Towards a Smart Highway Lighting System Based on Road Occupancy: Model Design and Simulation

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Abstract. Energy saving is a major aspect of smart cities, so optimizing highway lighting is essential, as it consumes considerable amounts of energy. However, there is a remarkable potential for reducing this consumption through smart lighting techniques. This paper introduces preliminary design and simulation for a smart highway lighting management system based on road occupancy. Wireless Sensors Network (WSN) detects the presence of vehicles along the road, and controls lamps accordingly. The system is simulated and optimized using a realistic probabilistic model for vehicles traffic, taking the advantage of simulation to provide estimation for expected energy saving rates; in contrary to previous works depending only on rough calculations or real-time results after implementation. According to simulation results, the proposed system can save up to 57.4% of power consumption compared to conventional lighting systems.

Keywords: Smart cities · Smart highway lighting · Energy saving · Wireless sensors network · Traffic modeling · Traffic simulation

1 Introduction

Smart cities-oriented research, towards green computing and information technology, attracts large number of researchers nowadays. One of the main challenges in smart cities is developing smart traffic and lighting management systems, saving more energy and minimizing polluting emissions.

It's essential to optimize highway lighting in smart cities, as it represents a significant portion of energy consumption, especially in densely populated and industrial countries. In the United States for example, 51TWh were consumed in roadway lighting in 2010 [1].

In conventional lighting systems, light was switched on at dusk and switched off at dawn by manual operation, and then smart controller was used to switch street lighting on and off automatically, based on sunrise/sunset times or light intensity of controller surroundings [2]. Most of city street lights use the pattern of "full night-lights, constant illumination lighting", which not only causes much energy waste, but also loss of lamp life [3].

E. Sucar et al. (Eds.): AFI 2016, LNICST 179, pp. 22–31, 2017.
DOI: 10.1007/978-3-319-49622-1_4

In highways, energy is wasted in lighting the whole road continuously, 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 [4] will ensure outstanding energy saving levels.

This paper introduces preliminary design and simulation 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 simulated and optimized using a realistic probabilistic model for vehicles traffic, including various traffic conditions. Simulation is based on "Nagel-Schreckenberg" discrete model for road traffic simulation [5].

The novelty of this work consists in providing a methodology for using traffic flow model to simulate the behavior of a smart highway lighting system. This methodology provides estimation for energy saving rates expected from the system when applied in real life, as well as other useful analytical data; in contrary to previous works which depend on rough calculations or real-time results after implementation [6, 7]. The same methodology can be very useful in simulating traffic-related solutions, such as Vehicular Cloud Computing (VCC) and Vehicle-to-vehicle (V2V) technologies.

The rest of this paper is organized as follows: Sect. 2 discusses the main idea and structure of our system. Section 3 introduces the mathematical model used for simulation. The simulation setup and the obtained results are presented in Sect. 4. Finally, Sect. 5 concludes the paper and highlights our future work.

2 Main Concept

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 Fig. 1.

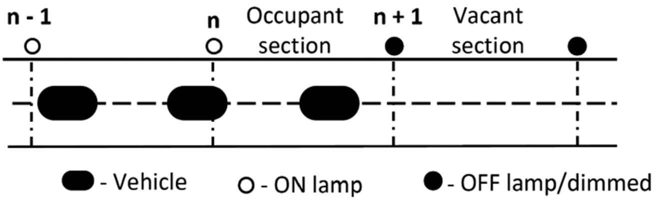

Fig. 1. Nodes distribution along road.

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 "$C\text{-}_n$" by 1, and when the vehicle leaves the section and enters the next one, the second node decrements the counter "$C\text{-}_n$" 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 Fig. 2.

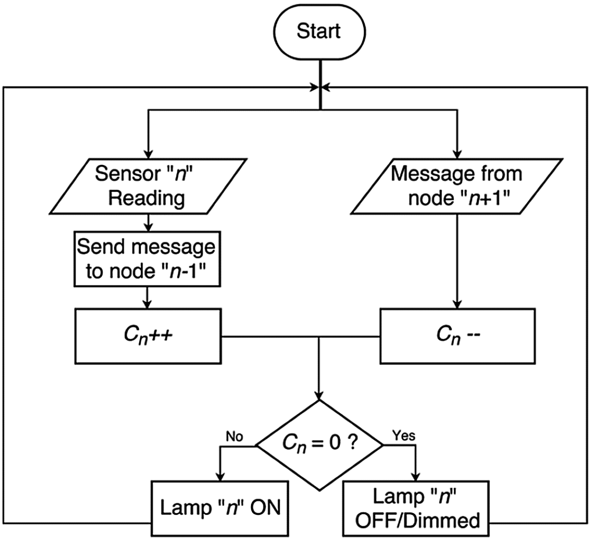

Fig. 2. Flowchart for node process.

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.

3 Mathematical Model

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's 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].

Our simulation is based on the pioneering "Nagel-Shreckenberg" cellular automaton discrete model for traffic simulation. More developed and complex versions of this model can be used in future work to provide modeling for more traffic conditions and scenarios [11].

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 [$v \rightarrow v + 1$].
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 $j - 1$ [$v \rightarrow j - 1$].
3. **Randomization:** with probability p the velocity of each vehicle is decreased by one [$v \rightarrow v - 1$].
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:

1. When the leftmost (site 1) is empty, we occupy it with a car of velocity zero.
2. 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 [5].

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 Fig. 3. Thus, we can use this matrix to simulate the behavior 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 Sect. 2).

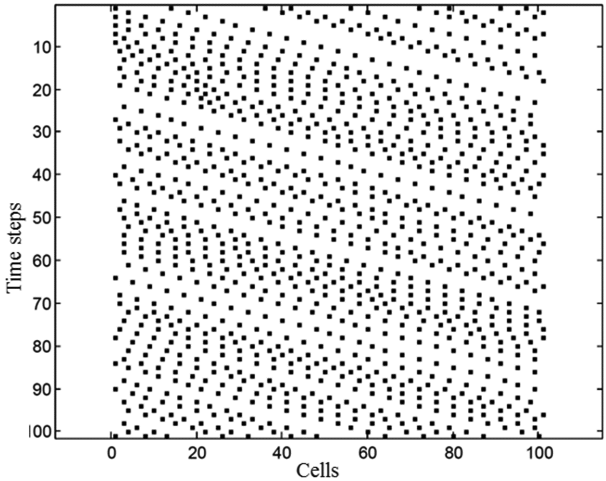

Fig. 3. 100 × 100 cells from traffic matrix, each empty cell is represented as a white pixel, and each occupant cell is represented as a black pixel.

By the end, we will have a new matrix representing the status of each light pole per time sample. This matrix is analyzed 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 Simulation

4.1 Simulation Setup

The model discussed above was implemented in MATLAB, using a PC with Intel Core-i7 2.00 GHz processor, and 8.00 GB 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 [5]. Thus:

$$Road\ length = 7.5\,m \times 4000\,cell = 30\,km \tag{1}$$

- $v_{\max}$ (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 7.5 m, 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 [5]:

$$1\,hr \rightarrow 110\,km$$

$$T_s \rightarrow 7.5\,m \times v_{\max}$$

$$\therefore T_s = 7.5\frac{m}{cell} \times 4\frac{cell}{timesample} \times \frac{60 \times 60}{110 \times 1000}\frac{s}{m} \approx 1\frac{s}{timesample} \quad (2)$$

- T (total simulation time): total number of samples is 40000, representing 40000 s (i.e. approximately 11 h.).
- 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.

$$N = 4000\,cell \div 4\frac{cell}{section} = 1000\,section \quad (3)$$

- 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

4.2 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 Fig. 4, $n(t)$ is plotted against time for section length $h = 4$ cells.

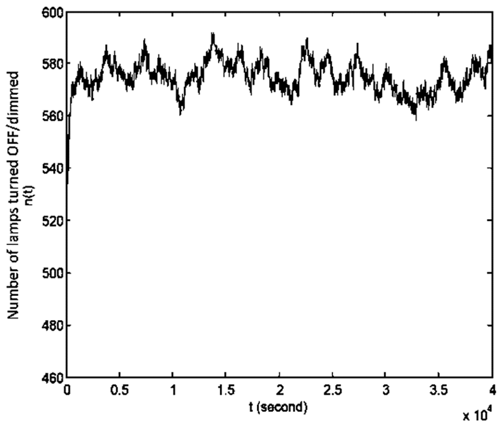

Fig. 4. Number of OFF/dimmed lamps *n(t)* plotted against time (s), at $h = 4$ cells.

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.

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 [12]. 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 neighborhood.

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

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

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.

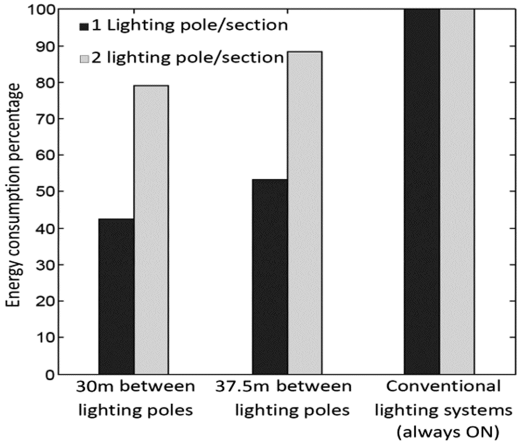

Fig. 5. Energy consumption rates before and after applying the system.

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 0.70 Hz, 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 [13].

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, 0.16 Hz 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 differnt section lengths.

h (Section length)	E_o (Energy saving factor)	f (Lamp switching frequency)
4 cells	57.40%	0.70 Hz
5 cells	46.70%	0.60 Hz
8 cells	21.00%	0.28 Hz
10 cells	11.60%	0.16 Hz

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 Conclusion

In this paper, a preliminary design for a smart highway lighting system has been introduced. The system was simulated using a realistic probabilistic model for vehicles traffic, including various traffic conditions. Simulation is based on "Nagel-Schreckenberg" discrete model for road traffic simulation.

The concept of utilizing discrete traffic flow model for smart lighting system simulation has shown its effectiveness in giving estimation for system performance. Our simulation results were obtained for energy saving rates, as well as other system parameters 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 resource management in highly dynamic environments, such as Vehicular Cloud Computing (VCC) and Vehicle-to-vehicle (V2V) communication. More mature and complex versions of the traffic model can be developed to provide efficient modeling for more traffic conditions and scenarios as well (e.g. considering multi-lane road traffic).

Acknowledgment. This work is a part of a graduation project at Department of Electrical Engineering, Faculty of Engineering, Alexandria University. We would like to thank all members of the team which yielded this research (Abdullah Nasser, Abdullah Fathy, Ahmed M. Samy, Ayman M. Abdel-Nasser, Ayman Adel and Amr Youssry). We would like also to thank the SmartCI research center at Faculty of Engineering, Alexandria University, Egypt for their support.

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