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Design of haul road lighting system. Part I: design based on optimal energy considerations

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Electrical energy consumption is a major cost component of haul road lighting. Haul road lighting depends on many parameters such as type and wattage of sources, mounting height and tilt angle of light fixtures. In this study a computer model has been developed for optimum energy consumption of any haul road lighting system. Using the program, illumination design was studied for a stretch of 800 m long haul road. Nine different types of light sources were considered for mounting heights of 12 and 16 m. High-pressure sodium vapour (HPSV) lamps of 100 W proved to be energy efficient at a 12 m height whereas at 16 m height, energy consumption was minimum for 150 W HPSV lamps. Thus the developed computer program proved to be successful in evaluating the performance of lighting designs from the point of view of energy consumption.

Keywords: Lighting; Haul road; Computer design; Energy optimization

1. Introduction

In surface mines where work is carried out at night, efficient artificial lighting is essential for both working efficiency and safety. Roadway lighting beyond daylight hours is very important and requires good illumination in terms of light levels, uniformity and glare in any circumstance. The principal purpose of haul road lighting is to provide instant, accurate and comfortable visibility at night. An important aspect of lighting design is to provide sufficient illuminance for visual tasks; this primarily depends upon the intensity of light sources used.

With the use of higher wattage lamps, the initial investment may be reduced as fewer poles are required than in a lower wattage system. In fact, high-pressure sodium vapour (HPSV) lamps have the advantages of a longer economic life and efficient penetration character in dusty and foggy environments (Aruna *et al.* 2003). High-pressure mercury vapour (HPMV) lamps are generally used where colour rendition is very important. However, unless properly oriented, these lamps may produce glare (Peretiatkoniez 1982). Due to typical environmental conditions in mining

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areas, the frequent breakage of fluorescent tube lamps (FTLs) is a major problem (Aruna *et al.* 2004). Fluorescent lamps are, however, very common in semi-mechanized mines due to their very good distribution of light and the fact that their twin tubes reduce the chances of blackness.

Good lighting is not only a matter of providing light but also ensuring its proper distribution. The uniform distribution of light depends on design features such as luminaire layout and aiming angle and positioning of light sources. The same illumination level may be achieved by different combinations of the design features. In each case energy consumption is different. Electrical energy consumption is the single highest cost component of any illumination system (Bright 1949). Optimization of energy consumption in illumination design would thus reduce overall lighting costs. This paper describes the development of software for energy-efficient illumination design for haul roads.

2. Principles of haul road lighting

Six different types of light pole layout are possible for haul roads—single sided, double sided opposite, staggered, twin central, central catenary and centrally suspended (CIE 1999). Of these, the single-sided pole arrangement is the most prevalent in mines as the installation of poles and the electrification process in this layout is simple. However, with this type of arrangement the illuminance of the road surface at the side farthest from the luminaire is usually much lower than that of the side nearest. This lowers the overall illuminance uniformity ratio, defined as the ratio of minimum illuminance to the average illuminance over an area.

2.1 *Mounting height*

Luminaire mounting height depends on the lighting arrangement and effective road width. The effective width is the horizontal distance between luminaire and the far curb. To achieve a good distribution of light across the roadway, mounting height, in general, is equal to or near the road width (Bommel and de Boer 1980). Mounting height also depends on the characteristics of the light source. In general, high-power lamps are mounted higher than low-power lamps.

2.2 *Spacing*

Luminaire or pole spacing for a given lighting arrangement and luminaire light distribution is dependent on the mounting height and the longitudinal uniformity planned for the installation. The greater the mounting height, the larger is the allowed spacing for a given longitudinal uniformity. Longitudinal uniformity is the ratio of minimum to maximum illuminance along a line parallel to the road axis through the observer's position. However, in practice, excellent illumination is considered to be that when the pole spacing is not more than eight times mounting height (Bommel and de Boer 1980).

2.3 *Overhang*

Poles are generally installed somewhat off-set from the road edge (curb) to provide vehicle clearance. Luminaires are mounted on ranging arms to provide adjustment of the distance between them and the curb. Sometimes, the projection of the luminaire lies inside the road from the curb; this is known as overhang. The main purpose of overhang is to provide a better uniformity of light across the road. In effect, the amount of luminaire overhang reduces the effective width of illumination of the road (see figure 1). If necessary the overhang can be adjusted such that, particularly in the interests of providing good visual guidance, the luminaries appear to form a smooth line in the driver's field of view.

2.4 *Inclination*

Inclining or tilting the luminaires up from the horizontal is sometimes carried out to increase the light coverage across the road width at a given mounting height. This measure is, however, not very effective. If the effective road width is large compared with the mounting height, tilting the luminaires will facilitate improving light levels at the far side of the road, but too much tilting will diffuse the light and reduce its distribution along the longitudinal direction of the road. It is recommended that the angle of tilt with respect to the normal height of mounting be limited to an absolute maximum of 10°, a top limit of 5° being preferable (Bommel and de Boer 1980). In practice, the tilt angle varies from 10° to 15°. High tilting, especially at bends in the road, also increases the chances of glare being produced, making it difficult to provide good visual guidance.

3. Mathematical model development

Two fundamental laws in lighting design are the inverse square law and the cosine law. Considering a source at a height of h metres, as illustrated in figure 2, the illuminance at a point

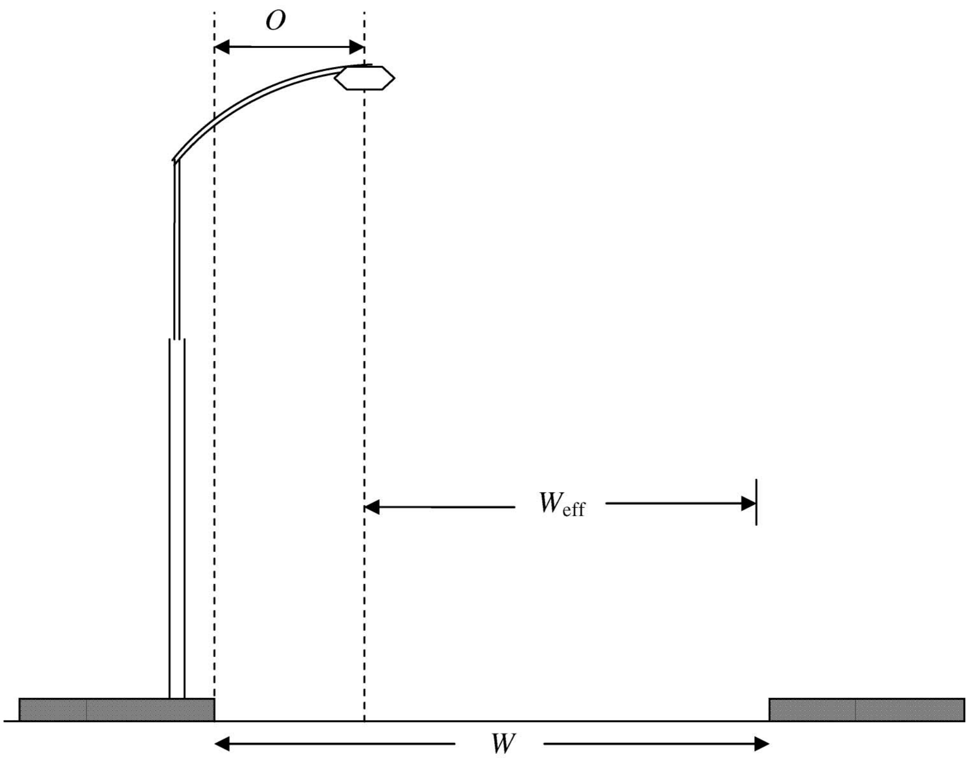

Figure 1. Effective road width (W_{eff}) equal to actual width (W) minus luminaire overhang (O).

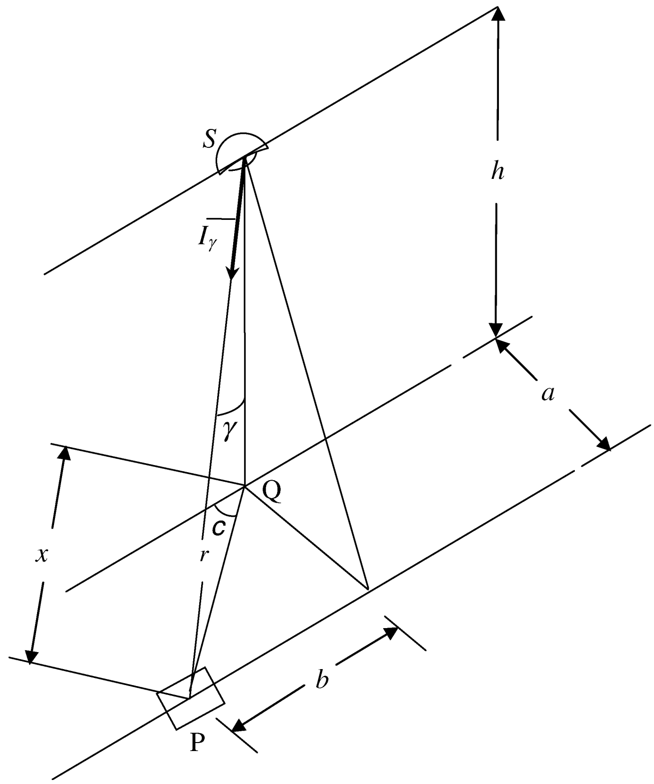

Figure 2. Illuminance on a horizontal plane.

vertically below the source is given by the inverse square law (Guptha 1973, Trotter 1982). So, illumination E at point Q is given by:

$$E = \frac{I}{h^2} \tag{1}$$

where $E =$ illuminance (in lux) at the point of measurement, $I =$ intensity (in candela) from the source to the point of measurement and $h =$ the inclined distance (in metres) from the source to the point of measurement.

Since calculations are made directly for a horizontal working plane, the light strikes the surfaces obliquely, except for the area directly under the lamp. At surfaces where the light strikes obliquely (figure 3), the illumination depends on the location of the point with respect to the pole. The location is governed by two angles—γ, the incident angle of the light ray with the vertical and C, the horizontal angle of the line joining the point and the pole base with the curb. The effect of C and γ at any given point is supplied by the luminaire manufacturer in terms of $I_{(C,\gamma)}$ in tabular form considering a source located vertically above the curb. The horizontal illumination E_{h} at any point can be expressed as:

$$E_h = \frac{I(C,\gamma)}{r^2} \times \cos\gamma \tag{2}$$

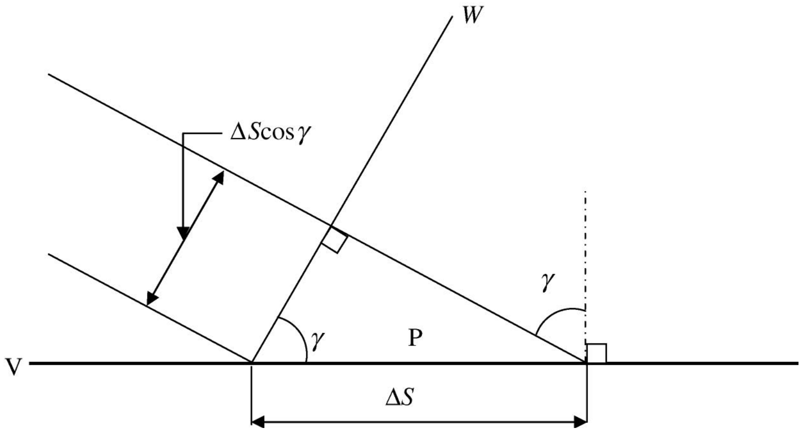

Figure 3. Diagram of the surrounds at point P in figure 2.

where γ = the angle between the vertical and the line joining the source to the point of measurement and r = the inclined distance from the source to the point of measurement. In figure 2,

$$\cos\gamma = \frac{h}{r} \tag{3}$$

$$r = \sqrt{a^2 + b^2 + h^2} \tag{4}$$

where a = the distance from the source to the point of measurement along the γ-plane and b = the distance from the source to the point of measurement along the C-plane.

From equations (2) and (3), the horizontal illuminance at any point P is given by

$$E_h = \frac{I_{(C,\gamma)}}{h^2} \times \cos^3\gamma \tag{5}$$

After installation of the luminaire the illuminance level at P will depend on two further factors—the utilization factor and the maintenance factor. The utilization factor is expressed as the ratio of utilized flux to the luminous flux emitted by the luminaire. This factor accounts for absorption by dust, lamp ageing and absorption in the fitting, drops in line voltage, ballast efficiency, the dimensions of the area to be lit, the shape of the candlepower distribution curve of the luminaire and surface reflectances. Though the utilization factor can vary to a great extent, under normal mine conditions, it lies in the range 0.6–0.8 (in general over the entire life of luminaires used in mines). The performance of a luminaire depends on the level of maintenance in terms of cleaning. The maintenance factor is expressed as the ratio of the average illuminance on the working plane after a specified period of use of a lighting installation to the average illuminance obtained under the same conditions for a new installation. Improper maintenance may reduce the light level by as much as 50–70% (Black 1956, Hottinger *et al.* 1982, Trotter 1982). The effect of maintenance is incorporated in equation (6) as the 'inverse maintenance factor' (IMF) whose value lies (under normal mine conditions) between 1.2–1.3

(Henderson and Marsden 1972). Considering the utilization factor (UF) and the IMF, equation (5) can be rewritten as:

$$E_{\mathrm{h}} = \frac{I_{(C,\gamma)} \times UF}{h^2 \times IMF} \times \cos^3\gamma \tag{6}$$

Equation (6) is valid when the luminaire is installed such that its axis strikes the illuminating surface vertically. In other words, the formula is valid for zero tilt of the ranging arm. For a generalized application, the effect of tilt angle must be considered and we have incorporated the effect of tilt angle in the following way:

$$E_h = \frac{I_{(C,\gamma m)} \times UF}{{r_m}^2 \times IMF} \times \cos\gamma_m \tag{7}$$

where γ_{m} = the modified incident angle of light ray with the vertical and r_{m} = the modified inclined distance between the source and the point of measurement. The luminance at any point P is then given by:

$$L = E_h \times \rho \tag{8}$$

where L = luminance at point P and ρ = the reflectance of the surface.

Using equation (7) and the luminous intensity distribution of a luminaire ($I_{(C,\gamma)}$) supplied by the manufacturer, point-by-point calculations of the illuminance levels at any point on a horizontal plane can be made. The $I_{(C,\gamma)}$ value for a particular luminaire is supplied by the manufacturer either in a $C-\gamma$ table or in the form of isolux map.

Knowing the optimum light source for a particular design, the energy consumption for the lighting system can be calculated. Energy consumption should take into account both the light source wattage and the ballast loss as supplied by the manufacturer.

4. Computer model development

For lighting design of a project, illuminance calculations can be made using photometric luminaire data presented in graphical form supplied by the manufacturer. But such calculations are rather tedious and time consuming, and they entail only a limited number of calculations. Use of digital computer would simplify the calculation procedure. For this purpose a suitable computer program was developed in MATLAB to calculate the illuminance and luminance using equations (6) and (7). A flow chart detailing the program is given in figure 4.

The International Commission on Illumination (CIE) recommends (Bommel and de Boer 1980) that tables giving the necessary intensities (termed *I*-tables) are drawn up according to standard formats. Intensity values for $C-\gamma$ combinations other than the table values can be derived by interpolation of values. These *I*-tables are given in a format compatible with the computer programs being used.

5. Selection of optimum design based on energy consumption

For a comparison of various types of lighting systems, an 800 m long stretch of haul road was considered. As per Indian mining guidelines (Kaku 1957), a minimum of 0.5 lux horizontal illuminance is necessary in haul roads in surface mines. Though Indian mining regulations do not

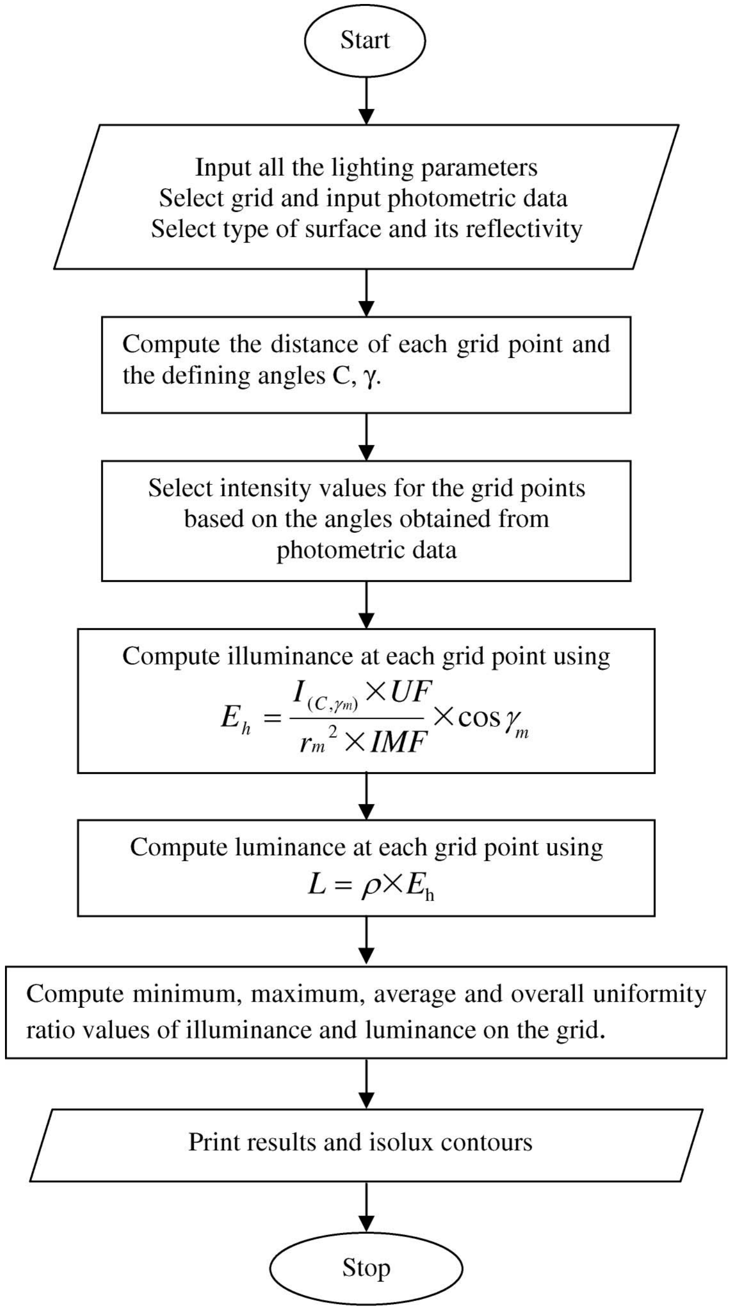

Figure 4. Flow chart for design program.

mention the overall uniformity ratio, the CIE stresses the uniformity ratio as well. It is suggested that for uniform distribution of light, the overall uniformity ratio should be at least 0.3 for a haul road (CIE 1988). The CIE also suggests 30 lux for the average horizontal illuminance level instead of the minimum light level (for 0.3 overall uniformity ratio).

As per the Bureau of Indian Standards (BIS 1970), average illumination level to be maintained in any light traffic roadways is 4.0 lux. Taking all these aspects into consideration, nine different types of light source were chosen for illuminating the haul road. These were modelled using the developed program to achieve the required minimum lighting standards in terms of uniformity ratio (0.3) and minimum (0.5 lux) and average (4.0 lux) light levels (for all cases it may not be possible to satisfy all three parameters). In the present design the tilt angle of light fixtures was kept constant at 10° since this tilt angle gives the best results as discussed earlier.

Computer output is obtained in tabular form, but graphical plotting of light levels along the haul road grid points can also be obtained if desired. A typical plot for a 100 W HPSV source is given in figure 5. In the computer program, there is also the capability of 3D colour plots of light levels over an area.

With the help of the computer-generated results, the number of poles required for each type of source to illuminate the entire length of road is calculated. Table 1 shows details of lighting installations for 12 m poles, along with energy consumption per year for different types of sources. In all the lighting arrangement systems the minimum light level and uniformity ratio are in compliance with the guidelines mentioned above. For some cases it is not possible to attain the minimum average light level satisfying the minimum uniformity ratio. With 12 m high poles it is not possible to achieve the minimum average light level of 4 lux by 80 W HPMV lamps for any combination of spacings: the mounting height must be lowered to achieve the required average light level. This aspect was not considered further in the present study.

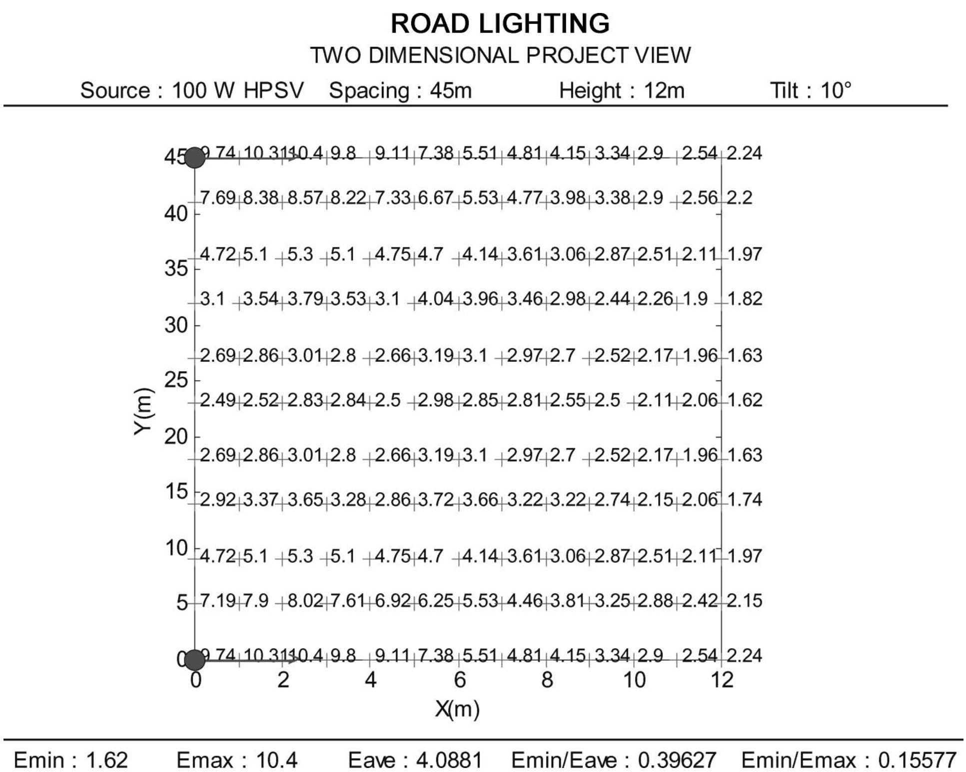

Figure 5. Spot illuminance levels with 100 W HPSV lamps at 12 m pole height.

As can be seen from table 1, the annual energy consumption for the design with 100 W HPSV lamps is the lowest (9737 kWh); the highest energy consumption is with 400 W HPSV lamps (30 835 kWh). In general, the energy consumption for low-wattage HPSV lamps is lower than that of high-wattage lamps. This is because, in order to achieve the desired uniformity ratio for high-wattage sources (say 400 W), both minimum and average light level values must be increased exorbitantly against minimum standards required.

Table 2 shows a comparative analysis of optimum design parameters for 16 m height poles. In this case 150 W HPSV lamps offer the minimum (7534 kWh) energy consumption followed by 100 W HPSV lamps (12 812 kWh). For 2 × 36 W FTLs, 80 W HPMV and 125 W HPMV lamps, it is not feasible to achieve all the lighting standards simultaneously under any combination of spacing. For example, the average light level cannot be maintained if the uniformity ratio and minimum light level are also to be satisfied, as may be observed from table 2.

A close comparison of tables 1 and 2 reveals some interesting points. For low-wattage (say 70 W and 100 W) HPSV lamps, energy consumption is less for 12 m pole heights than a corresponding design using 16 m poles. In contrast, for high-wattage (say 150 W, 250 W and 400 W) HPSV lamps, energy consumption is lower for the 16 m poles. This agrees with the finding

Table 1. Comparative analysis of proposed lighting arrangements with 12 m height poles.

Source	Spacing (m)	No. of poles	Minimum illumination level (lux)	Average illumination level (lux)	Uniformity ratio	Energy consumption per annum (kWh)
2 × 36 W FTLs	16	51	2.18	4.00	0.54	21 891.24
80 W HPMV*	41	21	0.51	1.29	0.39	8 738.10
125 W HPMV	20	41	3.2	4.08	0.78	25 679.94
250 W HPMV	47	18	1.36	4.49	0.30	21 681.00
70 W HPSV	28	30	2.05	4.11	0.49	11 169.00
100 W HPSV	45	19	1.62	4.08	0.39	**9 736.74**
150 W HPSV	40	21	3.27	11.5	0.28	15 820.56
250 W HPSV	62	14	2.66	9.05	0.29	17 046.96
400 W HPSV	52	16	6.56	21.66	0.30	30 835.20

*Not acceptable as the average values are less than the minimum standards of 4 lux.

Table 2. Comparative analysis of proposed lighting arrangements with 16 m height poles.

Source	Spacing (m)	No. of poles	Minimum illumination level (lux)	Average illumination level (lux)	Uniformity ratio	Energy consumption per annum (kWh)
2 × 36 W FTLs*	52	16	0.52	1.28	0.40	6 867.84
80 W HPMV*	42	20	0.52	0.88	0.58	8 322.00
125 W HPMV*	56	15	0.53	1.34	0.39	9 395.10
250 W HPMV	40	21	2.28	4.06	0.56	25 294.50
70 W HPSV	16	51	2.6	4.02	0.64	18 987.30
100 W HPSV	34	25	2.11	4.02	0.52	12 811.50
150 W HPSV	89	10	1.45	4.93	0.29	**7 533.60**
250 W HPSV	80	11	1.76	5.90	0.29	13 394.04
400 W HPSV	70	12	3.61	12.38	0.29	23 126.40

*Not acceptable as the average values are less than the minimum standards of 4 lux.

of Bommel and de Boer (1980) that higher wattage sources, in general, perform better at a greater mounting height. However, such a comparison could not be made for HPMV lamps as minimum design guidelines could not be achieved in most cases. In general, isolux contours for HPMV lamps are not suitable for haul road illumination if one wants to satisfy all three guideline parameters, i.e. minimum and average light levels and uniformity ratio.

It has to be borne in mind that energy-optimized design achieved through this study is valid only for the chosen illumination standards. Naturally, if the standards are changed, the design parameters, i.e. spacing and number of poles for a given height, will also change.

6. Conclusions

The study reveals that mounting height is very important in order to achieve all the required lighting standards at the same time. With low-wattage HPMV lamps, the pole height should be kept lowered to achieve the necessary lighting standards. HPSV lamps, in general, possess better isolux contour for haul road illumination. Mounting height should be higher for high-wattage HPSV lamps for better performance. For the light sources studies in this work, 100 W HPSV lamps at 12 m height give the optimum design (9737 kWh annual energy consumption), whereas at 16 m height the minimum energy consumption is 7534 kWh for 150 W lamps.

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