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RESEARCH PAPER

On the appropriacy of retrofitting conventional discharge lamps with light-emitting diodes for municipal public road lighting projects

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Abstract

A discernible shift in municipal engineering practices concerning public road lighting in developing countries such as India has made more and more municipalities display a trend of retrofitting conventional discharge lamps such as high-pressure sodium (HPS) vapour and metal halide (MH) lamps with light-emitting diodes (LEDs). This simulation-based study extensively simulated road illumination systems deploying HPS, MH, and LED luminaires and explored 104,976 installation combinations in total. Cataloguing the most appropriate system design configurations and prioritizing energy efficiency (ε_x) of lighting installations, the LED-based road illumination systems (ε_x: 26.25 to 31.50 lx*m^2/W) were found to be at least 13.63% more energy efficient as compared to the HPS-based ones (ε_x: 19.51 to 23.10 lx*m^2/W) and at least 125.22% more energy efficient as compared to the MH-based ones (ε_x: 10.18 to 11.66 lx*m^2/W). Moreover, the increment in road surface average illuminance per unit increase of luminaire power rating was the highest in the case of LEDs (gradient: 0.131). Furthermore, 140 W and 279 W LED-based road illumination systems were shown to maintain the primary requirements of average illuminance (E_{av}, lx) and overall uniformity of illuminance (U_0) of group A2 ($E_{av} \geq 15$ lx and $U_0 \geq 0.4$) and group A1 ($E_{av} \geq 30$ lx and $U_0 \geq 0.4$) lighting classifications of the Indian Standard IS:1944 (1970) respectively. This study reinforces the notion of transitioning to LEDs for municipalities in light of compliance with standards, superior energy efficiency, and better spacing-to-height ratio, and advocates the utility of photometric simulation methods in excogitating projects.

Keywords Road lighting · Street lighting · Illumination · Discharge lamps · LED · Energy efficiency of lighting installations · Lighting simulation

Introduction

Significance and evolution of municipal public road lighting practices

Road networks provide connectivity among various geographical locations and the economic performances of industries and enterprises depend on the conditions of public road infrastructure (Seitz 1993). Public road (inclusive of streets and other carriageways) lighting is generally in the domain of municipal affairs (Benito et al. 2015) and proper road illumination systems can increase municipal revenue collection as it beautifies the cities and promotes the nighttime economy in tourist locations (Pottharst and Könecke 2013; Pinke-Sziva et al. 2019). Municipal bodies deem road lighting to be an indispensable aspect of public service and its availability is not contingent on domiciliary considerations as no differentiation between residents and non-residents is made for rendering such service (Lorenzo and Sánchez 2007). In developing nations including India, road illumination systems are still based on high-pressure sodium (HPS) vapour and metal halide (MH)-based luminaires (Chakraborty et al. 2021; Thungtong et al. 2021).

Nevertheless, the proliferation of energy-efficient light-emitting diode (LED)-based public road illumination systems (Chakraborty et al. 2022) and the advent of adaptive control methods have coincided with the proclivity of municipal and other bodies to select solid-state technology-based smart street lighting solutions, a trend which is burgeoning (Polzin et al. 2016; Pagden et al. 2020; Gorgulu and Kocabey 2020; Deepaisarn et al. 2023). One recent

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simulation-based study expatiated the rational underpinnings of retrofitting conventional HPS luminaires with LED luminaires, demonstrated that LEDs direct more of the generated luminous flux onto road surfaces and owing to the higher correlated colour temperature (CCT) values of LEDs (3000 K or 4000 K) as compared to HPS luminaires, luminous flux (φ, in lm) outputs of LEDs of suitable power ratings could further be reduced by factors of 1.21 or 1.46 to match the brightness perception of roadways illuminated by 70 W to 150 W HPS luminaires (Brons et al. 2021).

Recent trends in road lighting research with simulative approaches and computational techniques

Computer programmes have been utilized to compute photometric parameters for road lighting applications for at least three decades and early computer predictions of luminance were shown to differ from measured values (Janoff 1993). Since then, advancements in simulation tools and computational techniques have increased the prediction accuracy of computer programmes. One influential study (Yoomak and Ngaopitakkul 2018) utilized the industry-standard tool DIALux to simulate various installation configurations of HPS- and LED-based road illumination systems for dry and wet road surfaces and made descriptive comparisons in terms of luminance and illuminance parameters. It was concluded that to ensure higher values of energy efficiency, 120 W LED luminaires should be mounted 8 – 9 m above the road surface while 150 W LED luminaires should be mounted 10 – 11 m above the road surface. A different study (Cengiz 2020) explored how luminaire aiming angles could influence road lighting quality parameters for opposite and staggered siting of luminaires and concluded that the staggered siting was advantageous as it offered the designer the option to increase the pole spacing by 4 m. A pioneering study (Rabaza et al. 2020) advocated the usage of a differential evolution (DE) algorithm, a stochastic optimization technique, for road lighting planning while maximizing the energy efficiency of lighting installations and validated their results with that obtained by the application of the industry-standard tool DIALux. An analytical study (Sikora and Markiewicz 2021) proposed the usage of new energy performance indicators considering reactive and distortion power flows and supplemented the results with photometric outputs in terms of luminance and illuminance parameters generated by the application of the industry standard tool DIALux. Another study (Viswanathan et al. 2021) developed a comprehensive model for street lighting incorporating variables and factors such as traffic volume, pedestrian density, ambient light levels, payback period, and life cycle costs and validated the same with traffic data worldwide. More recent studies (Roy et al. 2022; Bhattacharya et al. 2023, 2024; Ayaz et al. 2024) performed photometric simulations of road illumination systems (following both luminance- and illuminance-based approaches) with luminaire luminous intensity distribution data tables, performed multiple regression analysis with photometric simulation data to propound models, compared predictions of propounded models with that of standard lighting design software and contrasted field measurements with simulation predictions. Moreover, stochastic modelling of smart street lighting has been performed with a view of assessing maintenance models (França Filho and Tavares 2025). These studies emphasize the growing significance of simulation-based approaches, modelling, and statistical analysis in road lighting practice and research, and given the existing challenges in upgrading contemporary road lighting practices (vide: Sect. ”Challenges in upgrading current practices and the rationale of this study”**.**), this study adopts a simulation-based methodology which is detailed in Sect. ”Design Criteria and Methodology”.

Challenges in upgrading current practices and the rationale of this study

The Street Light National Program (SLNP) was launched in January 2015 in India for the replacement of conventional luminaires with energy-efficient LEDs. 1576 Urban Local Bodies (ULBs) (EESL) out of 4815 (Kishore 2022) (32.73%) were enrolled in the program as participation was voluntary. Necessary work was completed for only 1060 ULBs (22.01% of all ULBs in India) and this number is denotative of the limited adaptation of this program. In practice, municipal engineers in India still tend to prefer conventional luminaires for public road illumination projects, despite a bourgeoning body of literature supporting the integration of LEDs into existing road illumination systems (Spahiu et al. 2018; Babatunde et al. 2019; Morillas and de Andrés 2019; Gordic et al. 2021; Cho et al. 2024; Jamaludin et al. 2024), regional constraints, infrastructure compatibility, and other factors still influence the continued preference for conventional gas-discharge luminaires.

In order to facilitate municipal decision-making in the selection of luminaires for public road lighting projects, assist the evaluation of bids submitted by vendors to floated tenders, benchmark improvements in energy efficiency, and augment the best practices of public lighting in India, this study performed extensive photometric simulations with LED, MH, and HPS luminaires of appropriate power ratings, sorted installation layouts that were compliant with the primary requirements of the Indian Standard ‘Code of Practice for Lighting of Public Thoroughfares’ (IS:1944 – 1970) (Illuminating Engineering Sectional Committee 1970) for group A2 lighting installation classification of roads (Average illuminance or $E_{av} \geq 15$ lx and overall uniformity of illuminance or $U_0 \geq 0.4$), explored luminaire power rating—road surface average illuminance characteristics for standard design configurations and provided a compendium for the retrofitting of conventional luminaires with LEDs.

To address the issues and challenges in transitioning from conventional to LED-based solutions and provide empirical insights, this study was shaped by the following pertinent hypotheses (H1, H2 and H3) that were conceptualized with a view of recent literature:

H1 LED-based road illumination systems are more energy efficient as compared to conventional counterparts (HPS and MH) for municipal road lighting.

H2 The increment in road surface average illuminance with an increment in luminaire power rating is the highest for LED-based road illumination systems.

H3 LED-based road illumination systems with appropriate luminaire power ratings can be designed in compliance with the appurtenant standards for road illumination and geometric design in the Indian context.

Design criteria and methodology

Primary photometric and geometric selection criteria for road lighting

In India, major municipal roads comprising four lanes are often 14 m in width, and usually, luminaires are sited along the edges of the roadway in opposite arrangements. It is desirable for such roads to have adequate lighting provisions to enhance visibility, promote pedestrian safety, and increase energy efficiency. These roads often serve as arterial roads and qualify as the type of road for which the group A2 lighting classification (IS: 1944 – 1970) would be apposite. Withal, the ‘Geometric Design Standards for Urban Roads and Streets’ (IRC: 86 – 2018) (Highway Specifications and Standards Committee 2018) recommends that the pole height (luminaire mounting height) should be 10 – 12 m and the pole spacing (span) should be 30 – 33 m for roadways having width more than 9 m. In quotidian practice, municipal engineers strive to increase the span so as to lessen the financial incurrences of electricity including electricity bills and tariffs. This practice, driven by the obligation to reduce the electrical load for illumination, may impact lighting quality such as uniformity of illumination, and endanger public safety. This necessitates the meticulous utilization of simulation-based approaches to compute the lighting quality parameters of proposed lighting solutions and ensure compliance with the pertinent regional norms, design guidelines, and codes of practice. The next section (Sect. ”Procedure for the conduction of photometric simulations”.) delineates the procedure for conducting photometric simulations.

Procedure for the conduction of photometric simulations

Photometric simulations were conducted in the simulation environment of Relux, a validated photometric simulation program offering ‘robust simulation capabilities’ for artificial lighting (Shojaee Barjoee and Gendler 2024), for various installation configurations as enunciated in Table 1. In Relux, under the ‘new project’ heading, ‘road’ was chosen and it was beneath the ‘light and sensor planning for exterior scenes’ sub-heading. Thereafter, luminaire luminous intensity distribution files were imported and road characteristics (road layout and luminaire arrangements) were modified under the ‘project’ tab in consonance with the intended configurations. Particularly, 130 W, 150 W, 250 W, and 468 W HPS (Hubbell, Cooper, and GE), 140 W, 216 W, 279 W, and 323 W LED (GE LED, Sun Valley, Cooper, and Signify), and 283 W, 350 W, 397 W and 452 W MH (Cooper) luminaire luminous intensity distribution data tables were imported to the simulation environment. The selected luminaires had type III lateral distribution (50% of the maximum iso-candela trace is within 1.75 to 2.75 times the luminaire mounting height on the street side with reference to the luminaire position) and medium throw (50% of the maximum iso-candela trace is within 2.25 to 3.75 times the luminaire mounting height on both sides longitudinally with reference to the luminaire position). For the purposes of photometric simulation, h was varied from 8 to 12 m with nine steps and periodicity of 0.5 m, S was varied from 24

Table 1 Public road illumination system installation configurations for photometric simulation

Variable/parameter/descriptor	Particulars/details/description
HPS power rating (W)	130, 150, 250, 468
LED power rating (W)	140, 216, 279, 323
MH power rating (W)	283, 350, 397, 452
Photometric distribution type	Type III medium throw
Luminaire mounting height (h, in m)	8, 8.5, 9, … 12
Pole spacing (S, in m)	24, 25, 26, … 50
Road width (b, in m)	14
Luminaire tilt (δ, in °)	0, 2, 4, … 10
Luminaire overhang (y_l, in m)	0.5, 1, 1.5, … 3
Luminaire arrangement	Opposite
Maintenance factor	0.8
Luminaire orientation	Default
Road layout	Without central reservation

to 50 m with 27 steps and periodicity of 1 m, δ was varied from 0° to 10° with six steps and periodicity of 2° and y_1 was varied from 0.5 m to 3 m with six steps and periodicity of 0.5 m. Thus, a total of 104,976 installation combinations were simulated. For each combination, it was assumed that the spacing between any two successive poles was constant, the road segment was rectilinear and the luminaires had identical luminous intensity distribution properties for any particular installation configuration. Figure 1 depicts the same for a road segment of finite width with necessary labels for representational purposes. Illuminance calculations were made considering the entire calculation surface of the road segment, irrespective of the number of lanes.

Results

Installation configurations compliant with the pertinent lighting class and computation of energy efficiency of lighting installations

For each category of luminaires (HPS, LED, or MH), photometric simulations were made for 34,992 system design combinations. The results were filtered using relevant spreadsheet functions and the most appropriate installation (system design) configuration for each power rating was chosen so that the predominant dual condition ($E_{av} \geq 15$ lx and $U_0 \geq 0.4$) of group A2 lighting classification (IS:1944 – 1970) was met.

Table 2 provides a compendium of the same. The energy efficiency (ε_x) of lighting installations was computed utilizing the following formula (Rabaza et al. 2016) which is applicable to an opposite (coupled) luminaire layout:

$\varepsilon_x = 0.5 * \frac{S*b*E_{av}}{W}$ … (1).

From Table 2, it can be observed that the 397 W MH-based road illumination system demonstrated the lowest energy efficiency (10.18 lx*m^2/W) whereas the 140 W LED-based road illumination system demonstrated the highest energy efficiency (31.5 lx*m^2/W). LED-based road illumination systems were at least 13.63% energy efficient as compared to the HPS-based road illumination systems and at least 125.22% energy efficient as compared to the MH-based road illumination systems. As there is no settled regulation pertaining to installation energy efficiency, it should be as energy efficient as practicable (Peña-García et al. 2016) and the LED-based road illumination systems, in general, outperformed their conventional discharge lamp counterparts in that aspect.

Luminaire power rating to road surface average illuminance characteristics for a standard geometric design

The luminaire power rating—road surface average illuminance characteristics were explored for a standard system design configuration (b = 14 m, h = 10 m, S = 32 m, y_1 = 1 m, and δ = 10°) for HPS, LED, MH luminaire-based road illumination systems with the opposite arrangement

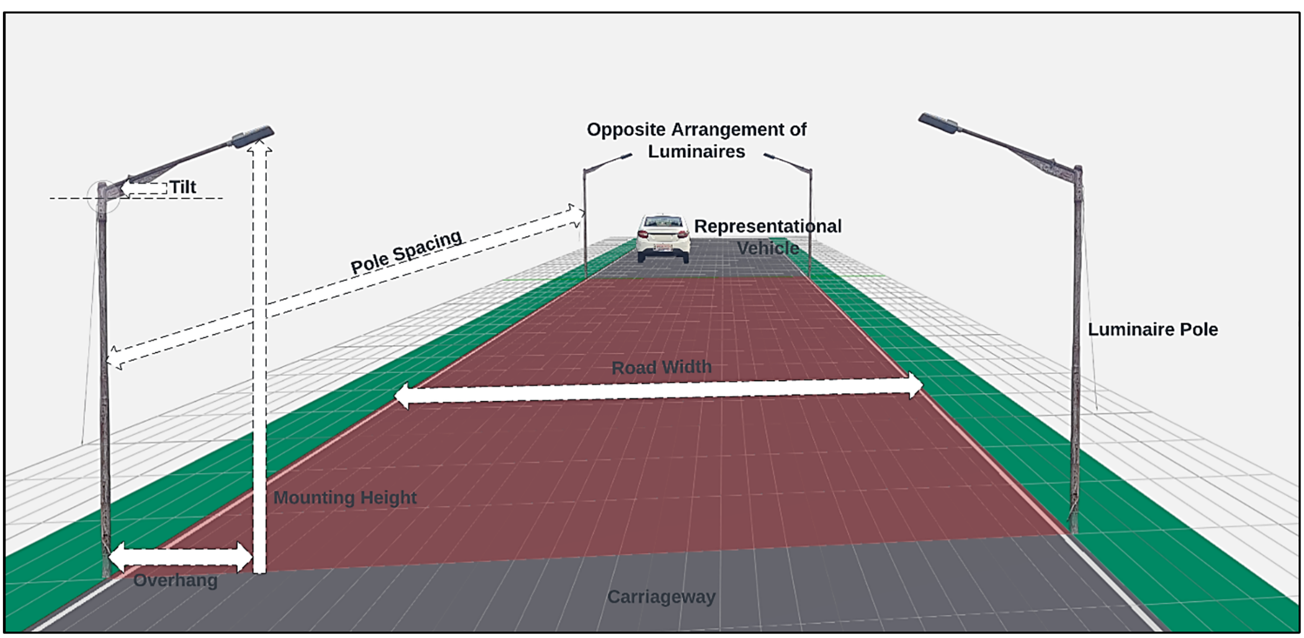

Fig. 1 Visualization of an archetype road segment with the opposite arrangement of luminaires

Table 2 A compendium of the most appropriate luminaire installation configurations of HPS, LED, and MH-based public road illumination systems

Luminaire type	Power rating (W)	Mounting height (h, in m)	Pole spacing (S, in m)	Tilt (δ, in °)	Overhang (y_l, in m)	Average illuminance (E_{av}, in lx)	Overall uniformity of illuminance (U_0)	Energy efficiency (ε_x in lx*m^2/W)
HPS	130	9	24	4	3	15.1	0.4	19.51
	150	11	33	4	3	15	0.41	23.10
	250	12	35	8	0.5	20	0.41	19.60
	468	12	34	10	0.5	44	0.4	22.37
LED	140	12	42	6	1.5	15	0.42	31.50
	216	12	50	10	0.5	16.2	0.44	26.25
	279	12	50	8	1.5	22	0.4	27.59
	323	12	40	10	0.5	32	0.4	27.73
MH	283	10	31	0	3	15.2	0.44	11.66
	350	11.5	37	2	3	15.1	0.4	11.17
	397	12	38	4	1	15.2	0.41	10.18
	452	12	39	6	0.5	17.4	0.4	10.50

of luminaires. Figure 2 demonstrates the same with fitted linear trendlines.

From Fig. 2, four cogent observations can be made. Firstly, the association between luminaire power rating and road surface average illuminance could satisfactorily be fitted with linear trendlines following the slope-intercept form of a straight line: $y = mx + c$. Secondly, the coefficient of determination (R^2) values were almost 0.99 for all three trendlines and this implied that for comparable power ratings of a particular category of luminaire, the road surface average illuminance values would not differ much. Thirdly, the slope (m) was the highest for the trendline fitted for LED luminaires and the lowest for the trendline fitted for MH luminaires and this connoted that the rate of change of road surface average illuminance with respect to luminaire power rating was the highest for LED luminaires. Fourthly,

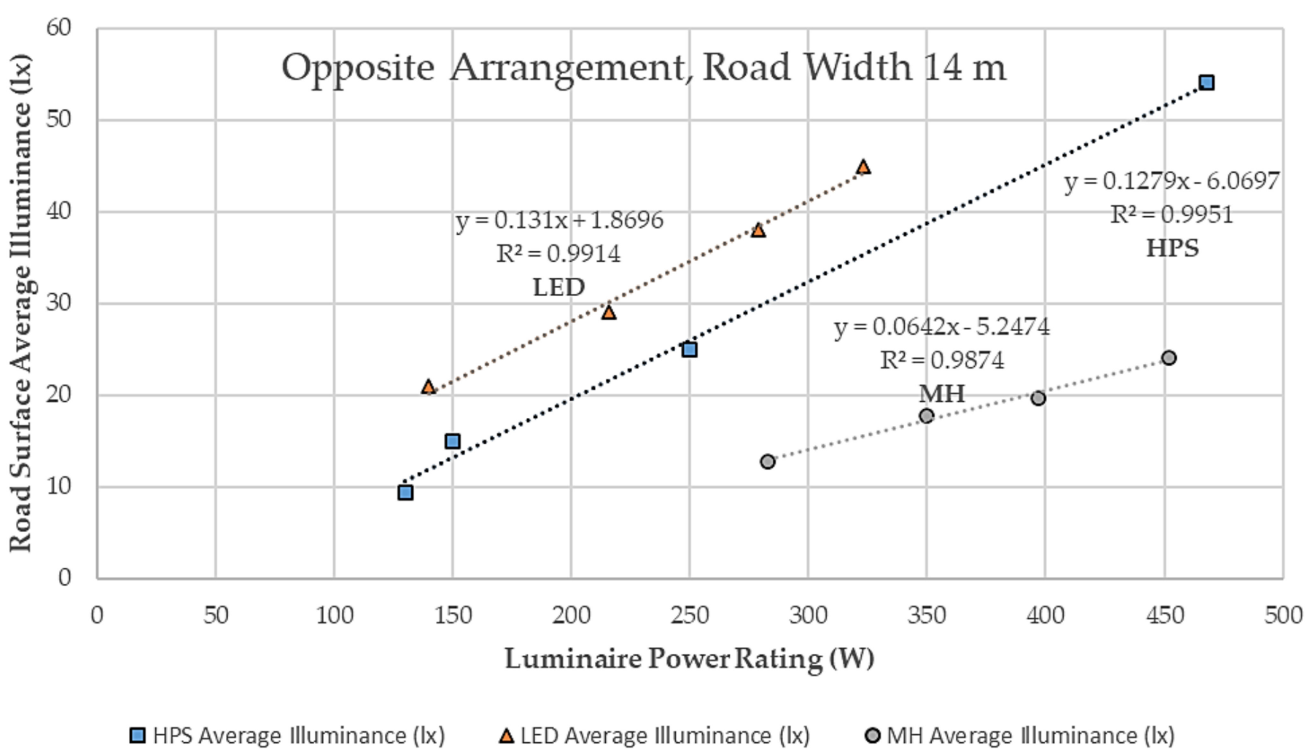

Fig. 2 Association between luminaire power rating and road surface average illuminance for a standard lighting system design configuration

the intercept (c) had the lowest absolute value for the trendline fitted for LED luminaires and this is an estimate of the error of the pertinent linear model as road surface average illuminance should be zero when the luminaires are not operational.

Discussion and analysis

The suitability of LEDs for retrofitting projects and recommendations

From the preceding sections, it is perspicuously evident that the prime road lighting solutions for municipal authorities and entrusted agencies should be LED-based and this is in consonance with the relevant observations and conclusions of previous studies (Rabaza et al. 2016; Brons et al. 2021; Roy et al. 2022). LEDs, in general, outperform both HPS and MH luminaires in terms of energy efficiency (Yoomak et al. 2018; Davidovic and Kostic 2022) and effectively maintain requisite average illuminance on the pavement. MH luminaires fared the worst in comparison to both LED and HPS luminaires. However, some practitioners display a penchant for MH-based road lighting owing to good colour rendering and perceived 'quality' of light over HPS luminaires (Belcher et al. 1999; Rea et al. 2009). Nevertheless, as the proclivity for sanctioning LED-based retrofitting projects and commissioning LED-based street lighting systems is on the rise, Table 3 provides a conspectus of recommendations for efficient retrofitting with LEDs in order to maintain the primary recommendations of the group A2 lighting classification (IS:1944 – 1970) as well as the recommendations of the IRC (IRC:86 – 2018) in terms of pole spacing and luminaire mounting height. Similarly, Table 4 provides a conspectus of recommendations for retrofitting with LEDs for maximum overall uniformity of illuminance.

From Tables 3 and 4, it can be observed that while 140 W LEDs are highly suited to maintain the group A2 lighting classification (IS:1944 – 1970), the 279 W LEDs can even maintain the primary requirements of the group A1 lighting classification ($E_{av} \geq 30$ lx and $U_0 \geq 0.4$) with a satisfactory installation energy efficiency. One recent study (Bhattacharya et al. 2024) propounded a comprehensive model of estimating photometric parameters and installation energy efficiency based on multiple regression analysis that could be applied to maintain the CIE C2 lighting class ($E_{av} \geq 20$ lx and $U_0 \geq 0.4$) and the foremost conditions of the group A2 classification (of lighting installations) of Indian roads and the recommendation tables (Tables 3 and 4) of this study could find usage in conjunction with that model among lighting practitioners, municipal engineers and contractors.

Exploration of the variations of overall uniformity of illuminance with changes in pole spacing to mounting height ratio

For road illumination systems, the pole spacing to mounting height ratio (SHR) influences the overall uniformity of illuminance (U_0) for different luminaires and installation configurations. Figure 3 provides SHR vs. U_0 plots for road illumination systems comprising luminaires of comparable power ratings (250 W HPS, 279 W LED, and 283 W MH) in opposite arrangement.

Each subplot in Fig. 3 is a cloud of 8748 data points, illustrating the variations in uniformity based on SHR. It can be perceived that the mandated minimum overall uniformity of illuminance ($U_{0min} = 0.40$) can be maintained for road illumination systems with a maximum SHR (SHR_{max}) = 3 for 250

Table 3 A conspectus of recommendations for retrofitting conventional discharge lamp-based public road illumination systems with LEDs

Mounting height (h, in m)	Pole spacing (S, in m)	Recommended tilt (δ, in °)	Recommended overhang (y_l, in m)	Suitable LED power rating (W)	Average illuminance (E_{av}, in lx)	Overall uniformity of illuminance (U_0)	Energy efficiency (ε_x in lx*m^2/W)
10	30	2	0.5	140	22	0.59	33
	31	4	0.5		22	0.57	34.1
	32	8	0.5		21	0.56	33.6
	33	10	0.5		20	0.54	33
11	30	0	0.5		21	0.64	31.5
	31	0	0.5		21	0.63	32.55
	32	10	0.5		19.8	0.56	31.68
	33	10	0.5		19.2	0.56	31.68
12	30	10	0.5		19.9	0.62	29.85
	31	10	0.5		19.2	0.62	29.76
	32	2	0.5		19	0.64	30.4
	33	2	0.5		18.4	0.62	30.36

Table 4 A conspectus of recommendations for maximization of overall uniformity of illuminance upon retrofitting of public road illumination systems with LEDs

Mounting height (h, in m)	Pole spacing (S, in m)	Recommended tilt (δ, in °)	Recommended overhang (y_l, in m)	Suitable LED power rating (W)	Average illuminance (E_{av}, in lx)	Overall uniformity of illuminance (U_0)	Energy efficiency (ε_x in lx*m^2/W)
10	30	0	0.5	279	41	0.74	30.86
	31	0	0.5		40	0.72	31.11
	32	0	0.5		39	0.7	31.31
	33	0	0.5		37	0.68	30.63
11	30	0	0.5		38	0.79	28.60
	31	0	0.5		37	0.77	28.77
	32	0	0.5		36	0.75	28.90
	33	0	1		36	0.73	29.80
12	30	0	0.5		36	0.79	27.09
	31	0	0.5		35	0.78	27.22
	32	0	0.5		34	0.78	27.29
	33	0	0.5		33	0.78	27.32

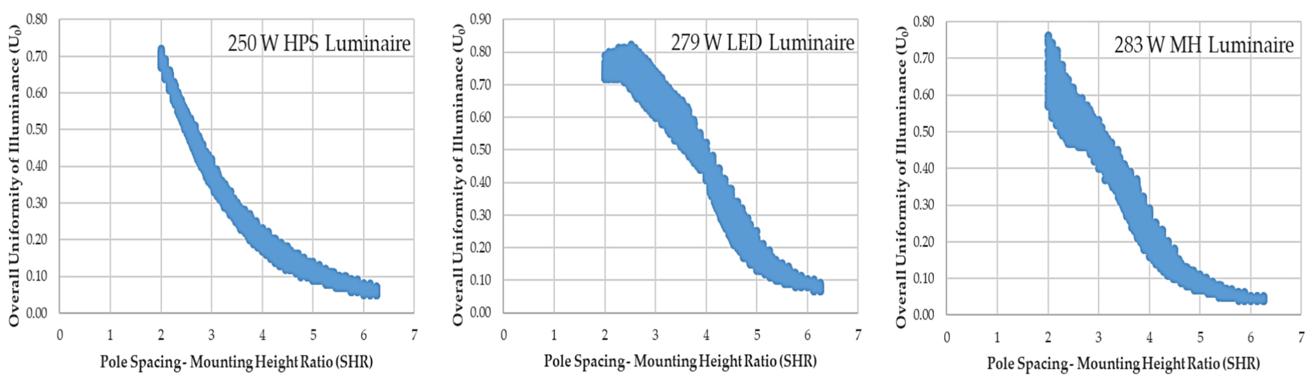

Fig. 3 Pole spacing to mounting height ratio (SHR) vs. overall uniformity of illuminance (U_0) plots for road illumination systems with comparable luminaire power ratings

W HPS luminaires, $SHR_{max} = 4.352$ for 279 W LED luminaires and $SHR_{max} = 3.529$ for 283 W MH luminaires. Thus, 279 W LED-based road illumination systems can maintain a U_0 value of at least 0.40 for the largest SHR as compared to HPS and MH luminaire-based road illumination systems of comparable luminaire power ratings. This attests to the appositeness of LED-based road illumination systems for achieving optimal lighting uniformity.

Financial and other considerations for retrofitting with LEDs

Despite the recent advancements in solid-state lighting technology, certain issues often obtrude the widespread adoption of LEDs for municipal road lighting projects (Jamaludin et al. 2023). LED-based road illumination systems often demonstrate high reactive power demand and total harmonic distortion (Blanco et al. 2013; Islam et al. 2015) which may be construed as undesirable attributes of low-voltage distribution networks and shall require the mitigatory implementation of small capacitors or inductor coils depending on the nature of the load (inductive or capacitive) and filtering circuits for harmonics reduction (Phannil et al. 2018). In addition, other issues such as perceptions of uncertainty, missing warranties, payback periods longer than the guaranteed lifetime of LEDs (inclusive of components), inadequate dissemination of technical and commercial information and a lack of qualified facilitators (consultancy services or similar agencies to support retrofitting procedure) often hinder the full-scale adoption of LED-based road lighting solutions and it has been argued that the acceptance of market-based solutions such as energy performance contracts (EPCs) can be propitious to the procurement of energy-efficient retrofitting solutions such as LEDs at the municipal level (Polzin et al. 2016). However, it is argued that EPCs are difficult to implement in practice due to convoluted regulations on public procurement, ownership rights, the ineptitude of public administration in handling projects, and other cogent reasons (Šeba and Mušec 2018). In general, it is agreed that municipality-owned LED-based road illumination systems would entail higher monetary savings as compared to LEDs leased from contractors or other utilities (John Bullough et al. 2015; Brons et al. 2021). Moreover, some studies (Raul and Ghosh 2019; Herzog et al. 2022) have demonstrated that higher ambient temperature and humidity may have an effect on expediting the luminous flux or lumen depreciation of chip-on-board as well as surface-mounted device type of LEDs and would cause chromaticity shifts and degradation of white LEDs.

Therefore, municipal authorities and public works departments shall have to take into consideration all these contentious issues and matters of solicitude before sanctioning LED-based road illumination projects *en bloc*, and qualified facilitators with validated credentials can assist in excogitating such projects giving priority to benefit-to-cost ratio (BCR), return on investment (ROI) and payback period.

Conclusion

General inferences and main highlights of this study

This study performed photometric simulations of road illumination systems in a validated proprietary software for different installation configurations of HPS, LED, and MH luminaires having type III (medium throw) luminous intensity distribution patterns. It was discerned that the usage of LEDs elicited the highest installation energy efficiency values whereas the alternative of deploying road illumination systems comprising MH luminaires was found to be the least energy-efficient one. For a standard installation layout, the increment in road surface average illuminance level per unit change in luminaire power rating was the highest for LEDs and lowest for MH luminaires. In addition, 140 W LED-based road illumination systems as per Table 3 were deemed to be compliant with the requirements of both the group A2 classification (of lighting installations) of Indian roads of IS:1944 – 1970 and the IRC:86 – 2018. 279 W LED-based road illumination systems as per Table 4 achieved the highest overall uniformity of illuminance levels and simultaneously satisfied the stringent requirements of the group A1 classification (of lighting installations) of Indian roads of IS:1944 – 1970. 279 W LED-based road illumination systems were also shown to maintain an acceptable level of U_0 ($U_0 \geq 0.40$) for the largest SHR ($SHR_{max} = 4.352$) as compared to HPS- ($SHR_{max} = 3$) and MH-based ($SHR_{max} = 3.529$) road illumination systems of comparable luminaire power ratings. All the formulated hypotheses (vide: Sect. "Challenges in upgrading current practices and the rationale of this study".) were accepted in the aftermath of the foregoing analysis. Thus, this study, in furtherance of a previous study (Brons et al. 2021), is posited to be of referential value to stakeholders and it shall enable municipal authorities, especially in India, to choose appropriate lighting installation configurations and commission projects that shall conform to the applicable national standards of geometric design and illumination of roads and thoroughfares.

Limitations of this study and suggested areas for future research

The conducted study utilized a simulation-based approach and generated photometric simulation data of LED-, HPS- and MH-based road illumination systems. As such, it precluded factors from the simulation environment such as environmental attenuation due to molecular scattering and absorption (generally negligible) (Hulburt 1935), anthropogenic sources of peripheral illumination which can increase the luminance levels considerably (Ayaz et al. 2024) and luminous flux emanating from vehicular headlamps. Withal, the results were obtained for design parameters that satisfy the Indian standards of illumination and road geometry and pretermitted the road lighting standards and codes of practice of other countries. Future research endeavours may focus on extending the findings of this study to other countries with different codes of practice of road illumination, regulatory frameworks, and varied road lighting infrastructure. Following the neoteric methodology of using aerial imagery in street lighting evaluation of a recent study (Rabaza et al. 2018), fieldwork, case studies, or pilot projects regarding light level measurements and energy efficiency computations can be carried out which may validate the simulation results and consolidate the findings. Such endeavours will undeniably upgrade contemporary practices in municipal road lighting and endorse the application of simulation-oriented approaches for proffering energy-efficient and sustainable LED-based road lighting solutions.

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Declarations

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