mathematics

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Simulation-Based Analysis for Verifying New Certification Standards of Smart LED Streetlight Systems

Seung-Wan Cho [1], Kyung-Min Seo [2,*], Jung-Min Yun [3] and Bong-Gu Kang [3,*]

1 Department of Industrial & Management Engineering, Hanyang University, 222, Wangsimni-ro, Seongdong-gu, Seoul 04763, Republic of Korea; swcho@nsl.hanyang.ac.kr
2 Department of Industrial & Management Engineering, Hanyang University ERICA, 55, Hanyangdaehak-ro, Sangnok-gu, Ansan 15588, Republic of Korea
3 Korea National Industrial Convergence Center, Korea Institute of Industrial Technology, Ansan 15588, Republic of Korea; jmyun@kitech.re.kr
* Correspondence: kmseo@hanyang.ac.kr (K.-M.S.); bgkang@kitech.re.kr (B.-G.K.)

Abstract: The need for certification standards for new convergence products, such as a smart LED streetlight system, has been identified as a critical issue. This study proposes simulation modeling for smart LED streetlight systems and suggests three certification standards: the minimum time to initiate dimming-up, the duration of the dimming-up period, and the number of concurrently controlled streetlights. We utilized Relux to model streetlights and roads in terms of luminance levels, and used analytical formulas to compute the braking distances of oncoming vehicles. The two models were integrated into a smart LED streetlight system model using Simio. Simulation experiments were conducted with two objectives: to provide certification standards, and to apply and verify them in real-world cases. We experimented with 630 scenarios, modeling various dynamic situations involving roads and vehicles, and applied the model to two actual roads in the Republic of Korea to test its validity. The model was subsequently applied to roads for which traffic-volume data were available, to determine potential energy savings. The proposed simulation method can be applied to a smart LED streetlight system and to new products that lack certification standards. Furthermore, the proposed certification standards offer alternative approaches to operating streetlight systems more efficiently.

Keywords: smart LED system; certification standard; dimming control; verification and validation; discrete event simulation

MSC: 00A72

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Citation: Cho, S.-W.; Seo, K.-M.; Yun, J.-M.; Kang, B.-G. Simulation-Based Analysis for Verifying New Certification Standards of Smart LED Streetlight Systems. *Mathematics* **2024**, *12*, 657. https://doi.org/10.3390/math12050657

Academic Editor: Gaige Wang

Received: 31 December 2023
Revised: 15 February 2024
Accepted: 21 February 2024
Published: 23 February 2024

1. Introduction

In the field of road lighting, countries globally have focused on the promotion and diffusion of light-emitting diode (LED) lighting because of its significantly lower power consumption. High-efficiency LED lighting is also being actively introduced into road lighting. For example, in Seoul, Republic of Korea, approximately 48% of all streetlights have been replaced with LED light sources as of 2019. In particular, there is a trend to actively introduce smart LED streetlights that can be linked to sensors, remotely controlled, and controlled for brightness by adding object-recognition sensors and communication capabilities to the LED light sources [1,2].

When operating road lighting, it is necessary to ensure consistent visibility of the road ahead so that drivers can drive properly [3–5]. For this purpose, road lighting standards define the average luminance and luminance uniformity of the road surface that must be satisfied for each road class. This standard must be met even when the average luminance of the roadway changes according to the dimming control of smart LED streetlights. Figure 1 shows the operation of a streetlight dimming control system based on vehicle approach.

As the vehicle is detected, a few streetlights illuminate brightly (M3), while the rest remain dimmer (M5). However, there are a lack of international and domestic standards for smart LED streetlights to maintain the average luminance of roads when dimming is controlled. In the case of the Republic of Korea, there are certification standards for streetlights under the KS C 7658 clause, but these are limited to the contents concerning lighting and components. Additionally, there are certification standards for high-efficiency energy equipment, but these are confined to the safety standards of indoor smart LED lighting. Some research has been conducted on test standards for indoor smart LEDs and dimming control according to traffic volume [6]; nonetheless, there is a lack of research on dimming control scenarios based on vehicle approach.

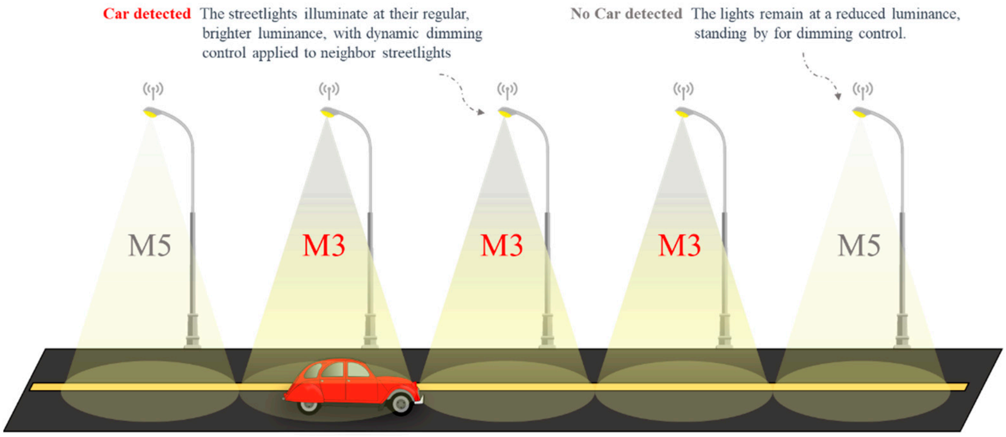


Figure 1. Operation of streetlight dimming control system according to vehicle approach.

Developing certification standards for streetlights is time-consuming and costly because of the need to install streetlights and to conduct tests manually. Owing to these practical constraints, there are several studies in various fields that provide certification standards and analysis results through simulation [7–10]. Using simulation methods, specific certification standards can be obtained through scenarios that consider diverse installation situations and conditions. In this study, we first identified new certification standards focusing on the dimming control of the LED streetlight system, which substantiates the significance of the efficiency of operation achieved by the system.

This study proposes a simulation modeling technique to verify the certification standards for a smart LED streetlight system. The proposed models are created for two different purposes, street lighting and vehicles, according to the characteristics of the target system. The streetlight model is designed and implemented using Relux, a lighting simulation tool that calculates the illuminance and luminance of light. The vehicle model uses an analytical method to apply the concept of stopping sight distance, which is key to providing certification standards. Simio, a discrete-event simulation tool, is then used to simulate the entire smart LED streetlight system by integrating the streetlight and vehicle models.

We conducted two primary experiments using the proposed model. In the first experiment, three certification standards were derived from 630 scenarios, considering the road environment and installation conditions of streetlights. We obtained the "Minimum time to begin dimming-up", which is the time required to increase the brightness through dimming control after recognizing a vehicle; "Duration of the dimming period", which is the time required to maintain the brightness until the vehicle passes; and "Number of streetlights controlled simultaneously" that are required to ensure a safe sight stopping distance according to the vehicle speed. In the second experiment, the proposed certification standards were verified using real cases on two roads in Anseong City, Republic of Korea. In this study, certification standards for satisfying the streetlight standards for various streetlight installation conditions and vehicle speeds in a smart LED streetlight system were obtained through the simulation method. This is expected to improve road safety by improving visibility for the driver.

The remainder of this paper is organized as follows: Section 2 describes related research on smart LED streetlight systems and certification standards through simulation methods, and analyzes the similarities and differences with this research. Section 3 describes the process and model for modeling the target system. Section 4 discusses the results of the experiments proposing certification standards using the model and applying it to real cases. Finally, Section 5 presents the conclusions drawn from this study.

2. Literary Review

According to a study conducted by Phillip et al. (2017) on the design of a smart LED streetlight system for smart city management, the integration of the Internet of Things (IoT) into urban infrastructure has paved the way for the development of advanced smart LED streetlight systems [11]. However, these cutting-edge technologies present an array of challenges and limitations. Jerome et al. (2002) focused on traffic simulations and found that the use of virtual environment simulations provided a means of preemptively understanding and tackling potential challenges, thereby ensuring the safety and efficiency of real-world road scenarios [12]. For instance, a study conducted by Fei et al. (2019) on the current status of digital twins demonstrated that simulations can proactively identify and alleviate conditions leading to traffic congestion or accidents, thereby enhancing road safety measures [13]. Additionally, the modeling of vehicular patterns and road network configurations facilitates a comprehensive evaluation of new streetlight network deployments, providing insight into their operational efficacy [14].

Table 1 presents an overview of the current research landscape pertaining to smart LED streetlight system. To effectively virtualize real-world circumstances, a comprehensive understanding of both mathematical and engineering analysis is indispensable. Broadly, the methodologies utilized for modeling can be divided into three categories: mathematical, physical, and simulation. Various techniques for essential dimming control have been examined in proposing certification standards for smart LED streetlight systems. Furthermore, we assessed whether existing research includes analyses of the energy-efficiency effects achieved through this dimming control.

Table 1. Comparison of smart LED streetlight research studies.

Related Research	Proposed Method	Modeling Approaches	Dimming Control	Energy Efficiency
[15]	LED streetlight model equation and certification standard	Mathematical model	Absent	Not Analyzed
[16,17]	Smart streetlight system based on sensor	Physical model	Sensor-based	Not Analyzed
[18,19]	Energy-optimized control system	Physical model	Time-based	Analyzed
[20,21]	Smart streetlight system with energy saving	Simulation model	Time-based	Analyzed
[22,23]	Energy-efficient streetlight control	Simulation model	Traffic-based	Analyzed
This study	Smart streetlight system certification and energy saving	Simulation model	Traffic-based	Analyzed

To model a smart LED streetlight system mathematically, a preliminary step involves the formulation of equations that delineate the spatial light distribution on various surfaces such as pavements, roads, and streets [15]. However, as the environment becomes more multifaceted, these equations become more complex, leading to the manifestation of several constraints. Such limitations can be circumvented using physical modeling. By crafting a miniature replica of a smart LED streetlight system and implementing sensor-based dimming technology, experimental insights into light-dimming controls can be garnered [16,17]. Moreover, time-based dimming experiments can offer valuable insights into the energy efficiency correlated with streetlight operations [18,19].

However, physical models have inherent limitations, particularly regarding their adaptability to diverse scenarios. Alterations in the environment require significant time and financial investment to fabricate and modify tangible prototypes. Such challenges can be overcome by employing simulation modeling. In simulation experiments with a smart streetlight system, it is feasible to modify both the voltage and the dimming intensity of the lamp, encompassing 15 distinct scenarios [20]. Moreover, the resulting data can be critically evaluated by gauging the energy consumption metrics aligned with the EN-15232 standard [21]. By integrating traffic-based dimming controls, simulation experiments offer a representation closer to real-world conditions [22–24]. In this study, we modeled a smart streetlight system with the aim of obtaining a certification standard through a comprehensive analysis of 630 scenarios and subsequently verifying its applicability to actual road conditions. Additionally, we implemented traffic-based dimming control based on the proposed certification standards and evaluated the subsequent energy-saving efficiency.

3. Proposed Method

This section presents the overall process for deriving certification standards, and the model-design method for each process in the streetlight dimming control system.

3.1. Overall Process

The proposed process consists of three parts (Figure 2): (1) simulation modeling, (2) derivation of certification standards, and (3) simulation-based experimental analysis. First, the simulation model describes the environment in which the smart LED streetlight dimming control system is deployed and operated in a real-world environment. Because luminance analysis is important in streetlight analysis, we have separated it into streetlight modeling to describe it in detail. We then modeled the installation conditions of streetlights according to the Korean Road Safety Facility Installation and Management Guidelines and constructed a simulation analysis environment using Relux, a simulation analysis tool used specifically for lighting analysis [25,26].

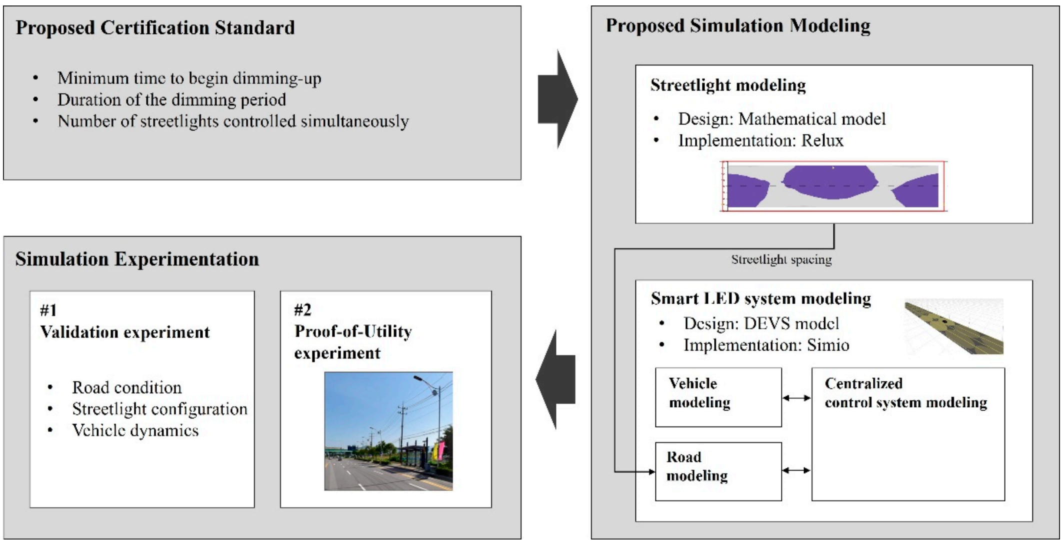


Figure 2. Proposed analysis process of the smart streetlight dimming control system.

This study modeled actual roads on which streetlights are deployed and operated. We designed models for multiple vehicles, and road models including streetlights, reflecting the results of the Relux lighting simulations, and a dimming control system that controls streetlights according to traffic. To implement a model that simulates discrete events such as the approach of a vehicle, we combined these into a simulation analysis environment using Simio, a discrete-event simulation tool. In the second step, we used the simulation environment to identify the certification standards that must be analyzed when installing an actual smart streetlight dimming control system. In this study, we identified three indicators, namely, the minimum time to begin dimming up, duration of the dimming-up period, and number of streetlights controlled simultaneously, which affect vehicle operation depending on the lighting environment, and defined them as the proposed certification standards.

Finally, the proposed process performs a simulation-based experimental analysis of the certification standards consisting of validation and proof-of-utility experiments. The former experimentally explains what certification standards a smart streetlight dimming control system should meet under various lighting specifications (e.g., streetlight pole height) and driving conditions (e.g., number of lanes and vehicle speed) within an ideal road situation. The latter presents the simulation-based analysis results in an actual operational environment. We described streetlights under the same conditions as actual roads in operation, performed a what-if analysis on cases where streetlights were installed and operated according to the proposed certification standards under those conditions, and presented additional analysis indicators (e.g., energy efficiency).

3.2. System Model Design

3.2.1. Streetlight Modeling

The lighting level of a road is determined by two factors specified in the Korean Road Safety Facility Installation and Management Guidelines: (1) the type of road, and (2) the type of traffic and vehicles. As listed in Table 2, highways that lack traffic control and other forms of road user separation require a high lighting class (M1), whereas low-priority connecting roads with good separation require a lower lighting class (M5). Streetlights can be operated at a maximum of two levels lower than the required lighting grade; however, the M5 grade must be guaranteed.

Table 2. Road lighting classification classes according to road and traffic type.

Type of Road	Type of Transportation and Vehicle Traffic	Class
a high-speed road with separate upper and lower lines and all intersections being multi-level intersections, with completely restricted access. Automobile road or highway	high traffic and complicated road alignment	M1
	high traffic or complicated road alignment	M2
	low traffic and simple road alignment, or dark surroundings	M3
high-speed roads, separated roads for two-way traffic	lack of traffic control, and no separation of other types of road users	M1
	traffic control implemented, and other types of road users are well separated	M2
major urban traffic routes, highways, and national highways	lack of traffic control, and no separation of other types of road users	M2
	traffic control implemented, and other types of road users are well separated	M3
low importance connecting roads, local connecting roads, main access roads to residential areas, to private land	lack of traffic control, and no separation of other types of road users	M4
	traffic control implemented, and other types of road users are well separated	M5

Based on these five road-lighting grades, four performance indicators were determined: average road surface luminance, overall uniformity, lane axis uniformity, and threshold increase. Table 3 lists the minimum performance indicators required to satisfy each road-lighting grade. The average road surface luminance refers to the minimum allowable value of the average luminance that the road surface must maintain, and luminance uniformity refers to the ratio between the minimum and average road surface luminance. The luminance uniformity for lanes indicates the uniformity of the brightness distribution across the road. The threshold increment is a value related to glare, and is the percentage of the difference in critical luminance depending on the presence or absence of glare.

Table 3. Four types of evaluation indicators according to road lighting grade.

Class	Average Road Surface Luminance L_{avg} (cd/m^2)	Luminance Uniformity (U_O=L_{min}/L_{avg})	Luminance Uniformity for Lanes (U_O=L_{min}/L_{max})	TI (%) (Max.)
M1	2.0	0.4	0.7	10
M2	1.5	0.4	0.7	10
M3	1.0	0.4	0.5	15
M4	0.75	0.4	-	15
M5	0.5	0.4	-	15

The four performance indicators are influenced by factors such as road surface, road lighting grade, and streetlight pole height, as indicated in Table 4. For example, a reduction in streetlight pole height or an increase in the power of streetlight LEDs will likely result in increased brightness on the roadway. Furthermore, the luminaire tilt and overhang play crucial roles in determining the area of road surface illuminated. In this study, simulation-based analysis was performed using these as the input parameters in Relux, which uses them to calculate the average road surface luminance at each location on the road and all four performance indicators from an overall road perspective based on the simulation. In addition, the tool derives the streetlight spacing that satisfies a specific road lighting class using an optimization algorithm included in the simulation tool, Relux. Under comparable conditions across various scenarios, the optimal spacing for streetlights was found to be the narrowest in a staggered layout, widest when positioned on both sides of the road, and intermediate when placed exclusively on one side.

Table 4. Parameter name and level of streetlight model.

Parameter Name	Parameter Description	Parameter Level
road type	pavement condition of the road, R1 is concrete road	R1
road lighting class	lighting level required for road operation	M1, M2, M3, M4, M5
streetlight pole height	pole height of streetlights installed on the road	10 m, 11 m, 12 m
streetlight array type	arrangement type of streetlights installed on the road	One, both sides, staggered layout
the number of lanes	the number of lanes on the road	One-way 1, 2, 4
streetlight LED power	LED power for streetlights installed on roads	100 W, 150 W
luminaire tilt	angle between streetlights pole and lamp	10°
overhang	horizontal distance between light source center and roadway end	1.5 m, 2.3 m

3.2.2. Vehicle Modeling

Dimming control means adjusting the brightness of streetlights when a vehicle approaches a road where streetlights are installed. It is necessary to secure time for drivers to stop in potentially dangerous situations. For this, we applied the concept of stopping sight distance (Figure 3) when modeling vehicles. This is one of several types of sight distance metrics used in road design, and refers to the minimum distance a vehicle driver must be able to see to stop before colliding with an object on the road, including a stationary vehicle [27]. Dimming control must be implemented in a way that the distance illuminated ahead of the approaching vehicle is greater than the stopping sight distance, otherwise the driver will not be able to see an obstacle inside the stopping sight distance in darkness and a collision cannot be avoided, even if the brakes are already applied [28].

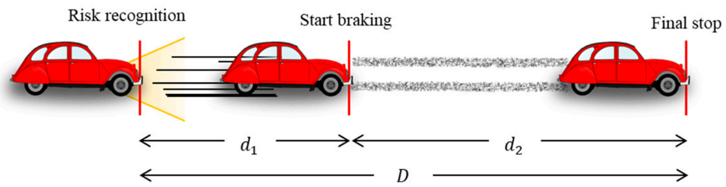


Figure 3. Stopping sight distance from risk recognition to final stop.

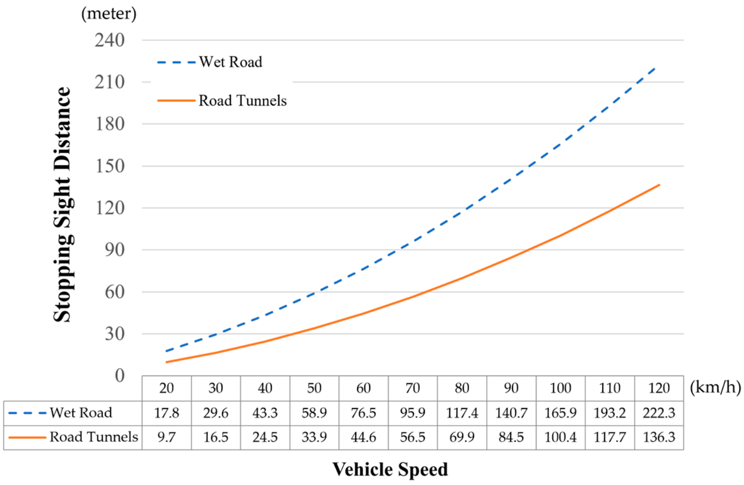
The stopping sight distance, as defined in Equation (1), is the aggregate of two components: the reaction distance (d_1) and braking distance (d_2). The reaction distance d_1, calculated in Equation (2), represents the distance a vehicle travels during the driver's reaction time t, which is the time taken to perceive a hazard and initiate braking when the vehicle's speed is V in kilometers per hour (km/h). The braking distance, d_2, detailed in Equation (3), is the distance covered from the initiation of braking to the point when the vehicle comes to a complete stop. When the speed v is given in meters per second (m/s) and gravitational acceleration (g) is taken as 9.8 m/s^2, the equation is standardized to form a quadratic relationship in terms of the vehicle's speed V in kilometers per hour and the coefficient of sliding friction f. The potential hazard recognition, or braking reaction time, is assumed to be 1.5 s, and the actual time taken to apply the brakes is designated as 1 s, cumulatively constituting a total reaction time (t) of 2.5 s. The stopping sight distance can be accurately calculated by applying the appropriate coefficient of friction (f), which corresponds to the specific road conditions, for instance, a value of 0.3 for a wet road at a velocity of 90 km/h.

$$D = d_1 + d_2 \tag{1}$$

$$d_1 = \frac{V}{3.6}t \tag{2}$$

$$d_2 = \frac{v^2}{2gf} = \frac{(V/3.6)^2}{2 * 9.8 * f} = \frac{V^2}{254f} \tag{3}$$

Figure 4 shows the required stopping sight distance depending on vehicle speed on a wet road surface and in a tunnel environment. The graph indicates that the required stopping sight distance increases as the vehicle speed increases and that wet road surfaces require a larger stopping sight distance than a tunnel environment [29]. In this study, we used the stopping sight distance calculated using a mathematical model as an input parameter for the vehicle model in streetlight dimming control system modeling.



	20	30	40	50	60	70	80	90	100	110	120
Wet Road	17.8	29.6	43.3	58.9	76.5	95.9	117.4	140.7	165.9	193.2	222.3
Road Tunnels	9.7	16.5	24.5	33.9	44.6	56.5	69.9	84.5	100.4	117.7	136.3

Figure 4. Required stopping sight distance against vehicle speed.

3.2.3. Streetlight Dimming Control System Modeling

Streetlight dimming control systems in real environments include interactions between multiple vehicles and streetlights. Because this has the characteristics of a discrete event system in which a series of processes is initiated by the event of vehicle approach, the models have been constructed based on the DEVS (Discrete EVent Specification) formalism, which can express a representative model for a discrete event system [30,31]. DEVS formalism is particularly suitable for modeling systems like vehicles or machines that undergo state changes driven by events [7,32,33]. Given these characteristics, a streetlight system is modeled using DEVS formalism. Additionally, this study implemented them through Simio, a discrete event simulation tool [34–36].

Equations (4)–(11) represent a set of expressions using the DEVS formalism to model the discrete events of the streetlight dimming control system. Equation (4) defines the input set, Equation (5) specifies the output set, and Equation (6) constitutes the state set. Additionally, Equation (7) represents the external state transition function, Equation (8) is the internal state transition function, Equation (9) defines the output function, and Equation (10) describes the time advance function. When the first streetlight is in the *Wait* state and a vehicle detection event occurs, it initially sends out a request to obtain the vehicle's information (speed, location). Once the *Vehicle_Info* is received, it transitions to the *Calculate* state to calculate the certification standards. Then, it stays in the *Ready* state for the calculated "*The minimum time to begin dimming up period*". After this period elapses, it sends *Req_Streetlight* to a *calculated number of streetlights* in the vicinity that are controlled simultaneously. Subsequently, it enters the *Control* state and operates at a brighter intensity for "*the duration of the dimming period*" before returning to the Wait state. If it is not the first streetlight, then while in the *Wait* state, it immediately moves to the *Control* state upon receiving *Res_Streetlight* from the preceding streetlight and proceeds with the dimming control for a set duration.

$$Streetlight\ = < X,\ Y,\ S,\ \delta_{int},\ \delta_{out},\ \lambda,\ t_a > \tag{4}$$

$$X : \begin{cases} Detect\_Vehicle \\ Res\_Streetlight \\ Res\_VehicleInfo \end{cases} \tag{5}$$

$$Y : \begin{cases} Cal\_Standards \\ Req\_Streetlight \\ Req\_VehicleInfo \end{cases} \tag{6}$$

$$S : \begin{cases} WAIT \\ DETECT \\ CALCULATE \\ READY \\ CONTROL \end{cases} \tag{7}$$

$$\delta_{ext} : \begin{cases} (WAIT) \times (Detect\_Vehicle) \rightarrow (DETECT) \\ (WAIT) \times (Res\_Streetlight) \rightarrow (CONTROL) \\ (WAIT) \times (Res\_VehicleInfo) \rightarrow (CALCULATE) \end{cases} \tag{8}$$

$$\delta_{int} : \begin{cases} (DETECT) \rightarrow (WAIT) \\ (CALCULATE) \rightarrow (READY) \\ (READY) \rightarrow (CONTROL) \\ (CONTROL) \rightarrow (WAIT) \end{cases} \tag{9}$$

$$\lambda : \begin{cases} (DETECT) \rightarrow (Req\_VehicleInfo) \\ (CALCULATE) \rightarrow (Cal\_Standards) \\ (READY) \rightarrow (Req\_Streetlight) \end{cases} \tag{10}$$

$$T_a : \begin{cases} (WAIT) \rightarrow \infty \\ (DETECT) \rightarrow 0 \\ (CALCULATE) \rightarrow 0 \\ (READY) \rightarrow The\ minimum\ time\ to\ begin\ dimming\ up \\ (CONTROL) \rightarrow The\ duration\ of\ the\ dimming\ period \end{cases} \quad (11)$$

Figure 5 illustrates the overall process of the control system. The first streetlight periodically monitors whether a vehicle is approaching the detection range, and then calculates the stopping sight distance after checking the vehicle's speed. Based on this value, we calculate three certification standards indicators, which are highlighted in red: (1) the minimum time to begin dimming up, (2) the duration of the dimming period, and (3) the number of streetlights controlled simultaneously.

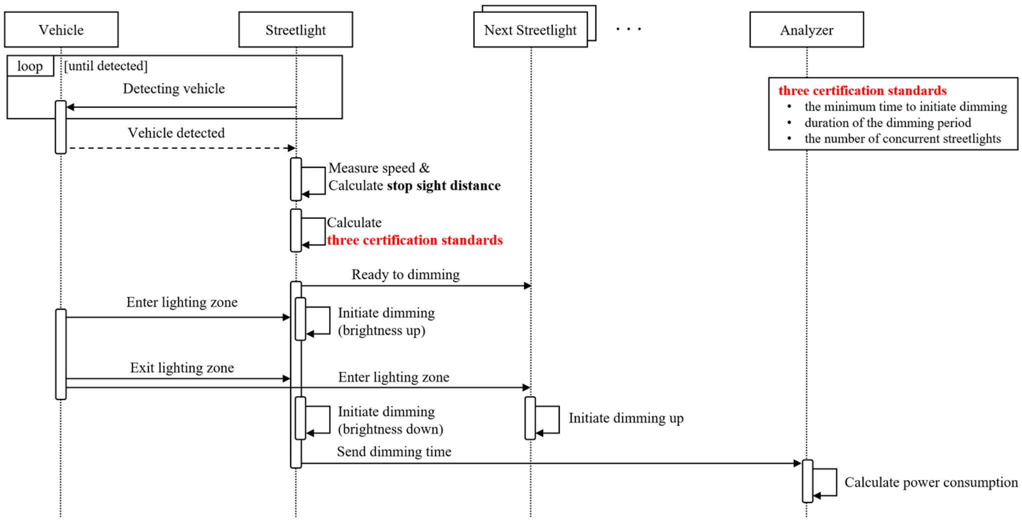


Figure 5. Sequence diagram of streetlight dimming control system.

This model calculates the minimum time until the initial dimming-up and then starts dimming-up as many streetlights as are needed to be controlled simultaneously [29]. Each time a car passes through the illuminated area of an individual streetlight, that streetlight is turned down. Each streetlight model transmitted the lighting operation time for these repetitive events to the analysis model, which then calculated the overall energy consumption.

4. Simulation Experiments

This section divides the research into two distinct phases. The initial phase focused on determining the three certification standards for the smart LED streetlight system through simulation, incorporating and validating real-world conditions from two domestic roads in the Republic of Korea. The subsequent phase entailed a simulation study assessing the power reduction achieved during dimming control based on the actual road-traffic volume.

4.1. Experiment 1: Certification Standards Simulation for a Smart LED Streetlight System

In Experiment 1, we constructed 630 scenarios to rigorously define certification standards under diverse road conditions and environmental factors. Based on the results, three certification standards were formulated. To further validate these standards, we examined the conditions of two specific roads in the Republic of Korea to ensure their applicability in real-world scenarios.

4.1.1. Scenario for Presenting Certification Standards Simulation

The 630 simulation experiments we conducted incorporated eight types of parameters. The 630 scenarios are composed of combinations from five road lighting classes, three numbers of lanes, three streetlight pole heights, two streetlight LED power levels, and seven vehicle speed variations. For example, one scenario would be a road with a condition of R1 (regular asphalt road), in wet conditions, with a required lighting class of M3, which is one-way two-lane highway; on this road, there is a smart streetlight of 100 W, 10 m in height, and with a vehicle detection distance of 50 m. The experiment determines the three certification standards when the speed limit of the road is 60 km/h. Furthermore, for the streetlights positioned along the road, a one-sided array is assumed for one-lane, a staggered layout for two-lane, and an arrangement on both sides for four-lane roads. For all lane configurations, the streetlights have a tilt of 10°.

Table 5 lists the input parameters for the certification standards calculation.

Table 5. Input parameters for certification standards simulation.

Model Type	Parameter Name	Parameter Level
road	road type	R1
	road condition	wet surface condition
	road lighting class	M1, M2, M3, M4, M5
	number of lanes	1, 2, 4 each way
streetlight	streetlight pole height	10 m, 11 m, 12 m
	streetlight LED power	100 W, 150 W
vehicle	vehicle sensing distance	50 m
	vehicle speed	30–120 km/h (in 15 km/h increments)
A total of 630 scenarios		

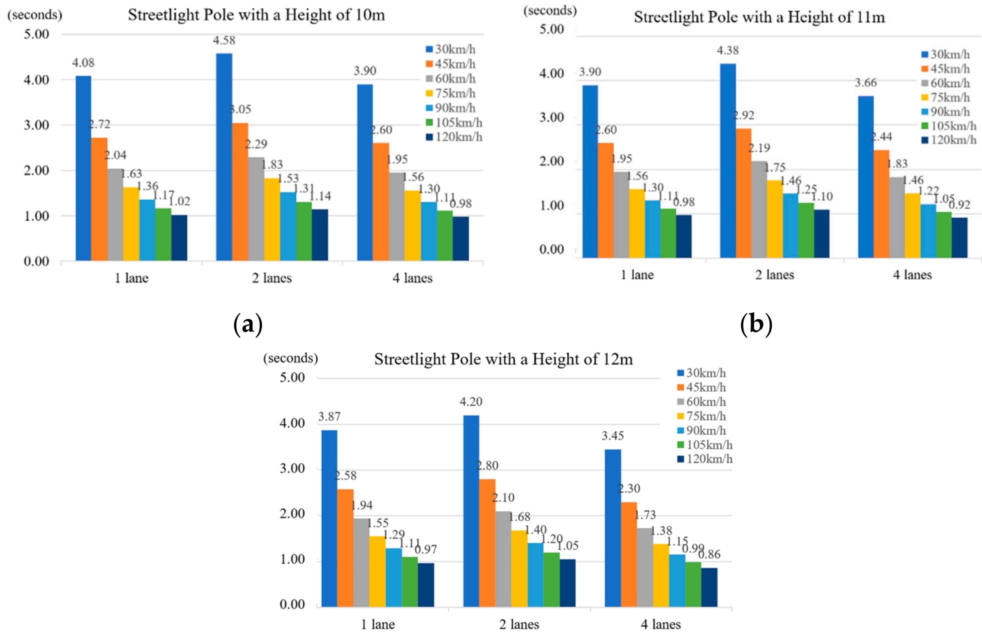
Through these experiments, this study determined three certification standards based on the conditions of the road, status of streetlights, and vehicle speed. Table 6 presents the three certification standards and their definitions. The first standard, “The minimum time to begin dimming-up”, represents the time taken from when a vehicle enters the detection range of a streetlight and is recognized to the actual onset of dimming control. This time must be short enough to ensure that the streetlight’s brightness is increased before the vehicle enters the luminance range of the streetlight so that drivers maintain consistent visibility of the road. The next standard, “Duration of the dimming period”, defines the minimum time a streetlight should maintain higher levels of brightness to cover the interval between a vehicle entering its luminance range and exit. Streetlights must sustain enhanced luminosity for at least this duration to guarantee consistent illumination while the vehicle is in transit, thereby supporting visibility for the driver. The safety of a road can only be ensured if the minimum brightness is guaranteed for each road. The last standard is the “Number of streetlights controlled simultaneously”. Instead of controlling only one streetlight during the dimming process, multiple streetlights must be controlled based on the speed of the vehicle to guarantee that at least a vehicle driver’s stopping sight distance is lit: it is only possible to cope with obstacles or dynamic situations when the field of view is longer than this distance.

Table 6. Simulation output parameters for the certification standards.

Output Parameter	Parameter
the minimum time to begin dimming-up	the minimum delay time required for streetlights to initiate dimming and the predetermined luminance level.
Duration of the dimming period	the minimum duration for which streetlights must maintain their set luminance level following undergoing dimming control.
Number of streetlights controlled simultaneously	the minimum number of streetlights that need to be controlled simultaneously to ensure that the lit area extends beyond the vehicle driver’s stopping sight distance.

4.1.2. Certification Standards Derived from Simulation Result Analysis

By analyzing the simulation results, we determined three certification standards. Among the various scenarios, we highlighted the results specifically based on the M3 road lighting class and 100 W LED power for streetlights. Figure 6 shows the relationship between the minimum time required to initiate dimming-up and the combination of lane numbers and streetlight pole heights. A clear trend indicates that an increase in vehicle speed necessitates a quicker initiation of dimming control. As illustrated in Figure 6a–c, irrespective of the streetlight height, the longest minimum dimming time was observed when the streetlights were positioned on both sides of a two-lane road. As discussed in the streetlight-modeling section, the spacing between streetlights is at its minimum in a staggered layout for two-lane roads, resulting in an extended distance from detection to the luminance range. For instance, for 100 W streetlights at 10 m height on one side of a one-lane road, a vehicle approaching at 120 km/h would require a streetlight to begin dimming within 1.02 s.



(**a**) (**b**)

(**c**)

Figure 6. Duration of the dimming period based on the number of lanes and height of the streetlight pole. (**a**) Height of 10 m. (**b**) Height of 11 m. (**c**) Height of 12 m.

Figure 7 shows the correlation between the duration of the dimming-up period, the number of lanes, and the height of the streetlight pole. Analysis of the graph indicates that a reduced vehicle speed requires the streetlight to remain at its increased luminance for a longer period of time. Remarkably, as shown in Figure 7a–c, the shortest duration was observed when streetlights were installed on both sides of a two-lane road, regardless of the height of the streetlight poles. This phenomenon can be attributed to the reduced spacing between streetlights in the staggered layout, which results in vehicles departing from the illuminated vicinity of the streetlight more quickly. For example, a streetlight with a power rating of 100 W and a height of 10 m, situated on one side of a one-lane road, would necessitate maintaining its heightened luminance for 0.96 s when a vehicle approaches at 120 km/h.

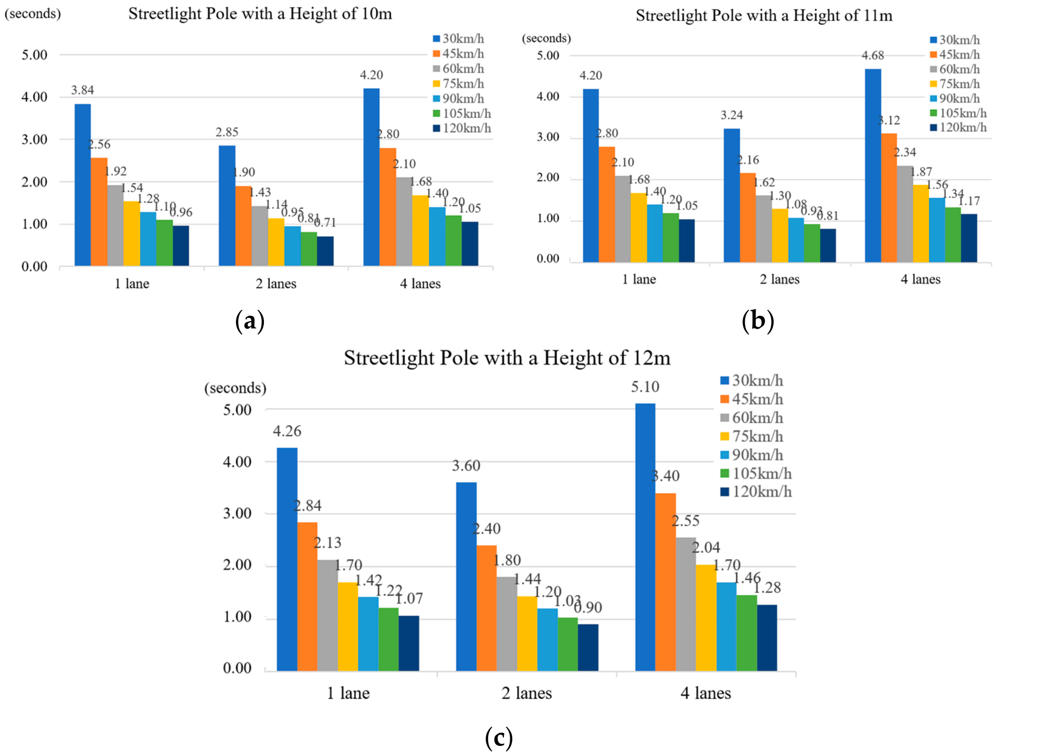


Figure 7. Minimum time required to initiate dimming based on the number of lanes and height of the streetlight pole. (**a**) Height of 10 m. (**b**) Height of 11 m. (**c**) Height of 12 m.

Finally, Figure 8 shows a graph of the number of simultaneously controlled streetlights in relation to the number of lanes and the height of the streetlight pole. It becomes apparent that increased vehicle speeds require the concurrent control of a larger number of streetlights positioned further ahead. Figure 7a–c demonstrate that on two-lane roads, the highest number of streetlights must be concurrently controlled, surpassing the number required for both one-lane and four-lane roads. The staggered layout, characterized by narrower spacing between streetlights, means that to ensure an adequate stopping sight distance for a vehicle, a greater number of streetlights must be controlled and dimmed up. For example, a 100 W streetlight, standing at a height of 10 m on one side of a one-lane road, demands the simultaneous dimming-up of eight consecutive streetlights ahead when faced with a vehicle approaching at 120 km/h to guarantee the driver's stopping sight distance.

4.1.3. Real-World Road Validation for Certification Standards

The real-world validation scenario was based on a report detailing road lighting installation conditions provided by Anseong in the Republic of Korea. Table 7 presents the road conditions and luminance analysis results for Anseong. For the experimental scenario, areas with lighting types other than LED, specifically Iljuk-myeon, Central Road, and 38 national highway, were excluded. According to the regulations of the Ministry of Land, Infrastructure, and Transport of Korea, roads requiring a road lighting class exceeding M5 require dimming control. Hence, the Anseong Terminal 1 Road was excluded. The scenarios chosen for the study were the second industrial complex and Anseong Terminal 2 roads. Using Relux to analyze the two roads, the actual second industrial complex road was found to have a required road lighting class of M3. However, with its current streetlight spacing of 39 m which is greater than the ideal spacing of 36 m, its lighting level corresponds more closely with the M5 class. In contrast, the Anseong Terminal 2 road adheres to its required road lighting class of M3. Although a spacing of 38.5 m is feasible on this road, it currently employs a spacing of 30 m. Consequently, we include all four cases, both real and ideal, in our experimental setup. For the modeling, vehicle speeds were assigned based on the legal speed limits for each road: 60 km/h for the second industrial complex and 50 km/h for Anseong Terminal 2.

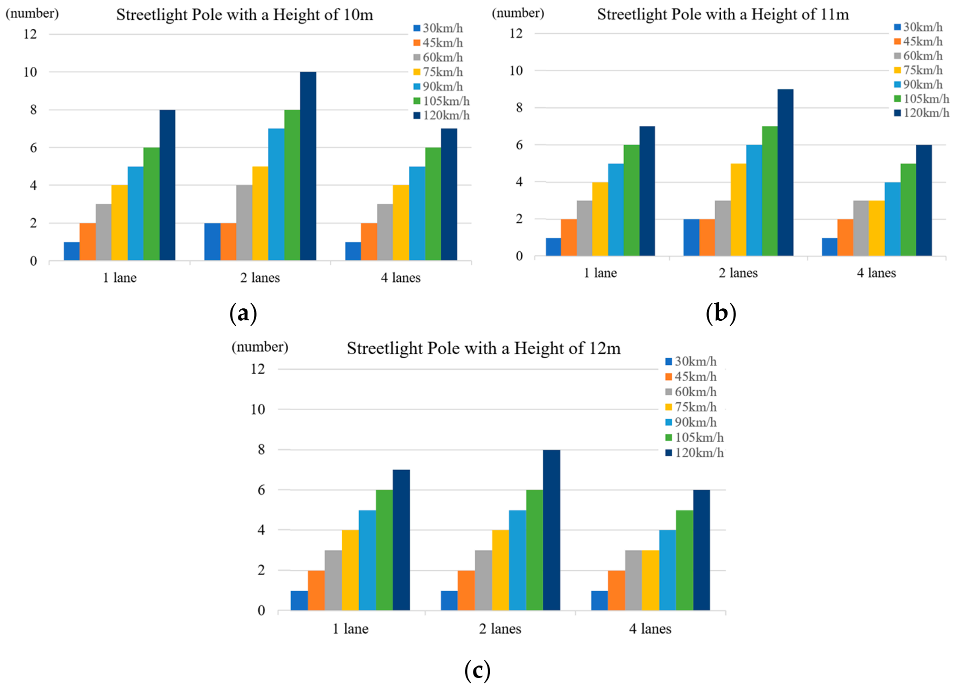
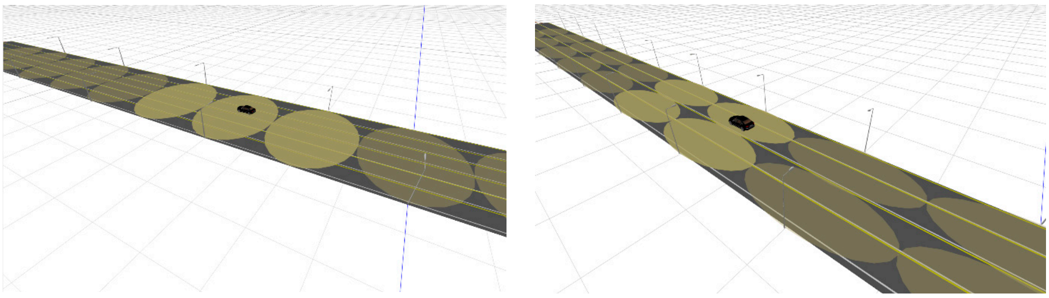


Figure 8. Number of streetlights controlled simultaneously based on the number of lanes and height of the streetlight pole. (**a**) Height of 10 m. (**b**) Height of 11 m. (**c**) Height of 12 m.

Table 7. Road conditions and luminance analysis in Anseong.

Parameter Name	Iljuk-Myeon	Second Industrial Complex	Anseong Terminal 1	Anseong Terminal 2	Central Road	38 National Highway
LED Power	CDM 150 W	LED 150 W	LED 150 W	LED 200 W	MH 350 W	HPS 50 W
Average road surface luminance (cd/m^2)	2.15	1.95	7.89	3.96	0.92	2.38
Luminance Uniformity	0.64	0.55	0.60	0.63	0.77	0.25
Luminance Uniformity for lanes	0.44	0.48	0.27	0.66	0.48	0.38
Road lighting class	M5	M5	X	M3	M5	X
Required road lighting class	M5	M3	M5	M3	M3	M3
Width of road [m]	5.5	16.0	6.0	18.5	8.4	16.0
Width of driveway [m]	3.5	4.0	2.7	3.0	2.8	3.5
Array type	both-sides	both-sides	one-side	staggered layout	one-side	staggered layout
Streetlight Spacing [m]	27.4	39.0	17.2	30.0	28.0	39.0
Height of streetlight pole [m]	8.2	10.2	9.6	9.0	10.0	10.0
Luminaire tilt [°]	8.0	10.0	20.0	20.0	5.0	7.0
Arm length [m]	1.8	3.0	2.4	2.6	1.6	2.2
Overhang [m]	−1.0	1.8	1.4	1.1	0.2	0.5

Figure 9a presents the simulation model of the second industrial complex, while Figure 9b shows that of Anseong Terminal 2. The second industrial complex depicts a six-lane road, with streetlights set in a staggered arrangement. Conversely, Anseong Terminal 2 road is delineated as a four-lane structure with streetlights positioned on both sides. These models accurately reflect their respective real-world configurations. Analyses were performed using both existing and optimal streetlight spacing for each case.



(**a**) (**b**)

Figure 9. Number of streetlights controlled simultaneously based on the number of lanes and height of the streetlight pole. (**a**) Second industrial complex. (**b**) Anseong Terminal 2.

4.1.4. Real-World Road Simulation Experimentation Results Analysis

Table 8 lists the three certification standards deduced from the simulations of the two domestic roads. Four distinct evaluations were performed to differentiate between the existing and optimal streetlight spacing to facilitate a comparative analysis. Currently, the streetlights installed on the roads have an older design layout and do not meet the optimal spacing requirements, thereby compromising road safety. A closer examination of Table 7 reveals that while the second Industrial Complex requires the M3 standard for road lighting, it only achieves an M5 rating. Furthermore, although Ansong Terminal 2 satisfies the required M3 standard, it warrants a reevaluation of its optimal spacing. Consequently, an experiment was conducted to evaluate the standards for streetlight dimming, including the hypothesis of reinstallation with modified spacing. For the second industrial complex in its prevailing configuration, the data suggest a minimum initiation time for dimming-up of 1.830 s, a dimming-up duration of 2.34 s, and a concurrency of three streetlights. Under the optimal spacing conditions, the initiation time could potentially escalate by approximately 5% to 1.92 s, whereas the dimming-up duration might decline by approximately 8% to 2.16 s. Because of the reduced spacing, the concurrent number of streetlights would increase to four.

Table 8. Three certification standards for the second Industrial Complex and Anseong Terminal 2.

Road Name	Streetlight Spacing (m)	The Minimum Time to Initiate Dimming (s)	The Duration of the Dimming Period (s)	The Number of Concurrent Streetlights (s)
Second Industrial Complex (Actual)	39	1.830	2.34	3
Second Industrial Complex (Ideal)	36	1.920	2.160	4
Anseong Terminal 2 (Actual)	30	3.06	1.08	4
Anseong Terminal 2 (Ideal)	38.5	2.907	1.386	3

Regarding Anseong Terminal 2, the initial dimming-up time is 3.06 s, the dimming-up duration is 1.08 s, and the concurrency stands at four streetlights. By transitioning to the optimal spacing, the initiation time was reduced by an estimated 5% to 2.907 s. In contrast, the dimming duration is likely to increase by 28.33% to 1.386 s, suggesting that the current arrangement of streetlights may be overly dense. Should adjustments be made to the placement, even though individual streetlight-dimming durations might increase, the total number of streetlights in operation may decrease; the concurrent number of streetlights was projected to decrease to three.

By defining the initiation time for dimming-up and effectively managing the concurrency of active streetlights, roads can comply with the prescribed road lighting classes and ensure an adequate forward stopping sight distance, consequently increasing road safety. Moreover, by adhering to the designated dimming-up durations, streetlight operations can be rendered more energy efficient, leading to a notable reduction in energy consumption.

4.2. Experiment 2: Energy Consumption Simulation for a Smart LED Streetlight System

In Experiment 2, we employed the three certification standards delineated in Experiment 1 to simulate energy consumption. This investigative procedure draws upon authentic traffic data from four distinct roads in Seoul, Republic of Korea, to elucidate their implications for energy consumption.

4.2.1. Scenario for Energy Consumption Simulation

In the pursuit of an energy consumption simulation, we employed traffic volume survey data from Seoul Metropolitan City for 2022. Although the dataset spanned from 1 January to 31 December, our analysis was particularly centered on December week-day data, where traffic volume was continuously monitored over 24 h cycles at the entrance of each road. The criteria for road selection excluded roads with: (1) consistently high traffic volumes that preclude dimming, conforming to the M1 lighting class; (2) low traffic volumes, operating at the M5 lighting class and negating any dimming potential; and (3) an absence of data owing to construction, system upgrades, or other interruptions. Bridge roads were also excluded, as they require additional localized lighting in accordance with domestic traffic regulations. The roads selected for the study were 262-35, Itaewon-dong, Yongsan-gu; 1-11, Oksu-dong, Seongdong-gu; 727-1154, Magok-dong, Gangseo-gu; and 322-3, Dongjak-dong, Dongjak-gu, all located in Seoul, Republic of Korea.

Table 9 lists the assumptions pertaining to the road, vehicle, and streetlight conditions for the quartet of selected roads in Seoul, which served as the foundation for the subsequent simulation. All roads were assumed to have a road type of R1 (standard asphalt road), road condition of a wet surface (typical moist condition), and a road lighting class of M3. Additionally, the smart streetlights on all roads were capable of detecting vehicles from a distance beyond 50 m, and the height of the streetlights was set at 10 m. Vehicles were assumed to adhere to the maximum speed limits on each road. The streetlight LED power, number of lanes, and array types of streetlights are also listed in the table.

Table 9. Input parameters for dimming control energy consumption simulation.

Road	Road Type	Road Condition	Road Lighting Class	Vehicle Sensing Distance	Vehicle Speed	Streetlight Pole Height	Streetlight LED Power	Number of Lanes
Itaewon-dong, Yongsan-gu	R1	Wet surface condition	M3	50 m	40 km/h	10 m	100 W	1 lane (one-side)
Oksu-dong, Seongdong-gu	R1	Wet surface condition	M3	50 m	50 km/h	10 m	100 W	2 lanes (staggered layout)
Magok-dong, Gangseo-gu	R1	Wet surface condition	M3	50 m	50 km/h	10 m	150 W	4 lanes (both sides)
Dongjak-dong, Dongjak-gu	R1	Wet surface condition	M3	50 m	80 km/h	10 m	150 W	4 lanes (both sides)

Figure 10 shows the hourly traffic volumes for the four designated roads. For illustrative purposes, the roadway located in Magok-dong, Gangseo-gu, registered a traffic count of 1473 vehicles between 6:00 PM and 7:00 PM. It is postulated that 1473 vehicles arrive within a one-hour interval, adhering to a Poisson distribution, with the inter-arrival times of these vehicles exhibiting an exponential distribution.

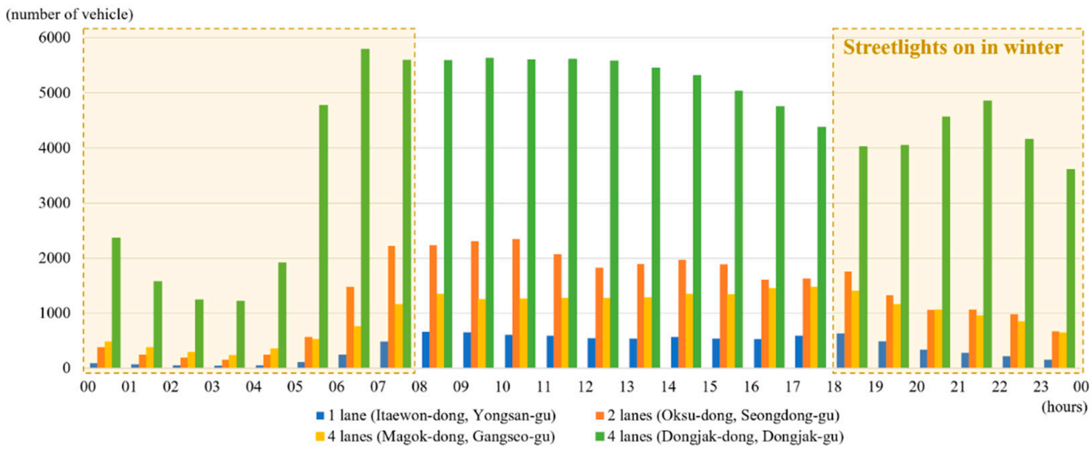


Figure 10. The 24-h traffic data in target four roads.

Although streetlights in Seoul are conventionally activated from approximately 5:30 PM to 8:00 AM in December, these timings can vary depending on meteorological conditions and specific calendar days. Thus, to ensure the fidelity of this simulation experiment, we posited that the streetlights functioned from 6:00 PM to 8:00 AM.

4.2.2. Smart LED Streetlight Energy Consumption through Simulation Experimentation

Energy consumption simulations were performed based on the stipulated input parameters and traffic volume scenarios. Figure 11 shows the hourly dimming ratios for streetlights over a 24 h duration, spanning the four selected roads. The experiment was conducted 30 times, and the results are presented as a box plot in the figure. Specifically, from 6:00 PM to 7:00 PM, the roadway in Magok-dong, Gangseo-gu, modulated the luminance of its streetlights up to the M3 level for approximately 91.3% of the duration (equivalent to approximately 54 min), and down to the M5 level for an estimated 6 min, thus providing insights into the energy utilization pattern for that period. The analysis revealed that, with an increase in the overall traffic volume, the duration of dimming up to a brighter level also increased. Specifically, between 6:00 PM and 8:00 PM, the roads exhibited a pronounced increase in dimming-up time compared with typical periods. Conversely, from midnight to 3:00 AM, as the traffic volume decreased, there was a prolonged span wherein the lights were sustained at a diminished luminance level of M5.

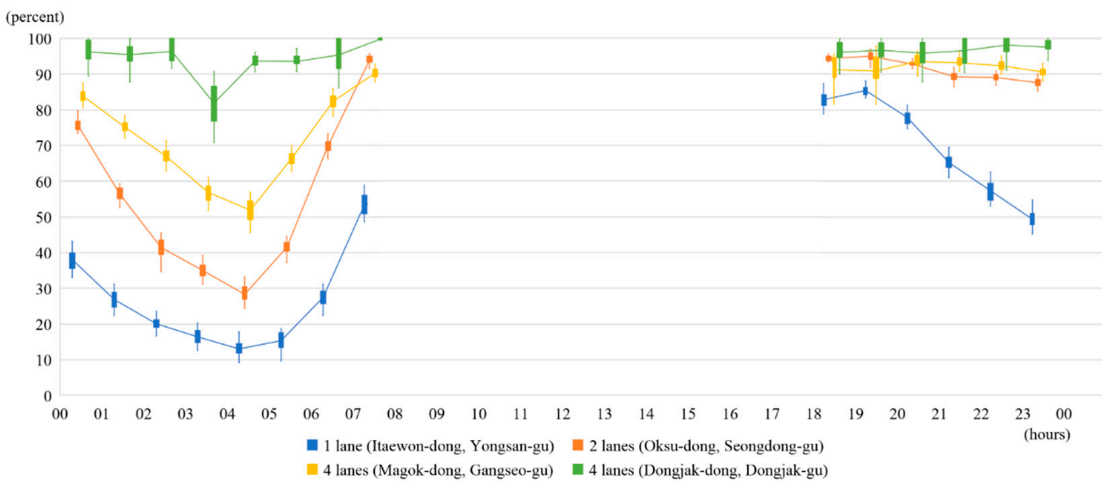


Figure 11. Percentage of streetlight dimming in 24 h relative to traffic volume in target four roads.

As illustrated in the graph, on the four-lane road in Dongjak-dong, Dongjak-gu, there was a notable decrease in the utilization rate of streetlights, dropping by 7% from 94% to 83% on average from 3:00 AM to 4:00 AM. This decline in utilization corresponds to a reduction in vehicular traffic, consistently observed from 2:00 AM to 4:00 AM. However, after 4:00 AM, an increase in vehicle traffic was observed, leading to an increase in the utilization rate of streetlights, reaching 93%. In Itaewon-dong, Yongsan-gu, the one-lane roads exhibited the lowest brightness ratio because of minimal traffic, thus operating predominantly under low-illumination conditions. Additionally, the two-lane roads in Oksu-dong, Seongdong-gu, demonstrated an operational rate exceeding 80% from 6:00 PM to 12:00 AM. However, similar to the one-lane scenario, these roads also operate at reduced brightness during the early morning hours, which correlates with diminished traffic flow.

Table 10 lists the total operating duration of streetlights, highlighting the average percentage and duration of brightness modulation through dimming control over a 14 h period. The road in Itaewon-dong, which had the lowest average traffic volume, exhibited the lowest dimming-up at 44.92%, whereas the road in Dongjak-dong exhibited the most extensive dimming-up at 95.25%. This suggests that in Itaewon-dong, the luminance was reduced by more than half compared to when no dimming control was applied. In contrast, in Dongjak-dong, luminance was reduced for merely 0.65 h (approximately 39 min) of the total 14 h duration.

Table 10. Percentage of streetlight dimming up time in target four roads.

Road	Average Dimming-up Time (Percent)	Average Dimming-up Time (Hour)
Itaewon-dong, Yongsan-gu	44.92	6.29
Oksu-dong, Seongdong-gu	70.77	9.91
Magok-dong, Gangseo-gu	80.42	11.26
Dongjak-dong, Dongjak-gu	95.25	13.35

Implementing a simulation experiment using the proposed model prior to operating streetlights can assist in making informed decisions on prioritizing the deployment of smart LED streetlight systems when resources are constrained. A greater effect can be achieved by installing a smart LED streetlight system at a location where the dimming-up time is further reduced. For example, assuming the number of streetlights is equal, since Dongjak-dong, Dongjak-gu operates at a high brightness for 95% of the time, it may be considered to prioritize the replacement of Itaewon-dong, Yongsan-gu, with a smart LED streetlight system first, as it operates at high brightness only 44% of the time and thus exhibits a greater reduction in power consumption. By strategically installing such a system in locations where the dimming-up time can be maximally reduced, enhanced efficacy of the streetlighting system may be realized.

5. Conclusions

This study conducted a simulation to determine certification standards for a new convergence product: a smart LED street lighting system. The suggested certification standards include the minimum time to initiate dimming-up, the duration of the dimming-up period, and the number of concurrently controlled streetlights, which are related to the brightness control of smart streetlights.

The proposed simulation model and certification standards were applied to actual roads in Korea. We found that one of the roads did not meet the required standard for average road surface luminance, considering the lighting arrangement and vehicle speed, because streetlights were too far apart. The other had streetlights installed at a shorter interval than the optimal spacing. A simulation was used to experimentally model the actual and ideal spacing and lighting conditions for each road, with the findings underscoring the need for ideal spacing in streetlight installations, and the implementation of a smart LED streetlight system that adheres to the three suggested certification standards. This setup guarantees that when vehicles approach the road, there are no shaded areas, and a visible distance exceeding the driver's stopping sight distance is secured. This strategy enhances the driver's visibility and adaptability, thereby significantly increasing road safety. Moreover, a dynamically controlled dimming method, adjusted according to traffic volume, was proposed and a second experiment using real traffic-volume data proved its ability to effectively lower energy consumption. By judiciously operating streetlights and balancing overuse and underuse, energy savings can be achieved, while also contributing to overall road safety.

Clear and consistent certification standards for new convergent products are essential for product development and improvements. In particular, smart LED streetlight systems are a crucial technology for building advanced transportation systems, and verified certification standards can increase road safety and enable more efficient operations. To date, our research has been conducted only on individual roads. However, future studies should expand to larger areas, such as urban districts, to assess safety and energy savings more comprehensively. Although the proposed methods have been validated through simulations, there is potential for future application and evaluation of real streetlight systems. Additionally, the present study was carried out under the premise that it remained unaffected by weather conditions or ambient lighting. Future research could encompass a variety of surrounding environments. Moreover, experiments in a dynamic setting, involving gradual changes in vehicle speeds and pedestrian movement, are feasible.

The method proposed in this study for modeling and integrating the suggested convergent product into existing smaller systems and conducting simulations can be applied across various fields. Using simulations, it is possible to experiment with various scenarios for a range of innovative products that do not currently exist, thereby establishing certification standards.

Author Contributions: Conceptualization, B.-G.K. and K.-M.S.; methodology, S.-W.C.; validation, B.-G.K. and S.-W.C.; formal analysis, J.-M.Y.; investigation, J.-M.Y.; resources, B.-G.K.; data curation, B.-G.K.; writing—original draft preparation, S.-W.C.; writing—review and editing, B.-G.K. and K.-M.S.; visualization, S.-W.C.; supervision, J.-M.Y.; project administration, B.-G.K.; funding acquisition, K.-M.S. All authors have read and agreed to the published version of the manuscript.

Funding: This paper was supported by Korea Evaluation Institute of Industrial Technology grant funded by the Ministry of Trade, Industry and Energy (Korea) (No. 20010644, The Development of the Criteria for the Certification of Compliance and the Support for New Convergence Products Improvement).

Data Availability Statement: Publicly available datasets were analyzed in this study. This data can be found here: [https://topis.seoul.go.kr/refRoom/openRefRoom_2.do].

Conflicts of Interest: The authors declare no conflicts of interest.

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