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Evaluation of a Traffic-Aware Smart Highway Lighting System

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Abstract

Highway lighting consumes considerable amounts of energy, yet smart lighting techniques provide significant potential for reducing this consumption. This paper introduces a preliminary algorithm, simulation studies and a small-scale hardware prototype for a smart highway lighting management system based on road occupancy. Wireless Sensor Network (WSN) detects the presence of vehicles along the road, and controls lighting accordingly. The system is evaluated through two different simulation studies: using a realistic model for vehicles traffic based on cellular automata (Nagel-Shreckenberg model), and using state-of-the-art Simulation of Urban Mobility (SUMO) traffic simulator. Simulations provide estimation for expected energy saving rates at different cases and scenarios. According to simulation results, the proposed system can save up to 57.4% of power consumption compared to conventional lighting systems.

Keywords: Smart Highway Lighting, Energy Saving, Wireless Sensor Network, Traffic Modeling, Traffic Simulation.

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1. Introduction

Optimization of highway lighting is essential, as it represents a significant portion of energy consumption in modern cities, especially in densely populated and industrial countries. The scheme of “full night-lights, constant illumination lighting” is used in most of street lighting systems, which not only causes much energy waste, but also loss of lamp life, as not all the road is occupied with vehicles during operation time.

One of smart street lighting techniques is controlling street lighting upon road occupancy. When there is less traffic in the road, some lamps can be turned off or dimmed, and the system can still meet the lighting requirements, saving energy and also ensuring traffic safety. The integration of this methodology with other smart lighting techniques can ensure outstanding energy saving levels.

This paper introduces a preliminary algorithm, simulation studies and a small-scale hardware prototype for a smart highway lighting system based on road occupancy. The proposed system uses Wireless Sensors Network (WSN) to detect the presence of vehicles along the road. According to occupancy of the road, the system determines whether to switch on, switch off or dim specific number of lamps. The whole road is divided into sections; when a section is occupied with vehicles, it will be illuminated; otherwise, the lamps will be turned off or dimmed.

The system is evaluated through two different simulation studies: using a realistic model for vehicles traffic based on “Nagel-Shreckenberg” cellular automata (CA) model, and using state-of-the-art Simulation of Urban Mobility (SUMO) traffic simulator; expanding our study in [1] which presented the CA model-based simulation only.

SUMO-based simulation is used to add more realistic traffic conditions and scenarios which are not covered in the CA model-based simulation and to study the impact of these conditions on our system performance evaluation. Both simulations provide estimation for expected energy saving rates. A comparison between the results of both simulations is presented as well.

The rest of this paper is organized as follows: Section 2 highlights some of the related literature. The main idea and structure of our system is discussed in Section 3. Section 4 introduces the CA model-based simulation study and the obtained results. Section 5 introduces SUMO-based simulation study and compares it with the previous simulation. A small-scale hardware prototype for our system is represented in Section 6. Finally, Section 7 concludes the paper and highlights our future work.

2. Related Literature

Many studies have been proposed in the field of smart street lighting, introducing various techniques and strategies to reduce energy consumption of street lighting systems, yet meeting traffic safety needs [2][3]; traffic occupancy adaptive street lighting is one of these strategies.

In their work, S. Lau et al. [4] proposed an adaptive lighting scheme based on traffic sensing, which adaptively adjusts streetlight brightness based on current traffic conditions. The intelligent streetlight inspects whether or not any road users are within its sensing radius. Once road users are detected, their distance to the lamppost is computed and the brightness level is controlled accordingly. In [5], they also proposed a simulation environment for their system "StreetlightSim", combining OMNeT++ and SUMO tools to model both traffic patterns and adaptive networked street lights.

Another traffic adaptive street lighting automation technique is proposed by E. Nefedov et al. [6]. The proposed algorithm utilizes a sensing model that is based on segmenting the roadway into sensing zones*;* each zone is monitored by one vehicle sensor. The system is simulated by implementing CA traffic model through integration of Matlab with IEC 61499. In [7], simulation scenario is extended taking into consideration bi-directional traffic and pedestrians. However, this work only studies the energy consumption as a function of probability of vehicles or pedestrians entering the road, and it doesn't utilize simulation to acquire more meaningful analytical data on system performance and design aspects.

The novelty of our work consists in providing a methodology for using CA traffic flow model to simulate the behaviour of a simple algorithm for traffic occupancy adaptive smart highway lighting system, and verifying this methodology through comparing its results with results obtained from a well-known traffic simulation tool (SUMO). This methodology provides estimation for energy saving rates expected from the system when applied in real life, as well as other useful analytical data.

The results of the CA model-based simulation were found to be consistent with the results of SUMO-based simulation. This means that CA model is efficient in capturing traffic flow properties despite its simplicity compared to SUMO. The same methodology can be very useful in simulating traffic-related solutions, such as Vehicular Cloud Computing (VCC) and Vehicle-to-vehicle communication (V2V) technologies.

3. Switchable Lighting Algorithm

The idea of our proposed system is based on dividing the road into sections; each section represents the distance between two successive light poles. WSN node is attached to each pole; including a sensor to detect vehicles presence, and a wireless transceiver for communication between nodes.

When a section is momentarily unoccupied with vehicles, the lighting pole on the head of this section is turned off or dimmed; otherwise, the lighting pole will be working in full capacity, as shown in figure 1.

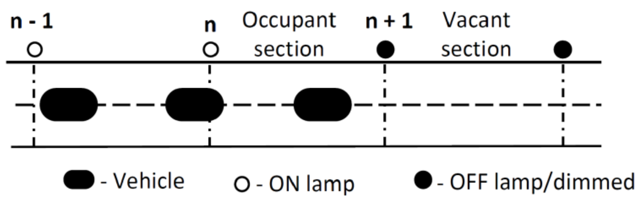

Figure 1. Nodes distribution along road

The concept of presence detection depends on counting the number of vehicles occupying a section continuously. Each section has two nodes on its terminals, one responsible for controlling its corresponding lamp, and the other responsible for controlling the next lamp. When a vehicle enters a section "n", the first node increments the counter "C_n" by 1, and when the vehicle leaves the section and enters the next one, the second node decrements the counter "C_n" by 1. Lamp turns off or dims only when counter is equal to 0 (i.e. section is unoccupied). The same process is repeated along the road for all sections. A flowchart for the mentioned process is shown in figure 2.

This distributed control approach is more efficient and reliable than more centralized approaches [8][9]. When a node fails, it will have a very limited effect on the whole system (i.e. the preceding section and succeeding section only). This also insures less complexity in communication between nodes.

The data collected by WSN nodes, representing number of vehicles in each section, can be very valuable in monitoring traffic status along the road. Each node can be equipped with a remote communication module (e.g. GPRS module) to send this data to a central traffic monitoring and control server.

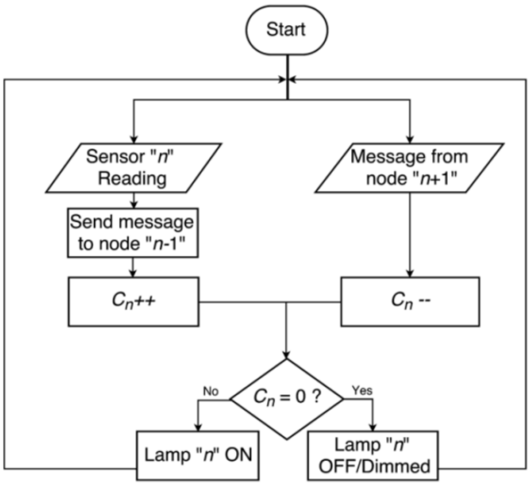

Figure 2. Flowchart for node process.

4. CA model-based Simulation

Modeling and simulation are essential procedures when implementing a novel solution, especially when the simulated model involves numerous variables including random ones. This is the case with our intelligent lighting system methodology.

In order to simulate smart lighting system based on road occupancy, a realistic model for traffic flow is a necessity. It is crucial to build a model for traffic flow that captures the characteristics of real traffic, yet sufficiently simple to allow efficient numerical treatment.

The best way to realize a traffic model on computer is discretization of continuous quantities. Continuous analogue numbers could be treated at user programming level by software, but there would be considerable performance degradation [10].

4.1 Mathematical Model

Our first simulation study is based on the pioneering "Nagel-Shreckenberg" cellular automata (CA) discrete model for traffic simulation [11]. More developed and complex versions of this model can be used to provide modeling for more traffic conditions and scenarios [12].

The "Nagel-Shreckenberg" model is defined on a one-dimensional array of L sites and with open boundary conditions. Each site may either be occupied by one vehicle, or it may be empty. Each vehicle has an integer velocity with values between 0 and v_{max}. For an arbitrary configuration, one update of the system consists of the following four consecutive steps, which are performed in parallel for all vehicles:

1. **Acceleration:** if the velocity v of a vehicle is lower than $v_{\max}$ and if the distance to the next car ahead is larger than $v + 1$, the speed is advanced by one [$v \to v + 1$].
2. **Slowing down** (due to other cars)**:** if a vehicle at site i sees the next vehicle at site $i + j$ (with $j \leq v$), it reduces its speed to $j – 1$ [$v \to j - 1$].
3. **Randomization:** with probability p the velocity of each vehicle is decreased by one [$v \to v - 1$].
4. **Car motion:** each vehicle is advanced v sites.

This model was mainly used to simulate traffic in single-lane ring (closed system) or bottleneck situation. To make the model suitable for highway traffic simulation, we use bottleneck situation as following:

5. When the leftmost (site 1) is empty, we occupy it with a car of velocity zero.
6. At the right site (i.e. the end of the street), we delete cars on the right most six sites, thus producing an open boundary [11].

These rules are repeated each time sample of simulation. By the end of the simulation, we have a two-dimensional matrix expressing traffic characteristics through definite road length and simulation time, as shown in figure 3. Thus we can use this matrix to simulate the behaviour of our smart lighting system accordingly. When a section (i.e. number of consecutive cells) is empty, the light pole corresponding to it is turned off or dimmed (see section 3).

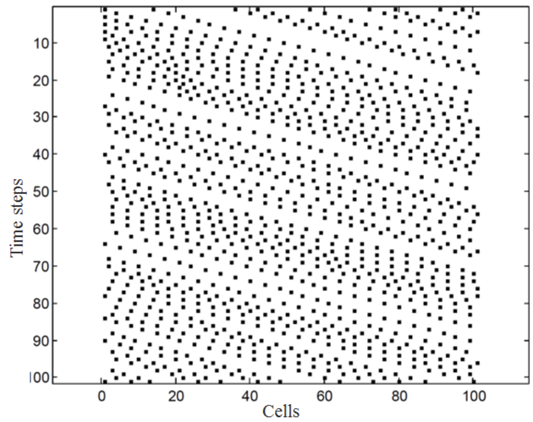

Figure 3. 100 x 100 cells from traffic matrix, each empty cell is represented as a white pixel, and each occupant cell is represented as a black pixel.

By the end, we will have a new matrix representing the status of each light pole per time sample. This matrix is analysed to get estimated energy saving levels and other system parameters. This procedure is repeated for different scenarios and cases (i.e. different spacing between light poles, different dimming levels, etc.).

4.2 Simulation Setup

The model discussed above was implemented in MATLAB, using a PC with Intel Core-i7 2.00GHz processor, and 8.00GB of RAM. The following parameters were used:

- L (road length) = 4000 cell. Each cell represents 7.5 m, which is the space occupied by a single vehicle in complete jam [11]. Thus:

$$Roadlength = 7.5m \times 4000\ cell = 30km \tag{1}$$

- v_{max} (maximum velocity) = 4 cells/time sample (110 km/h).
- p (probability of each vehicle to decrease its velocity by 1) is 0.2 with uniform distribution. The deceleration rate depends on the road condition and also on the skill and personality of driver [10].
- T_s (time of sample): as the length of one cell is 7.5m, and maximum velocity (v_{max}) is assumed to be 110 km/h, which is common speed limit in highways, we can deduce time for one sample[11]:

$$1\ \text{hr} \rightarrow 110\ \text{km}$$
$$T_s \rightarrow 7.5\ \text{m} \times v_{max}$$

$$T_s = 7.5\ \frac{m}{cell} \times 4\ \frac{cell}{time\ sample} \times \frac{60 \times 60}{110 \times 1000}\frac{s}{m} \approx 1 \frac{s}{time\ sample} \tag{2}$$

- T (total simulation time): total number of samples is 40000, representing 40000s (i.e. approximately 11 hrs.).
- ρ (traffic density): initial density is assumed to be 0.15 car/cell. However, density changes w.r.t. time due to the open boundary conditions assumed in simulation. After simulation, density was found to have decreased reaching a mean value of 0.106 car/cell.
- N (number of light poles): equals to number of sections, as each section has 1 light pole.

$$N = 4000\ cell\ \div 4\ \frac{cell}{section} = 1000\ section \tag{3}$$

- h (section length): section length is the distance between two consecutive light poles. Simulation is repeated for different values of h (4, 5 cells), and for treating each two consecutive poles as one section (i.e. h = 8, 10 cells).

The discussed parameters are summarized in table 1.

Table 1. Simulation parameters.

Parameter	Value
Fixed parameters	
L (road length)	4000 cells
v_{max} (maximum velocity)	4 cells/time sample (110 km/h)
p (deceleration probability)	0.2
T_s (time of one sample)	1 s
T (total time)	40000 s
ρ (initial density)	0.15 car/cell
Variable parameter	
h (section length)	4, 5, 8, 10 cells

4.3 Simulation Results

Energy Saving

Before applying the smart lighting system, lamps are ON during the whole operation time, but after applying the system, some lamps will be OFF/dimmed when their sections are empty. Thus the energy saving factor E_o is the ratio between the sum of number of OFF lamps per second after applying system $n(t)$,and sum of number of ON lamps per second, before applying system (i.e. all lamps = N). In figure 4,$n(t)$ is plotted against time for section length h = 4 cells.

Equation (4) calculates the energy saving factor E_o:

$$E_o = \frac{\sum_{t=1}^{T} n(t)}{N \times T} \tag{4}$$

When simulation was performed according to mentioned parameters at h = 4 cells, energy saving factor appeared to be (57.4%), assuming that the lamp will be turned OFF when its section is vacant. This ratio indicates the energy saving achieved after applying the system to conventional lighting systems.

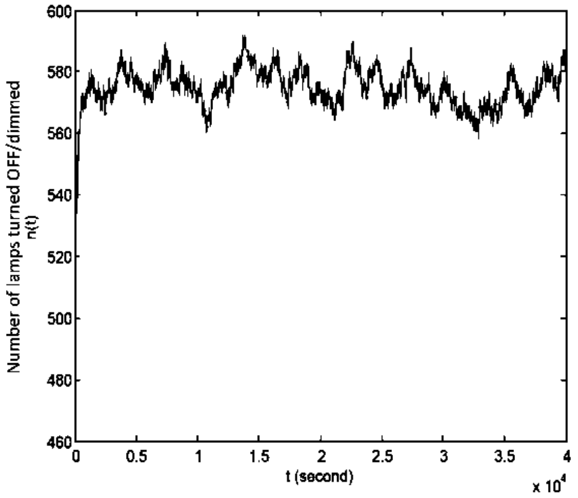

Figure 4. Number of OFF/dimmed lamps *n(t)* plotted against time (s), at *h* = 4 cells.

If lamps are dimmed instead of being turned OFF, the energy saving factor will decrease according to dimming level *D*, knowing that the ratio of LED dimming and energy saving is roughly 1:1 [13]. For example, if lamps are dimmed by 50% instead of being turned OFF, energy saving factor decreases by 50% accordingly, so energy saving factor is (28.7%).

However, the dimming approach seems to be more eligible in practice; taking into account the necessity of providing the driver with sufficient lighting ahead, to ensure safety measures and driver's comfort, as well as the lighting condition of road's neighbourhood. According to [14], an experimental study showed that such approach meets perceived personal safety needs of the experiment participants.

Equation (5) calculates the energy saving factor when lamps are dimmed *E*:

$$E = \mathrm{D} \times \frac{\sum_{t=1}^{T} n(t)}{N \times T} \quad (5)$$

Simulation was repeated for different section lengths *h* (other parameters unchanged) to study the effect of changing section length on energy saving. When section length (i.e. the separation between two consecutive light poles) was changed to 5 cells (37.5 m), energy saving factor decreased to (46.7%).

Simulation was also repeated for treating every two consecutive light poles as one section (i.e. section length is 8 cells and 10 cells), energy saving factor appeared to decrease at (21%) and (11.6%) respectively.

Figure 5 shows that increasing section length has negative impact on energy saving, which is logical, as increasing section's length means that section is less likely to be unoccupied with vehicles, which means that lamps are less likely to be turned OFF or dimmed.

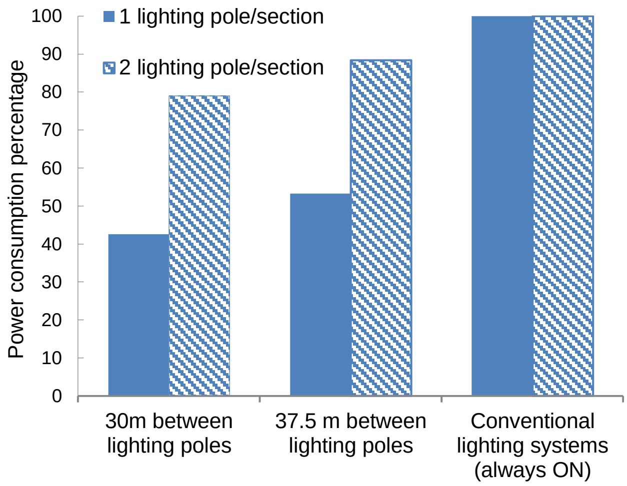

Figure 5. Energy consumption rates before and after applying the system.

Lamp Switching Frequency

When simulation was performed with the initial parameters, lamps appeared to be changing their state (ON/OFF or dimmed) with a mean frequency *f* of 0.70Hz, which means that the lamp will change its state 42 times per minute. This can only be implemented with systems that use LED lamps with very fast on/off response times [15].

When simulation was repeated for different section lengths *h* (5, 8, 10 cells), mean lamp switching frequency *f* was found to be 0.60, 0.28, 0.16Hz respectively. This shows that when increasing section length, there is a trade-off between energy saving factor *E* and lamp switching frequency *f*, as shown in table 2.

Table 2. Energy saving factor and mean lamp switching frequency for different section lengths.

h (Section length)	E_o (Energy saving factor)	*f* (Lamp switching frequency)
4 cells	57.4%	0.70Hz
5 cells	46.7%	0.60Hz
8 cells	21.0%	0.28Hz
10 cells	11.6%	0.16Hz

The mentioned results, as well as more results that can be obtained for other system parameters, can play an important role in design and optimization of smart lighting systems, as they give an indication for system's performance in various cases and scenarios.

5. SUMO-based Simulation

Extending our study, we have introduced another simulation for our system, based on Simulation of Urban Mobility (SUMO) traffic simulator. SUMO is an open source traffic simulation package including the simulation application itself as well as supporting tools, mainly for network import and demand modeling [16]. SUMO provides more realistic and sophisticated traffic scenarios than the CA traffic simulation introduced earlier; such as: real topologies from geographical locations, multi-lane traffic flow, heterogeneous traffic using different types of vehicles, etc.

A real geographical location was used in our scenario, covering approximately 10 km of 4-lane highway, as shown in figure 6. Two types of vehicles were used with different maximum speeds of 110 km/h and 70 km/h, with ratio of 5:1 respectively. The simulation was repeated at different traffic flow rates and different section lengths (see section 4). Simulation time step is 1 s, and the total simulation time is 2 h of traffic flow. Simulation parameters are summarized in table 3.

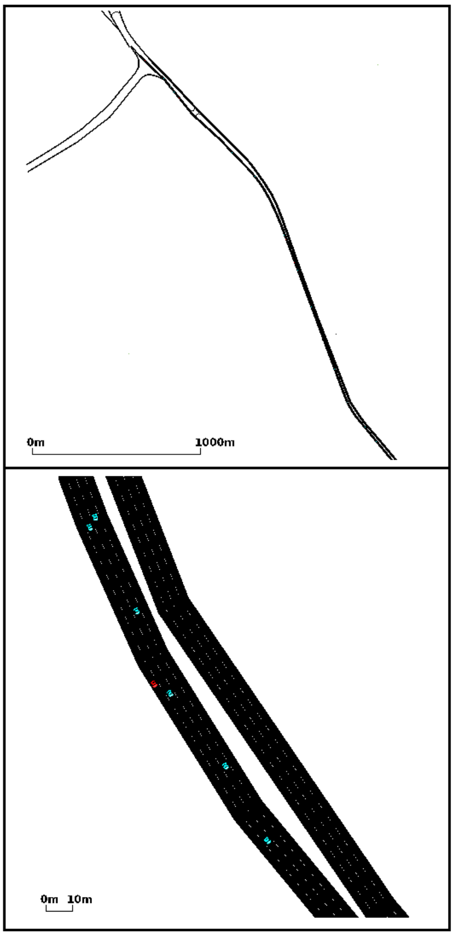

Figure 6. Screenshots for our scenario from SUMO GUI

Table 3. SUMO-based simulation parameters

Parameter	Value
Fixed parameters	
Road length	20 km
Maximum speed	110 , 70 km/h
Time step	1 s
Total time	2 h
Variable parameters	
Section length	30 – 80 m
Traffic flow rate	600 – 3800 vehicle/h

The XML file generated from simulation is parsed and analyzed using Python script to implement our switchable lighting technique on the simulated road, and to calculate results at different cases. These results are also compared with results from the previous CA model-based simulation.

Figure 7 shows the effect of changing section length on power saving rates (in case of turning OFF) for both CA model-based simulation study and SUMO-based study. For a valid comparison, a realistic probabilistic traffic flow demand was configured for SUMO resembling the traffic flow of the CA model. A flow of 1 vehicle/s and 0.2 vehicle/s of the two types of vehicles is introduced respectively. Section length is swept from 30 m to 80 m.

The results show that increasing section length has negative impact on energy saving as shown before in section 4. The results from SUMO-based study are found to be consistent with the results from the CA model-based simulation.

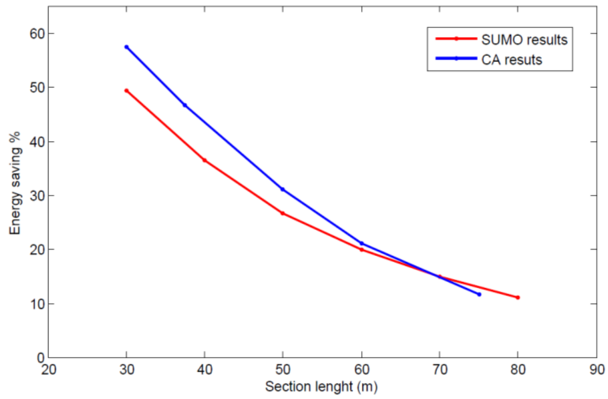

Figure 7. Energy saving % plotted against different section lengths

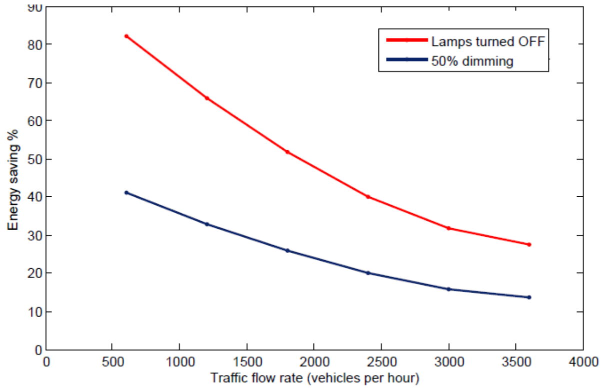

Figure 8. Energy saving % plotted against traffic flow rates

Figure 8 shows the effect of increasing traffic flow rate on energy saving rates, at fixed section length of 30 m, in both cases of turning OFF and dimming with ration of 50%. Traffic flow rate is swept from 600 vehicle/h to 3600 vehicle/h. The results show that energy saving factor decreases with the increase of traffic flow rate, as sections become less likely to be vacant. For example, the power saving ratio in case of 50% dimming at 1800 vehicle/h, which is a realistic flow rate, is 25.8%.

6. Hardware Prototype

A preliminary hardware prototype was implemented as a proof of concept. The prototype consists of 3 nodes, forming two sections. Node components are: 1) Arduino Nano microcontroller. 2) NRF24L01 radio frequency transceiver, operating at 2.4 GHz. 3) HC-SR04 ultrasonic sensor for vehicles detection. Each node controls a simple LED lantern; LEDs can be turned ON/OFF or dimmed. Dimming is done using pulse width modulated (PWM) Arduino output and a simple relay circuit. Nodes are assigned unique identifiers to ensure node-to-node communication, and each node acts as section's vehicles counter as shown in Figure 9. Figure 10 is taken from a live demonstration of the prototype in Faculty of Engineering, Alexandria University.

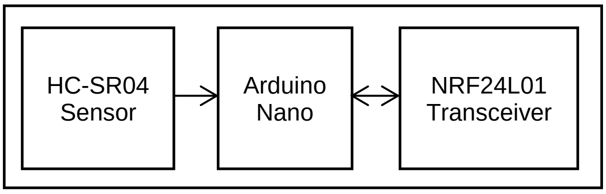

Figure 9. Node block diagram

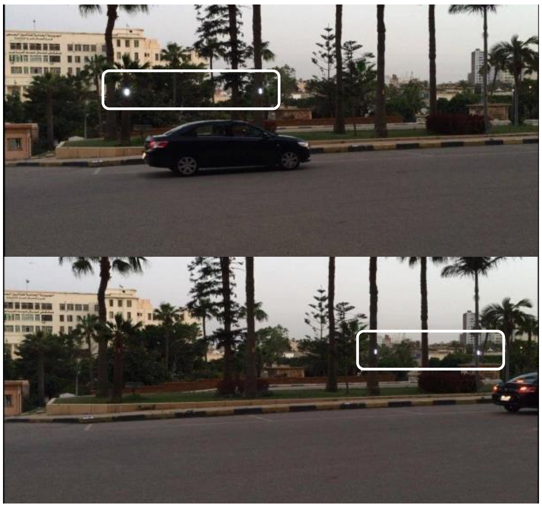

Figure 10. Prototype live demonstration

7. Conclusion

In this paper, a preliminary algorithm for a smart highway lighting system has been introduced. The system was evaluated through two different simulation studies: using a realistic model for vehicles traffic based on cellular automata (Nagel-Shreckenberg model), and using SUMO traffic simulator.

The concept of utilizing discrete traffic flow CA model for smart lighting system simulation has shown its effectiveness in giving estimation for system performance. The results of the CA model-based simulation were found to be consistent with the results of SUMO-based simulation. This means that CA model is efficient in capturing traffic flow properties despite its simplicity compared to SUMO. A small-scale hardware prototype was demonstrated as well.

Simulation results were obtained for energy saving rates at various studied scenarios. Obtained results were used for leveraging the capability of having optimized system design, reaching up to 57.4% of hypothetical energy saving rates.

Our future work includes adapting the same methodology for simulating traffic and resources management in highly dynamic environments, such as Vehicular Cloud Computing (VCC) and Vehicle-to-Vehicle (V2V) communication. Additionally, we target employing our proposed methodology in our previous work [17] for enhancing data routing and forwarding based on predicting on runtime locations of mobile resources adopting data semantics reasoning techniques as presented in [18].

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