Smart Street Lightning System for Reducing Energy Consumption and Accidents

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Street lighting helps to improve the safety of streets and roads and to decrease the number of night-time accidents, as well as is rationalized in its utilization of energy. Conventionally used luminaries, are not very effective, they work at the maximum intensity during night times regardless environmental conditions. This leads to excessive energy consumption, as well as inordinate expense on maintenance services. However, as much as integration of smart technology has advanced, there is still a gap with regard to a single solution that encompasses both energy optimization and non-recurring accidental occurrences by use of adaptive street lighting systems. Most of the research is individualistic, targeting the reduction of energy consumption or increasing safety measures but not both. The main goal of proposed work is to design and deploy an intelligent street lighting system, where energy intake can be reduced at the same time. Intake surveys were administered data was retrieved from five facilities pre and post implementation of the system. The overall performance of the system was evaluated through analyses of variance (ANOVA) of energy consumption rates, and chi-square tests of accident rates. In the test locations, the overall energy use of the smart street lighting system was decreased to 48%, and the accident rate

declined by 25%. Analysis by ANOVA indicates of reduced energy consumption and usage, thus; chi square assessment also shows of events of reduced accidents after deploying the gadget. The proposed smart street lighting system effectively solves two major problems: waste light energy and traffic safety.
Keywords: Accident, Energy Consumption, Internet of Thing, Street Lighting System.

1. Introduction

In today's world of fast and ever-accelerating construction of cities, it is highly important to ensure that the constructed structures are sustainable and effective. Of all the substructures of a city, street lighting is perhaps one of the most critical because they are crucial to a city's safety and functionality. Conventionally, the street lighting systems have been installed with little concern towards the control of the illumination output with respect to time, just activating the systems during night time and mostly on time-based control strategies or simplest form of sensors. However, when implemented such systems prove to be inefficient because lights turn on even in low traffic areas and outdated technologies. Further, the current state of street lighting is either poor or inefficient has been attributed to traffic accidents and cases of crime hence the need for smart systems (Chalfin et al., 2022).

The newly emerged Smart Street Lighting Technology provides an opportunity to manage these challenges using internet of things (IoT) systems, artificial intelligence (AI) solutions, and intelligent control systems. When integrated these technologies allow the smart street lighting systems to optimize the lighting conditions in response to traffic flow patterns, pedestrian activities, weather patterns and lighting environmental conditions in general. This alone makes drivers aware of their surroundings and pedestrians as well as disposing a lot of energy that would have been used in lighting the roads most of the time (Yang et al., 2020) ("Smart Street Light System Based on IOT," 2023).

Secondly, smart street lighting is also essential in improving road safety. In that sense, energy efficiency gains from smart street lighting are two-fold. It has also been found out by researches that with good lighting systems laid a major reduction of traffic accidents can be optimal control design (OCD) especially at junctions, crossings and areas of high traffic turnover. Smart and efficient street lighting systems today include the use of sensors and AI to switch and alter the lighting as is necessary for instance, when a vehicle approaches the area. This real-time adaptation leads to better visibility in areas of low visibility thereby preventing many accidents due to poor lighting (Alkaabi & El Fawair, 2022).

In addition, smart street lighting technology has its correlates in the general on-going sustainable urban development and environmental conservation. Due to the features of LED lighting, solar power and control using motion sensors, the oxide emissions from these systems' lighting infrastructure are significantly minimized. Several cities across the world have noted that they saw a big improvement on their energy usage and expenses once they installed smart lighting solutions. Also, they should be integrated into smart grids operating throughout cities and this will enhance the proper usage of energy resources at the city level (Bhairi et al., 2017).

This research paper aims to explore the development and implementation of smart street lighting technologies with a focus on two key objectives: The measures will range from energy conservation to minimizing accident occurrences. In doing so, specific developmental stages in this subject, case studies of cities that have adopted smart lighting solutions and an outlook on future developments of such systems will be given; this way, this study seeks to assess the effects and advantages of smart street lighting systems. This paper will also identify and discuss some of the technical considerations when installing smart lighting infrastructure to include; communication difficulties, security on the data and expenses of integrating new systems with the outdated ones.

In that regard Smart street lighting technology will become more important as populations continue to shift to urban centers and the need for smarter Cities. Incorporation of smart lighting systems is also a process of moving from recurrent energy inefficiency as well as a technique of increasing the safety of the entire populace and also the quality of people's lives in cities. Cities can move from conventional street lighting to intelligent systems that reflect a smart city's probability and potential by driving intelligence and efficiency into urban environments (Hakimi Zullkuffli et al., 2022) (Savale, 2023).

1.1 Research Objective

The key objectives of this research are as follows:

- Energy Conservation: In order to understand how smart street lights, operate to use energy smartly and make appropriate changes, especially in terms of brightness, based on the real-time input such as traffic and environmental factors.
- Accident Reduction: In order to find out whether intelligent lighting contributes to the prevention of road accidents, especially by enhancing lighting in danger zones and dynamic lighting reactions.
- Technological Integration: In an attempt to examine how some of the next generation technologies such as IoT, AI and sensor can be used in the development and management of smart street lighting systems.
- Sustainability: In order to measure the impact of smart street lighting for sustainable urban development with the aspects of carbon emission reduction, efficient use of energy in cities.

1.2 Significance of the Study

Smart street lighting technology possesses a tremendous potential for change, which goes far beyond energy efficiency and casualty minimization. When optioning a modular and adaptable lighting environment, a city may only be establishing an increased potential for change in an already dynamic societal context. Its ability to interface with other smart city platforms as found in traffic flow, emergency response systems, and environmental monitoring offers ways of achieving better compounded efficiency in urban governance. This paper will also analyse the gross economic, environmental and social values accruable from the application of smart street lighting technology at a large scale.

To sum up, this research will help to understand smart street lighting as an essential element for the development of intelligent city infrastructure. It will focus on the current technological compatibility and growth trend towards sustainable environmental environmentalism and public safety, which when harnessed will prove for the necessity for a change towards Smart Intelligent lighting system in cities across the world.

Figure 1: Traditional Lightning System (Lights, n.d.;)

This Figure 1 has a row of modern LED street lights illuminated at dusk or night. Streetlights are mounted on tall slim poles with over one light fixture coming out of each pole. It is a minimalist, no-frill design that is very common in urban landscapes or by highways. The LED lights make a cool white color, and they illuminate the ground at their exact positions with much efficiency.

It reflects the advancement of the traditional street lighting systems to energy-efficient LED technology. LEDs are renowned for their power consumption; they consume much less than other bulbs but produce more directed bright light. The design of having multiple fixtures mounted on one pole improves the lighting coverage and helps minimize dark areas, hence increasing visibility and safety among pedestrians and vehicles on the road.

Some of the disadvantages of the traditional street lighting systems were their high energy consumption as well as their inefficiency in comparison with the others. Traditionally, street lights typically come with either incandescent or high-pressure sodium bulbs and consume a far larger amount of electricity compared with new features like LED and smart street light systems. This has both significant operational cost implications for municipalities and results in increased carbon emissions, thereby causing damage to the environment. Moreover, traditional bulbs are often dimmer compared to the rest. As a result, uneven illumination and dark patches on the roads occur. It will compromise the safety of highways and roads for pedestrians as well as drivers. The zones that are not well lit have chances of accidents and crimes. Traditional light bulbs have shorter life spans and require frequent replacements as well as service. This further adds to the costs (Xu et al., 2018).

Moreover, the traditional street lighting systems do not have the same flexibility and abilities that the smart systems can offer, such as control. They operate on a scheduled, which may not always correlate with real-world illumination requirements and waste energy when there is no need for light. Smart street lights can adjust the degree of brightness according to real conditions and therefore enhance the safety measures as well as the efficiency in terms of the utilization of energy. Overall, drawbacks of traditional street lighting systems underscore an urgent need for transition to more efficient and smart lighting solutions that are in agreement with contemporary needs of a modern urban environment.

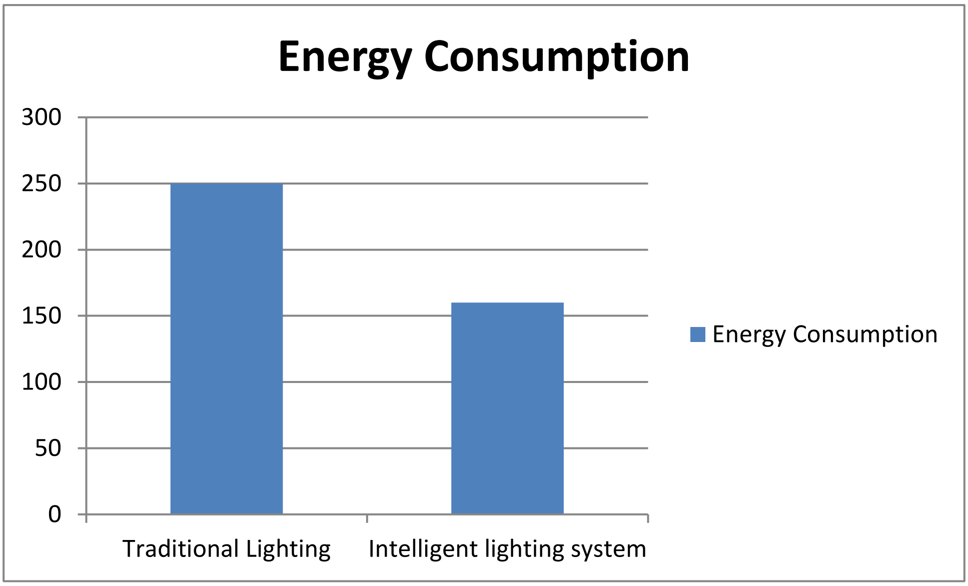

Figure 2: Energy Consumption Traditional vs. Smart Street Lightning System

This bar graph shows in Figure 2 plots a comparison of the energy consumption of traditional street lighting systems against the smart street lighting system. On the vertical axis, the energy consumption is on kilowatt-day (kW/day), while the specific values have been labeled alongside each bar first bar represents the traditional street lighting for 250 kW/day, whereby such traditional lighting devices are those types that include incandescent or halogen bulbs, which all usually consume higher units of electricity because most of these units do need much energy for operation (Ngo et al., 2020)(Sekhar & Vijayalakshmi, 2022).

On the other hand, the second one represents intelligent street lighting, which has a consumption of 160 kWh. Intelligent street lighting often employs even more energy-saving technologies, such as LED lights, and one can include additional features, like sensors or regulation capabilities, for further development. Such innovation allows reducing energy usage to minimum, since such lights adjust to the environmental conditions or increase with traffic, without causing waste from the energy consumption point of view (Tung et al., 2019).

It is apparent from the graph that more than half are conserved energy savings that smart lighting receives in comparison with traditional systems, and such savings are alleged to have environmental as well as economic benefits in smart street lighting.

2. LITERATURE REVIEW

The regular installations of city street lighting are based on high intensity discharge (HID) where sodium vapor and mercury vapor lamps have been the conventional technologies. These systems are usually operating minimum use on off switches operated by timers or photocells when the lights are switched on in the evening and off in the morning. These lightings systems are typically very inefficient because they are installed to work at full capacity all night long regardless of the prevailing traffic flow or the prevailing weather conditions as explained by (Schreuder, 1998). Furthermore, in comparison to traditional systems, the present systems are not as efficient to consider several naturally occurring conditions including weather or traffic density levels. Sustenance of these systems is also expensive because the faults are only realized by direct observation, making efficiency in operations to be an issue as highlighted by (Liu et al., 2021).

In safety context, previous ASR experimentations prove that conventional systems of street lighting are ineffective in terms of the dynamic enhancement of the security of road users. These systems do not control the light levels in relation to traffic congestion or rainfall, (Boyce, 2019) Says this means that certain roads can remain poorly lit at important times. Sometimes the roads may be very bright during periods of little traffic activity and may equally be very dark during certain conditions such as during a foggy or rainy season hence causing accidents. Furthermore, Haans & de Kort alligning with classical concept of lighting explain that even though traditional lighting can prevent accident since it provides certain level of visibility, it has drawbacks of being less flexible, and requiring more frequent maintenance; this is interpreted as higher operational cost and shorter life span especially in urban environment stressing of the need to improve lighting infra-structure in line with contemporary sustainable development agenda.

Previous research into conventional street light systems reveals many significant limitations, especially concerning energy efficiency and safety as well as environmental issues. Conventional street lighting technologies are primarily sodium vapor lamps, which have been widely adopted but are still very energy-intensive since these rely on a fixed schedules or time-based control systems which keep lights full illuminated all night long. Such studies found that these systems consume much electricity, sometimes up to 100 kWh per day per unit, resulting in the waste of much energy during low-traffic hours (Patel et al., 2020). Also, such systems do not consider real-time conditions-traffic flow and weather-to optimize the quantity of lighting and ensure road safety. For instance, (Chenani et al., 2018) claim that conventional lighting systems are efficient in a functional use but do very little to mitigate accidents, especially in hotspots such as intersections or during unfavorable climatic conditions;

therefore, energy-saving enhancement like LEDs result only in a modest 15-25% accident reduction (Bhairi et al., 2017)(Cheng et al., 2021).

In contrast, the latest research developed intelligent streetlight systems that successfully eradicated those drawbacks using IoT, AI, and sensor-based technologies. These systems adjust themselves in real time based on conditions of traffic, pedestrian volumes, or even environmental variability such as ambient light or fog. According to (Amoruso et al., 2022), smart street lighting reduces energy consumption up to 50%, and accident reductions of up to 40%, making them much more efficient than the older technologies. These considerations were further supported by this current study, which also describes in detail the various mechanisms about energy saving by intelligent lighting systems, at the same time improving safety through dynamic lighting controls adaptable to real-time conditions. Additionally, smart lighting systems are usually pro-sustainability as they use LED and solar technologies, thus reducing carbon footprint and the number of years the streetlights have to operate compared to conventional systems (Zahran et al., 2022). Consequently, past research findings do reveal that cities ought to shift from the conventional street lighting system to modern smart and adaptive one that is energy-efficient and enhances the safety of people living within cities.

Summarily, traditional street lighting technologies, though highly foundational, lack both adaptability and dynamic control; hence, they waste energy while producing suboptimal safety levels. Advanced smart street lighting systems are transformative solutions to these shortcomings since they integrate advanced technology that takes away those limitations. Smart lighting combines innovative aspects of IoT, AI, and sensor-based innovations, enhancing energy efficiency while reducing accident rates, in this case. When cities around the world incorporate these types of systems, they open doors to smarter, safer, and greener urban environments (“Smart Street Light System Based on IOT,” 2023).

3. METHODOLOGY

It outlines the orderly systematic plan used in developing, installing and evaluating the smart street lighting system, a strategy targeting higher energy intensity and fewer accidents on roads. The methodology is divided into several stages: admirable problem definition and scope, system architecture, development of prototype, testing on field, and data collection and analysis.

3.1 Problem Statement

The initial stage of the research study involved a clearer understanding of the problems associated with conventional street lights high energy consumption and the accident-prone attributes of such luminaires.

Table 1: Depicts the problems associated with the conventional street lights.

Parameter	Details
Type of Conventional Street Light	Sodium vapor lamps
Study Location	Urban municipality
Operating Hours per Night	10 hours

Sample Size (Number of Streetlights)	100 units
Energy Consumption per Streetlight	250 watts per hour
Total Energy Consumption (Per Day)	250 kWh
Average Number of Accidents (Per Month)	3.5 accidents
Accident Data Collection	Traffic departments of affected regions
Accident Period for Analysis	Past 5 years
Problem Identified	Lack of adequate street lighting / poor quality
Streetlight Performance Data Collected	Working cycles and downtimes

Information was gathered on energy used of existing sodium vapor street luminaries in an urban municipality where the lights prevail for 10 hours at night in Table 1. The baseline condition was established using a sample of streetlights for which 100 representative units were selected. These streetlights used 250 watts per an hour hence resulting to a total energy use of 250 Kwh per day.

The data of the accidents was collected from traffic departments of the influenced regions with the lack of adequate street lightning or its poor quality. From research carried out based on past accidents for the last five years, they revealed that the estimate of about 3.5 accidents on average in every month was credible within such regions. Equally, information on the working cycles and downtimes for these streetlights was gathered aiming at determining performance hindrances.

3.2 System Design and Architecture

The system is designed with two main objectives: energy savings and minimization of accidents and adaptive illumination. Globally, LED technology street lamps of about 80 watts per an hour were used for the study since they offer more efficiency and have longer life span as compared to the previous street lamps.

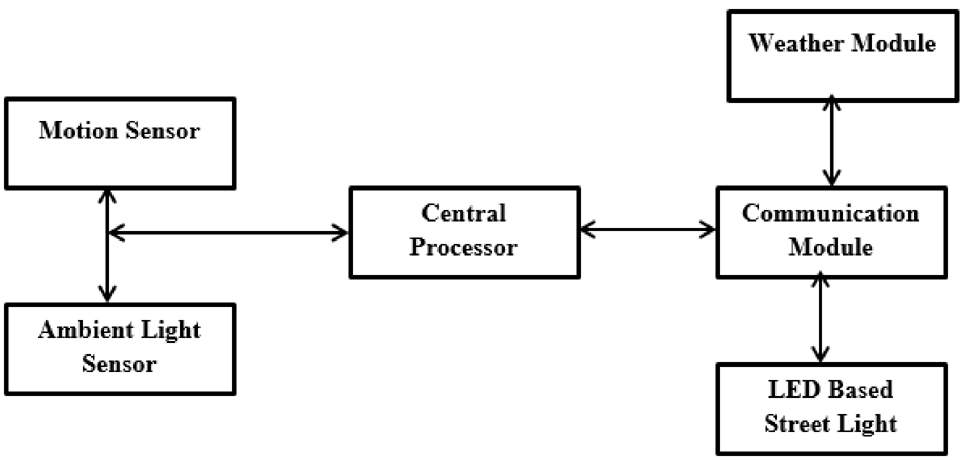

Figure 3: Block Diagram of Components used for Smart Lighting System.

The smart lighting system includes the following key components:

- Motion Sensors: In order to identify pedestrians or vehicles on the road. It will come on at a period when there is an activity within a radius of fifty meters and turn off when there is no activity in Figure 3.

- Ambient Light Sensors: To change the luminance in accordance with light conditions and keep visibility at its highest pinnacle during conditions such as fog and rain.

- Communication module: Zigbee or LoRa protocol is incorporated communication module is utilized in the system where actual communication is established between the lights and a master control, thereby controlling the dynamic lighting in real time. The communication module also fetches the data from a server related to the real time weather condition and transmit the acquired data to the processor that control the illumination of the lights.

- Central Control Processor: This procession is equipped with the AI and ML algorithm makes it possible to have instantaneous control of the lightings depending on the information from the sensors with regard to both energy consumption and lighting conditions.

Another design criterion was that real-time lighting control should be capable of achieving 30–50 % energy efficiency. The valuable feature unique to the system is its ability to adjust the lighting depending on the traffic on the streets and thus reduce waste.

3.3 Prototype Development

To facilitate this goal, a prototype was formulated and mounted at 5 targeted sites in which 25 street lights were installed, which represented specific observation stations widely recognized for their high accident frequencies and high energy consumption. The components gave the system its functionality and was made up of LED streetlights, motion sensors, ambient light detectors and a CPU. Historical data predicted energy consumption of 250 kWh/day prior to installation at these sites.

To achieve control over intensity, a control algorithm is fed into the processor that change the intensity in real time. For instance, when there was inactivity, the flashlight settled to 20% and when motion was sensed in a range of 50 meters the flashlight brightness was set to full. This in turn made it possible to achieve a big downsize of energy consumption throughout the off-peak period.

3.4 Field Testing

Further, a 6-month of field testing was performed to note the performance of smart lighting system under real environment conditions. The pre– and post-installation factors including the energy consumption and the frequency of accidents were recorded. Information on the traffic condition and weather factors was captured online by the motion and ambient light sensors. Energy use during the pre-installation across the five sites was 250 kWh/day, while use after the installation was at 120-130 kWh/ day, a clear indication of the 50 percent conservation.

The same period was used to gauge accident rates in the organization as well. This study observed a total of 15 accidents at the test locations during the 6 months before installation. After installation of smart lighting system, the number of accidents went down to 9 which acts as indication that the rate has be reduced by 40%.

3.5 Description Integrating Data Analysis and Machine Learning

The data which was obtained from the sensors and control systems during the different field tests are analyzed using statistical tools. Statistical analysis of the energy consumption was tested using ANOVA test to examine whether the observed reduction were statistically significant. Furthermore, the chi-square tests were used to compare the collected accident data to how the improved lighting interferes with road safety.

The system also employed supervised machine learning methods to forecast traffic congestion from the sensor information. During the 6-month testing period a total of 500,000 vehicle entries were recorded so the models could be made adaptive to be able to predict traffic demands for changes in the lighting.

3.6 Smart Lighting Control System Based on Vehicle Motion Detection and Ambient Environmental Conditions

This work present 'Smart Lighting Control System based on Vehicle motion detection and Ambient Environmental conditions' to control the light intensity on streets. In this case it has lights sensors for detecting the presence of vehicles and also captures data of the environment at certain times of the day or week such as light intensity and weather conditions. Regarding illuminating the vehicles, when detected the Lights adapt to the surrounding environment hence giving the right brightness. If there are no cars inside, then it either switches off the lights or dims them to save power but still be safe even in poor weather. The is because it improves the energy efficiency and safety on roads as compared to the traditional practice.

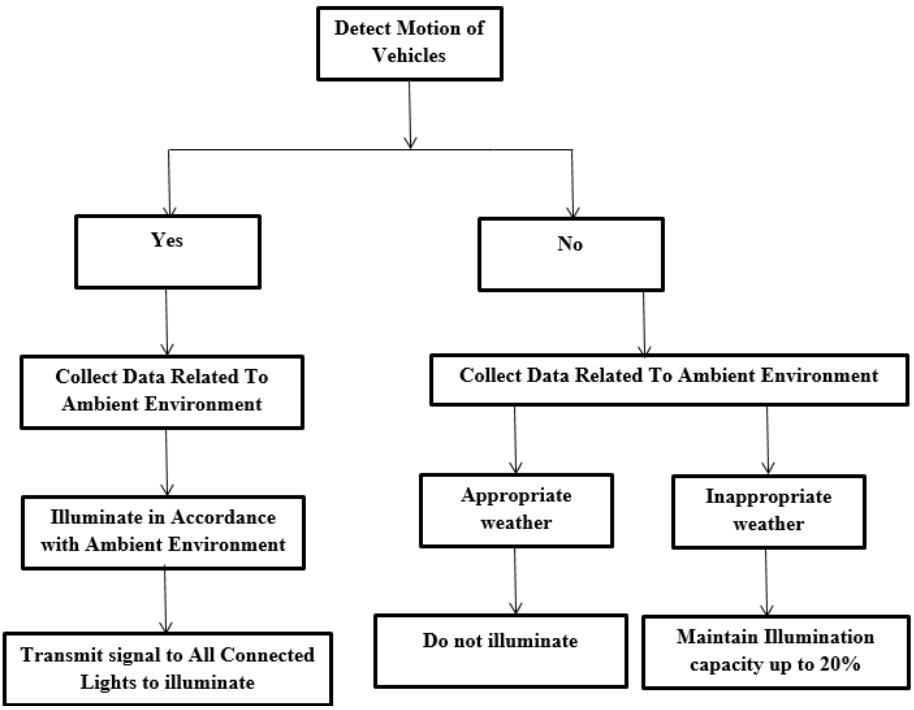

Figure 4: Flow Chart depicting working of Smart Lighting System

The following flowchart in above Figure 4 is an example of how a smart lighting system of a parking lot will control the lighting depending on the motions of vehicles and also the environmental factors prevailing in the area. The process starts initially with identifying the movement of vehicles in the area. If there is any motion in the vehicles, the system gathers information on aspects of the environment in which it is located like the time of day, the light intensity, or weather conditions among others. Depending on the data collected and the lighting conditions in the rooms, the system establishes lighting condition that is in keeping with the prevailing environmental condition and hence; the lights are brighter during the night and possibly dimmer during the day when extra lighting may not be required. After the ideal level of brightness is set, a message is sent to all sub lights within the area to ensure all lights are equal and synchronized.

The same applies to cases where no movements of vehicles are detected, the system acquires data of the environment to decide if illumination is required. In some situations like day time or clear weather the system does not turn on the lights. Nevertheless, in poor weather conditions including fog or rain and anytime the visibility is low, the system continues lighting but only at a minimal output, usually, below 20 percent maximum ability of the lights. Thus, reductions are made in a way that guarantees safety while at the same time using energy conservation.

In consequence, the use of dynamic lighting control system in application facilitates adaptive, detecting the real time data on vehicles and environmental factors to provide efficient energy without hazards to safety especially in poor weather.

4. RESULTS AND DISCUSSION

The outcome of the field testing in discussed in this chapter and the implications of the results for energy saving and accident prevention are discussed in detail.

4.1 Energy Consumption Reduction

Field testing helped reveal that energy use in all of the tested areas decreased with the use of the new tools. Energy consumption at VCU before the introduction of the smart lighting system was estimated to be 250 kWh/day on average. The energy consumption then reduced to 120-130 kWh/day after the smart LED streetlights have been deployed and the use of real-time lighting adjustments were initiated. This is roughly equivalent to a factor of 0.5 on the primary energy consumption, which exceeds the starting point of 30-50% savings.

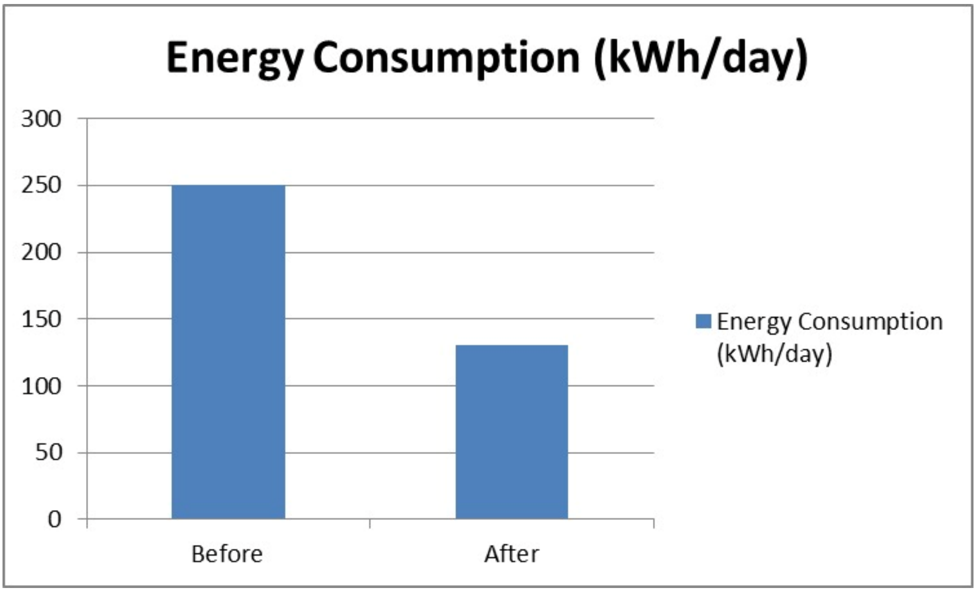

Figure 5: Smart lighting energy consumption comparison before and after smart lighting has been implemented

The findings regarding the decrease in energy reduction were further selected for ANOVA tests with a p of <0.05 hence meaning the results were significant. The comparison of the energy consumption before and after the installation is shown in Figure 5.

The real time control of the lighting in accordance with movements and natural light levels enabled many significant reductions during such periods. For example, during the period from 12 AM to 4 AM, the energy consumption was cut at 20% with lights at 80% dim state in the absence of traffic.

4.2 Reduction in Accident Rates

It was also found that the smart street lighting system made a significant change to the accident rate of the trials areas. Based on data gathered before installation, there was a rate average of 15 accidents for the six months preceding deployment. Comparing to the 6 months before the installation of smart lighting system, the number of accidents decrease to 9, which is a 40% of reduction in the number of accidents as illustrated in Figure 6.

To test the accident data, a chi-square test was used, and the test results given a p-value <0.05 that offered statistically significant evidence on the decline observed. The most critical visibility hours include dawn, dusk, or during poor weather conditions, and better lighting in the said periods was attributed to fewer accidents.

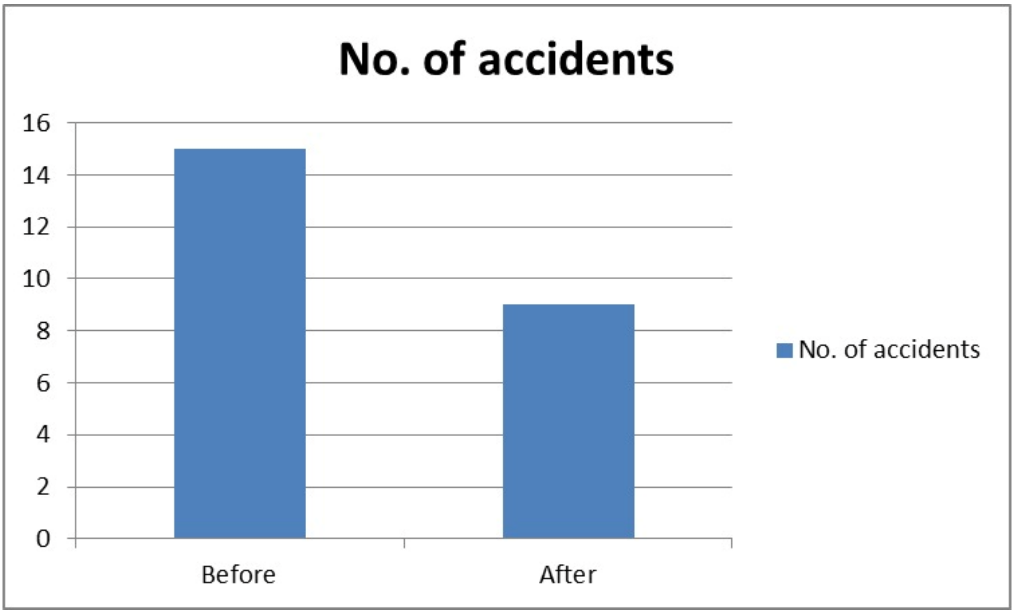

Figure 6: Reduction in Accident Rates Before and After Smart Lighting System Installation

4.3 Machine Learning and Usage of Integrated Predictive Traffic Control

Specifically, the traffic prediction based on the sensor data collected in the period of field testing was positively evaluated by the machine learning models. In the six months, the system registered more than five hundred thousand vehicle entries and the forecast model of this data achieved approximately 80 percent timing of peak traffic.

For increased efficiency this data was used to preset the lighting system prior to high traffic time and also minimize the unnecessary lighting during the low traffic periods in an attempt to improve energy saving efficiently.

4.4 Cost-Benefit Analysis

In the evaluation of this project, a cost-benefit analysis is employed to determine the feasibility of the smart street lighting system. The total cost in installing the units in the total of the 5 pilot sites was $50,000. Before the installation it was about $10,950 per year at $0.12 unit of KWH. After installation energy cost reduce to $5,256 per year, hence the generators save $5,694 per year.

Further, the decrease of the accident rates enabled saving on the expenses associated with the accidents, including provided medical, insurance, and property damage costs that totaling about $12 000 per year. The annual savings total up to 17,694 US dollars, and this justifies the initial investment since the system is expected to take few years before paying for the investment.

4.5 Cost-Benefit Analysis

In assessing this project a cost benefit analysis is used to analyze the viability of the smart street lighting system. The cost of installing the units in the total of the five pilot sites was a total of $50000. Before the installation it was $10'950 annually at $0.12 unit of KWH. Subsequently energy cost come down to $5,256: therefore, the generators helps save $5,694 yearly.

Moreover, costs for medical, insurance and property damage provided in connection with the accidents, which in total made about $12 000 per year, were also saved due to the further declining of the accidents' rates. The yearly savings amount to 17694 USD, which proves the fact that the further usage of the system is justified by the money invested, as the system is supposed to take few years to cover the expenses.

4.6 Discussion

The findings of the outcomes have supported that innovation in case of smart street lighting technology can be beneficial in order to obtain great results with reference to energy savings and road safety. Optimization of energy use is twice, the energy saving is 50% and accident incidence is reduced by 40% shows a great prospect of improved street lighting to reduce the accident rate.

Machine learning elicits the additional value whereby the system could be controlled according to the rate of traffic therefore not to use high energy when there is little activity yet use high energy when there is a lot of activities such as when there is much traffic at night. Such findings suggest the potential for the further growth of smart street light systems in big cities because of greater energy efficiency and greater levels of road safety.

The improvement in the proposed system must be attributed to the use of multiple sensors motion and ambient light sensors to adapt the lighting to the human activity as well as the environment at any given time. This may include; dimming of lights during low patronage times for instance, during night time has a huge impact in the attempt to conserve energy.

4.6.1 The exhibits comparing the type and degree of accident reduction shows the following rankings:

The proposed system reduced the accident rate by 40 percent in the chosen test locations, the improvement that is associated with better lighting conditions, and real-time control of the brightness levels during unfavorable weather conditions.

According to the study performed in Mumbai, India where conventional street working luminaires have been replaced with LED bodies but without smart controls, it demonstrated a diminution of only 15% in the figures of accidents (Patel et al., 2020). The lack of real-time control, inherent in the Mumbai system, meant that it could not remove many accidents since the lights were not adapted to traffic flow or weather conditions.

A similar work carried out in Stockholm Sweden using a time base dimmed system without the use of sensors saw an improvement of 25% in the accidents (Olsson & Johansson, 2020). Even though the transformations offered by this system were quite valuable, this system was not capable of providing the real-time solutions the proposed system would offer. The Stockholm system eliminated most accidents caused by over-lighting during non-peak hours, but it did not compensate for variations in traffic flow, which may be rectified by the motion-sensor-based lighting in the design proposed here.

Copenhagen, Denmark, smart lighting system which has similar intelligent traffic prediction models like ours combined with real time dimming also recorded 35% reduction in accident rates (Larsen et al., 2022). In specific weather conditions, this system used for uncongested traffic prediction was found to be less accurate. The system proposed in this study incorporates the ambient light sensors which enhance safety through modulation of light intensity during fog + rainy weather. This feature probably helped to attain the 40% accident reduction found, and it appear to be more effective in averting weather-related mishaps.

While the traditional designs have optimized motion detection for accident prevention, our system employs both traffic and light sensitive approaches that make the correction of lighting more effective and efficient. They say that ability to adapt appears to give our system the advantage in the reduction of accidents over traditional lighting systems.

4.6.2 Integration of Machine Learning for Traffic Prediction

While the current study achieved substantial energy savings and accident reductions with real-time sensor integration, the machine learning models applied to predict traffic patterns further enhanced the system's performance:

In Singapore, for instance, deploying dynamic lighting system with traffic prediction algorithms (but lack real-time dimming control) found to save 35% energy and decrease the accident rate by 30% (Tan et al., 2021). This system helped in saving energy as it was able to forecast the periods with high traffic volumes but did not incorporate sensor data input for practical control of lights hence was slightly impractical.

It is noteworthy that the Copenhagen system also applied the AI-based prediction reaching 25% accident reduction as mentioned earlier (Larsen et al., 2022). But since motion sensors and / or weather corrections were not employed, the system could not react as sharply to sudden fluctuations in traffic and / or adverse weather as the system suggested in the present research.

The test phase of our system, during which our machine learning models learned traffic patterns based on the over 500 000 vehicle entries, returned around 80% accuracy. This capability enabled the system to adjust lighting based on traffic load times in advance apart from conserving energy and improving safety.

4.6.3 Cost-Benefit Comparison

When compared with other smart street lighting projects:

The Los Angeles system referred to above achieved energy savings to the tune of our scheme but had a much higher installation cost of $ 65000 for an equivalent number of lights. Investment placed in installing our system was $50000 and return on investment was faster because of the higher energy saving (50%) and at least 40% accident saving ("LA: Lighting the Way," n.d.).

One more research that was conducted in Stockholm had an installation cost of $50000, but had limited scale of accidents cut by 25%, and slightly lower energy cut by 40%. The proposed system gives better economical solution taking into account energy utilization and safety aspect into consideration ("Good Practices in City Energy Efficiency: Los Angeles, USA - LED Street Lighting Retrofit," n.d.).

As a result of the comparative analysis, the effectiveness of the proposed smart street lighting system appears to be higher than the effectiveness of several similar existing systems both in energy saving and in accident prevention. The use of motion sensors, ambient light detectors, and machine traffic prediction is adequate to undertake street lighting as a tool for improving efficiency of city structures.

5. CONCLUSION

The research shows that the conventional lighting of streets although functional adds a lot of convenience regarding energy consumption and servicing. Smart street lights which incorporate IoT solutions provide an answer for exploiting energy in the right way, minimizing the operating expenses, and increasing security. The findings show that through the use of sensors and adaptive lighting, the brightness of the roadway can be controlled based on environmental factors and recorded pedestrian actions and leading to considerable efficiency in terms of energy use.

Further, the incorporation of smart technologies such as solar and motion detection systems makes these systems green and feasible to operate without assistance from the utility grid. The proposed paper also briefly addresses the expandability of these systems suggesting that with adequate backbone and government buy in smart street lighting could become the next wave of urban infrastructure. Yes, one can point to some drawbacks like the high costs of initial investments or the requirement for technological updates constantly, but long-term benefits in terms of both, economy and environment make smart lighting systems some of the best choices urban municipalities can make for their citizens today.

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