with LED luminaires.

The main advantages of a LED lamp with respect to a traditional HSP (High Sodium Pressure) lamp are:

- Less energy consumption.
- More durability.
- Regulation: possible, without harming the quality of the light.
- Higher flux.
- Higher velocity in adjustment between 0-100% of the maximum of brightness.

In fact, the possibility of regulating the system allows having other ways of saving energy consumption, as explained in the section “Algorithms integrated for intelligent use” in the same level of the current section.

Therefore, having a lighting system composed by LED luminaries in a tunnel is of great interest for the administrator, as an intelligent use of the system can be integrated through the algorithms:

- Algorithm that makes the lighting system work only when it's required.

- Algorithm that adapts internal conditions to external conditions in real time.

This is because the adjustment between 0-100% of its maximum brightness is very quickly, what permits integrating an effective control algorithm.

Also, it has been verified that a LED luminaire working in a regulated way maintains the quality of the light, which is essential to meet the standards of lightings for tunnels. The HSP luminaires, however, don't have the same performance when it comes to working in less than a certain percentage and they aren't as quickly as LED luminaires in adjusting between 0-100% of their maximum brightness.

In addition, a feature of a LED lamp is that the light is focused on a specific place. In the case of road tunnels, this is interesting, because its lighting system must illuminate the road. On the contrary, a HSP lamp provides much diffusion of light.

To sum up, a lighting system for a tunnel composed by LED luminaires offers several advantages that make this system be more sustainable.

Some equipment also exists for guidance, using the LED technology, which may be useful for the entrance of a road tunnel, where the user's eye must adapt to the new lighting conditions.

**Different boundary or geometrical conditions:**

As explained previously, having different boundary or geometrical conditions lead to having different inputs when it comes to designing the internal lighting system. This can be advantageous as far as reducing the energy expenditure is concerned.

In this section, a further analysis of these kinds of factors involved will be carried out:

- Minimizing and maximizing brightness of the road and walls:

The aim of the lighting system, as told before, is to adapt the users' eye from the outside conditions to the inside conditions. When we talk about conditions, we mean to say the reflectivity of the road, as this is what the human's eye is able to appreciate.

The reflectivity of a road represents the ratio between the light that arrives at a surface and the light that is effectively reflected (luminance). Therefore, the higher the reflectivity is, the higher the luminance in the road is. Besides, in order to adapt correctly the levels of lighting from the outside to the inside, the higher the brightness on the road, the higher the reflectivity is as well.

As a conclusion, one way to achieve to reduce the lighting required in the inside of a tunnel is by **minimizing the reflectivity in the outside and maximizing it in the inside** of the tunnel.

- Reduction of the authorized velocity:

On the other hand, the required level of lighting on a road is proportional with the speed of the vehicles in the tunnel, as the aim is to adapt the human's eye as fast as possible to the new conditions. The part of the lighting system that is affected by that issue is the one placed in the entries, for sunny and cloudy adaptation.

Therefore, one way for the required level of lighting to become lower is by **reducing the authorized speed of the vehicles in the tunnel.**

- Placement of the lamps:

Furthermore, the lighting standards focus especially on two requirements:

- The level of luminance (reflected lighting) on the road.
- The uniformity factor.

Another way of meeting these requirements while reducing the supply of energy is by **choosing the optimal placement of the lamps**.

**Algorithms integrated for intelligent use.**

The lighting system is designed to get the human's eye adapted from the outside to the inside conditions of lighting. Usually, the lighting system is designed to be working permanently and only change its level when the outside lighting conditions require it.

The research done has revealed that there are basically two algorithms that can be integrated in the lighting system in order to reduce the energy consumption:

An algorithm may make the lighting system work only when it's required. It's possible to set a control system that permits the lighting system to work when vehicles are approaching and passing through the tunnel. This way, when there is no vehicle in the tunnel, the lighting system is not working, which is traduced in savings of power consumption.

Another possibility consists in implementing an algorithm that seeks to adapt internal conditions to external conditions in real time. As told previously, the lighting system has to be adapted depending on the conditions in the outside of the tunnel.

Driving in an over- lighted or poorly lighted tunnel is a potentially dangerous situation, as well as a waste of energy. The traditional systems up to now in tunnels control the lighting intensity according to parameters linked to the design stage and to its current date and hour. However, environmental and external factors are not completely considered in the design phase.

An improvement can be established by installing sensors in the outside and in the inside of the tunnel. These sensors compile information about external environmental conditions, which is treated and then employed to adapt the inside lighting conditions. The result of this is an adaptive lighting that permits to adjust the energy consumption and, thus, reduces the electricity bill and the tons of CO2 rejected to the environment.

Alternative way of detecting vehicles at a specific place:

Piezoelectric materials are able to convert mechanical energy into electrical energy.

This characteristic can be used for detection of vehicles, as it permits to send a signal of a vehicle passing by a specific place to the sensor control device described above. The signal can be sent immediately, thanks to the existence of a communication cable, which links the sensor and the control device.

For the detection to take place, a cylindrical tube made by a piezoelectric material is spread on the road, in the opposite direction of the traffic.

- When a vehicle is circulating on the road, it passes over the piezoelectric tube.
- A mechanical pressure is applied on the tube.
- The piezoelectric tube transforms the mechanical effort into an output voltage.
- This voltage can be used to send an electronic signal to the control device that adjusts the energy of the lamps.

The place where to install the equipment to detect vehicles depends on the characteristics of the tunnel: maximum velocity authorized, slope of the road, etc. What seems to be essential is to place the equipment in such a distance that there is enough time for the lighting system to turn on completely.

The adequate equipment can be even used to discriminate Heavy Goods Vehicles from private cars, what can be useful to estimate the time required for the vehicle to arrive at the entrance of the tunnel.

Furthermore, in order to accomplish the aim of adjusting appropriately the lighting of the tunnel, the moment when the vehicles have left the tunnel has to be known. The piezoelectric equipment, therefore, can be useful both for detecting the arrival of vehicles and the moment when the vehicles are no longer inside the tunnel.

### 2.3.2. Ventilation system.

The ventilation system is an essential part of the whole safety installations system of a tunnel. It contributes both to preventing dangerous situations derived from the concentration of pollutants as in case of a fire appearance.

In case of overpassing the admissible margins of pollution in the tunnel, the ventilation system is activated in order to dilute the pollutants. In case of fire, the aim of this system is to keep safe the tunnel's users. For unidirectional tunnels with longitudinal ventilation, if a fire is detected, the ventilation system is activated in order to keep safe conditions for users upstream of the fire.

In the normal operation of a tunnel, the most common scenario is the one involving dilution of pollutants. The case of a fire appearance is a more remote situation. Since the ventilation system operation is related to the transit of vehicles, it's clear that a significant proportion of the energy consumption is related to this system.

The standards about safety in road tunnels state the conditions for every category of road tunnel concerning the mechanical ventilation system. The design of the ventilation system is realized by taking into account the fire situation, since it's the most power demanding situation.

Given that the ventilation system may be working at any moment in a road tunnel, it seems evident that an energy saving can be achieved through different measures. After the research phase realized, the following measures in order to increase energy efficiency are outlined:

#### 2.3.2.1. Modifying geometrical factors

A longitudinal ventilation layout is chosen usually for unidirectional tunnels. In this case, the gain of pressure proportionated by the jet fans must be enough to compensate the generation of pressure in the seat of fire.

The procedure is based on extracting the smoke is the direction of the traffic, so as to protect the users who are positioned upstream of the fire. Protocols are programmed within the control system to permit this procedure to take place.

When it comes to optimize the performance of the jets, some studies have demonstrated through CFD studies that an improvement in the performances is reached by varying the geometry of the fan itself:

- The thrust given by a fan is proportional to the outlet surface and the square of the outlet velocity.
- The power demanded by a fan is proportional to the outlet surface and the third power of the outlet velocity.

The aim is to reduce the power required, but not harming the thrust given. Therefore, a compromise must be taken as far as outlet velocity is concerned.

At the same time, an increase in the diameter of the outlet of the fan is positive, as it permits to maintain the thrust while limiting the outlet velocity.

Therefore, the best solution should **maximize** the **outlet diameter** of the fan while **minimizing** the **outlet velocity**.

On the other hand, an optimization of the different efficiencies involving jet fan performances can be carried out. The different efficiencies as far as the longitudinal ventilation system are outlined in the following lines:

- Electrical efficiency of the engine: typically over 90% for three-phase engines in tunnel applications.

$$\eta_e = \frac{T \cdot v_a}{P} \qquad (1)$$

Where:

T: thrust given by the fan.

va: outlet velocity in the fan.

P: power demand of the fan.

- Fan efficiency: it represents the ratio between the power proportionated by the fan and the power required to give this performance. Its typically ranges are 40-70%, depending on a variety of parameters (fan rotational speed, blade pitch angle, operating point of the fan, etc).

$$\eta_f = \frac{P_t \cdot \dot{V}}{\dot{W}_s} \qquad (2)$$

Where:

Pt: total pressure rise across the fan.

$\dot{V}$: Volumetric flow rate through the fan.

$\dot{W}_s$ : Shaft power.

- Installation efficiency: it represents how much of the aerodynamic thrust is converted into useful work in accelerating the air in the tunnel.

$$\eta_i = \frac{T}{\rho \cdot A_a \cdot v_a \cdot (v_a - v_\infty)} \qquad (3)$$

Where:

ρ: density of the air in the outlet of the fan.

va: outlet velocity in the fan.

v∞: velocity in the tunnel beyond the direct influence of the jet fan intake and discharge.

It's been estimated that the proportion of the thrust given by a jet fan that is wasted due to aerodynamic friction varies between 15-27%.

Therefore, an improvement in terms of performance can be obtained by **<u>modifying the outlet direction</u>** of the air of the fan.

The **Figure 2.3.2.1** shows an example of a jet fan in which the outer case has been reoriented in order to direct the air flow towards the tunnel centerline, comparing with a conventional jet fan.

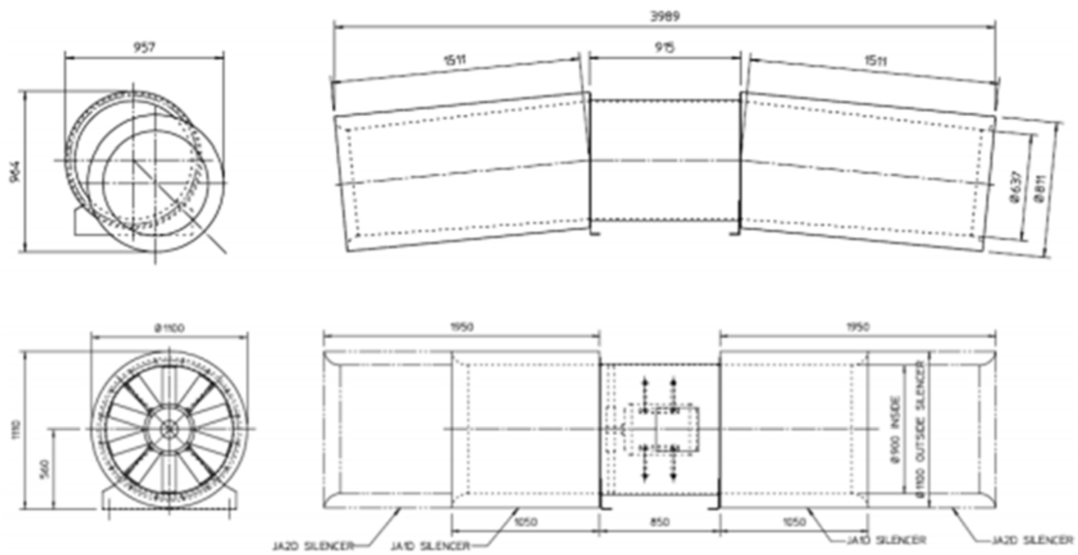


**Figure 2.3.2.1**. – Comparison between a conventional jet fan and a jet fan with the outer case modified to direct the flow.

To sum up, we may retain two main measures that are positive in order to reduce the power consumption of the ventilation system:

- Maximize the outlet diameter of the jet fan while minimizing the outlet velocity.
- Variation of the direction of the air in the outlet of the fan, in order to minimize pressure losses due to friction with the walls.

### 2.3.2.2. Integration of algorithms for intelligent use of the system

As it's been explained previously, the ventilation system is due to work in two situations:

- When the visibility or the pollutants gases (CO, NOx) have overpassed the admissible margins stated, according to safety standards.
- When a fire takes place.

The first situation is quite common in every road tunnel, and is more notorious when the rate of traffic is higher. The more vehicles there are in a tunnel, the more quantity of contaminant gases are retained in the inside, and the higher frequency the ventilation system is working.

On the contrary, the fire situation is not common, but when it takes place, the amount of kW consumed is much higher than in the first situation.

In order to optimize the use of this system, some algorithms can be integrated. This permits to make use of the ventilation system only when required.

**Algorithm that controls the activation of the ventilation system:**

A predictive control can be integrated in the control system for the ventilation system supervision.

Traditional ventilation systems usually work as described in the following lines:

- A network of sensors for detection of pollutant levels is and the visibility is installed in the tunnel, to know in real time their current concentration.
- The capability of evacuating the pollutant gases depends on the power of the fans and on other factors: traffic density, tunnel parameters, and weather conditions.
- An algorithm is integrated so that the necessary fans will be activated in a specific sequence.
- There are feed backs of the levels of pollutants in real time, what affects the ventilation system, which starts to turn off progressively the fans.

The classical procedure is based simply on the fact that, whenever the admissible margin for any pollutant is overpassed, the ventilation system is activated automatically. When the situation recovers and the level of remaining pollutants is acceptable, the ventilation system starts to turn off the fans.

Therefore, the ventilation system is activated as many times as the admissible margins of pollutants are overpassed. An improvement can be established with respect to consumption, through the integration of an algorithm based on controlling not only the concentration of pollutants, but rather its rate of change.

If the rate of change of pollutants concentration is controlled, it may be possible to maintain the ventilation system working in periods with the same length altogether but with fewer switchings. If this is achieved, energy savings can be achieved, since having fewer switchings of the system means decreasing the energy consumption, as this is more elevated when switchings take place.

The optimization of the ventilation algorithms is conditioned by the availability of fans that can be programmed to work in lower levels than the 100% of their maximum performance. It should be required to compare the necessary investment for having this type of fan and the economic benefits in terms of energy savings thanks to those optimization algorithms.

**Algorithm that controls time zones when the electricity is lower:**

The price of the energy is not constant, but varies during a whole day.

Although the research phase has revealed that an algorithm has been integrated to take the price of the energy as a design condition in the Underground of Madrid, this is not applicable in the case of a road tunnel. The ventilation working periods in a road tunnel are independent of any criteria about energy price, but depend only on the concentration of pollutants in the atmosphere.

### 2.3.3. Other sources of energy.

**Energy from the sun:**

In order to collect energy from the sun and reuse it to cover the electrical needs of a tunnel's installations, a photovoltaic or thermoelectric (with the cylindrical parabolic collector technology) would be needed.

This means the necessity of having a big surface where to construct this kind of park. Also, it should be needed to build the necessary installations to convert the energy accumulated in the fluid into electrical energy, in the case of using the thermo electrical technology or to send it to the grid, in the case of a photovoltaic park.

When it comes to small scale needs, it is possible to install photovoltaic panels close to installations with small electricity needs, like electrical panels for signalization on the road access of the tunnel.

There are also other principles that allow taking advantage of the sunlight. Given that a high proportion of the energy expenditure of the lighting system is due to the daylight luminaires, it is possible to use an artificial translucent structure at the entrance of a tunnel. This permits to have free lighting in the part of the tunnel where the daylight luminaires should be placed.

Also, another way of having free light in a certain region of a road tunnel consists in capturing the sunlight somewhere and then deviate it to the place due to be illuminated. It is also possible to charge photo luminescent panels with the sun's light, in such a manner that these panels can aid to differentiate the border of every lane on the access road of a tunnel, during the night.

**Wind energy:**

In order to collect the energy from the wind, a network of aero generators would be necessary. The kinetic energy of the wind would be transformed into electrical energy and then sent to the grid and used to cover the electrical needs of the installations.

Apart from using the external wind as a source of supplementary energy, it is important not to forget that in many cases, there is an appreciable air flow due to the transit of vehicles in the traffic direction. If a turbine is installed in the tunnel and the kinetic energy of the air flow is taken and then transformed to electrical energy, this becomes a new source of energy for the tunnel.

**Geothermal energy:**

As explained previously in this report, the earth beyond a depth of 10-15m can be considered as a reservoir at a constant temperature. This technology has been applied in the last years in the building sector. However, these principles can be useful for the needs of a tunnel:

- Need of cooling:

The first situation described above, in which the temperature of a room is higher than the temperature of the reservoir, may be identified with a tunnel. In fact, in the technical rooms for the equipment that provide secure power for critical needs, a large amount of heat is created and so for the rooms for the transformers of high voltage.

Therefore, there is a need of cooling in order to guarantee that the equipment is in proper conditions.

- Need of heating:

The second situation mentioned above, which reflects a room where the temperature is lower than the one of the reservoir, can be identified with a tunnel as well.

The room where the fire protection pumps that the temperature of the room has to be over a stated temperature. The reason for this is for preventing the water in the tank and in the pipes to freeze, which occurs when the temperature attained is below zero degrees.

In this case, the measures usually taken are: passive protection of the pipes and installation of heaters, which are activated automatically when the temperature reaches a level below a certain admissible limit.

The use of geothermal heating can be useful in this case, as it permits to maintain the temperature of the room over the admissible value established.

The result of the application of this source of energy is positive, because:

- It's a clean way of energy and it avoids the rejection of tons of CO2 to the environment.
- It permits to accomplish the requirements with respect to cooling or heating if the difference of temperature is enough.

The main disadvantage of this energy source is that, despite the reservoir's temperature is practically constant throughout a year, the environment's temperature isn't. Thus, it's not possible to establish a permanent supply for the whole year.

**<u>Heat extraction:</u>**

The heat generated by the engines of the vehicles that pass through a road tunnel may be likely to be reused. The heat generated in a process of fuel combustion is wasted into the environment, but it may be reused somehow. The most evident use for thermal energy can be hot water distribution.

As explained in the case of geothermal energy, the thermal energy produced can be useful to heat some places like the room where the fire protection pumps are placed.

Thermal energy from combustion process is defined by:

$Q_{veh} = C \cdot D \cdot Q_{comb} \cdot v$

Where:

- $Q_{veh}$: the thermal energy from vehicle (kJ/s)
- C: the fuel consumption ($m^3/m$)
- D: the fuel density ($kg/m^3$)

- $Q_{comb}$: the combustion energy (kJ/kg)
- v: vehicle speed (m/s)

This heat released by the vehicles may be reused for other purposes in the tunnel.

**Conversion from mechanical into electrical energy:**

As explained previously, there exists currently some equipment capable of converting mechanical energy into electrical energy. The interest of this kind of equipment for the particular case of a tunnel is based on taking advantage of the passing of the vehicles through the tunnel.

The mechanical energy that can be obtained becomes higher in the same measure as it does the traffic rate through the tunnel. A study concerning how to realize the installation of the equipment should be carried out, in order to estimate the amount of energy that can be obtained. During the research phase, no tunnel has been found that has already implemented this sort of technology in its daily use.

Furthermore, research is being done in order to study whether electromagnetic inductions can provide electrical energy. When there is a change in a magnetic flux in a system, an electromotive force is induced. The change of flux can be obtained by moving a conductor in a stationary magnetic field or by moving a magnetic field in a stationary conductor. Generating electricity by moving a permanent magnet in a coil of wire can be achieved with the passage of vehicles. The equipment for this purpose would be installed on the road and the electricity generated may be used to lighten installations with little energy consumption.

Another way of taking advantage of the circulation of vehicles on the road consists of generating kinetic energy. The method is based on some equipment installed in the road: a lever is placed on the road in such a way that the vehicles create a pressure on it. As a result, a flywheel will rotate, generating kinetic energy, which can be transformed to electrical energy by a DC generator. This electrical energy can be used to cover the electrical needs of installations with little energy consumption, such as panels.

## 3. REAL APPLICATIONS IN TUNNELS ALL OVER THE WORLD

Throughout this section, it will be outlined and with further detail in detail the real cases of road tunnels where the ideas explained before have been put in practice.

In some cases, there has not been a real put in operation, although it is planned to do it maybe in a near future.

## 3.1. LIGHTING SYSTEM

In this section, it will be explained which real cases of road tunnels have undertaken the ideas previously presented as far as the lighting system is referred.

### 3.1.1. More efficient equipment: LEDs

Currently, more and more tunnels are refurbishing their old lighting systems based on High Sodium Pressure (HSP) luminaires by LED luminaires. The advantages of these luminaires have been outlined before.

In this section, several examples of tunnels that have equipped their lighting system with LED luminaires will be given.

- **Tunnels in Norway:**

- Ljabru tunnel:

LED luminaires installed in 2004 with a life time higher than 8 years.

- TINNSJØ tunnel:

The basic lighting was refurbished, from 58W fluorescent lamps to LED luminaires, while maintaining HPS luminaires for entrance and transition zones.

The energy savings attained approximately 40%.

- **Tunnels in Spain:**

- Tunnel of Laredo:

The tunnel's length is 220m.

The measure undertaken has been the refurbishment of old lighting system by LED luminaires.

There is an expected 86% saving on energy consumption and an additional saving because of the power contracted, which is lower.

- Tunnel of Somosierra:

It's a unidirectional tunnel composed by two tubes.

The measure undertaken has been the refurbishment of part of the old lighting system composed by HSP luminaires by LED luminaires.

An improvement has been obtained, passing from having a ratio of 40,32 kWh/m2 per year to a new ratio of 19 kWh/m2 per year, with energy saving over 50%.

- **Tunnels in Philippines:**

- Tunnel of Boni (underground):

The measure undertaken has been the refurbishment of old lighting system by 94 – 22W LED luminaires.

A 19% of the power demand comes from solar panels, achieving a 51% of energy savings.

- **Tunnels in United Arab Emirates:**

- Tunnel of Salaam:

The measure undertaken has been the refurbishment of old lighting system based on 2x58W fluorescent luminaires by a one-to-one 48W-40 LED luminaires.

The savings are a 60% in energy consumption.

The life time estimated is 80.000h, face to the 10.000h of the old system.

- **Tunnels in USA:**

- Tunnel of Elk Creek:

It's a bidirectional road tunnel with a length of 329,21m.

The measure undertaken has been the refurbishment of part of the old lighting system based on 196 – 400W and 34 – 150W HSP luminaires by 34-200W + 196-200W (respectively) induction lighting fixtures.

The result has been:

- Savings of 52% in energy consumption and 5.000$ on maintenance (an 8-10 years lamp replacement).

- Longer lamp life: 100.000h, which means less maintenance.

- Improved lighting quality: better color rendering, contrast and distribution of light, less glare.

- Fewer tunnel shut downs, which means improved safety for workers and drivers.

- Reduced landfill waste and reduced GHG emissions.

- Tunnel of Lincoln:

The measure undertaken has been the refurbishment of the old luminaires of the tunnel and the bridge by 45W LED luminaires.

The results are:

- Savings of 1,2 million kW h in energy consumption per year.

- Life expectancy of 15 years per luminaire, compared to 1,4 years for the old system.

- Holland tunnel:

It’s a unidirectional tunnel composed by 2 tubes with a length of 2.608,48m (direction west) and 2551,48m (direction east).

The measure undertaken has been the refurbishment of the 3.336 old fluorescent luminaires by LED lamps.

The results are:

- 250.000$ of saving in energy consumption per year.

- Interior of the tunnel brighter and safer for users.

- **Tunnels in China:**

- Tunnel of Xiamen Fujian:

Refurbishment of the old lighting system of 9 road tunnels, which total length is 40km, with 30.000 LED luminaires.

Important energy savings are expected.

In addition, the LED technology has been applied to the guidance system for road tunnels. In the research phase it has been found a small guidance module, from the manufacturer Swaroline, to be installed in order to aid to the adaption of the user's eye from the external to the internal lighting conditions.

These guidance modules have been installed in the following road tunnels:

- Jinma Tunnel, in Taiwan (China).
- Yusui Expressway, in Chongqing (China).
- Nan Qiu Tai Tunnel, in Yanan (China).
- BaiYanXi Tunnel and pedestrian emergency exit, in Yichang (China).
- Wenzhou Tunnel (China).
- Shanxi Tunnel (China).

In the **Photography 3.1.1** it is shown this kind of technology:

**Photography 3.1.1**. – LED guidance equipment

### 3.1.2. <u>Different boundary or geometrical conditions:</u>

Some of the information related to this matter has been collected from a research project on illumination energy saving for highway tunnels in China. The available information didn't indicate the tunnels where the measures were realized.

However, there are some interesting measures from some documents from TEKNA, concerning road tunnels in Norway:

- <u>Tunnel of Brekk:</u>

The measure was washing luminaires (maintenance), with a 15,6% of increasing in the luminance.

- <u>Tunnel of Arnanipa:</u>

The measure was washing luminaires (maintenance), with a 4,3% of increasing in the light and also painting with white color the walls, with a 12,3% increasing in the luminance.

- <u>Tunnel of Damsgård:</u>

The measure was painting with white color the walls, with a 168% increasing in the luminance.

- <u>Tunnel of Askimporten:</u>

The measure was washing luminaires (maintenance), with a 100% of increasing in the luminance.

### 3.1.3. Algorithms integrated for intelligent use.

In the research phase, two algorithms have been found that are likely to be applied to the particular case of a road tunnel:

- Algorithm that makes the lighting system work only when it's required.
- Algorithm that adapts internal to external lighting conditions.

**Algorithm that makes the lighting system work only when it's required.**

One case of application has been found for a tunnel in Japan (the name of the tunnel is not given in the information available).

The algorithm described in the section 2.3.1. –"***Lighting system***" has been put in practice in a Japanese tunnel. The report "Energy-saving lighting system for road tunnel" (S. Nagai, S. Ishida, M. Shinji & K. Nakagawa) shows the results obtained in a Japanese road tunnel where this technology has been tested. The name of the tunnel is not provided, so its characteristics are not known.

The results for one year obtained are provided in **Table 3.1.3.I**:

| Tunnel in Japan | Daily Traffic Rate (veh.) | New consumption / older consumption | Tons CO2 reduced per year |
|---|---|---|---|
| - | 175 | 28,1% | 8,4 |

**Table 3.1.3.I. -** Results obtained per year in Japanese tunnel with intelligent lighting system integrated.

Some more detailed results are provided in **Table 3.1.3.II**, which shows the results for one single month:

| May Day | Air temperature (°C) | Lighting time by circuit (h) | | | | Passage (times) | | Measured electric energy (kWh) | Assume electric energy of a conventional system (kWh) | Effect (measured value/ assumed value) | $CO_2$ reduction (kg-$CO_2$) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Entrance lighting | | Basic | Outside the pit (nighttime) | Vehicle detection | Pedestrian push button | | | | |
| | | Cloudy | Clear | | | | | | | | |
| 1 | 17.1 | 11.2 | 6.6 | 24.0 | 10.8 | 116 | 0 | 25.89 | 98.35 | 26.3% | 26.1 |
| 2 | 19.0 | 10.7 | 8.5 | 24.0 | 10.8 | 113 | 0 | 26.68 | 102.19 | 26.1% | 27.2 |
| 3 | 17.3 | 9.4 | 1.1 | 24.0 | 11.1 | 103 | 0 | 22.30 | 80.29 | 27.8% | 20.9 |
| 4 | 15.4 | 7.5 | 0.0 | 24.0 | 11.3 | 75 | 2 | 20.46 | 73.40 | 27.9% | 19.1 |
| 5 | 14.6 | 11.9 | 7.7 | 24.0 | 10.5 | 119 | 0 | 27.97 | 102.62 | 27.3% | 26.9 |
| 6 | 15.4 | 11.5 | 4.4 | 24.0 | 10.4 | 223 | 0 | 28.98 | 93.17 | 31.1% | 23.1 |
| 7 | 17.1 | 11.7 | 4.3 | 24.0 | 10.5 | 302 | 0 | 28.35 | 93.38 | 30.4% | 23.4 |
| 8 | 18.2 | 11.5 | 4.8 | 24.0 | 10.5 | 102 | 0 | 26.16 | 94.24 | 27.8% | 24.5 |
| 9 | 18.4 | 7.7 | 2.0 | 24.0 | 11.2 | 67 | 0 | 20.43 | 78.98 | 25.9% | 21.1 |
| 10 | 19.0 | 9.0 | 3.9 | 24.0 | 10.8 | 82 | 0 | 22.61 | 86.60 | 26.1% | 23.0 |
| 11 | 16.7 | 8.5 | 2.9 | 24.0 | 11.2 | 72 | 2 | 20.87 | 83.04 | 25.1% | 22.4 |
| 12 | 20.6 | 10.8 | 4.5 | 24.0 | 10.5 | 288 | 0 | 26.44 | 91.95 | 28.8% | 23.6 |
| 13 | 17.5 | 4.2 | 0.5 | 24.0 | 12.0 | 60 | 0 | 19.07 | 67.78 | 28.1% | 17.5 |
| 14 | 17.9 | 11.0 | 6.8 | 24.0 | 10.4 | 324 | 0 | 29.39 | 98.31 | 29.9% | 24.8 |
| 15 | 15.3 | 10.9 | 0.0 | 24.0 | 10.7 | 70 | 0 | 21.35 | 80.56 | 26.5% | 21.3 |
| 16 | 17.2 | 10.2 | 0.2 | 24.0 | 11.0 | 65 | 1 | 20.96 | 79.66 | 26.3% | 21.1 |
| 17 | 17.8 | 10.6 | 2.7 | 24.0 | 10.7 | 286 | 0 | 24.98 | 86.91 | 28.7% | 22.3 |
| 18 | 17.9 | 11.9 | 3.7 | 24.0 | 10.3 | 320 | 0 | 26.91 | 92.19 | 29.2% | 23.5 |
| 19 | 13.8 | 6.9 | 0.0 | 24.0 | 11.2 | 297 | 0 | 21.45 | 72.07 | 29.8% | 18.2 |
| 20 | 13.9 | 8.3 | 0.0 | 24.0 | 11.1 | 177 | 0 | 21.79 | 75.07 | 29.0% | 19.2 |
| 21 | 19.3 | 10.6 | 4.9 | 24.0 | 10.2 | 205 | 0 | 25.57 | 92.46 | 27.7% | 24.1 |
| 22 | 17.8 | 12.0 | 4.2 | 24.0 | 10.2 | 60 | 1 | 23.98 | 93.67 | 25.6% | 25.1 |
| 23 | 15.4 | 11.3 | 5.5 | 24.0 | 10.1 | 84 | 2 | 25.17 | 95.50 | 26.4% | 25.3 |
| 24 | 15.9 | 11.4 | 3.9 | 24.0 | 10.0 | 357 | 0 | 27.53 | 91.54 | 30.1% | 23.0 |
| 25 | 16.9 | 11.4 | 3.1 | 24.0 | 10.1 | 386 | 0 | 27.57 | 89.50 | 30.8% | 22.3 |
| 26 | 19.5 | 11.6 | 5.2 | 24.0 | 10.3 | 340 | 0 | 27.76 | 95.43 | 29.1% | 24.4 |
| 27 | 19.9 | 11.7 | 2.9 | 24.0 | 10.0 | 126 | 0 | 23.34 | 89.60 | 26.0% | 23.9 |
| 28 | 21.6 | 12.0 | 3.6 | 24.0 | 10.1 | 403 | 0 | 28.70 | 92.09 | 31.2% | 22.8 |
| 29 | 19.5 | 7.7 | 0.2 | 24.0 | 10.6 | 69 | 1 | 20.30 | 74.14 | 27.4% | 19.4 |
| 30 | 22.3 | 8.3 | 3.2 | 24.0 | 11.1 | 56 | 2 | 22.39 | 83.36 | 26.9% | 21.9 |
| 31 | 17.4 | 6.1 | 0.0 | 24.0 | 11.6 | 86 | 1 | 21.83 | 70.46 | 31.0% | 17.5 |
| Total (※ Avg.) | 17.6 ※ | 10.0 ※ | 3.3 ※ | 24.0 ※ | 10.7 ※ | 175.3 ※ | 0.4 ※ | 757.18 | 2698.51 | 28.1% ※ | 698.9 |

**Table 3.1.3.II. -** Results obtained per month in Japanese tunnel with intelligent lighting system integrated

It is of great relevancy to point out that being accurate when it comes to detecting the vehicles approaching the tunnel is important. Some equipment have been employed in real road tunnels, for particular cases where being accurate when detecting a vehicle approaching the tunnel was essential.

In the case of the Aragnouet – Bielsa's tunnel, a cross bordering bidirectional tunnel, between France and Spain, a network of vehicle detection equipment has been installed in both accesses. In this road tunnel, the accuracy in detecting vehicles in real time, as well as discriminating whether they are Heavy Goods Vehicles or private cars were two key factors. The network for detecting vehicles was based on the installation of two piezo sensors installed in a parallel position and a loop for detection between them.

**<u>Algorithm that adapts internal conditions to external conditions in real time.</u>**

The first case of application of this algorithm is in several tunnels in the region of Trento, Italy.

TRITON is a project that is currently being carried out, whose aim is to save energy and public funds, as well as improving safety in tunnels. This project is composed by several members: University of Trento, some research Centres, the Autonomous Province of Trento and big Companies.

The meaning of TRITON is "Trentino Research and Innovation for Tunnel Monitoring".

The system outlined in the section 2.3.1.3. - "Algorithms integrated for intelligent use" has been tested by TRITON in some tunnels that make part of the road network of Italy, in the proximities of Trento. This system is composed by:

- The outside sensors collect information about environmental conditions.

- The collected data is analyzed by an elaboration node, which is composed by a mini computer, a set of sensors and a radio – chip. The nodes are small and self-powered, which permits energy savings.

- The transmission of the data is done via wireless, without cables. This facilitates the setup of all the elements of the network and the analysis of large number of different places in the outside, with a reduced cost.

- A software automation system permits all the actions happening without human surveillance: after the analysis phase, the tunnel's lamps are adapted according to external conditions.

The rate of savings depends on the sort of tunnel: typical environmental conditions, season of the year, etc.

The tests have been done in the following tunnels:

| Tunnel | Length (m) | Characteristics |
|---|---|---|
| Cadine | 630 | Artificial tunnel, double carriageway |
| Montevideo | 1.415 | Natural tunnel, single carriageway with unidirectional traffic (towards Trento) |
| Forte | 816 | Natural tunnel, single carriageway with unidirectional traffic (towards Riva del Garda) |
| S. Vigilio | 400 | natural tunnel, single carriageway with unidirectional traffic (towards Trento) |

The results found are not discriminated by tunnel and there is only the global result: energy saving varies from 25-60% of the current consumption.

The second case of algorithm likely to be tested in real conditions is the case studied by the State Key Laboratory of Modern Optical Instrument, Department of Optical Engineering, Zhejiang University, Hangzhou, China.

Some engineers of the Zhejiang University in China have proposed a system quite similar to the previous one exposed. The main difference is that, according with the document, this system has not been tested yet.

Therefore, the results presented are estimations obtained with simulations software. In any case, they conclude that there are savings in energy by integrating an algorithm that adapts the internal lighting conditions to the external ones.

This system has been exposed in the **Second international symposium on Tunnels and ITS in Bergen (18-20 September 2013)**.

The architecture of the system in charge of the adjustment of the internal conditions is similar to the one explained above:

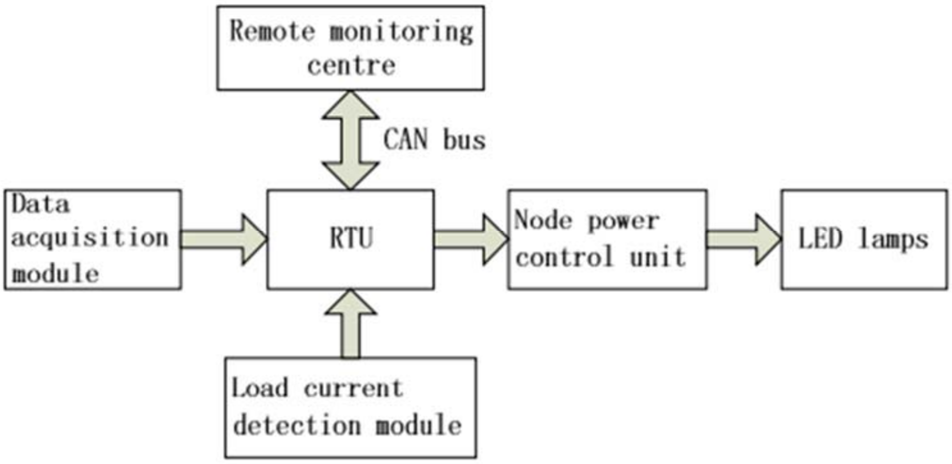


**Figure 3.1.3.I**. – Architecture of the system to integrate adaptive lighting system of a tunnel

The way of working is the same as explained in the previous example of TRITON:

- A network of sensors located at the entrance of the tunnel is in charge of collecting data from: brightness, illumination, traffic flow, wind speed, visibility.

- RTU (Remote Terminal Unit): in charge of monitoring and controlling on-site signals. Once the data collected received and analyzed by the RTU, it is transmitted to the remote monitoring Centre.

- The remote monitoring Centre deals with all kinds of information within the tunnel. After receiving the data from the RTU, the internal and external conditions are compared and then, a signal is sent to the node power control unit to adjust the light – dimming.

- The node power control unit receives the light – dimming signal of the RTU, and then, it sends a signal of corresponding duty cycle to LED power.

The main conclusion of the article is that it exists enormous energy savings when internal conditions of lighting are adapted to external ones, but no real test has been done so far.

It's important to point out that several cases of algorithms for adapting the internal to the external luminance have been found, but in this report only the most representative cases are exposed.

## 3.2. VENTILATION SYSTEM.

As far as the ventilation system is referred, it this section it will be presented the results of the real cases of application of the ideas previously explained.

The results exposed in the following sections give the results of the following measures applied in real cases of road tunnels:

- Modifying geometrical factors of the fans.
- Integrating algorithms for an intelligent use of the ventilation system.

### 3.2.1. <u>Modifying geometrical factors</u>

Some tests have been effectuated to verify whether there is a significant improvement in the ventilation system performances with the measure described in the section 2.3.2.1. –"***Modifying geometrical factors***".

The measure due to verify is the change of orientation of the outlet air flow of a jet fan. The tests seeked to know whether changing a conventional jet fan by a fan with convergent nozzles enhanced the energy efficiency of the ventilation system.

**<u>CFD simulations:</u>**

Some CFD simulations have been carried out in order to verify whether the effects of having convergent nozzles in a jet fan are notorious. These simulations reproduced a road tunnel in London, where the ventilation system was due to be refurbished.

The calculations have been realized modelling 100m of the tunnel, with the fans located 20m from the portal. This way the jet was allowed to mix out reasonably well across the cross – section of the tunnel by the time it reached the outlet portal.

The **Figure 3.2.1.I** shows the model used to carry out the CFD simulations:

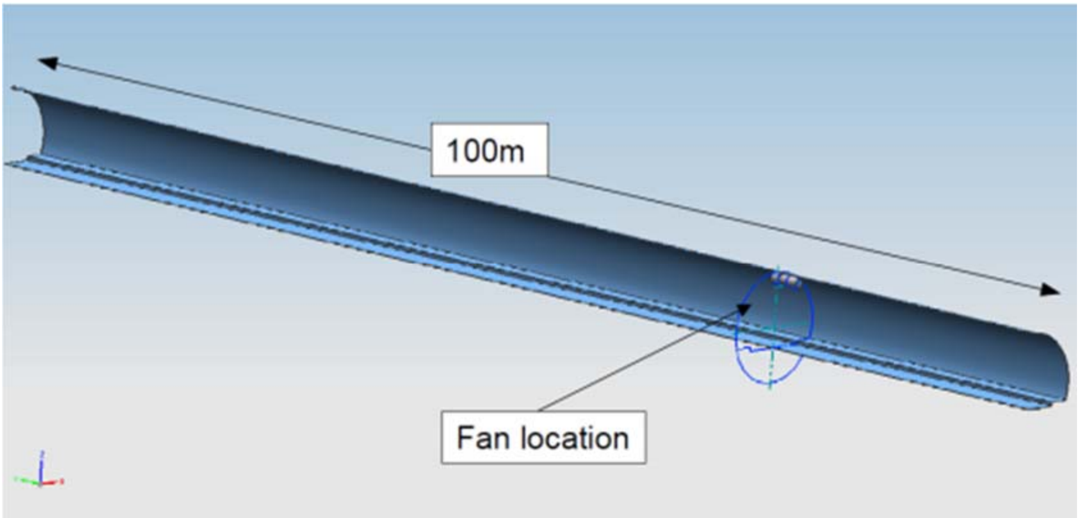

**Figure 3.2.1.I.** – CFD model used to realize the simulations

The calculations were realized with commercial CFD code CFX. The grid consisted of a total of 2 million cells and the turbulent model was the k-ε model.

The **Figure 3.2.1.II** shows the 3D results for the flow of a jet fan with convergent nozzles:

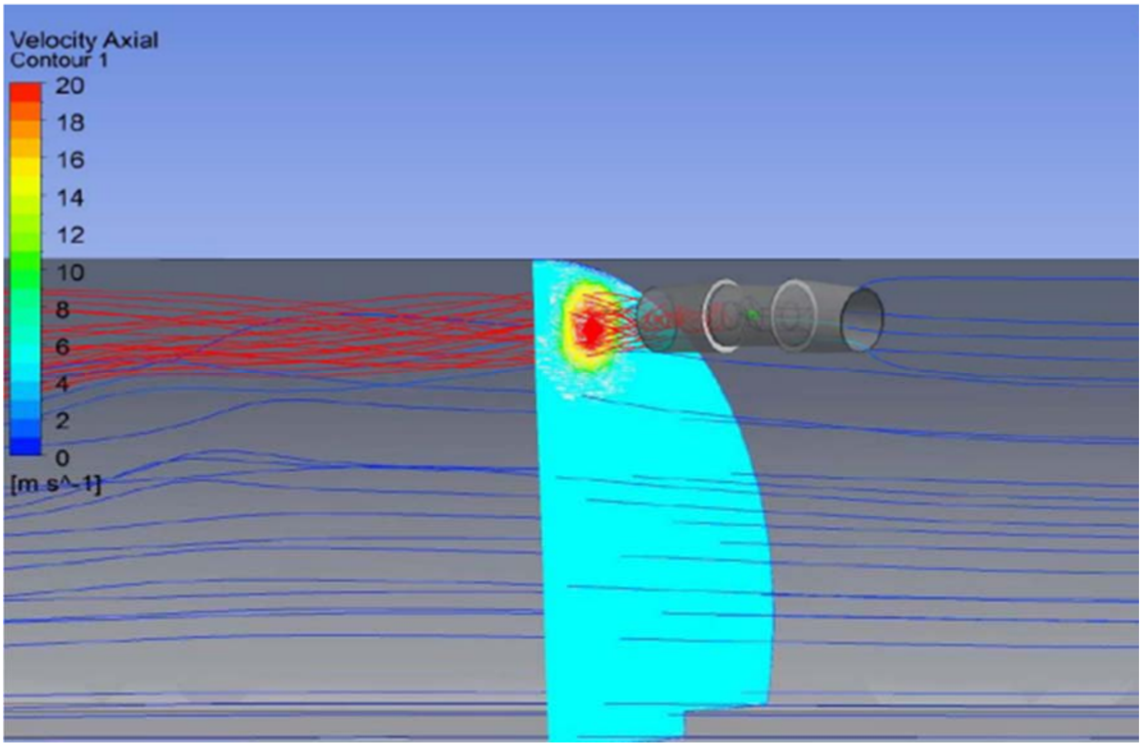


**Figure 3.2.1.II**. **–** CFD calculations of flow turning through jet fans with convergent nozzles

The reason why it was thought that there was a decrease in the efficiency of the ventilation system is because of the Coanda effect. The Coanda effect is the tendency of a fluid to be attracted to a nearby surface. In the case of ventilation in a road tunnel, it means more contact of the air with walls, which provokes friction to the fluid.

The CFD results concluded that there is a marked reduction of the Coanda effect thanks to the change in orientation of the outlet air flow. Therefore, modifying the direction of the outlet air flow in a jet fan towards the centerline of the cross - section increases the efficiency of the ventilation system.

**<u>Tests in bench with a prototype:</u>**

In order to confirm with real tests the results obtained with the CFD code, some bench tests were undertaken with a 1m diameter jet fan with 20º blade pitch angle and a 50Hz 4-pole motor.

A nozzle area convergence ratio of 1,6 for both sides of the jet fan was chosen, based on prior calculations which considered the expected fan characteristic. Straight silencers were manufactured as well, in order to compare the effects of straight and convergent silencers.

Both “Form A” (flow drawn over motor) and “Form B” (flow pushed over motor) thrust tests were conducted; the allowable uncertainty was + 5% and + 2% for the thrust measurements and input power respectively.

The **Table 3.2.1** outlines the results obtained with the real tests effectuated:

| Mean values measured in Form B | | | Mean values measured in Form A | | | Comments |
|---|---|---|---|---|---|---|
| Input power (kW) | Current (A) | Thrust (N) | Input power (kW) | Current (A) | Thrust (N) | |
| 8,89 | 18,43 | 281 | 8,89 | 18,43 | 280 | Straight nozzles |
| 8,37 | 17,88 | 299 | 8,16 | 17,6 | 299 | Convergent nozzles (area ratio 1,6) |

**Table 3.2.1.** – Summary of Prototype Measurement Results

As it is demonstrated in Table 3.2.1, fan with convergent nozzles offers bigger thrust with less power demand. Therefore, changing the direction of the output air flow of a jet fan towards the centerline increases the energy efficiency.

### 3.2.2. Integration of algorithms for intelligent use of the system

As described previously, an intelligent use of the ventilation system can be obtained thanks to the integration of algorithms.

Both algorithms outlined in section 2.3.2. –“***Ventilation system***” have been tested in real tunnels, as it is explained in the following lines:

**Algorithm that controls the activation of the ventilation system:**

An algorithm designed by ABB was put into operation in the Učka tunnel (Croatia) in December 2009. This is a bidirectional tunnel of 5.062m length open to circulation since 1981.

A predictive fuzzy logic mathematical model has been integrated in the ventilation system. The aim of this algorithm is to evaluate the rate of change of visibility and the different pollutants that may appear in a road tunnel operation: CO, NOx.

This algorithm works in a different way as the conventional one, which makes the ventilation system activate when the admissible margins of concentration of CO, NOx and visibility are overpassed.

The elements involved in this algorithm are shown in **Figure 3.2.2.I**:

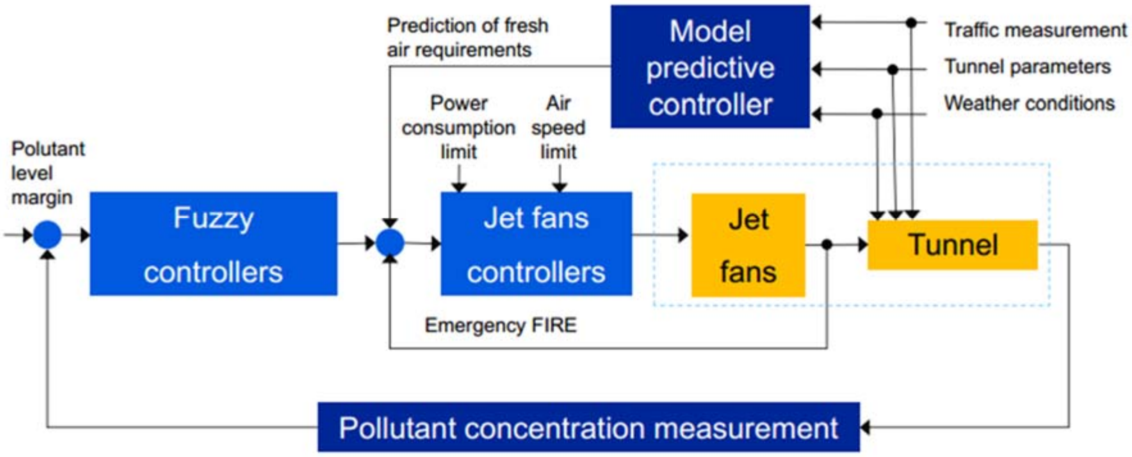


**Figure 3.2.2.I**: control elements that make part of the ABB's algorithm

The procedure of the algorithm is the following one:

- The network of sensors detects in real time the level of CO, NOx and visibility.

- The tunnel has its own characteristics: traffic, tunnel parameters, weather conditions, etc. Therefore, thanks to the existence of sensors for measuring the rate of traffic and environmental conditions, a predictive model for control of ventilation is created and integrated in the control system. This permits to estimate the rate of increasing of the different pollutant given a specific level.

- If the level measured of CO, NOx or visibility is such that the rate of change may be important and, therefore, overpasses the admissible margins, the ventilation system is activated.

- The mode of ventilation (number of jets working, speed, location, etc) is part of the ventilation already designed and integrated in the control system.

In **Figures 3.2.2.II** and **3.2.2.III** it's shown:

- A distribution of the vehicles in the Tunnel of Učka in 350 minutes – time period, which permits to compare the old and the new algorithm for ventilation control.

- The distribution of the activation of jet fans and the concentration of CO during this period.

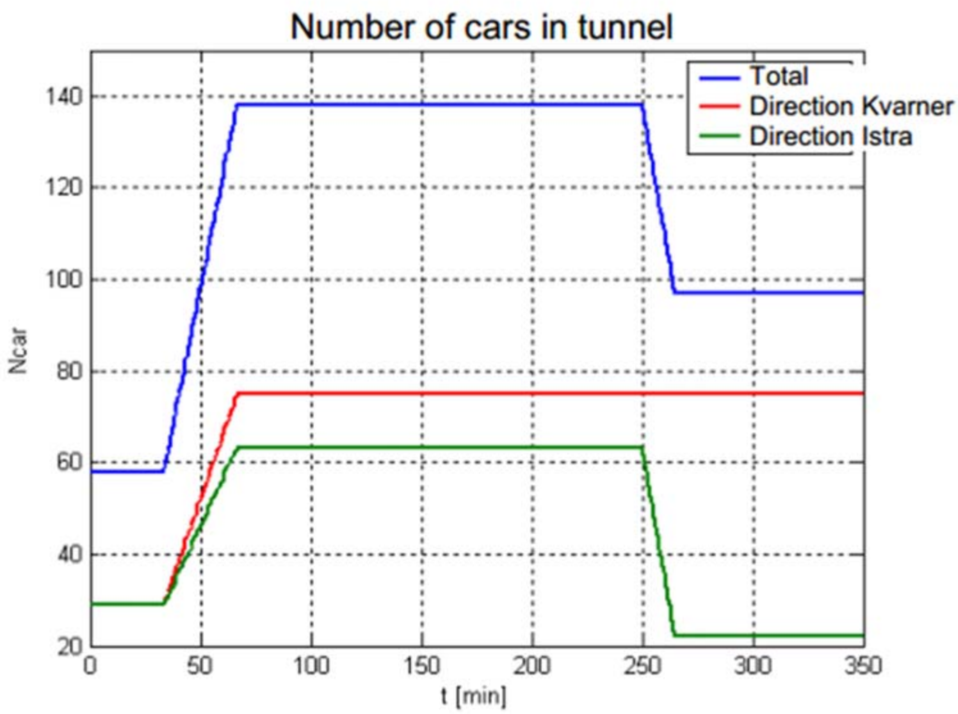


**Figure 3.2.2.II. –** Distribution of cars in a period for the Tunnel of Učka during a 350min – time period

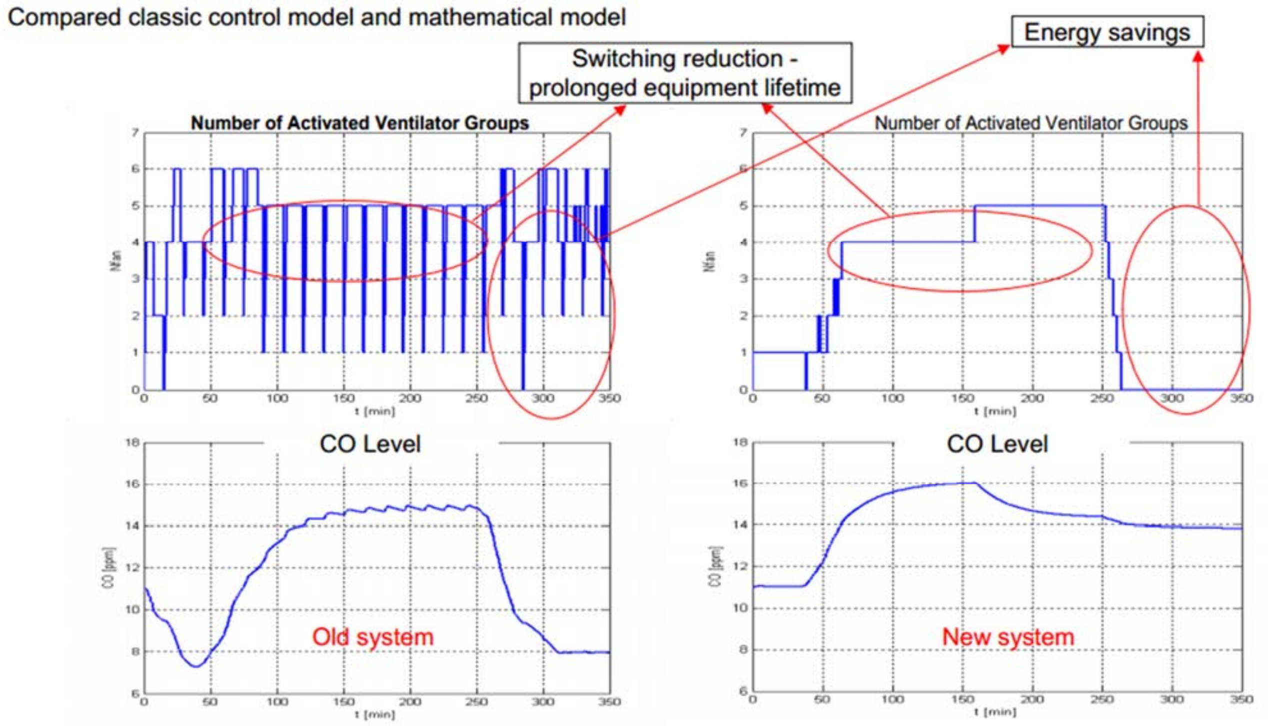


**Figure 3.2.2.III. –** Comparison of the old and new algorithms

Since this new algorithm was put in practice in this tunnel, it has been possible to register the consumption data. This permits to compare these figures with previous years and obtain the energy savings due to the integration of this algorithm.

The **Figure 3.2.2.IV** presents the comparison between the average energy consumption during the period 2000-2009 and the year 2010.

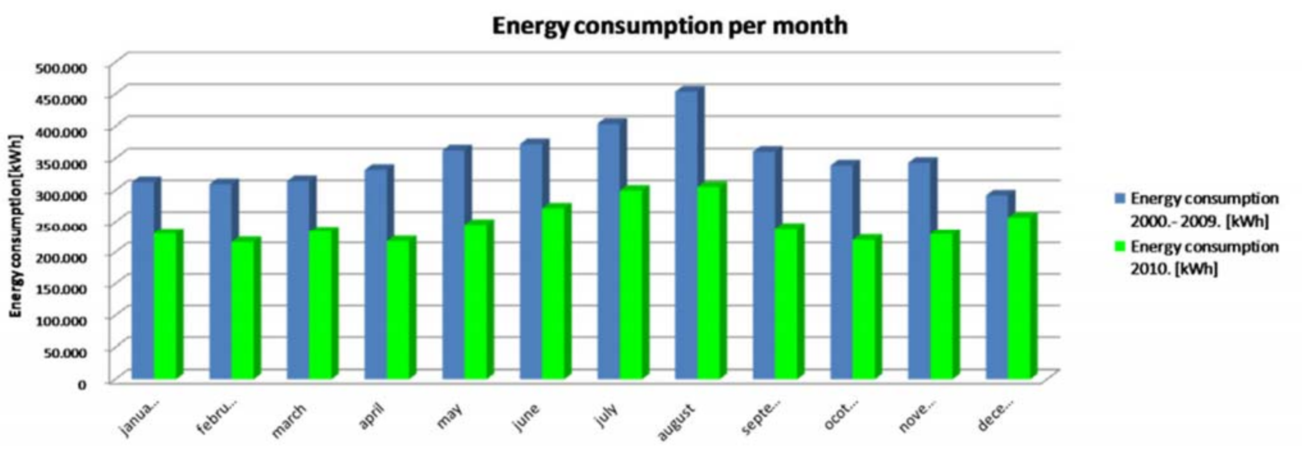


**Figure 3.2.2.IV. –** Comparison between energy consumption in the period 2000-2009 and the year 2010.

Since the energy consumption of the ventilation system is due to the traffic of vehicles in the inside of the tunnel, the **Figure 3.2.2.V** shows the graphic of the average energy consumption per vehicle, comparing the average of the period 2000-2009 and the year 2010.

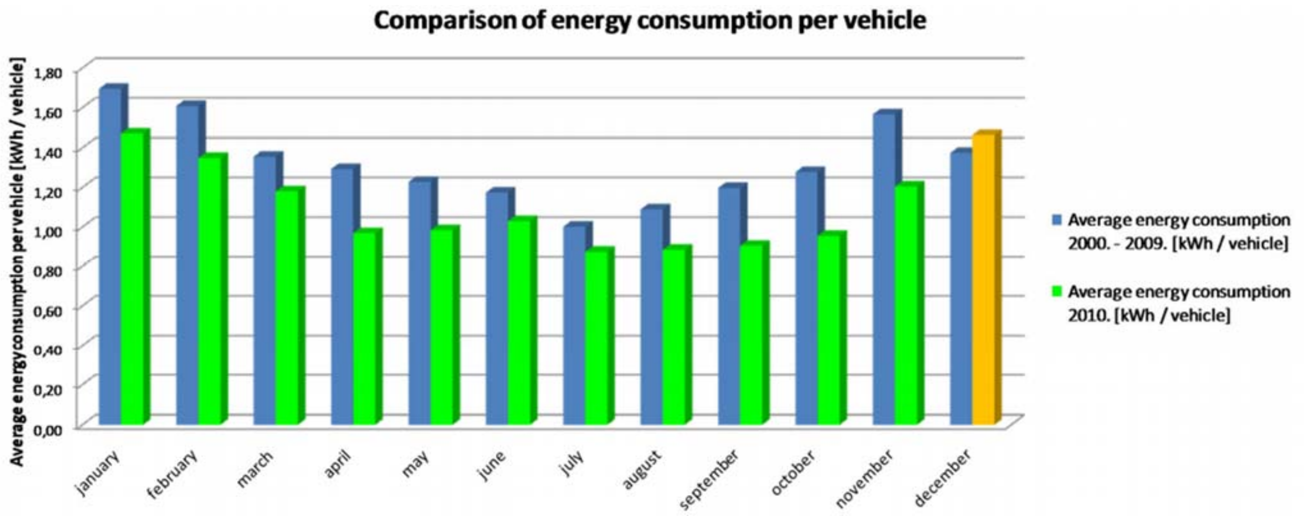


**Figure 3.2.2.V. –** Comparison between average energy consumption in the period 2000-2009 and the year 2010 per vehicle.

The graphics presented in **Figures 3.2.2.IV** and **3.2.2.V** permit to calculate the estimated savings in the tunnel exploitation in the year 2010 with the new algorithm of ventilation incorporated.

The estimated savings in energy consumption in the year 2010 are shown in **Figure 3.2.2.VI**:

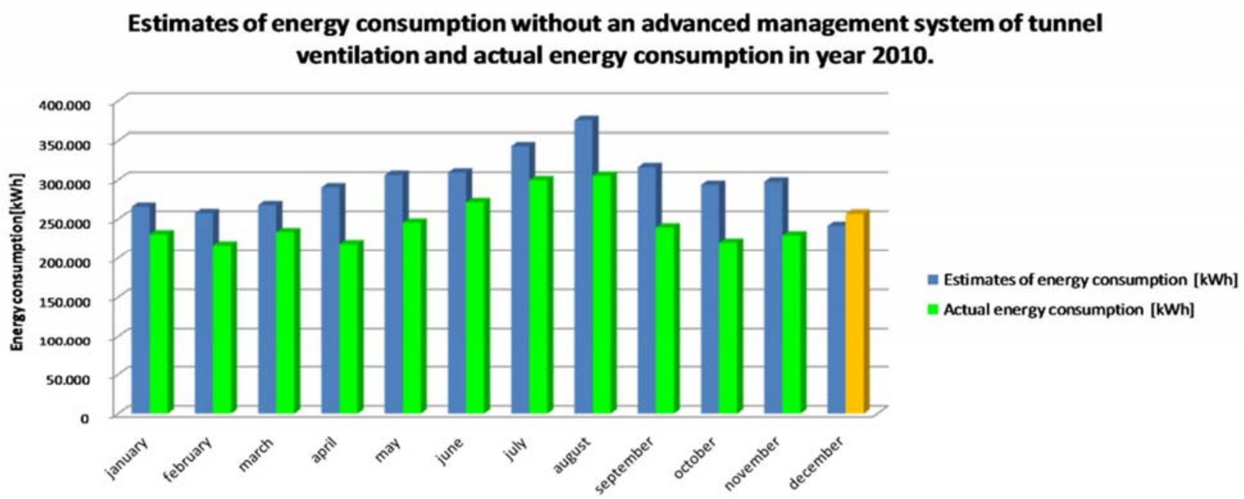


**Figure 3.2.2.VI**. – Estimation of the energy savings obtained in the year 2010.

The results obtained show a decreasing in the energy consumption since the new algorithm was tested in real conditions:

- Saving in the average consumption (total) of energy per a vehicle for 2010 compared to the previous ten-year period amounts to 16.89 %.

- Financial indicators of savings are also very significant. Taking the average consumption per vehicle in the previous ten year period and the traffic in 2010 as a starting point, the estimated financial savings reach a 16.28%.

- It should be noticed that the savings are achieved during the day when the traffic is increased, and electricity is more expensive, and higher financial savings are to be expected with rising annual traffic levels.

- Also, a reduction in subscribed demand has been achieved, which will contribute to savings and reducing the financial cost.

The mean value of saving in energy consumption per a vehicle for all months in 2010 compared to the ten-year average which is 16.89% is used as the value of efficiency. The share of consumption of the ventilation system (estimate) is 50.87% of total energy consumption, and efficiency of the mathematical model is $\eta$=33%.

The results obtained with the integration of this model permit to extract the following conclusions:

- The control over the concentration of pollutants is reliable and effective, respecting the admissible margins for CO, NOx and visibility.

- The number of on- and off-switching of jet-fans has reduced, what means an increased lifetime of the jet-fans and electrical switching equipment.

- Savings have been achieved in maintenance, due to the lower times that the jet-fans are activated.

- Increase of the safety in the tunnel, since the maximum value of velocity is lower.

- Savings obtained in the electricity bill.

- Increase of the energy efficiency.

**Algorithm that controls time zones when the electricity is lower:**

Some energy saving measures have been implemented in the underground of Madrid.

Among them, there is one that deals with control of ventilation: reprogramming the software of the ventilation systems, which will enable them to activate in periods when the temperature is more appropriate and power consumption has a lower price.

It is of great importance to point out that, in the particular case of the underground of Madrid, this measure can be implanted, since the use of the ventilation system can be programmed to work in some periods. However, this is not the case for a road tunnel, because the use of the ventilation system is related to overpassing the admissible margins of pollutants. Therefore, this algorithm is not applicable in the case of a road tunnel.

## 3.3. OTHER SOURCES OF ENERGY.

In this section, it will be presented the results of the application of the different alternative sources of energy.

**Energy from the sun:**

In many cases of roads, there are examples of installations that have a little energy consumption. Due to the fact of this very little consumption, a PV (photovoltaic) panel can be installed, in order to cover the electricity needs. The installations usually taking advantage of a PV panel are those for signalization in most of the cases. This is very common in the Spanish road network.

No cases of road tunnels using large scale installations (like photovoltaic parks or thermo electrical infrastructures) have been found in the research phase. However, the article "*Zero Energy Tunnel: Renewable Energy Generation and Reduction of Energy Consumption*", found in the research phase, includes some calculations or a model tunnel.

The model tunnel considered, tries to reproduce the typical Dutch tunnel and has the following characteristics:

- 1km length.
- Traffic rate of 5.000 veh. per hour during the rush hour.
- Cross sectional area of 75m$^2$.

The example in the article considers energy contribution by both wind and sun energy. It is supposed that a photovoltaic park is built in a 1000m2 surface with PV models of 3,2kWp and wind energy generation is achieved by two wind turbines with fully rated converter of 0,5MW single power.

The results obtained are:

- Energy fed back to the grid: 1.209 MWh per year.
- Generation: 3.333 MWh per year.

As far as payback periods are concerned, the following results have been obtained:

- Wind turbines: 8 years.
- PV system: 18,5 years.

It is remarked that depending on renewable energies to cover the electrical needs of a tunnel is challenging because of their uncontrollability.

In addition, some tests have been carried out by researchers of the University of Granada to test the placement of a translucent structure as the threshold zone of a road tunnel. This allows having the sunlight in the role of luminaires for the entrance of the tunnel.

The **Photography 3.3** shows the aspect of the artificial translucent structure:

**Photography 3.3**. – Artificial structure to illuminate the threshold region of a road tunnel

The research effectuated has revealed that a compromise has to be taken between optical and mechanical parameters, to that the structure has the necessary stability and integrity.

Some tests have been carried out in a road tunnel in Granada, but it is not indicated which tunnel is the one where the tests have taken place. The results of the tests have revealed that for a maximum authorized velocity in the tunnel of 100km/h, energy savings reach a 76% as far as daylight power demand is referred. If the maximum allowed velocity in the tunnel is reduced to 80km/h, then the savings reach the 100% of the daylight power demand.

As well as the measure explained in the previous lines, there is another way of taking advantage of the sunlight in the case of road tunnels. Sunlight can be captured at the entrance of a tunnel with the proper equipment and then deviated and introduced in the place due to be illuminated.

During the research phase, some equipment has been found that is able to capture the sunlight and then deviate it somewhere else. However, this equipment is for building applications and no evidence has been found about its applications for the particular case of road tunnels.

The **Figure 3.3.I** shows this equipment:

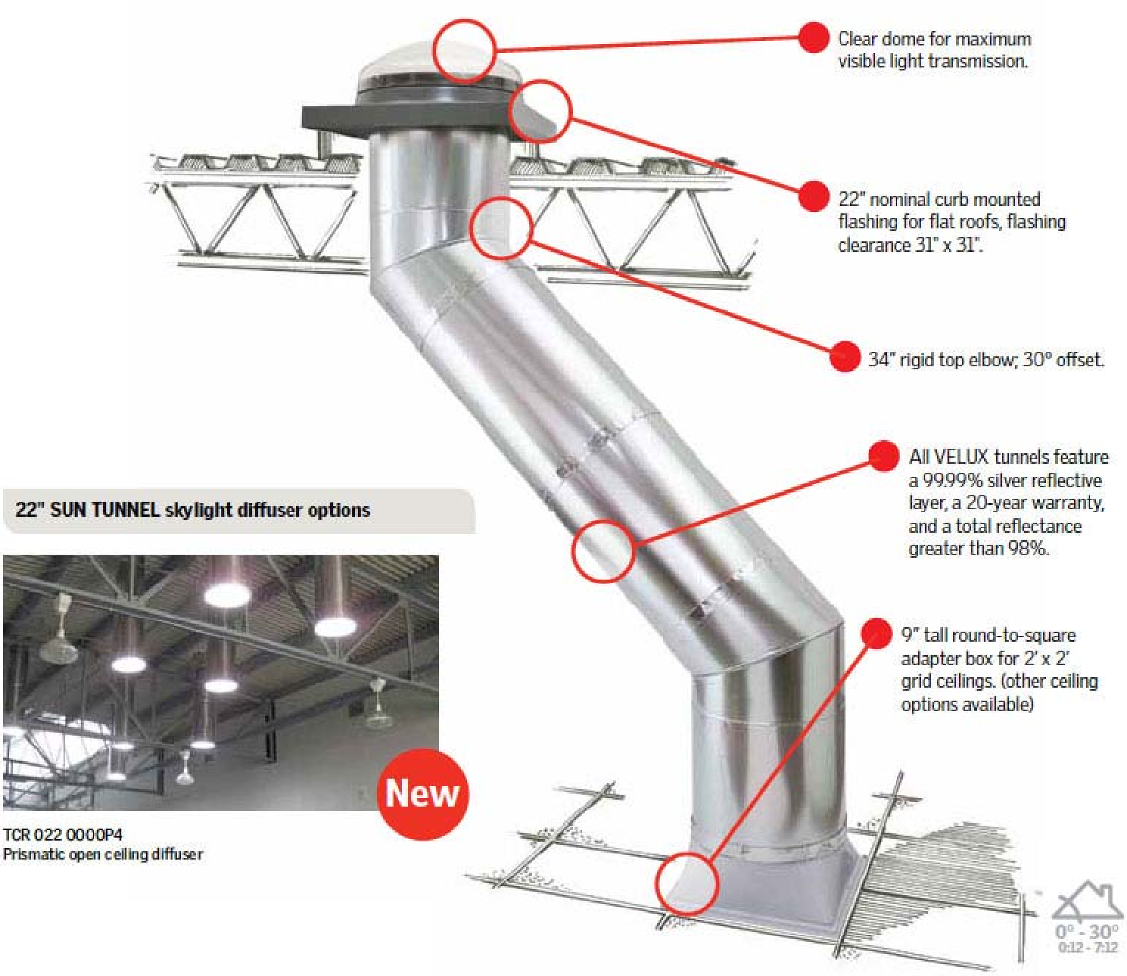


**Figure 3.3.I**. – Equipment to capture the sunlight and deviate it.

With respect to photo luminescent panels, an example has been found in a 500m stretch of highway N329 in Oss, in the Netherlands. A photo luminescent painting has been realized in this highway that it is charged by the sun during the day, and it illuminates the road during the night. This may be of application for the road access of a road tunnel.

**Wind energy:**

As well as in the case of the energy from the sun, the article "*Zero Energy Tunnel: Renewable Energy Generation and Reduction of Energy Consumption*", found in the research phase outlines the results obtained for a typical Dutch tunnel.

The results have been explained in the "***Energy from the sun***" section above.

Also, as far as taking advantage of the kinetic energy of the air flow due to the vehicles, some progresses have been achieved:

A research project is being carried out by the University of Jaén, which deals with transforming the kinetic energy of the air flow in a road tunnel into electrical energy.

Also, the Green Energy Technologies company has developed a wind tunnel product. A wind cube is placed in the up part of the cross sectional area of the tunnel; the wind due to the transit of the vehicles is deviated into the area where a turbine resides. The air flow transforms its kinetic energy into electrical energy thanks to the turbine.

The **Figure 3.3.II** shows the installation of the wind cube:

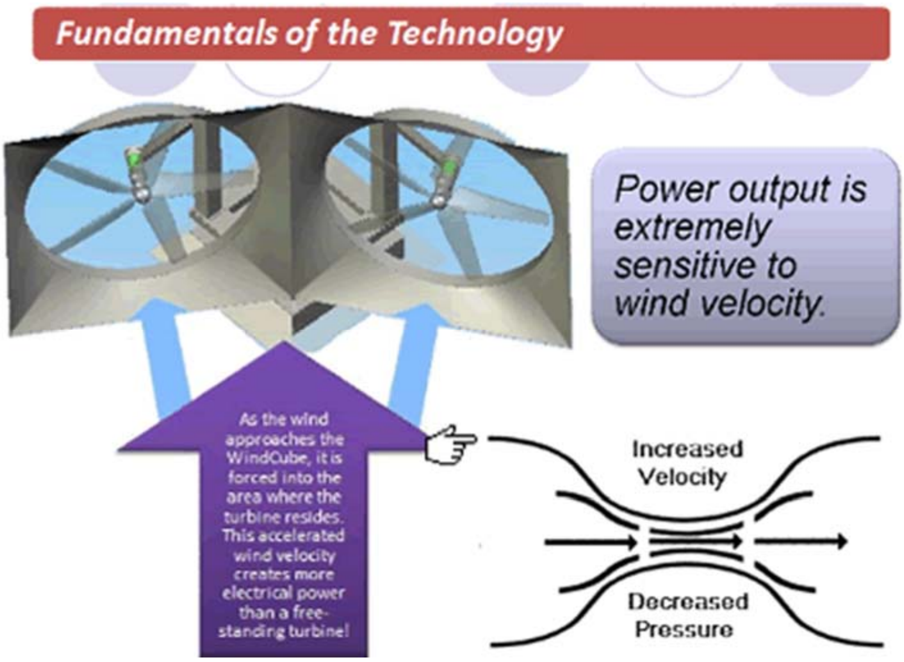


**Figure 3.3.II** - Installation of the wind cube

Moreover, other equipment have been designed with the purpose of converting the kinetic energy of the air flow of the vehicles into electrical energy. The Airoad device is a fin that deforms itself with the wind produced by the vehicles passing by a road. Up to now it hasn't been confirmed that this device has been installed in road tunnels.

**Geothermal energy:**

No road tunnel has been found in the research phase that has included a geothermal energy installation to cover their energy needs. The examples found through this phase are related to the building sector.

**Heat extraction:**

A project to extract the heat trapped in the northern line tubes of the London Underground is going to start in order to warm up homes on the surface.

In a shaft that connects the underground with the surface, some finned tubes in spiral are placed in the shaft. These tubes transport water, which captures the heat from the air that goes up through the shaft.

A heat exchanger is used at the surface to recover the heat accumulated in the water.

The aim of the project is to install 1,4 miles of pipes in ventilation shafts so that 700 homes will be supplied with heating.

The **Figure 3.3.III** shows the installation to recover the heat from the air in the underground:

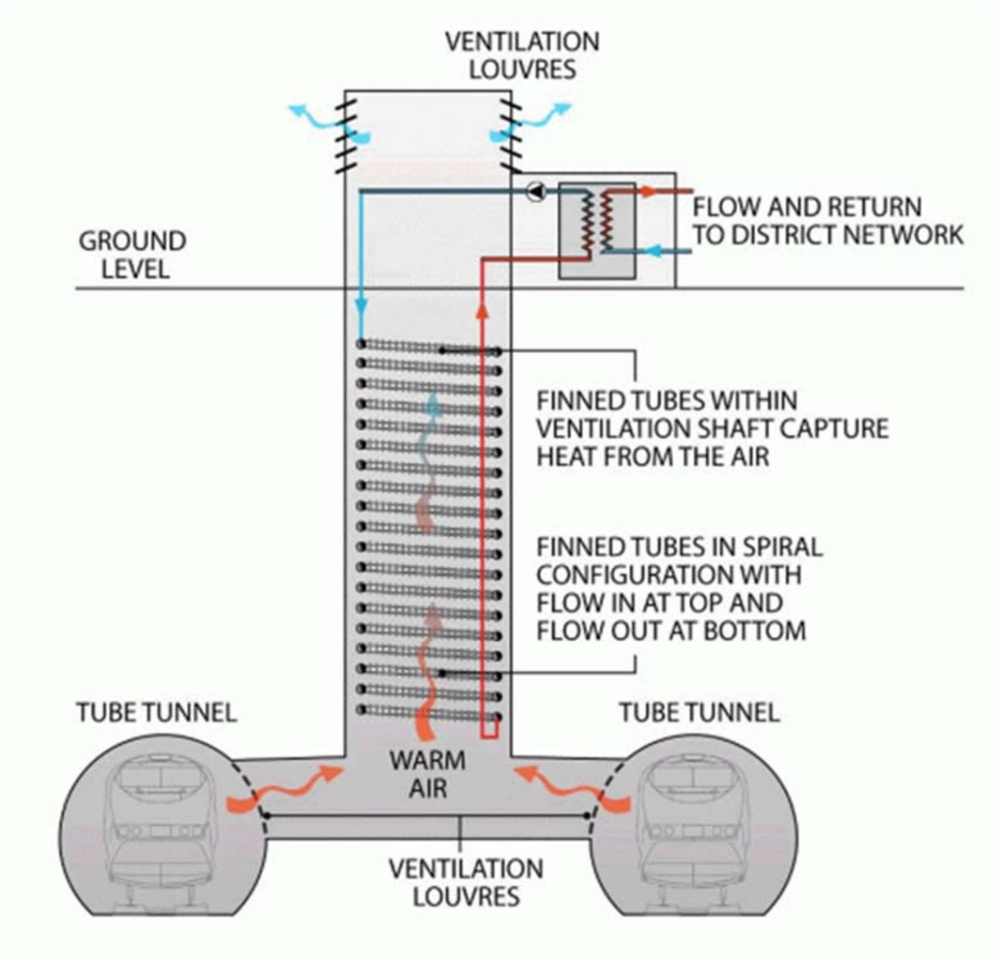


**Figure 3.3.III.** – Installation to recover heat from the London Underground

In addition, the article "*Zero Energy Tunnel: Renewable Energy Generation and Reduction of Energy Consumption*", found in the research phase, includes some calculations or a model tunnel.

The beforehand assumptions are made before calculating the energy collected:

- The composition of the traffic is: 70% private cars (35% diesel engine, 35% gasoline engine), 30% buses and trucks.

- The heat dissipation inside the tunnel is 85%.

- The average length for a car is 3m, while 10m is retained for buses and lorries. The distance between two consecutive vehicles is 2m.

- The average air flow velocity due to the piston effect is 3m/s.

The temperature raise of air inside the tunnel is estimated from the following expression:

$L = Q / (C_p \cdot \rho \cdot (T - T0))$

Where:

L: air volume, equal to 225m3/s for air flow velocity of 3m/s.

Q: heat power extracted from the tunnel (kW)

$C_p$: specific heat capacity for the air, equal to 1,005kJ/(kg·K)

ρ: density of the air, equal to 1,2kg/m3

T: air temperature in the tunnel (K)

$T_0$: ambient air temperature (K)

The results give the figure of 0,9 MW of thermal power that might be extracted in each tube.

**Conversion from mechanical into electrical energy:**

No road tunnels have been found with equipment able to convert mechanical into electrical energy up to now. Neither for the method of generating electricity by an electromagnetic induction nor the method of generating kinetic energy when a vehicle circulates have been found.

# 4. CONCLUSIONS.

In the following lines, the conclusions of the research phase are presented:

- Current exploitation of road tunnels is likely to be optimized, as far as energy consumption is concerned.

- It has been proven that important energy savings can be obtained through the following measures:

- By integrating algorithms for an intelligent use of the lighting and ventilation systems.

- The use of LED luminaires is positive: it provides higher energy efficiency than the conventional HSP luminaires and it permits to integrate appropriately the algorithm that makes the lighting system be working only when it is required.

- Studying how to optimize the geometrical aspects of a jet fan may allow finding an increasing in the energy efficiency.

- In the cases where it is possible, taking advantage of renewable energies as a new source is interesting, since it permits a road tunnel to become more sustainable, while reducing the energy bill.

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- **Events information:**

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- http://www.ianvisits.co.uk/
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- <u>Articles concerning the lighting system:</u>

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