Photovoltaic Lighting System with Intelligent Control based on ZigBee and Arduino

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Abstract- In this article, the design and implementation of an innovative photovoltaic system prototype intelligent control lighting based on Arduino and ZigBee described. The lighting system is connected to a power generation system composed of isolated photovoltaic cells. The lighting control system is subject to a vehicle detection permitting variation of the light intensity when vehicles circulating on the highway. The variation of the light intensity and control of the lighting system is managed through an Arduino microcontroller which in turn transmits information wirelessly to other luminaires distributed along the highway. Thus, it is expected that the lighting system present a significant savings in energy consumption by making use of innovative technologies.

Keywords Arduino, Lighting, LED, ZigBee.

1. Introduction

In the last decade, a great concern about transforming major transit routes into innovative smart highways has surfaced in industrialized countries. These highways provide a series of features and innovative technologies associated with their infrastructure. The integration of smart systems on highways has allowed for energy on savings for illumination and publicity systems. It also helps drivers, users and maintenance brigades by changing roads into sustainable and interactive environments.

During the last few years an ambitious highway construction plan has been implemented in Ecuador. Needless to say, a large investment has been made in construction, reconstruction, improvement, widening, rectifying, rehabilitating, finishing, maintaining and remodelling roads, bridges, ports and airports throughout the country. Per the Ministry of Transportation and Public Works, there are 8,653 km of roads. 6,741 km of which are administrated directly, 1,350 km are concessioner and 562 km are delegated to the provincial governing councils [1].

A comparative study between LED luminaries and luminaries of High Pressure Sodium, considering technical and economic parameters and the human visual perception was presented in [2]. The study of LED luminaires sustained based on the novel technology trend of the High Brightness LED, Low Power HB-LEDs and Power HB-LED, where the luminaires with high LEDs brightness and low power consumption have a current rating of 20mA. The different from high-consumption HB-LEDs, which provide a current flux which oscillates between 350 and 1000 mA. In the above work, it was shown that a 250W luminaire can be replaced with LED luminaires with a minimum value of 97, 53 W and a maximum value of 120 W. It is also mentioned that the between the two technologies is the harmonic distortion rate, in terms of Anglo-Saxon, THD, with values of 22.4% for Low Power HB-LEDs and 3.33% for Power HB-LED fixtures.

In Mexico, in 2012, the Federal Electricity Commission evaluated the impact of replacement of conventional luminaires by LED luminaires. The energy savings was estimated of 64%, equivalent to 33,192 tonnes of carbon which will not be emitted into the atmosphere [3].

The development of new road infrastructures reveals a hidden necessity associated with investigation topics regarding management and control technology for public illumination technology needed on streets, roads and highways. The illumination systems for public lighting represent a high consumption of electricity. The electricity consumed by illumination systems represents an estimated 19% of electric energy world-wide. Likewise, the public lighting service of highways represents an annual total of 14 thousand million kWh. An amount equal to 3% of the total, electric consumption per the Energy Administration of Information, EIA [4]. The previously mentioned amount is increased to 6% in China [5]. In the United Kingdom, there are almost 9 million lampposts with a yearly turnover of 110 million pounds, [6]. 4,4 million luminaries exist in India which consume 3 billion kWh annually, the equivalent of 2,3 million tons of CO2 emissions to the atmosphere [7].

In Ecuador, the percentage of high consumption luminaries, high pressure sodium, mercury vapour, halogen and incandescent lamps exceeds the total existing amount by 99%. The Ecuadorian state spends over 100 million dollars per year on public illumination systems for streets, roads and highways.

The illumination systems' energy consumption will increase significantly with the construction of new, modern highways and inclusion housing.

Currently, all investigations related to illumination systems are focused on the use of low consumption devices and elements which significantly reduce electric energy consumption, such as the integration of cloud IoT control, operation and system management platforms. Such platforms will connect to interior, exterior, street, road and highway illumination.

2. Illumination Technology

The highway illumination service is possible thanks to the use of luminous sources, also called, luminaries. The following paragraphs give a brief description of the different luminaries currently used by the masses.

Fluorescent: Fluorescent bulbs are covered by a fine glass tube. In its interior are small amounts of mercury vapour, as well as, an inert gas, such as argon or neon. It is highly efficient providing approximately, 10,000 hours of use [8].

Mercury Vapour Luminaries: These luminaries are made from mercury vapour which produces a high amount of ultraviolet radiation which is harmful for the environment. Mercury vapour heats up faster than fluorescent luminaries, but it isn't instantaneous. This fact lowers the efficiency of these luminaries. They provide between 5000 and 10000 hours of use. Moreover, the maintenance and treatment given to the residue of these luminaries require high amounts of economic, energy and logistic effort [9].

High Pressure Sodium Vapour Luminaries: These luminaries integrate a ceramic tube for their discharge. The tube contains two electrodes at the ends that provide the electric tension necessary for the light transformation process [9]. These luminaries have a useful life of between 15000 and 24000 hours. They are commonly used in the public lighting of streets, roads and highways.

LED Luminaries: They are made by light emitting diodes which don't generate ultraviolet radiation. LED luminaries are easy to control and modulate electronically. They have the best useful life of all, which is between 40000 and 90000 hours. These luminaries possess a great advantage: they can operate in direct current electric systems, as well as, alternate current electric systems. The latter work through electric transformers. This important advantage allows LED luminaries to link to photovoltaic systems [9].

Induction Luminaries: They are a new technology which is slowly starting to introduce itself into illumination systems. Its efficiency is intermediate, saving 20% regarding sodium vapour luminaries and 50% in comparison to mercury vapour. On the other hand, these luminaries require a continuous energy source for optimal efficiency. This makes them vulnerable when integrating said luminaries into a photovoltaic system.

The base parameters for the comparison between luminaries are: luminous efficiency regarding lm/W, the performance of the colour emitted by the lamps, the hours of use of each type of lamp. Table 1 shows a summary of the characteristics pertaining to each kind of luminary.

Table 1: Comparison between Technologies Luminaires [8].

Type of Lamp	Luminous efficient lm/W	Rendering Properties	Timelife	Observations
High pressure Mercury	36-65	Normal	10000/15000	High use of energy reduces its lifetime
Metal halide	70-130	Excellet	8000/12000	High luminous efficiency, lifetime reduced
High pressure Sodium	50-150	Normal	15000/24000	Energy efficiency, low yield of color
Vapor de baja presión de Sodio	100-190	Very poor	18000/24000	Energy efficiency, low yield of color
Low pressure	30-90	Good	5000/10000	The bad life of the lamp, the

Sodium				average power consumption is only available at low powers
Tubular Lamp Energy Efficiency	100-120	Very Good	15000/20000	Energy efficient, long lamp life, is only available in low power
Light emitting diode LED	70-160	Good	40000/90000	A large energy savings, low maintenance, long life, no mercury. emerging technology

The previously shown table indicates that LED luminaries have a larger efficiency in comparison to the traditional luminaries used in public lighting service.

By the other hand the control system of lighting is an important point for this study. In the following paragraphs, any examples of lighting control system are described.

In 2012, a smart illumination control was implemented in India [10] which was based on a wireless network that permitted the road illumination system to be adaptively monitored in real-time. The monitoring system is based on a wireless network consisting of GPRS technology, a microprocessor and computer terminals. The adaptive monitoring system includes five subsystems: detection equipment of the edge of the road, a power system, a local control of the system, a local control system for central supervision and a network communication system.

The illumination system's control allows a 40% reduction of the luminosity level during hours in which there isn't heavy traffic flow. A reduction of the luminosity surpassing 50% affects human vision. This is because that luminosity level is imperceptible by the human eye. On the other hand, luminary communication is established through a ZigBee GPRS interface where the data is processed by a free scale MC9S08DZ60 microcontroller, figure 1.

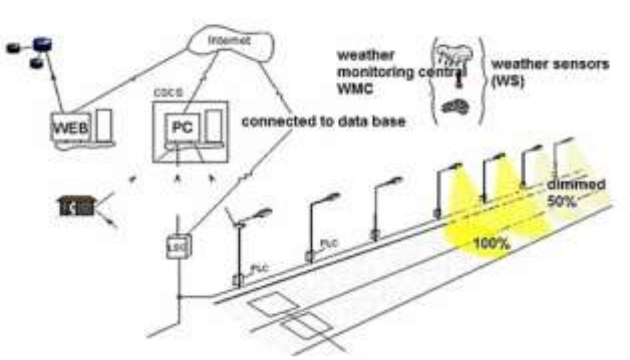

Figure 1: Monitoring system of adaptive lighting [10].

The Electrical Engineering Faculty of the Osijek University in Croatia presented a new vehicle detection system in 2012. It was based on a ZigBee network of information transmitting sensors [11]. Afore mentioned project sets two stages. In the first stage, vehicle flow and atmospheric conditions are monitored during the day. In the second stage, a real-time traffic monitoring system is implemented for existing traffic. If vehicles are circulating on the highway, the system predicts its movement and sends wireless signals to the luminaries. These luminaries then increase their luminosity based on a range ratio of 350 meters, figure 2.

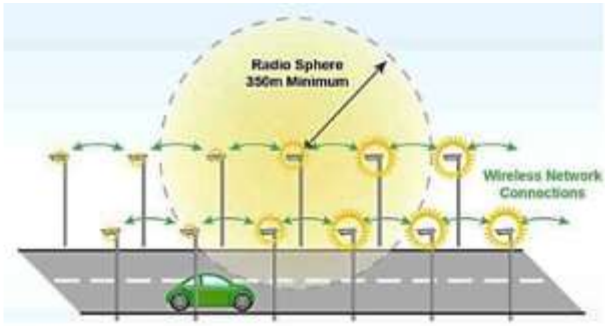

Figure 2: Lighting system based vehicle tracking [11].

In 2014, the Technological Engineering Institute of Chennai, in India, proposed an illumination system based on a cloud monitoring platform. The illumination system's operating status will update automatically through the Internet [12]. Moreover, the information will be available at a base station in case of an emergency. On the other hand, the luminosity level control is integrated by infrared sensors and ZigBee devices which detect the movement of people and ZigBee devices that establish wireless communication between the base station and the luminaries.

In 2014, the Al Akhawayn University, in Morocco, developed a network of sensors which transmit information through ZigBee modules. Together, the ZigBee devices and the luminaries are integrated into an efficient illumination system.

A maximum distance of 15 meters between luminaries is established to obtain an efficient level of illumination. If the vehicle is detected on a section of the highway, the sensors transmit the information to a control unit. This unit then processes the information and increases the luminosity flow, figure 3 [13].

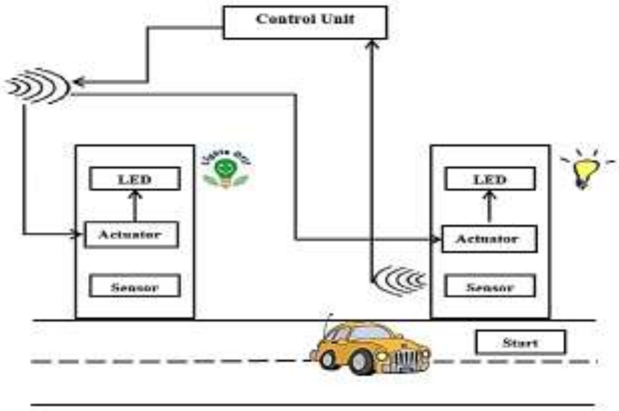

Figure 3: Diagram of the lighting system with sensors and efficient network [13]

Furthermore, new techniques to transform conventional highways into smart highways have been developed and implemented in Europe, Japan and the United States since

2014. For example, in Holland, the Smart Highway Project consists of illuminating a section of Dutch highway N-329 by using dynamic paints, figure 4 [14]. The projects that are developed in Holland integrate new control, management and operation systems for vehicle control and public illumination which guarantee quality service with huge benefits.

Figure 4: Dynamic Paintings on Highway [14].

Likewise, the SolaRoad Project in north-eastern Holland is an experimental project that consists of paving every 100 meters of the highway with 2,5 to 3,5 meter concrete modules. Photovoltaic cells are integrated into the concrete modules and are protected by a layer of one centimeter thick, tempered glass. The highway's lanes would transform into electric generator renewable systems. Moreover, a similar project is taking place in the United States. Its objective is to group and coordinate the operation of a network of highways by utilizing solar photovoltaic systems [14]. Therefore, it is important to develop illumination control systems based on open hardware.

On the other hand, the renewable illumination systems will optimize the public lighting service which presents big advantages over the conventional systems. The integration of renewable systems reveal a substantial evolution in technology regarding supplying streets, roads and highways with electric energy. In Lebanon in 2011, it was estimated that 90% of the energy produced is based on fossil fuels. Furthermore, the demand for energy in the previously mentioned country increases year after year. The public illumination system consumes 180 MWh/year. 35% of it is destined for the illumination of international highways. Per the energy department of Lebanon, the energy consumed by the public illumination system will reduce by half if the high-pressure sodium luminaries were substituted for LED luminaries. Additionally, the amount of energy saved would be much more considerable if hybrid generation systems based both on solar and wind energy were used. The CO2 emissions would also reduce significantly.

Figure 5 presents a block diagram of a hybrid generation system to be used in the public lighting service. The initial investment is $24 million for illuminating 285 km of highways. The energy department in Lebanon estimates that the money will be regained in 12 years.

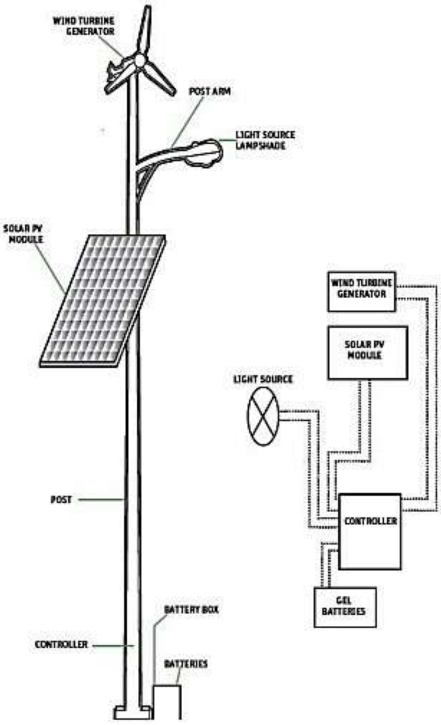

Figure 5: Block diagram of a hybrid generation system [8].

In December of 2011, the electronic engineering department of the National Science and Technology University in Taiwan presented a solar-powered photovoltaic illumination system. Figure 6 shows two scenarios: (a) and (b). Scenario (a) depicts that solar radiation is transformed into electric energy during the day and then stored in batteries. Scenario (b) depicts the stored energy being sent to the luminaries at night. The luminaries used are of high intensity discharges because they present a high level of luminosity, good color production and a long utility life. These luminaries are controlled through a device known as a ballast where the point of maximum power transference is applied, [9].

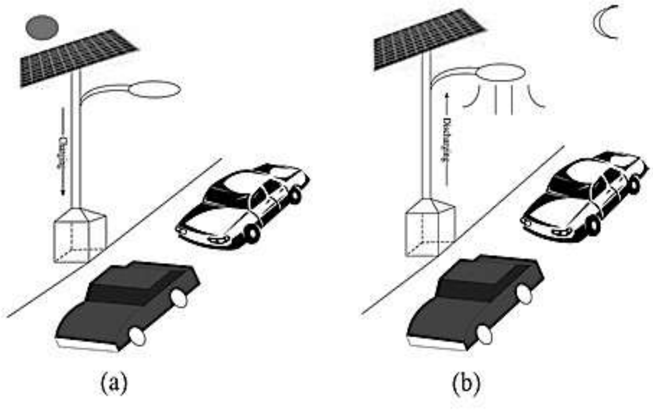

Figure 6: Scenarios lighting system operation [9].

3. Design and Implementation of an Illumination Control System using Arduino and ZigBee.

The design for an intelligent illumination control system is described in this document. The design is based on a detection system, which functions through an ultrasound sensor and ZigBee transmission devices. These devices control the luminosity of LED luminaries which are feed by a photovoltaic solar cell. The purpose of the controller is to save energy and money on public illumination systems used on Ecuador's highways. The smart, photovoltaic illumination controller will consist of a vehicle detection system, a group of LED luminaries, a photovoltaic generator system, a control unit and wireless communication modules. This project is developed in two parts. The first part corresponds to the designing and experimental application of the smart, photovoltaic illumination control system on a small scale. Afterward, the controller's energy and economic savings provided by the smart, photovoltaic illumination control system will be theoretically evaluated.

The theoretical study will be based on the following:

- Substitution of inefficient luminaries.
- Integration of the photovoltaic systems.
- Luminosity control of luminaries in relation to the vehicle detection time.

3.1 Comparison of the vehicle detection systems

Table 2 presents a comparison of the non-invasive vehicle detection systems [13].

Table 2: Vehicle detection systems [13].

Vehicle detection Systems		
System Technology	**Advantage**	**Disadvantages**
Image processing and video	Tested in large areas systems and information captured by the camera it can be linked to other cameras	Affected by weather conditions, errors in processing the shadows cast by vehicles.
Microwave Radar	This system is insensitive to inclement weather, in short detection distances.	Continuous wave emitted produces the doppler effect. It can not detect stopped vehicles
Laser radar	Emits various signals detected: the size, position, speed and vehicle class	It is affected by the presence of fog or when visibility is less than 6m.
Ultrasound	This system measures the speed of vehicle	The sensitivity of the sensor is reduced to bad weather
Acústica Pasiva	Insensitive passive sensing rainfall	Low temperatures will seriously affect the sensor

From table 2 it can be noted that the microwave radar offers big advantages over the meteorological conditions which sometimes occur on roads. Never the less, its disadvantage is that it can't detect stopped or parked vehicles.

The ultrasound system is chosen for the vehicle detection system because of this disadvantage. The ultrasound sensor will oversee detecting circulating vehicles based on sound wave emissions. The ultrasound sensor's operation principle is the Doppler Effect. The sound waves are emitted by the TX transmitter and detected by the RX receptor. The emitted acoustic sound waves measure approximately 40 KHz which exceeds the frequency range heard by the human ear [16].

The HC- SR04 sensor presents a series of advantages:

- It doesn't require physical contact to detect objects.
- A good quality-price ratio. This elevates its efficiency.
- The sensor is lightweight and compact in comparison to other similar devices.

Figure 7 shows the connection diagram of the vehicle detection system for highways which is controlled through Arduino microcontrollers.

The microcontrollers were chosen because of their rapid scalability capacity. The programming is executed per information received by the microcontroller through the ultrasound sensor which allows for an optimum operation of the system. The illumination controller's behaviour is analyzed on a small-scale highway prototype. A small symmetric central illumination system was installed which illuminated both sides of the simulated highway.

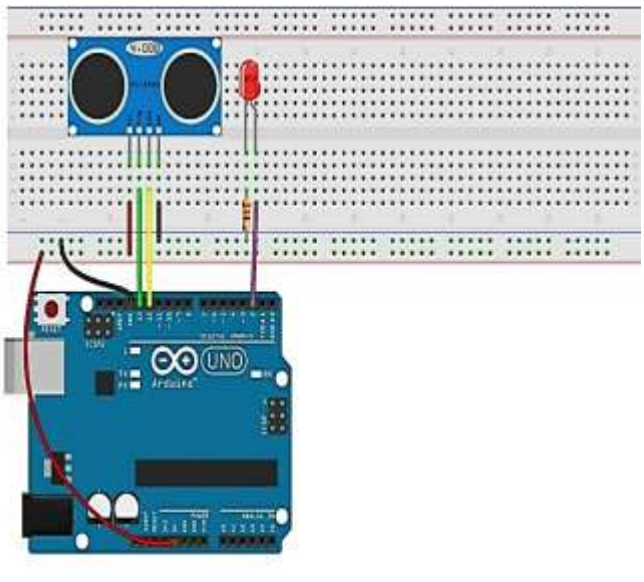

Figure 7: Connection Diagram vehicle detection system.

A vehicle detection system will be implemented on the posts of the highway prototype. It will consist of an ultrasound sensor which will emit signals when detecting a vehicle on the highway. Afterwards, these signal will be processed by a central unit in order to regulate the intensity of the luminaries. Finally, the signals will be transmitted wirelessly to the remaining luminaries. Likewise, a photocell will be used to activate and deactivate the illumination control system.This simulation will take place during hours established by the ARCONEL or in case of meteorological events that might affect daylight illumination.

3.2 Communication system description

This document proposes the use of a wireless network to control and manage the public illumination system. Wireless communication minimizes the use of physical means to control the luminosity level. There are many wireless communication systems, but the one which stands out the most is the standard IEEE 802.15.4. It is also called ZigBee and possesses the best characteristics related to energy consumption and cost. This standard uses XBee modules. XBee modules are integrated solutions which provide wireless interconnection and communication between devices. These modules are classified into:

XBee Series 1: They are the easiest devices to work with. These modules permit point to point, multipoint and star type network topologies.

XBee Znet 2.5o Series 2: These modules operate in transparent and AT modes or through an API interface. The AT mode is the easiest to use and permits the introduction of information manually through a console. API mode is more complex because it creates frameworks for information transmission. Moreover, they can support mesh type network topologies creating configurable communication and high availability nodes thus figure 8.

Figure 8: XBee module Series 2.

XBee modules require a feed between 2.8 and 3.4 V DC. Voltage regulator cards can be used to feed these modules. XBee modules can communicate with through X-CTU software by using XBee USB programmers. This software can be obtained from Digi which is the same company that commercializes the XBee modules. The XBee configuration is done based on a mesh type topography. That way, one XBee module can be configured as a coordinator in API mode and the remaining modules will be configured as AT routers. Table 3 shows the configuration parameters of an XBee module as a coordinator in API mode.

Table 3: XBee module configuration as coordinator

COORDINATOR API		
IDENTIFIER	**NAME**	**VALUE**
NI	Node identifier	Coordinador
ID	PAN ID	1991
MY	Network Address	10
SD	Time Scanner	3
CH	Channel operation	11
SC	Examines only the selected channel	40
DH	Destination address high	0
DL	Destination Address in low	FFFF
SH	Serial number high	13A200
SL	Serial number low	40C0D069
AP	API	1
D0	Configuration AD0/DI0	1
D5	Configuration asociada /DI05	1
P0	Configuration DIO10/PWM0	1

Communication is established with Xbee modules configured as AT routers, table 4.

Table 4: XBee module configuration as a router

ROUTER AT		
IDENTIFIER	**Name**	**VALOR**
NI	**Node identifier**	Router
ID	**PAN ID**	1991
MY	**Network Address**	10
SD	**Time Scanner**	3
CH	**Channel operation**	11
SC	**Examines only the selected channel**	40
DH	**Destination address high**	0
DL	**Destination Address in low**	FFFF
SH	**Serial number high**	13A200
SL	**Serial number low**	40C0D09E
AP	**API**	1
D0	**Configuration AD0/DI0**	2
D5	**Configuration asociada /DI05**	2
P0	**Configuration DIO10/PWM0**	1

3.3 Illumination control system

The illumination will be controlled by the modulation method: pulse width PWM on LED luminaries. Thus, the luminaries will reach their maximum intensity in a controlled way avoiding glare for the drivers and also guaranteeing a longer period of public illumination service with solar photovoltaic energy. The ultrasonic sensor will detect any vehicles circulating on the highway. If one is detected the luminaries will remain lit at maximum luminosity. The same luminaries will function at minimum luminosity if no vehicles are circulating on the highway, offering a constant and automated illumination service, figure 9.

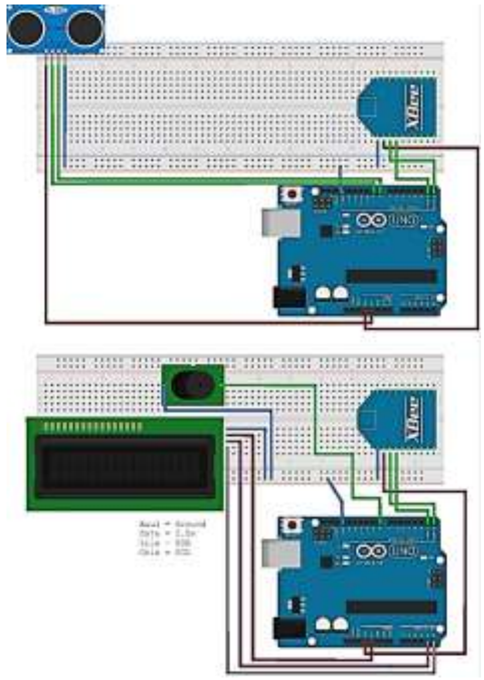

Figure 9: Block diagram of the Integrated Detection System-Lighting

3.4 Practical implementation of the illumination control

The proposed illumination controller uses photovoltaic solar energy as an electric generator source. This presents the idea of mounting each post with photovoltaic panels to supply electric energy. Small photovoltaic panels were attached to each luminary for this project. These panels were connected in series allowing an increase in the sources voltage. The energy was then stored in small rechargeable batteries.

The implementation of a prototype will allow the system's behavior to be analyzed in regard to the highway's traffic flow. First off, a one-way traffic flow will be simulated, figure 10. Only the lane in use will be illuminated. This method will save electric energy on the highway.

Figure 10: Simulation of vehicular flow in one direction of the freeway

Figure 11 shows the luminaries functioning per vehicles detected on the highway. The vehicular detection process permits the luminaries to activate and increase their luminosity. Thus, the highway's luminosity will increase to full power when it detects a vehicle. The luminaries will only function at 20% during periods of low traffic flow. A group of luminaries will transform into individual smart devices by controlling the LED luminaries.

Figure 11: Luminaires lit with vehicular flux [15]

Likewise, a two-way traffic flow will be simulated using the luminaries at their minimum power. And will continue at that power level while no traffic flow exists. The system will remain enclosed as long as there are vehicles circulating, figure 12.

Figure 12: Lighting in two directions of traffic from the highway [15].

4. Illumination Controller's Impact on Energy Scenarios

Several scenarios have been analyzed for a better understanding of the proposed controller. These scenarios relate to existing traffic flow upon the main highways in Ecuador. The following work establishes an illumination controller which functions during a period of 6 hours. The period starts at midnight and ends at 6 am. The simulation will be carried out during 6 of the 12 hours corresponding to public illumination. The 12-hour period was established by the CONELEC, figure 13. A minimum traffic flow is foreseen during this 6-hour period. The reduced traffic flow will allow for a more efficient illumination control.

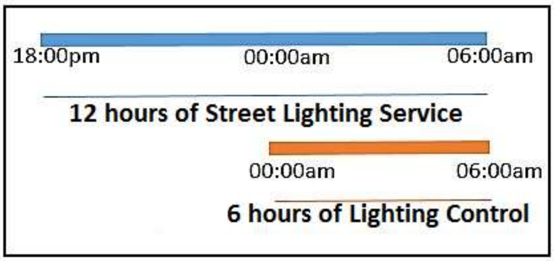

Figure 13: Hours of public lighting control [15].

4.1 One vehicle per hour scenario

A vehicle circulating at 40 km/h is calculated to travel one kilometer of the highway in approximately 90 seconds. Figure 14 shows the first illumination control scenario. The luminaries were set to full power in two minutes, while the vehicle traveled the section of the highway previously mentioned. This way a particular case is foreseen. This case will permit maximum energy saving during illumination controlled hours.

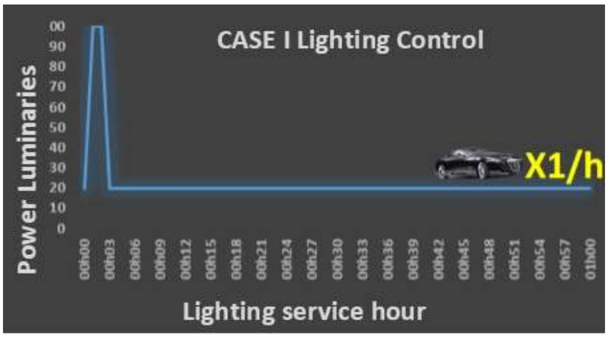

Figure 14: Scenario 1 lighting [15]

4.2 Two vehicles per hour scenario

In this case, one vehicle is expected to travel a 1 km section of the highway every half hour. This implies that two vehicles will be detected in an hour. Maximum illumination will last 4 minutes for every hour of the public illumination service, figure 15.

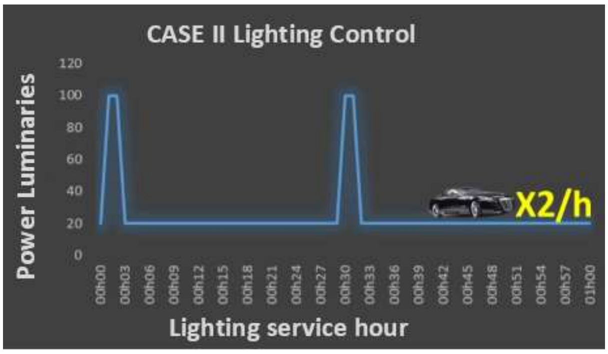

Figure 15: Scenario 2 light [15].

4.3 Three vehicles per hour scenario

In this scenario, one vehicle will travel 1 km every 20 minutes. Maximum illumination will last 6 minutes for every hour of the public illumination service, figure 16.

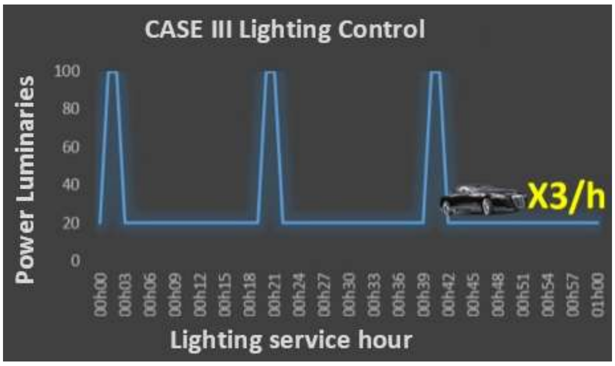

Figure 16: Scenario 3 light [15].

4.4 Four vehicles per hour scenario

In this scenario, the traffic flow will consist of 1 vehicle traveling 1 km every 15 minutes. Maximum illumination will last 8 minutes for every hour of the public illumination service. 4 vehicles are expected to circulate for every hour of the public illumination system as well, figure 17.

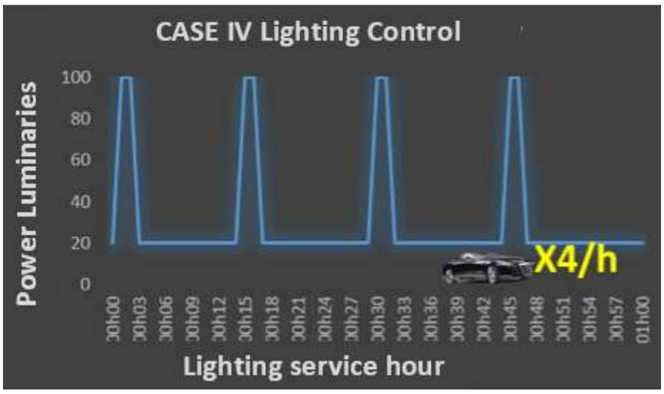

Figure 17: Scenario 4 light [15].

4.5 Mixed illumination control scenarios

The previous paragraphs show different illumination control scenarios. Never the less, traffic flow on a highway can more or less than those stated above depending on private vehicle circulation. Due to this, various mixed scenarios may occur which combine the previously mentioned scenarios. Figure 18 presents an example of a possible mixed scenario. This scenario may happen during public illumination control hours.

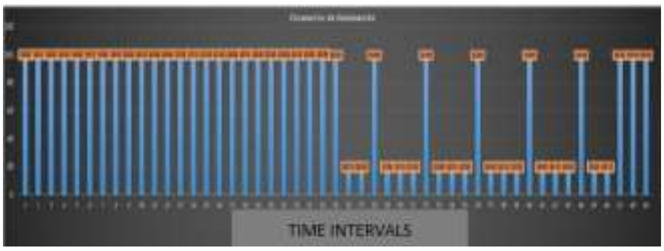

Figure 18: Mixed Stage lighting control [15].

Table 4 shows the energy saving generated in each of the illumination control scenarios described in the paragraphs above. Controlled energy consumption produces an economic saving which may be used in strategic financial projects.

Tabla 5: Ahorro energético del control de iluminación [18].

Economic cost of lighting control scenarios				
Lighting scenarios	Power luminaire	Annual consumption (kWh)	Spending nationwide Millons of USD	Millions cost savings USD
Scenario 1	112 W	55.60	6.93	129.67
Scenario 2	112 W	62.14	6.76	129.84
Scenario 3	112 W	68.68	7.75	128.85
Scenario 4	112 W	75.22	9.38	127.22
Scenario 5	112 W	88.30	11.01	125.59
Scenario 6	112 W	121	15.09	121.51

5. Conclusion

Millimetric wave radars are the best alternative for detecting vehicles in circulation. Their incessant technological advancement makes them into smart systems capable of determining the velocity and number of vehicles circulating the highways regardless of the number of lanes being circulated.

LED technology used in public illumination allows the luminaries to be easily integrated into photovoltaic illumination systems. Furthermore, LED luminaries permit better control of their luminosity flow which helps to save an important amount of energy and reduces costs of public illumination.

The luminosity flow of the luminaries was controlled by vehicle detection which changed their intensity from minimum to maximum during the hours established by the public lighting service.

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