Comparisons of Energy-saving Strategies for Parking Garages Based on Smart Lighting Systems

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Abstract
In the context of increasingly pressing global energy issues, the lighting energy efficiency of large urban parking lots is gradually becoming a focal point of interest in building energy conservation. This study delves into energy-conserving approaches for parking garage illumination, specifically examining traditional, sensor-based, and parking space allocation methods. In sensor-based mode, the lights turn on when a vehicle arrives in the parking lot. In allocation mode, a target parking spot is assigned to the vehicle, and the lights along its path are illuminated. Through simulation experiments conducted on a prototypical garage, it is found that sensor-based and parking space allocation modes exhibit superior energy efficiency compared to the traditional mode, while maintaining functionality. These findings suggest the potential for wider adoption of these advanced strategies.
Keywords:
parking garage, energy-saving strategies, smart lighting system, parking space allocation, simulation experiment

1. Introduction

Parking lots are essential components of urban life, making their energy consumption a critical issue that cannot be overlooked. Currently, many parking lots utilize round-the-clock lighting, leading to significant energy waste. According to a study conducted in mainland China, the majority of energy consumption in underground parking lots is attributed to lighting. Furthermore, in cases where no lighting energy-saving measures are implemented, 80% of the lighting is ineffective, as there are no pedestrians or vehicles passing by[1]. In the context of global efforts toward energy conservation and carbon reduction, mitigating lighting energy consumption while satisfying parking garage requirements has emerged as a significant challenge in contemporary architectural energy conservation. This paper addresses this challenge by examining potential solutions through simulation experiments on various energy-saving strategies for parking garage lighting.

2. Strategies chosen for simulation experiment

To curtail the energy consumption of parking garage lighting, three prevalent modes are currently employed:

a) Mode 1: traditional mode

The most common and straightforward method for conserving energy in parking garages involves adjusting the number of active lights. Typically, lights are intermittently illuminated, maintaining uniform lighting conditions without necessitating structural modifications to the garage. However, this approach reduces light output by half, resulting in a dimmer environment than initially designed, which may impede vehicle usage. Moreover, manual operation by garage personnel is usually required, placing a significant burden on them and prompting some garages to remove half of their lights outright, leading to inadequate illumination [2].

b) Mode 2: sensor based mode

In this mode, sensors linked to the lights are installed in the garage to automatically determine the usage status of lighting fixtures based on vehicle or pedestrian activities. This mode is also the main method adopted in energy-saving renovation projects for parking garages[3,4,5]. This mode does not require extensive rewiring of the garage but replaces traditional lights with smart lights that can be controlled via a wireless mesh network, allowing for flexible and targeted energy-saving lighting in the garage.

c) Mode 3: parking space allocation mode

The primary objective of parking space allocation is to mitigate congestion in large parking garages during peak hours by predetermining parking spaces for each entering vehicle and employing parking guidance algorithms to provide each vehicle with the most efficient route, thereby reducing congestion resulting from vehicles repeatedly searching for parking spaces. This approach can also efficiently regulate lighting conditions based on the specific movements of vehicles, resulting in significant energy-saving benefits for garage lighting. Presently, this approach has been successfully implemented in projects like the Shenzhen Children's Hospital, yielding positive outcomes [6]. Given the future outlook of widespread adoption of autonomous driving technology, this approach holds promising prospects for further application.

3. Experimental Design

This paper conducts simulation experiments on the aforementioned three modes for typical parking garage scenarios to compare and analyze the strengths and weaknesses of each.

3.1 parking garage:

The parking garage utilized in the experiment is depicted in Figure 1. Situated on the second basement floor of an office building in Guangdong Province, China, it comprises 64 parking spaces, all allocated for internal use by the office building. The garage features a reinforced concrete frame structure covering an area of 2351.22 square meters, with dimensions of 52.6 meters in length, 44.7 meters in width. Column spacing measures 8.4 meters and 5.5 meters.

3.2 Vehicles:

All vehicles are standard cars, accessing the upper floors via left car ramps. Vehicle speed adheres to the relevant national standards, set at 20 km/h [7]. Vehicles follow a unidirectional driving trajectory in accordance with the driveway guidance lines depicted in Figure 1. Parking spaces are all perpendicular parking, and the time required for reverse parking is set according to reference data, with a duration equivalent to the median value of 61.59 seconds for manual reverse parking [8].

3.3 Personnel:

As the garage solely serves parking functions, personnel arriving at the garage are presumed to arrive by car at their designated parking spaces before proceeding to the elevator lobby via relatively short main lanes. For this garage, parking spaces 1-16/48-64 are accessed via the left lane, illuminated by lights o-n-m, while parking spaces 17-34 are accessed via the right lane, illuminated by lights f-g-h. Parking spaces 35-47 are accessed via the upper lane, illuminated by lights i-j-k-l. Personnel walking speed is set within the standard range of 3.2 to 5.43 km/h [9].

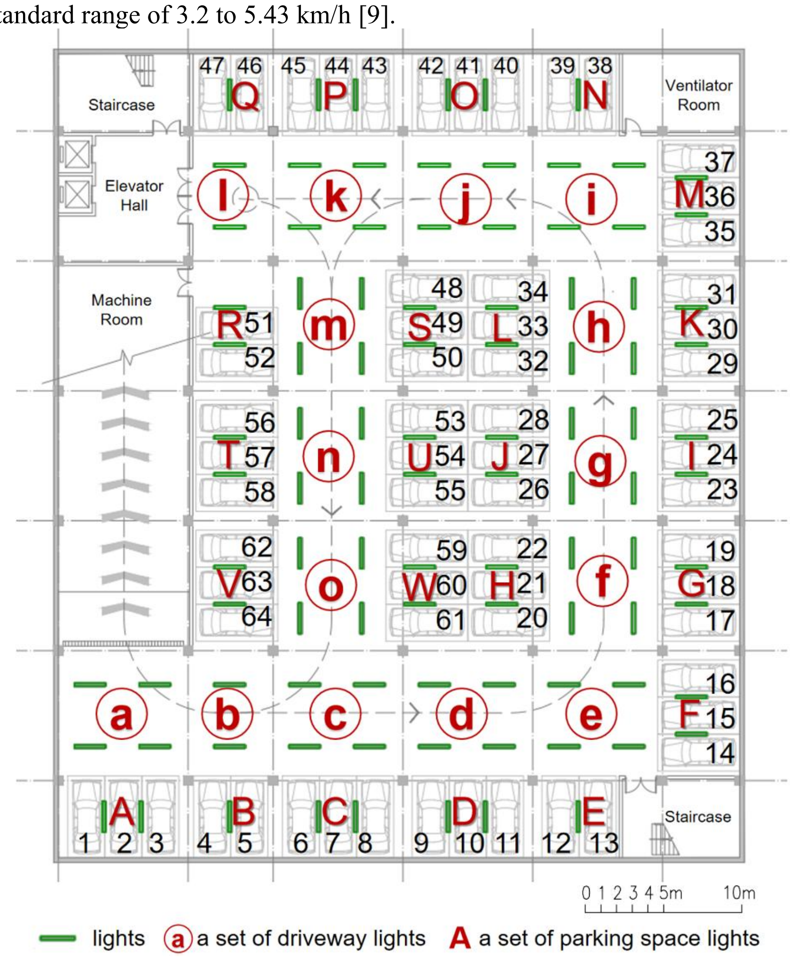

Figure 1: Typical parking garage Layout

3.4 Lights:

Lighting in the vehicle area comprises driveway lights and parking space lights. Driveway lights are arranged in two columns along the direction of vehicle movement, with 1-2 fixtures per column based on span size. These are radar sensing LED bracket lights, standing at a height of 2.4 meters from the ground and consuming 15w/h per light. The simulation experiments have verified that the requirements for illumination specified in the parking garage design standards can be met, specifically 50 lx for driveway illumination and 30 lx for parking space illumination[10]. Parking space lighting fixtures are arranged between parking spaces according to span size, with 1-2 fixtures per span. To optimize reverse parking conditions with bright lighting condition between column spans, each set of lights within each column span is organized into groups and numbered, totaling 15 groups for driveway lighting fixtures (labeled as a/b/c...o) and 23 groups for parking space lighting fixtures (labeled as A/B/C...V/W), as illustrated in Figure 1.

3.5 Experiment Period:

The experiment is conducted on a regular workday morning. Based on interviews and surveys with garage management personnel, the specified time interval spans from 6:00 to 12:00 in the morning. This time-frame is further segmented based on variations in vehicle entry frequency: 20% of vehicles enter from 6:00 to 7:59 (approximately 13 vehicles based on the total parking space count), 65% enter from 8:00 to 9:29 (approximately 42 vehicles, representing the peak morning period), 10% enter from 9:30 to 12:00 (approximately 26 vehicles), and the remaining 5% represents empty parking spaces (approximately 3 vehicles).

3.6 Lighting Modes:

Building upon the three primary lighting energy-saving modes for parking garages outlined in the preceding section, specific lighting configurations for each mode are established as follows:

a) Mode 1: traditional mode

Intermittently, half of the driveway lights are switched off. The number of parking space lights per group, initially set at 2, is reduced to 1, while those originally set at 1 remain unchanged. The lighting pattern remains constant irrespective of the time period.

b) Mode 2: sensor based mode

Both this mode and Mode 3 implement control of all lights in the garage via a wireless mesh network. The detailed lighting control strategy is as follows:

Vehicle and lighting demand: Throughout a vehicle's trajectory, timely illumination is essential in its current position and a certain distance ahead to facilitate driving decisions. According to relevant research, the minimum required front distance should be no less than 16.3 meters in this scenario [11]. Considering the garage layout provided in this experiment, with span sizes of 8.4 meters and 5.5 meters, and factoring in the proximity and fewer number of spans of 5.5 meters, for a single vehicle's trajectory, it can be assumed that this distance is consistently within three spans. When multiple route options are available, each path should offer adequate illumination.

Personnel lighting demand: Similar lighting criteria apply to pedestrians, ensuring illumination in the direction of travel to alleviate apprehension in dim areas. In this instance, the lighting standard for personnel is set to within three spans, with the shortest route leading toward the elevator lobby.

Lighting strategy: The trigger point for lighting fixtures occurs when each lane light group detects that a vehicle or pedestrian is about to enter its span. At this juncture, the lights within that group, as well as the lights in the subsequent two spans ahead of the vehicle's direction, are activated. Lane lights utilize full brightness or low brightness sensing (15 W/3 W), while parking space lights employ full brightness or full-off sensing control. The lighting delay requirement is set at 3 minutes during non-peak hours (6:00-7:59 and 9:30-12:00) and 5 minutes during peak hours (8:00-9:29), based on data from reference projects [12]. Considering the estimated speeds of vehicle movements and pedestrian walks, coupled with the span sizes, it is determined that 3 minutes is adequate to complete a series of vehicle actions within the span, such as passing through, entering, reverse parking, or exiting. Hence, 3 minutes and 5 minutes are adopted as the lighting delay strategies for this experiment, in line with the reference case.

c) Mode 3: parking space allocation mode

In this mode, each vehicle is assigned a predetermined parking space. To mitigate the impact of reverse parking in adjacent spaces on parking efficiency, the designated parking spaces are arranged based on the distances from each column of parking spaces to the elevator lobby. The lighting requisites for vehicles and pedestrians mirror those in the preceding mode, except that the vehicle's forward path no longer necessitates multiple options. The lighting strategy for lane lights aligns with that in the previous mode, whereas for parking space lights, only the lights at the location of the parking space need to be activated.

4. Simulation Experiment

4.1 Experimental Method

The experiment employs Excel for initial data compilation and Python for data input and calculation. The calculation process comprises the following steps:

① Based on the experimental design from the preceding section, determine the driveway and parking space lighting requirements for each vehicle selecting a parking space, and allocate the necessary lane and parking space lighting numbers to each parking space.

② Segment the three time periods into one-minute intervals, and randomly select the same number of time points as the number of entering vehicles in each period as the assumed entry time points for vehicles.

③ Assign each entering vehicle a destination parking space, randomly assigning the final distance from the elevator lobby for Mode 2, and sequentially assigning parking spaces based on the distance from each lane column to the elevator lobby for Mode 3.

④ Identify the time points for illuminating each light group for each entering vehicle, considering the lighting delay time of 5 minutes during peak hours and 3 minutes during non-peak hours, and input the data into the Python program. Using a greedy algorithm to identify overlapping time intervals, the actual lighting duration for each light group is calculated.

⑤ Calculate the total energy consumption for lighting based on each mode, and the situation where no energy-saving measures are taken is listed as the "Normal" mode in the first row for comparison, as shown in Table 1.

Table 1 Comparison of total lighting energy consumption for each mode

Mode	Driveway Lighting Duration (min)	Driveway Idle Duration (min)	Parking Spaces Lighting Duration (min)	Total Consumption (kW·h)	Energy Saving Ratio
Normal	20160	-	15120	8.82	100.0%
Halved	10080	-	8280	4.59	52.0%
Sensor	6620	13540	3990	3.33	37.7%
Allocation	6600	13560	337	2.41	27.3%

4.2 Analysis of Experimental Results

Based on the experimental findings, the following conclusions can be drawn: Mode 1 effectively conserves energy, but halving the number of light sources may impede garage usability, posing safety risks. Modes 2 and 3 exhibit superior energy-saving effects compared to Mode 1 without compromising garage functionality, suggesting broader adoption.

5. Conclusions

This study addresses the issue of wasted energy consumption due to ineffective lighting in parking garages, and through simulation experiments, compares the energy consumption metrics of three typical garage lighting energy-saving modes. It illustrates the significant energy-saving potential of implementing sensor based smart parking systems and parking space allocation systems, reaching 37.7% and 27.3% energy saving ration. While the latter demonstrates better energy-saving indicators than the sensor system, its current application is primarily in large garages with peak-hour congestion due to limited application scenarios. However, it is foreseeable that with the widespread adoption of autonomous driving technology, this approach can have a broader scope of application and contribute more substantially to garage lighting energy conservation.

The limitation of this study lies in analyzing lighting energy consumption based on vehicle behavior during working hours in a single-fire-zone office building parking garage. Further research is needed to refine scenarios involving multiple fire zones, multiple elevator lobbies, and pedestrian behaviors.

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