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Undertittel
Prototype to increase the energy efficiency in road tunnels

Forfatter
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Godkjent av
Harald Buvik

Emneord
Varige konstruksjoner, fremtidens tunneler, ENERTUN, energieffektive tunneler, energiforbruk

Sammendrag
Denne rapporten er den siste 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 oversikt over tiltak for å optimalisere energiforbruket og spesielt system for å utnytte ytre luminans(sollyset) og transportere dette inn i tunnelen. Rapporten gir en beskrivelse av en prototype av et slikt system, test i laboratorium og tester i felt

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Title
Energy efficiency in tunnels- ENERTUN - D5.1

Subtitle
Prototype to increase the energy efficiency in road tunnels

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Summary
This report is the last 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 an overview of measures to optimize energy consumption and special system for utilizing external luminance (sunlight) and carry this into the tunnel. The report provides a description of a prototype of such a system, test in laboratory and field tests

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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 *Luis Miguel Gonzalo, Geocontrol*.

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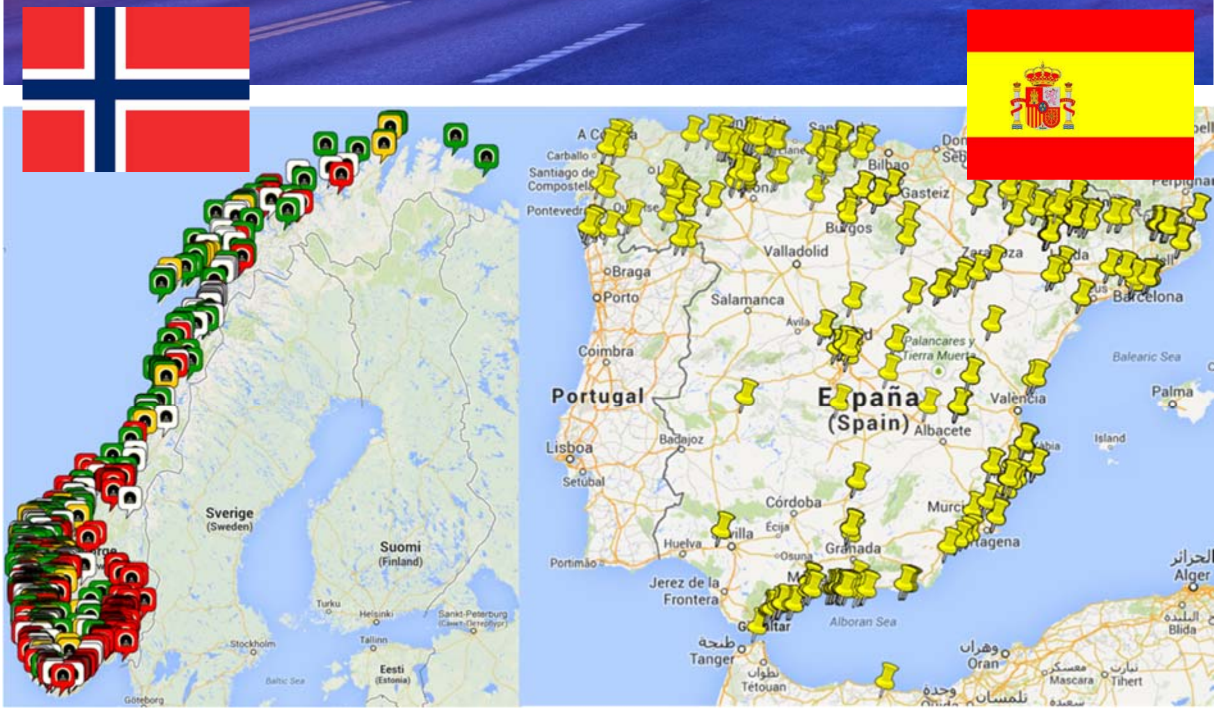

DELIVERABLE 5.1.- PROTOTYPE TO INCREASE THE ENERGY EFFICIENCY IN ROAD TUNNELS			
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ENERTUN
DELIVERABLE 5.1.- PROTOTYPE TO INCREASE THE ENERGY EFFICIENCY IN ROAD TUNNELS

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ENERTUN
DELIVERABLE 5.1.- PROTOTYPE TO INCREASE THE ENERGY EFFICIENCY IN ROAD TUNNELS

1. INTRODUCTION

In previous stages of the project, the economic viability of the implementation of several efficiency measures was analysed.

Among the studied measures, there was much interest in studying the establishment of a system able to take advantage of the external luminance and to transport it inside the tunnel.

In order to make a more realistic assessment of the viability of a system able to take advantage of the external luminance, in the WP5 framework a prototype is developed.

In the present document, it is described the work that has been done and the results that have been obtained in the WP5 framework, which are divided into the following tasks:

- T5.1 Design of the prototype.
- T5.2 Manufacture of the prototype and test in laboratory.
- T5.3 Field tests of the prototype

2. DESIGN OF THE PROTOTYPE

The daily lighting system uses electrical energy to convert it into lighting energy when more solar energy is available in the outside of the tunnel, which makes evident the fact that if it were possible to redirect the external light to the tunnel, it would be possible to reduce completely the energy consumption associated to the lightning system.

2.1. INITIAL APPROACH

For a circulation speed in the tunnel of 80 km/h, according to the L20 method included in the CIE-88 annex 1, the internal luminance in the region close to the entrance of the tunnel is obtained by multiplying L20 by 0,06. That is Lth = L20 * 0,06.

The tunnel's lighting intensity decreases in the same measure as one is advancing into its interior, according to the adaptation curve shown in the **Figure 2.1.I**:

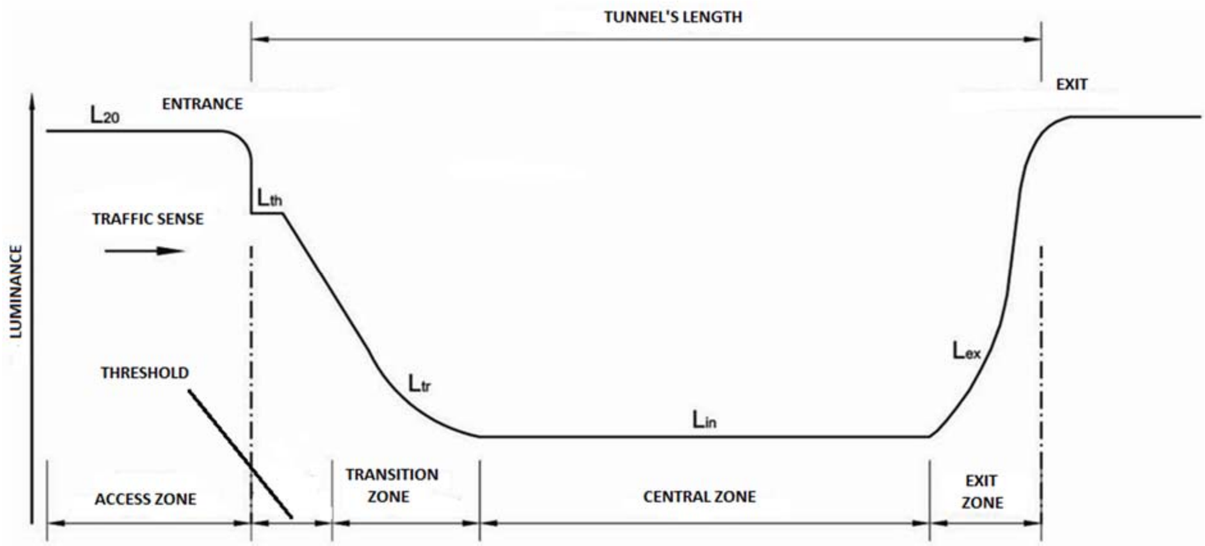

Figure 2.1.I.- Adaptation curve for a unidirectional tunnel.

In a long tunnel with a L20 equal to 5.000 cd/m^2, the integration of the illuminance due to the daily lighting over the tunnel gives an average value of 19.800 cd/m. If this integration is considered taking into account a 10m width of the road, it is obtained that a luminance intensity of 198.000 cd is required.

In order to obtain this luminance intensity with the external illuminance it would be necessary a surface equal to 198.000 / 5.000 = 39,6 m^2.

Thus, if it is possible to capture the light incident over 39,6 m^2 of external road and redirect it inside of the tunnel, then there would not be any need for the daily lighting. Actually, it would be necessary to capture the solar light in a bigger surface since the system will always have an efficiency lower than 1.

2.2. IMPLEMENTATION IN FOLGOSO TUNNEL

In this point it will be analysed a possible way to put in practice the previous theory in a real case, more specifically the Folgoso Tunnel, which presents the following characteristics:

- Maximum illuminance measured in the entrances (L20): 5.000 cd/m^2.
- Maximum illuminance provided by the lighting system (Lth): 200 cd/m^2.
- Permanent lighting illuminance: 6 cd/m^2 (in the first half of the tunnel).
- Authorised velocity: 100 km/h.

The above parameters lead to the curve presented in the **Figure 2.2.I**.

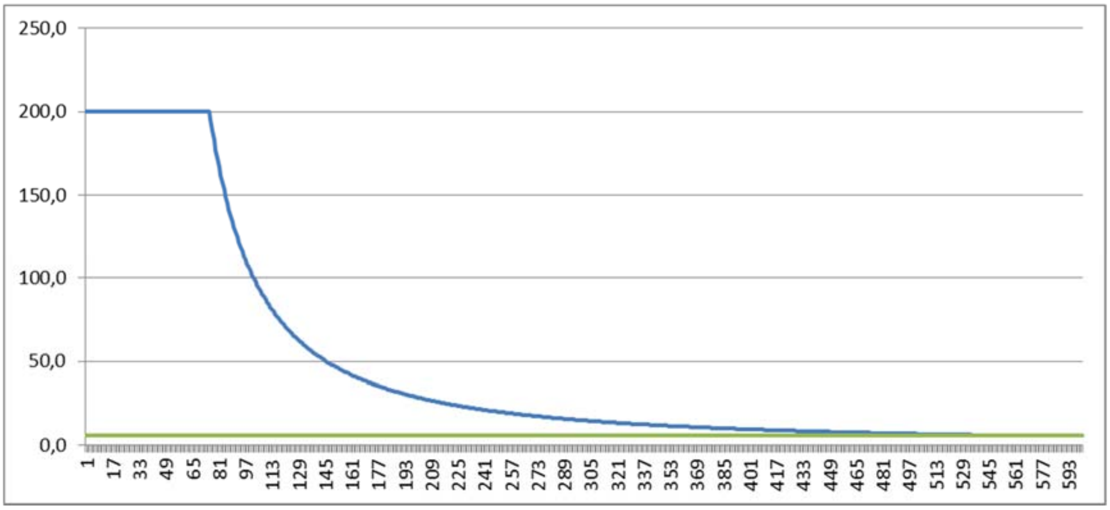

Figure 2.2.I.- Adaptation curve for Folgoso Tunnel.

The surface between the adaptation illuminance curve (blue colour) and the permanent lighting illuminance line (green colour) presents a value of 16.583 cd/m.

The tunnel's cross-section is shown in the **Figure 2.2.II**:

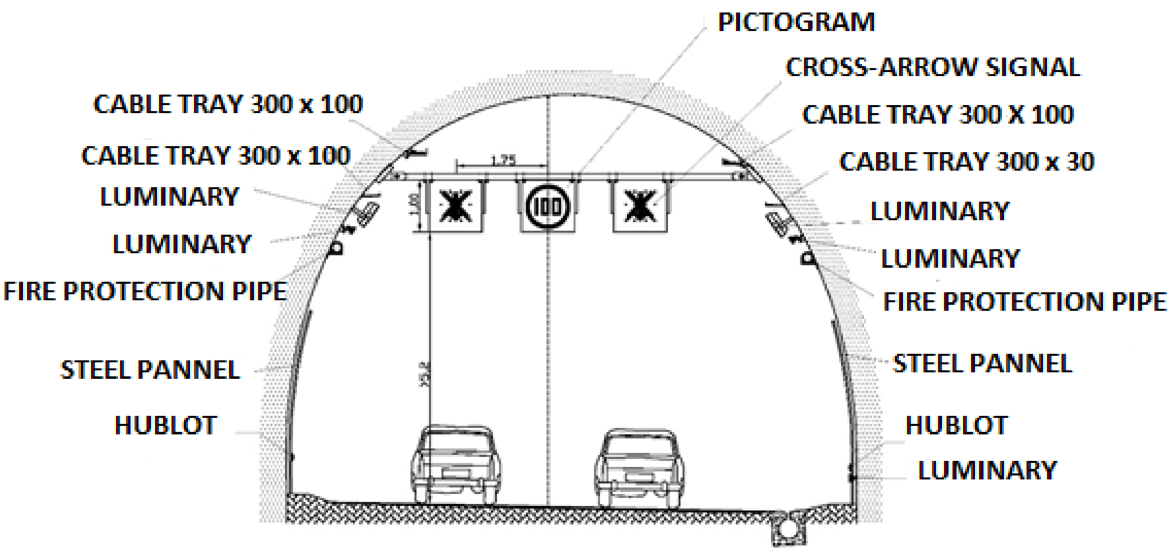

Figure 2.2.II.- Cross-section of the Folgoso Tunnel.

Although the road's width is 9m, in this document it is considered that it is required to illuminate 10m of the 10,68m of the complete width.

The necessary lighting intensity required to replace the current daily lighting would be Itot =16.583 * 10 = 165.830 Cd.

In order to capture this lighting intensity it will be necessary an external capture surface of at least 165.830 / 5.000 = 33 m^2.

As it is appreciated in the cross-sectional area of the tunnel, the only available area to install the equipment in charge of transmitting the lighting intensity from the outside to the inside is the one between the signalisation lintel and the tunnel's roof. This is a 6 m^2 – surface.

In order to transmit the lighting intensity through this space it will be necessary to increase the external lighting density in a factor of (165.830/6)/5.000 = 5,5, which will be rounded to 6.

To sum up, in the following points it is necessary to design a system able to:

- Capture the external lighting intensity in a surface of 33 m^2.
- Concentrate the captured light with a factor of 6.
- Transport the concentrated light above the signalisation lintels to the tunnel inside.
- Diffuse the transported light over the road's surface, according to an adaptation curve.

2.3. SOLAR LIGHT CAPTURE AND CONCENTRATION

The lighting capture process will be achieved through moving mirrors, which adapt their positions depending on the sun's position. This method is widely used in experimental solar thermo electrical plants.

By using curved mirrors, it is achieved simultaneously both the process of capture and concentration of light.

A combination of two parabolic mirrors that concentrate the light symmetrically is chosen, as it is shown in the **Figure 2.3.I.**

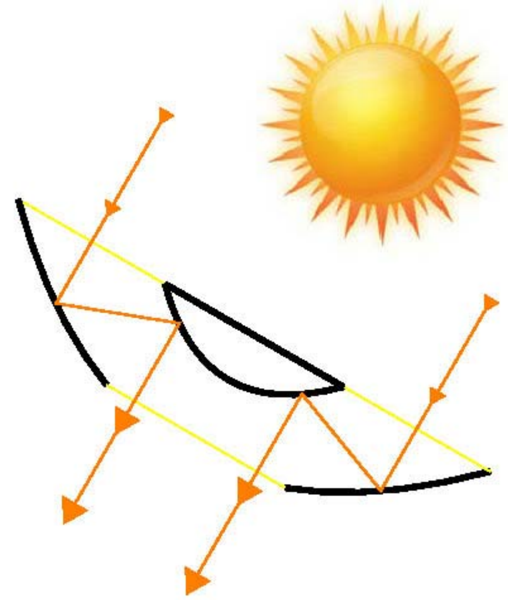

Figure 2.3.I.- Functional scheme of the solar collector.

3m – diameter mirrors are chosen, which allow concentrating the received solar light in a surface of $6m^2$. Firstly, in order to cover the lighting needs, it would be necessary 33/6 = 5,5 mirrors (rounded to 6 mirrors).

The **Figure 2.3.II** shows the zones that should cover every mirror:

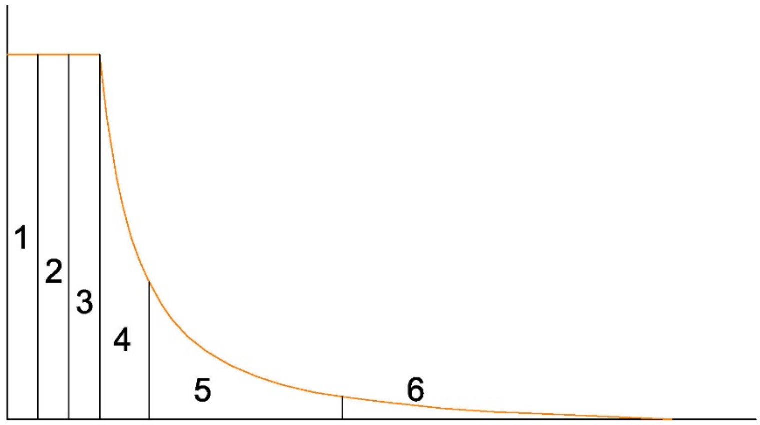

Figure 2.3.II.- Reparto de zonas de influencia de los espejos.

Following the usual terminology in systems involving solar capture, the group of mirrors sought to function for capturing and concentrating solar light will be referred as “solar collector”.

In **Figure 2.3.II** it can be seen that in order to illuminate the first region of the tunnel, where the luminance keeps constant, only 3 solar collectors are required, with each collector due to illuminate a 16m distance in the tunnel.

Ii is required a tracker system called “solar tracker” in charge of maintaining the solar collector oriented towards the sun, so that the solar collector will be able to capture the sun’s light during the day.

2.4. SOLAR LIGHT TRANSPORTATION

The transportation system is the one in charge of transmitting the light captured by the solar collector inside the tunnel.

The transportation system must be compatible with the movements made by the solar collector during the tracking process.

The designed system is represented in the **Figure 2.4.I** and it is able to carry out 3 direction changes with mirrors places at 45º.

Within the 3 direction changes, the first two of them are used to redirect the light from any capturing position to a vertical direction, making the final result independent of the solar collector position.

The last direction change is used to introduce the light beam into the tunnel in a direction that is parallel to the tunnel’s axis.

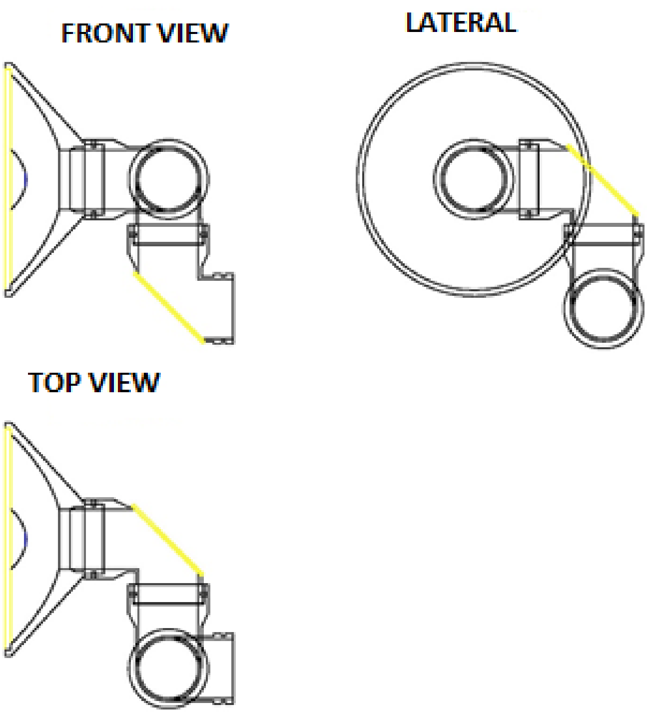

Figure 2.4.I.- Transportation system.

It is possible to install 3 of those systems according to the following lay out shown in the **Figure 2.4.II:**

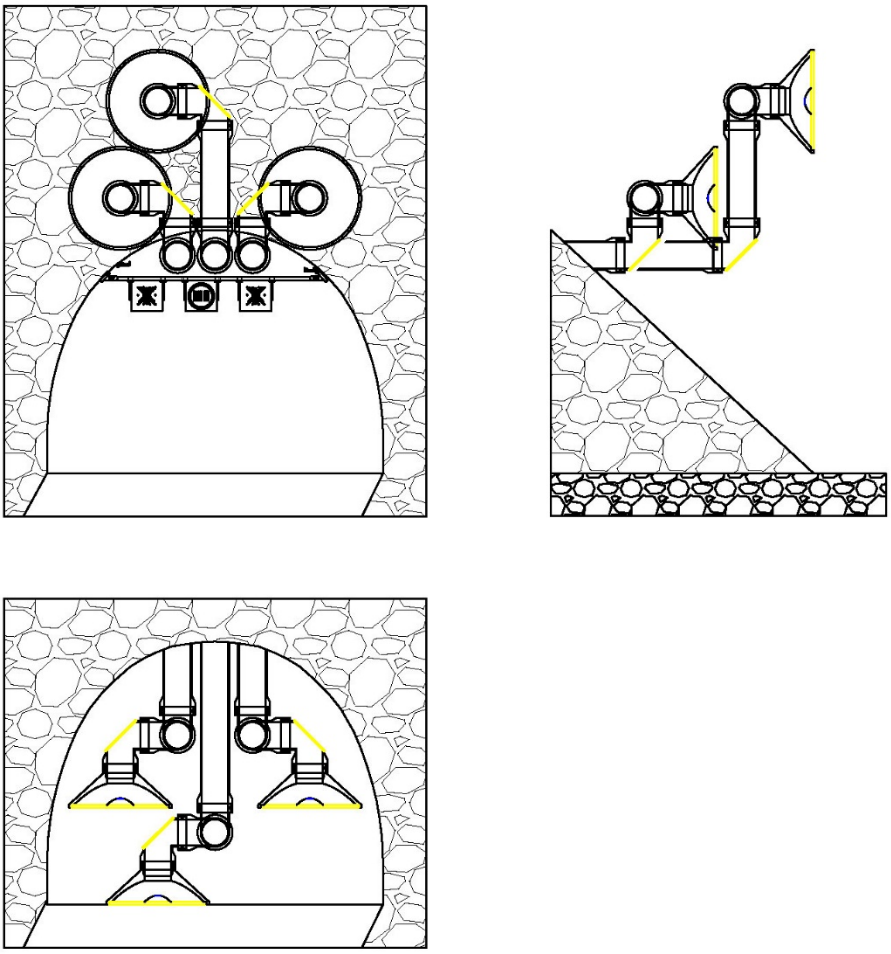

Figure 2.4.II.- Transportation system.

The calculations done so far are just approaches in which the efficiencies related to the optical systems have not been included, since it is quite variable depending on the materials used and their manufacturing tolerances.

If those efficiency reductions were taken into consideration, it is quite probable that it would be necessary to duplicate or triplicate the amount of solar collectors.

The final part of the transportation system consists of a straight pipe that links the tracking system to the diffusion system. This pipe forbids the access of any particle to the light's path.

2.5. DIFFUSION

Once the light has been introduced in the tunnel, it is necessary to diffuse it over the road lanes, so a mirror is due to be designed.

In the diffusion system's design, it is considered that during the capture and transportation of the light, the efficiency has de3creased up to a 50%, so each diffuser must cover a half of the surface previously calculated.

The mirror is designed sought to distribute the light over the 8m length portion of the road in the tunnel's direction and transversally over the 10m width of the road.

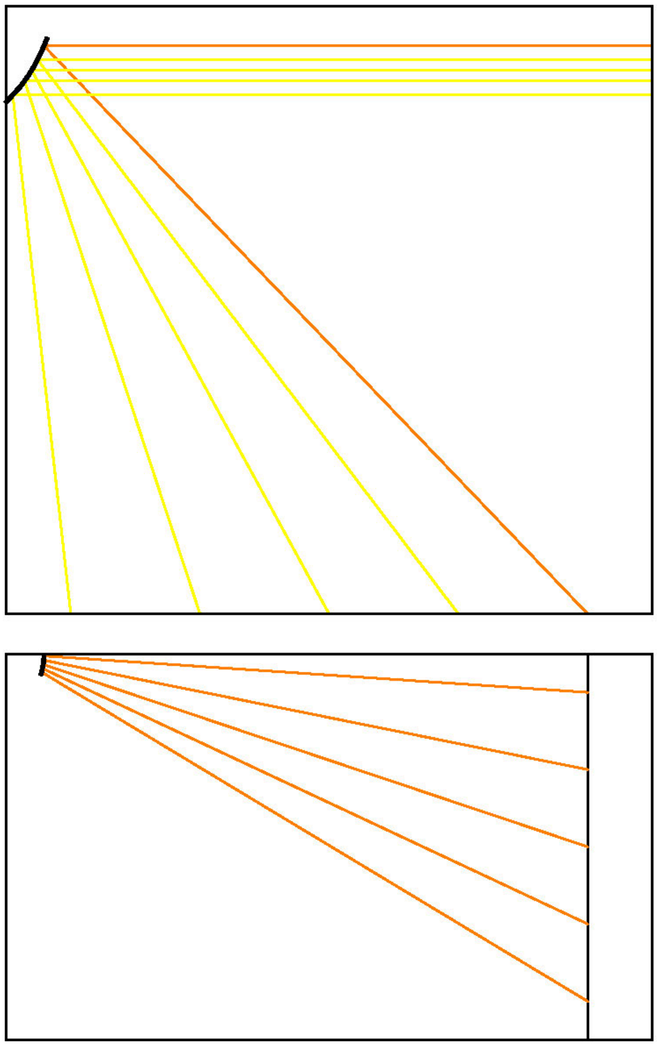

Figure 2.5.I.- Design of the mirror through projection of rays' trajectories.

The method that has been used for the design is based in dividing the area source of the light and the area of destination of the light into the same number of sub areas. Then, several rays are projected between the areas in the source and in the destiny, as shown in the **Figure 2.5.I**, in order to determine the angle that must have the mirror's surface.

Before making the final modelling of the mirror, its curves are treated with the use of splines (differentiable curves defined in portions with the aid of polynomials).

The mirror that has been obtained is complex, as it can be appreciated in the 3D – model shown in **Figure 2.5.II**:

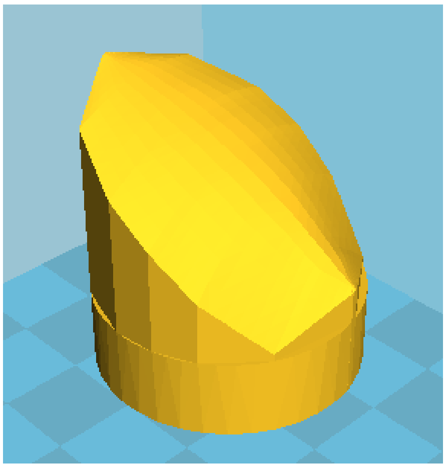

Figure 2.5.II.- 3D - model of the diffusion mirror.

The system that has been designed may produce some lighting in the opposite direction of the tunnel users, which may induce some effects of glare.

Another diffusion system may be based in the use of optical methacrylate. It consists of methacrylate sheets which are perforated in one of their surfaces with the aid of a cutting tool.

The perforations are responsible for the light entering by one of their boundaries is diffused uniformly on the surface directed to the road.

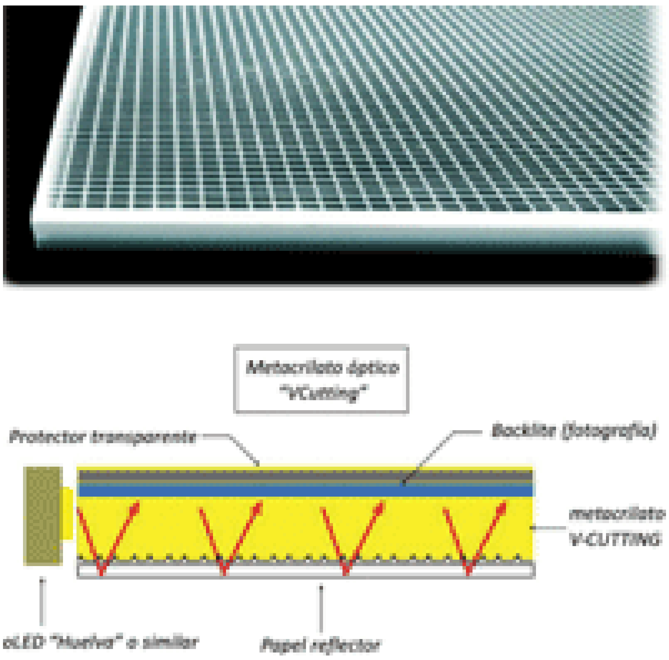

Figure 2.5.III.- Operating principle of the optical methacrylate.

The optical methacrylate would have been much easier to integrate in the prototype but it wouldn't have represented the reality, since this system is not available in the adequate dimensions for the real scale.

3. MANUFACTURE

Once the system is designed, the next step is the manufacturing of a prototype to assess and solve the handicaps that may arise in the implementation of a system in a real scale.

The design that has been considered is based on geometrical optics, which is not affected in the results in real scale, since the angles do not vary when it comes to carrying out scales on models.

The prototype must be small, so that it is easy to be used in a laboratory but at the same time, it must be big enough to allow their elements to be manufactured.

Initially, a 1:20 scale was chosen, which verifies both requirements, but finally this scale was changed to 1:26, so that it is possible to use commercial pipes with a 40mm – diameter in the transportation system, making easy its manufacturing.

The manufacturing is supplemented with efficiency tests in a laboratory and the manufacturing of a prototype of the tunnel's entrance.

3.1. SOLAR LIGHT CAPTURE AND CONCENTRATION

There are several ways for the manufacturing of parabolic mirrors for the solar dish in a real scale:

- The manufacture of the optical mirrors is done in most of the cases with polished glasses covered with a metallic layer after a chemical or physical process.
- The manufacture of solar collector mirrors (solar dish, from now on) is done with glasses covered with silver in plane surfaces and with polished and anodised aluminium in curved surfaces.

The manufacture of scale equipment with the previous methods is not affordable in small scale, being affordable only in big scale productions, overall taking into account that at a prototype scale, the manufacturing process is iterative and it is commonly needed the manufacture several prototypes before obtaining the desired results.

As an alternative, initially the mirrors ABS forming is chosen with a 3D print and the fixation of a PET commercial sheet with a chromed surface to obtain the reflecting surfaces.

Before moving a step forward, it is foreseen that the results obtained through this process will not be similar in quality terms to the results that would be obtained through the manufacture with industrial processes and its efficiency will be lower.

The process starts with the 3D modelling of the solar dishes, as shown in **Figure 3.1.I:**

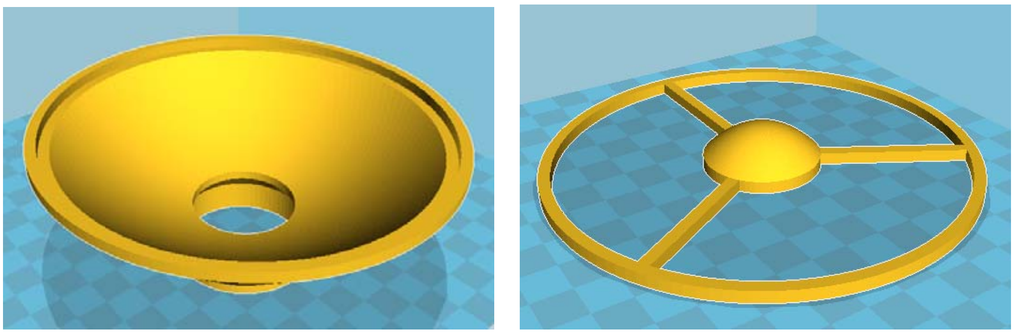

Figure 3.1.I.- 3D models of the two solar dishes for the solar collector.

Subsequently, the dishes are manufactured with a 3D print in ABS plastic, as shown in **Figure 3.1.II**:

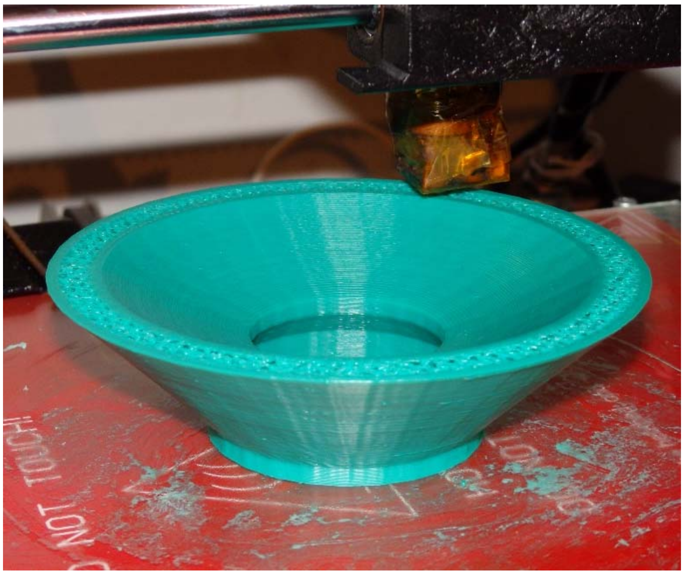

Figure 3.1.II.- 3D print process of the solar dish.

The reflecting surface is a commercial type and based on PET plastic with a deposition of chrome by chemical mediums. In order to impose a parabolic shape in the commercial PET sheets, a micro cutting tool with numerical control is used, before being put on the ABS pieces as shown in **Figure 3.1.III**:

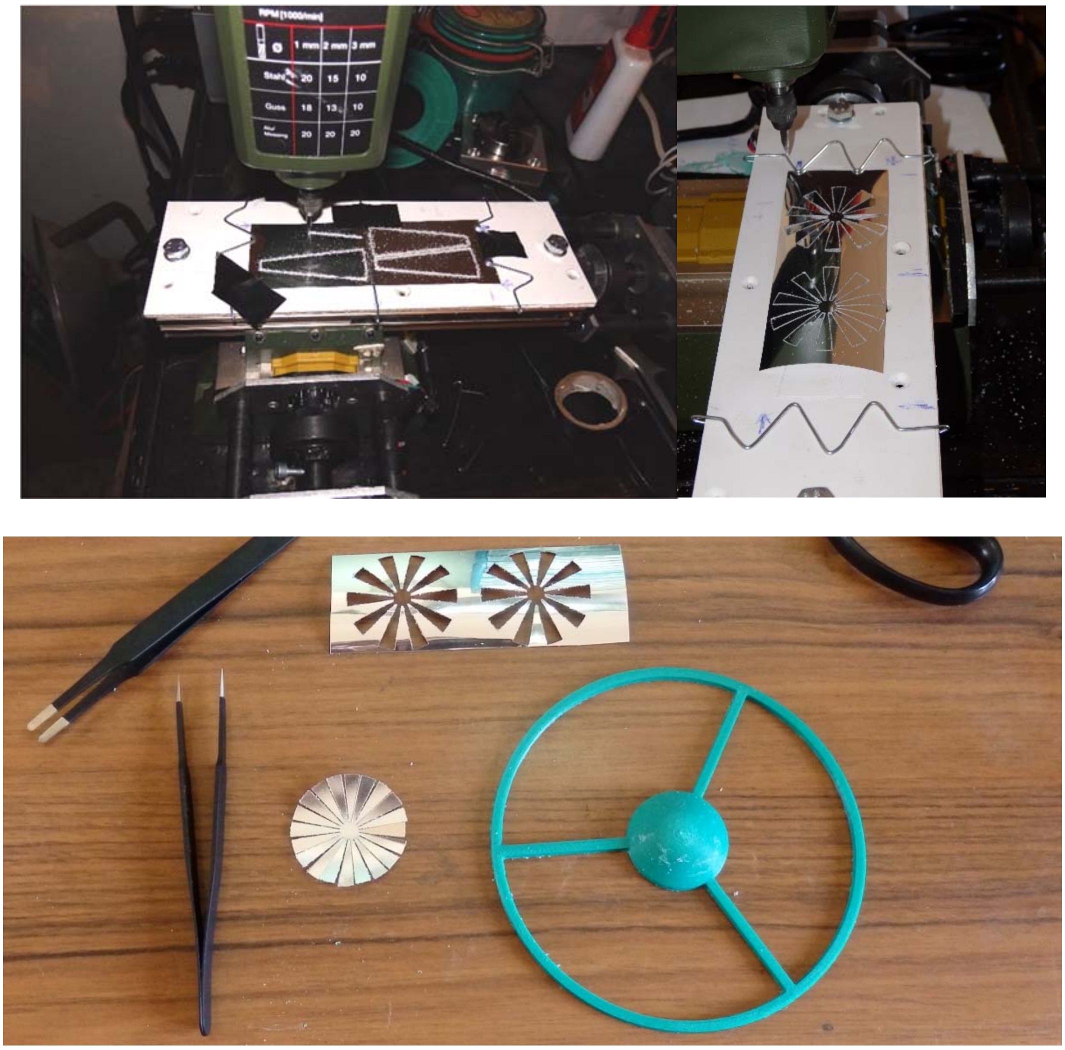

Figure 3.1.III.- Manufacturing of the solar collector's reflecting surfaces.

Although the result of the collector seems to be correct, when some tests are done with a laser several relevant deficiencies are observed.

3.2. TRANSPORTATION

A similar procedure for the manufacturing of the solar collector is chosen for the transportation system.

All the elements of the transportation system are linked with the same union type, which allows 360 degrees twists.

The changes in direction (elbows) are modelled in 3D and manufactured with a 3D ABS plastic printer. As reflecting surfaces, glass mirrors are used, fixed with threaded rod.

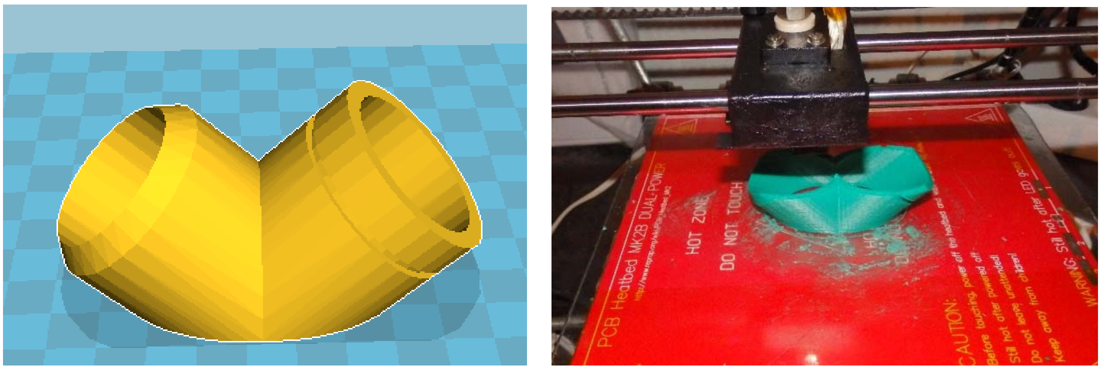

Figure 3.2.I.- 3D model and ABS printing for an elbow.

A commercial PVC pipe is used for the transportation, which is mechanised in both limits to adapt itself to the elbows. The **Figure 3.2.II** shows all the elements of the transportation system manufactured:

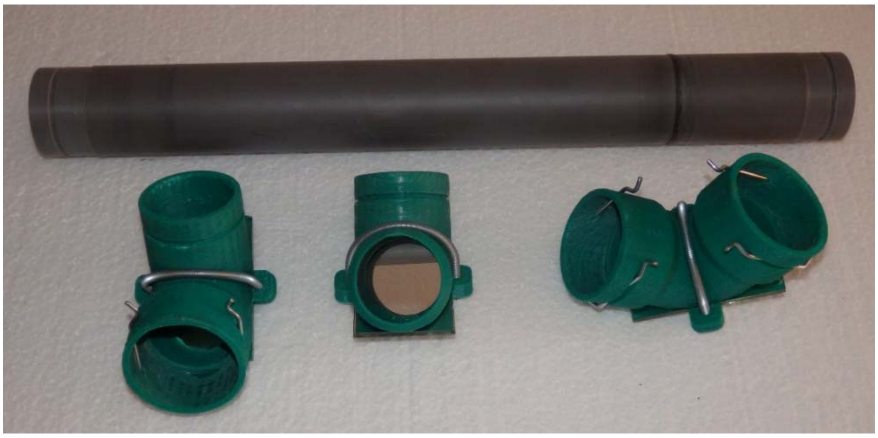

Figure 3.2.II.- Elements that make part of the transportation system.

The images of the **Figure 3.2.III** show an example of the correct change of direction:

Figure 3.2.III.- Example of the transportation system operation.

3.3. DIFFUSION

The manufacturing is based on the same process explained previously; using a 3D printer for the conforming, but in this case, chromed vinyl is used to create the specular surface. The vinyl has a lower width and a bigger flexibility than the PET that has been used for the parabolic solar dishes.

Due to the restrictions of the manufacturing through 3D printers such as FDM type (print based on deposition of melted material), the diffusion system is divided into two pieces: the mirror and the adapter to the transportation system.

Both pieces, separately and after their assembly, are shown in **Figure 3.3.I:**

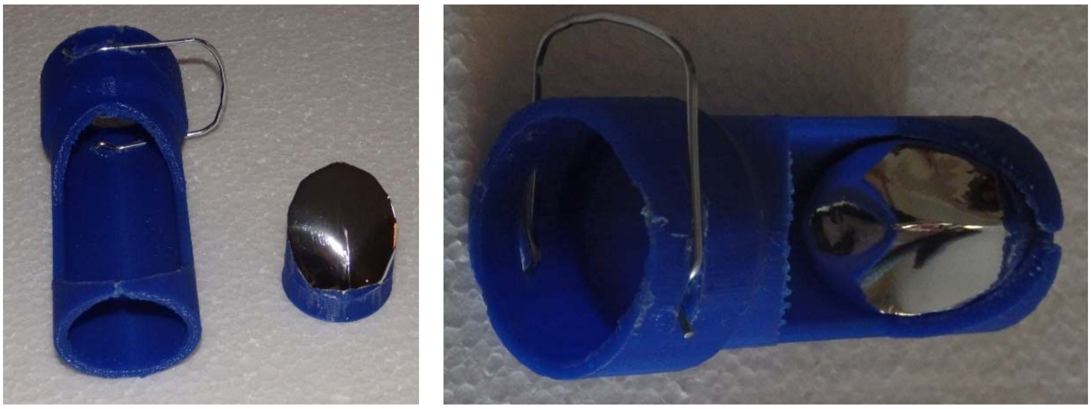

Figure 3.3.I.- Elements that make part of the diffusion system.

Once all the system's elements are manufactured, they are assembled, as shown in **Figure 3.3.II**:

Figure 3.3.II.- Assembly of all the elements that make part of the prototype.

3.4. SCALE MODEL OF FOLGOSO TUNNEL

In order to have a more realistic idea of the proportion of the system manufactured compared to the real dimensions of the tunnel, it has been manufactured a prototype of the tunnel's entrance as well, with the same scale as the one used for the optical equipment.

The following images show the process of manufacturing and the result:

Figure 3.4.I.- Manufacturing process of the tunnel's entrance prototype.

4. <u>TEST IN LABORATORY</u>

The elements that have been manufactured are set under verification through some tests, in order to have an idea of the system's optical efficiency.

The tests start with the transportation system, as it is the most simple, and finish with the solar collector, which is more complex to be manufactured.

4.1. TRANSPORTATION

The transportation system must be the one with the biggest efficiency, as it uses commercial glasses and its geometries are easy to manufacture.

The test that has been done consists of measuring the reflected light in several surfaces directly and through the transportation system, as it is shown in **Figure 4.1.I**:

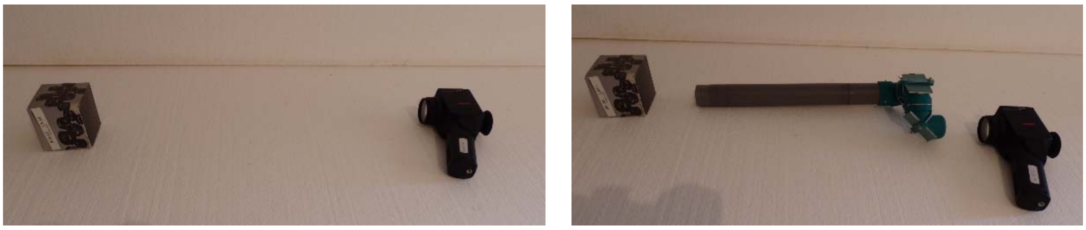

Figure 4.1.I.- Stages for the transportation system's tests.

The comparison between the luminance measured without and with the transportation system gives the system's efficiency.

Direct luminance	Luminance with Transportation system	Efficiency
112,5	80,3	71,3%
150,6	105,9	70,3%
14,3	10,2	71,4%

Table 4.1.I.- Measures.

The average efficiency is 71,0 %.

If it is considered that the three transportation system's mirrors have the same efficiency, the individual average efficiency of each mirror would be 0,71^(1/3)=89%. The material commonly used in solar systems can attain efficiencies higher than 93%.

4.2. DIFFUSION

The manufactured diffusion system uses chromed vinyl as reflecting material, with an 86% efficiency on plane surfaces. A geometrical factor must be applied to take into consideration the curves; then, the efficiency expected to have is 0,86*0,90=77,4%.

However, in the diffusion system, it is much more important achieving a correct distribution of the light rather than a high efficiency; then the test is based on injecting light in the entrance and verify that the distribution is homogeneous.

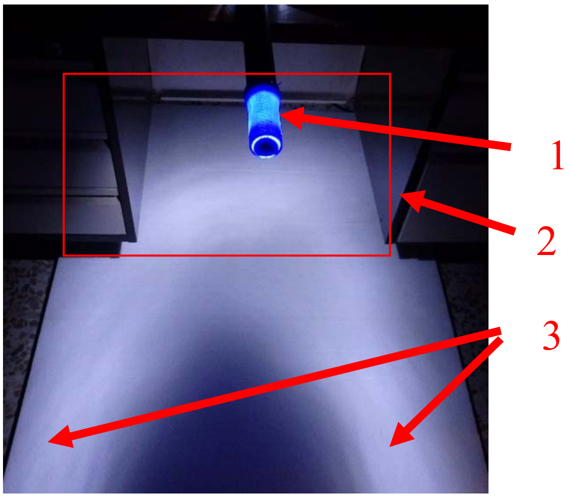

Figure 4.2.I.- Diffusion system test.

During the test (shown in the figure), it can be appreciated that:

1. The adapter that links the mirror to the transportation system allows the leak of great light amounts.
2. A quite homogeneous distribution of the light is achieved in the place to illuminate.
3. There are two located tails with light that shouldn't be illuminated.

The lighting losses through the enclosure and in the undesired places are not worrisome, since they are due to the fact that the light source used in the test is a punctual source that doesn't generate parallel light beams.

Once the diffusion system is assembled on the prototype of the tunnel, it is verified that the area over which the light is diffused has dimensions of 39x30cm, which corresponds to the design area. This area should have an equivalent area of 10x8m in a real scale.

However, there are still light tails and losses in the enclosure, as a consequence of using a discretised calculation method, through which it is obtained a cross sectional area of the mirror with polygonal type instead of being perfectly circular, as seen in the 3D model shown in **Figure 4.2.II**.

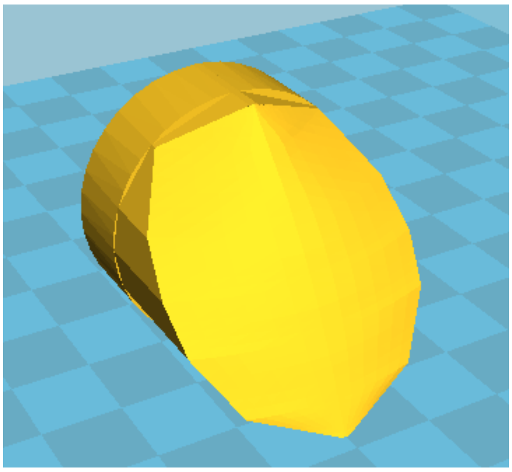

Figure 4.2.II.- Detail about the polygonal profile of the diffuser mirror.

4.3. SOLAR LIGHT CAPTURE AND CONCENTRATION

The solar collector included PET chromed sheets as reflecting material, which can attain a very high efficiency, but that presents the drawback of being quite rigid, making it hard to have a parabolic shape.

The first tests were effectuated analysing the behaviour of a laser on the created surfaces, as seen on the photos on the **Figure 4.3.I**.

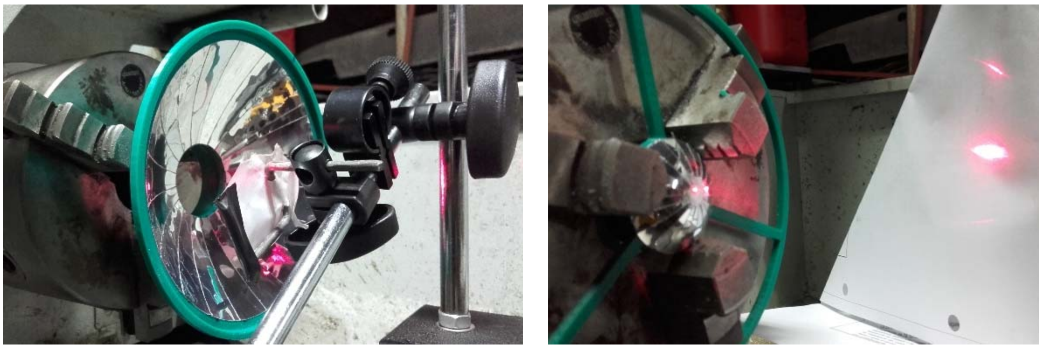

Figure 4.3.I.- Test concerning the solar dishes.

During the tests on the mirror with a bigger diameter, it is observed that it does not redirect the beam towards the focus of the parabola in their outer zones.

This is because in those zones, the slope of the parabola is bigger and small errors in the manufacturing process due to mechanical tolerances lead to great deviations in the behaviour.

During the tests on the small mirror, it is observed that in the inner zones, the laser is divided into several reflected beams.

This is because in inner zones, the separation among individual mirrors is lower than the beam’s width and, therefore, it always finds geometrical discontinuities.

The results of the tests reveal that the behaviour of the solar collector is not going to be good in the outer zones nor in the inner ones; thus, an acceptable efficiency is not expected.

Given those results, a new solar collector is designed with the following changes:

- The final slope of the mirrors is changed by a lower value.
- Chromed vinyl is used (more flexible than the PET) for the reflecting surface of the small mirror.

Additionally, the test bank is manufactured as shown in **Figure 4.3.II** and a laser is used to verify the correct operation of all the elements altogether, allowing identifying the corrections needed to consider in the mirrors’ surfaces during the manufacturing process.

Figure 4.3.II.- Test bank for the mirrors.

Once the results of the solar collector have improved, the first tests are carried out in the same place of the tunnel, obtaining the first results shown in **Figure 4.3.III**.

Figure 4.3.III.- First tests of the prototype.

5. <u>FIELD TESTING</u>

Once all the system’s elements are manufactured and verified, some field tests are carried out. These tests are done with a prototype on a floor with the same composition as the road on the entrance towards the tunnel, annulling the light rays from the surroundings.

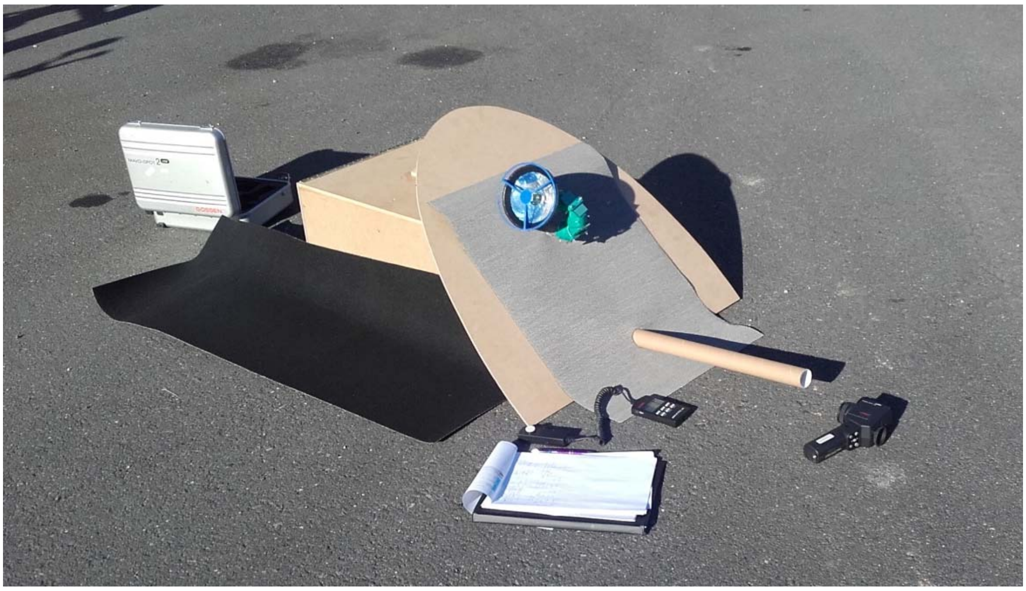

Figure 5.I.- Test methodology.

The tests are done during several days and are aimed at verifying the results under different meteorological conditions; they consist of measuring both the external and internal illuminance and luminance.

Before the measures being carried out, the solar dish is oriented towards the sun.

The internal luminance is measured, as it is shown in **Figure 5.II**, through a pipe that allows to make the measure at a certain distance, in such a way that the light from the environment can't enter the prototype.

Figure 5.II.- View of the road through the measurement pipe.

DAY CLASSIFICATION	LUMINANCE [cd/m2]				ILLUMINANCE [LUX]			
	External		Internal		External		Internal	
	Entrance Dir	Solar Dir	Maximum	Average	Direct	Total	Maximum	Average
Sunny	1.387	5.300	79	57	104.333	110.593	2.058	1.203
Cloudy	380	380	0	0	245	14.897	5	3

Table 5.I.- Summary of the obtained results.

The **Table 5.I** shows a summary of the obtained results in which it is outlined:

- The average luminance in the road in the sense of traffic (East – West).
- The average luminance measured on the road in the direction of the solar position.
- The maximum and average luminance measured in the portion of the road that is illuminated by the prototype (in the inside of the prototype).
- The external luminance that arrives directly at the solar dish (in the same direction as the solar dish's axe).
- The external illuminance that arrives at the solar dish (both directly and obliquely).
- The maximum and average illuminance measured on the portion of the road illuminated by the prototype (in the inside of the prototype).

From the tests that have been done it can be concluded, as expected, that the amount of light that the system transports to the inside of the tunnel is proportional to the amount of light that arrives at the solar dish in the solar dish's axe direction.

During the sunny days, when the shadows are quite well limited by their boundaries, if the solar dish is well oriented, most of the light arriving at the dish makes it in the axe's direction.

Since the solar dish tracks the sun's trajectory during the whole day, the variation of the available luminous intensity in the inside of the tunnel during sunny days is due to the variation of the atmosphere's width through which the sun's rays pass. This variation affects in the same measure both the solar dish and the access' luminance; therefore, it is not substantial to the system.

However, during cloudy days, the higher the density of the clouds is, the lower the luminous intensity is and so for the proportion of sun rays that arrive at the solar dish in the solar dish axe's direction. While the reduction of the luminous intensity affects the solar dish and the access' luminance equally, the reduction due to the lack of parallelism with the dish's axe affects just the solar dish itself.

Then, the tests show that the capturing system won't have a high efficiency during cloudy days and that it must be restricted to sunny days or days with low cloudiness.

During the tests effectuated at the end of November of 2015, levels around 57 cd/m2 were registered in the inside of the prototype.

Taking into account that the maximum solar radiation in the latitude where the tests were done is a 14% higher during Jun than during November, it is expected to have average levels of 57*1,14= 65 cd/m^2.

The materials used for the manufacture of the prototype have a reflectivity of 85% (chromed vinyl) and 89% (commercial mirror). The prototype at a real scale would be built with materials with a reflectivity higher than 90%; thus, it would be obtained at least an average luminance of 57*0,90^6/(0,85^3)/(0,89^3)=80 Cd/m^2.

Additionally, the handmade manufacture of the curved mirrors involve an efficiency reduction of at least 10% for every curved mirror. Thus, the use of industrial mirrors would mean an average luminance of 80/0,9^3=110 Cd/m^2.

6. MIXED SYSTEM FEASIBILITY ASSESSMENT

With the information that has been provided by the prototype, it is ruled out the installation of a solar capture system that provides the tunnel with the necessary illumination in such a way that all the daily lighting luminaries can be eliminated.

As an alternative option, it is chosen a new design that allows attaining the required daily lighting through the coexistence of the solar capture system and the internal luminaries. The **Figure 6.I** shows how the interior lighting would be in a day with maximum exterior luminance in the access zone.

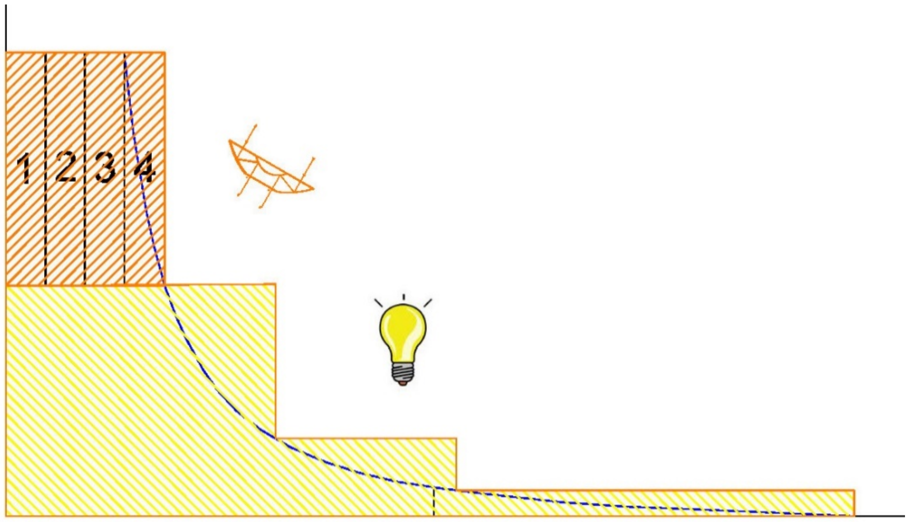

Figure 6.I.- Curve of the interior lighting levels during a day with maximum exterior luminance in the access zone.

During the days with higher solar intensity, 4 solar dishes with a single 14m^2 surface would provide a 50% of the daily lighting in the first 66 m of the tunnel. The rest of the lighting requirements would be achieved through a lighting system composed by luminaries allowing the intensity regulation.

During the days or the moments when the luminance in the access is lower, the interior lighting levels are obtained through the maximum provided by the solar dishes and also through the internal luminaries, in order to cover every moment's needs, as shown in the Figure 6.II. In order to manage this system, one or several luminancimeters must be placed in the interior of the tunnel, which will be in charge of calculating the amount of luminance to be provided by the internal luminaries.

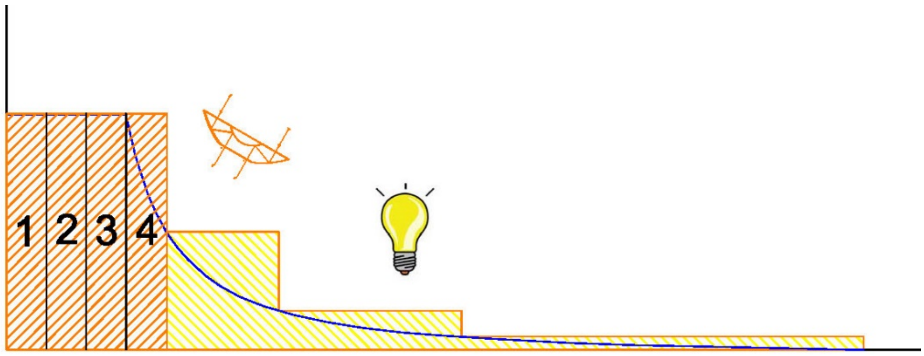

Figure 6.II.- Curve of the interior lighting levels during a sunny day with a medium solar luminance.

Due to the fact that the lighting system is redesigned, it has to be assessed the possibility of a mixed lighting system.

The investment budget for a mixed lighting system is shown in **Table 6.I**.

INVESTMENT COST				
Item	**Unit**	**Quantity**	**Unitary Price (€)**	**Total Price (€)**
Support structure	unit	4	4.600,00	18.400,00
Solar dish	unit	4	52.000,00	208.000,00
Servomotor	unit	8	1.200,00	9.600,00
Control system	unit	1	4.120,00	4.120,00
Transport pipe	m	354	132,00	46.728,00
Diffusion system	unit	4	35.000,00	140.000,00
Adjustment and setting up	unit	1	3.090,00	3.090,00
			TOTAL	429.938,00

Table 6.I.- Investment Budget.

The mathematical model for energy consumption has to be modified in order to take into account the consumption that would take place in the Folgoso tunnel with a mixed lighting system, which leads to the results shown in **Figure 6.III**.

Conventional lighting	Mixed lighting

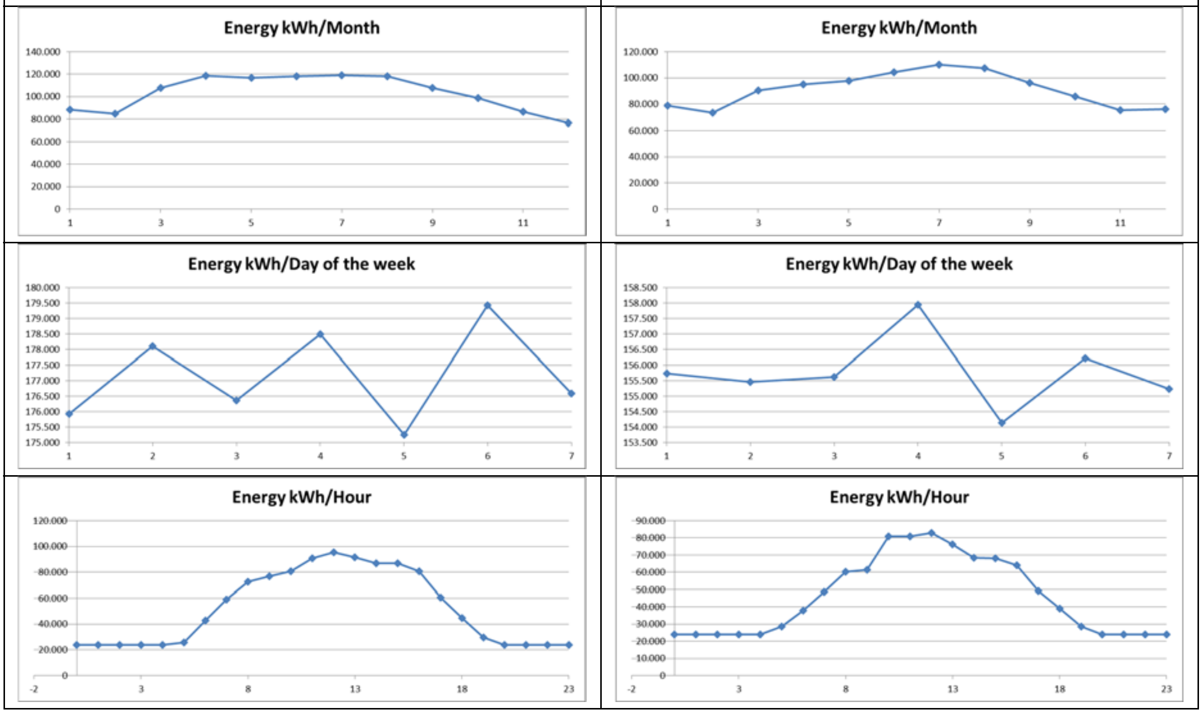

Figure 6.III.- Consumption curves before and after the integration of the mixed system.

The results show that the electrical consumption would change from 1.240.153 kWh to 1.090.352 kWh, with a reduction of 149.801 kWh (a 12,1% reduction).

The mixed system also needs some maintaining, which is taken into account with an annual provision of 8.300€, which will increase annually because of the inflation.

The cash flows related to the investment would be the ones shown in **Table 6.2.II**.

Year	€/KWh	Consumption [kWh]	Maintenance [€]	Cash flow	Cash flow year 0	Accumulated
0	0,1217583	0	0	-429.938,00 €	-429.938,00 €	-429.938,00 €
1	0,12516513	149.801	8.300	10.449,86 €	10.204,94 €	-419.733,06 €
2	0,12866728	149.801	8.499	19.274,49 €	18.381,58 €	-401.351,47 €
3	0,13226743	149.801	8.703	19.813,79 €	18.453,03 €	-382.898,44 €
4	0,13596831	149.801	8.912	20.368,19 €	18.524,76 €	-364.373,68 €
5	0,13977274	149.801	9.126	20.938,10 €	18.596,77 €	-345.776,92 €
6	0,14368362	149.801	9.345	21.523,95 €	18.669,05 €	-327.107,86 €
7	0,14770392	149.801	9.569	22.126,19 €	18.741,62 €	-308.366,25 €
8	0,15183672	149.801	9.799	22.745,29 €	18.814,46 €	-289.551,78 €
9	0,15608515	149.801	10.034	23.381,71 €	18.887,60 €	-270.664,19 €
10	0,16045245	149.801	10.275	24.035,94 €	18.961,01 €	-251.703,18 €
11	0,16494196	149.801	10.521	24.708,47 €	19.034,71 €	-232.668,46 €
12	0,16955708	149.801	10.774	25.399,82 €	19.108,70 €	-213.559,76 €
13	0,17430133	149.801	11.033	26.110,51 €	19.182,98 €	-194.376,79 €
14	0,17917833	149.801	11.297	26.841,09 €	19.257,54 €	-175.119,25 €
15	0,18419178	149.801	11.569	27.592,11 €	19.332,39 €	-155.786,85 €
16	0,18934552	149.801	11.846	28.364,15 €	19.407,54 €	-136.379,32 €
17	0,19464346	149.801	12.130	29.157,78 €	19.482,97 €	-116.896,34 €
18	0,20008963	149.801	12.422	29.973,63 €	19.558,70 €	-97.337,64 €
19	0,2056882	149.801	12.720	30.812,30 €	19.634,73 €	-77.702,91 €
20	0,21144747	149.801	13.025	31.675,04 €	19.711,43 €	-57.991,48 €
21	0,217368	149.801	13.338	32.561,94 €	19.788,43 €	-38.203,06 €
22	0,2234543	149.801	13.658	33.473,68 €	19.865,72 €	-18.337,33 €
23	0,22971102	149.801	13.985	34.410,94 €	19.943,32 €	1.605,99 €
24	0,23614293	149.801	14.321	35.374,45 €	20.021,23 €	21.627,22 €
25	0,24275493	149.801	14.665	36.364,93 €	20.099,44 €	41.726,65 €

Table 6.II.- Cash flows related to the investment.

The economic assessment factors that turn out of the investment are shown in **Table 6.III**.

Lifetime [years]	Net Present Value [€]	Internal Rate of Return [%]	Payback Period of the Investment [years]
25	41.726,65 €	3,1%	22,9

Table 6.III.- Investment economic factors.

All the investment economic factors reveal that, although the investment is profitable, the Internal Rate of Return is very low and would not be acceptable under the private investor's criteria.

7. CONCLUSIONS

Throughout the Enertun project, many work projects have been undertaken aimed at increasing energy efficiency in the road tunnels domain:

- A research campaign has been carried out concerning the current technologies that allow to improve the energy efficiency in several domains and investigate the likeliness of their use in a road tunnel.
- A system for tracking and energy consumption measurement has been developed, which is aimed at road tunnels' installations.
- A mathematical model has been developed as well, which is aimed at studying road tunnels' energy consumption. This model has been achieved thanks to, among others, the knowledge of the team members on this subject, the data obtained by the Norwegian and Spanish tunnels' operators and the experimental data obtained with the prototypes that have been created.
- A study about likely measures for increasing energy efficiency has been done, assessing their technical viability.
- The economic viability of the implementation of the efficiency measures considered as feasible has been assessed, under the assumption that the best choice is the use of the exterior lighting. This option is quite innovative, since there is not any other system like this one put in place on record anywhere.
- A scale - prototype has been built for the Folgoso Tunnel, which has been tested, verifying that its global efficiencies were lower than expected and that its performance depends more than expected on meteorological factors.
- Some modifications on this prototype have been proposed, in order to eliminate the undesired dependence between efficiency and meteorological change; thus the new prototype is a mixed system. Although the modifications that have been implemented reduce the economic viability for private companies, it may be still interesting for public companies since other parameters are taken into consideration, such us the environment.

As a result of the project, it has been obtained a system able to make profit of the external luminance but that needs the support of an artificial lighting system during cloudy days.

Although they are out of the scope of the current project, it may be interesting to build new prototypes in order to:

- Verify the mixed system before its establishment.
- Verify the rest of the efficiency measures that were considered as feasible both technically and economically throughout the project.

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