



Vertical Illuminance Measurement for Clear Skies in Tehran

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ABSTRACT: To effectively design daylight in buildings, daylight availability data are necessary. Although there is a great potential for daylight energy in Iran, its use has been hampered by the absence of measured data. In this paper the illuminance data on the vertical south facing surfaces of Tehran were estimated using the IESNA model. For this propose an illuminance measuring set was used in order to measure the vertical illuminance for standard times over 17 days at one minute intervals from 9 a.m. to 4 p.m. Then, the measured data were compared with the IESNA model calculated data. A regression model between measured and calculated data was developed, which showed an acceptable linear correlation ($r^2=0.9535$). Also mean hourly and monthly vertical illuminance was obtained from the new equation between measured and calculated data for a whole working year. To estimate daylight availability, Iso-Klx lines for working hours and frequency curves for vertical illuminance on south facing surfaces were produced.

Keywords: daylight availability, vertical illuminance, Tehran.

INTRODUCTION

Energy use in buildings accounts for a large percentage of total energy consumption worldwide, which leads to a great amount of CO₂ emission to atmosphere. European studies on energy consumption show buildings are responsible for 40% of energy use and 30% of CO₂ emission (Maccari, 2001). The recent interest in energy efficiency and sustainability has led to the implementation of design strategies in buildings that aim to achieve optimal utilization of daylight with minimum energy consumption for lighting, cooling, and heating. Daylight provides about 110 lm/W of solar radiation, while fluorescent lamps produce about 75 lm/W of electrical input and incandescent lamps about 20 lm/W. Therefore, daylighting generates only 1/2 to 1/5 of the heat that equivalent electric lighting produces, thus significantly reducing the building cooling load (Kandilli, 2008). In best cases, active and passive systems

that use daylight and control components are known to reduce lighting energy consumption by as much as 65% (Hasdemir, 1995). The combined savings from reduced lighting and cooling loads can be substantial, since electric lighting can account for 25–40% of a commercial building's energy requirements (Kandilli, 2008). Similarly in Iran, 25% of the electricity consumption in an office building relates to artificial lighting (Paknejad, 2009). Not only does daylight allow one to save on energy consumption, but also studies show that people actually perform better when exposed to daylight (Boyce, 2003). Additionally daylight has physiological as well as psychological benefits for users (Robbins, 1986). So, strategies for more daylight inclusion are needed for office interiors within any city (like Tehran), which has a growing demand for electricity. In offices within Tehran, artificial light is considered as the main contributor to the visual environment, even though there is an abundance of daylight during that part of the day known as 'working hours'. Therefore, by reducing reliance on artificial lighting, daylighting can be an effective means

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of saving on lighting energy (Muneer, 2000). Such savings are dependent on several variables. These relate to the characteristics of the internal and external spaces of the buildings and also the amount of external daylight available.

Daylight illuminance is measured and daylight availability is studied in different countries including Iran. At three stations, Eshtehard, Hamadan and Kerman, horizontal and vertical illuminance were measured only within 15 days and a new equation was obtained between measured and calculated data which was proposed for all cities of Iran ($r^2= 0.796$), (Shekari, 2007). To estimate daylight variations in Tehran, the mean hourly and mean monthly illuminance on a south facing vertical surface were measured using a correspondent linear model obtained throughout a whole working year. Moreover, frequency curves for vertical illuminance on the same surface were represented.

Daylight Availability

Daylight consists of direct (or beam), diffuse and ground reflected elements. To accurately estimate daylight in the interior, it is necessary to estimate daylight availability outdoors.

Daylight availability data describes the availability of the average amount of natural light from the sun and the sky on a given surface at a given period of time (Kandilli, 2008). This could be represented by an hourly, daily or monthly data. Such data can be obtained either by measurements or by calculations from other meteorological quantities. One of the crucial problems in predetermining the role of daylighting in energy efficient buildings is the need for reliable local data on daylight availability (Alshaibani, 2001). Considering the lack of data regarding sky luminance and illuminance in Tehran, external illumination was estimated by equations proposed by the "Illuminating Engineering Society of North America" (IESNA). Based on IESNA equations, basic data, beam normal illuminance and solar altitude and azimuth were calculated using the following equations. Calculation of daylight availability at a site begins with a determination of the solar position, which is a function of the site's latitude and longitude, the day of the year (Julian date) and local time. Finally, for a particular sky condition, the daylight availability equations are used to compute daylight illuminance (IESNA, 2002).

$$[1], ET= 7.637 \sin \left[\frac{2\pi(J-2.5)}{365.25} \right] - 9.863 \sin \left[\frac{2\pi(J-81.6)}{365.25} \right] 1/60$$

Where ET is equation of time (the difference between solar time and clock time) and J is Julian date (a number between 1 and 365).

$$[2], Ts=td-1$$

$$[3], t=t_s + ET + \frac{12(SM - L)}{\pi}$$

Ts, td and t are standard time, daylight time and solar time in decimal hours.

$$[4], \delta = 0.4093 \sin \left[\frac{2\pi(J-81)}{368} \right]$$

Where δ is solar declination in radians The solar altitude is given by

$$[5], a_i = \arcsin \left[\sin \delta - \cos l . \cos \delta . \cos \left(\frac{\pi}{12} \right) \right]$$

Where a_i is solar altitude in radians, l is site latitude in radians. The solar azimuth is given by

$$[6], as = \arctan \left(\frac{- \left[\cos \delta . \sin \left(\frac{\pi}{12} \right) \right]}{- \left[\cos l . \sin \delta + \sin l . \cos \delta . \cos \left(\frac{\pi}{12} \right) \right]} \right)$$

where as is the solar azimuth in radians. The other variables are the same as in Equation [5,4]. The solar elevation azimuth gives the azimuthal angle between the sun and the normal to a vertical surface of interest. It is given by

$$[7], a_z = a_s - a_e$$

where a_z is solar elevation azimuth in radians, a_s is solar azimuth in radians, and a_e is elevation azimuth in radians. The incident angle is the angle between the normal to a vertical surface of interest and the direction to the sun and can be computed from

$$[8], a_i = \arccos (\cos a_i . \cos a_z)$$

where a_i is incidence angle in radians, a_i is solar altitude in radians, a_z is solar elevation azimuth in radians.



The extraterrestrial solar illuminance, corrected for the Earth's elliptical orbit, is

$$[9], E_{xt} = E_{sc} \left[1 + 0.034 \cos \frac{2\pi(J-2)}{365} \right]$$

Where E_{xt} is extraterrestrial solar illuminance in Klx, E_{sc} is solar illumination constant in Klx (current standard 128 Klx). The direct normal illuminance at sea level, E_{dn} , corrected for the attenuating effects of the atmosphere is given by

$$[10], E_{dn} = E_{xt} \cdot e^{-cm}$$

Where E_{dn} is direct normal solar illuminance in Klx, c is atmospheric extinction coefficient (0.21 for clear, 0.8 for partly cloudy and very high for cloudy sky so $E_{dn}=0$), m is optical air mass (dimensionless). Values for the atmospheric extinction coefficient, discussed below, vary with sky conditions. The equation that is the simplest and the most often used representation for the optical air mass is

$$[11], m = \frac{1}{\sin a_i}$$

where m is the optical air mass (dimensionless) and a_i is the solar altitude in radians. The direct sunlight on a horizontal plane is expressed by

$$[12], E_{dh} = E_{dn} \cdot \sin a_i$$

Where E_{dh} is direct horizontal solar illuminance in Klx, E_{dn} is direct normal solar illuminance in Klx. The direct sunlight on a vertical elevation is expressed by

$$[13], E_{dv} = E_{dn} \cdot \cos a_i$$

Where E_{dv} is direct vertical solar illuminance in Klx, E_{dn} is direct normal solar illuminance in Klx, a_i is incidence angle in radians. The horizontal illuminance produced by the sky can be expressed as a function of solar altitude.

$$[14], E_{kh} = A + B \cdot \sin^c a_i$$

Where E_{kh} is horizontal illuminance due to unobstructed sky in Klx, A is sunrise/sunset illuminance in Klx, B is solar altitude illuminance coefficient in Klx, C is solar altitude illuminance exponent and a_i is solar altitude in radians. Diffuse vertical illuminance is expressed by

$$[15], E_{kv} = A + B \cdot \cos^c a_i$$

Where E_{kv} is diffuse vertical illuminance in Klx, a_i is incidence angle in radians and the other variables are the same as in Equation [14]. The quantity of A, B and C for three conditions of sky are in table 1.

Table 1. Daylight availability constants

Sky condition	A(Klx)	B(Klx)	C
Clear	0.8	15.5	0.5
Partly Cloudy	0.3	45.0	1.0
Cloudy	0.3	21.0	1.0

Ground reflected illuminance is expressed by

$$[16], E_g = \rho \cdot (E_{dh} + E_{kh})$$

Where E_g is ground reflected illuminance in Klx and ρ is the coefficient of ground reflection. Total vertical illuminance includes direct vertical solar illuminance, diffused vertical illuminance and ground reflected illuminance and is expressed by

$$[17], E_{v_{total}} = E_{dv} + E_{kv} + E_g$$

RESEARCH METHODOLOGY

Daylight measurements were carried out in one station in Tehran. Illuminance values on south facing vertical surfaces were taken using one illuminance measuring equipment of TES, 1339 R. A measuring set which consists of a vertical stand to hold the vertical sensor facing south on the roof of the Architecture Faculty in Tarbiat Modares University. Vertical illuminance values were taken over 17 days at one minute intervals between 25th June and 11th July 2011 from 8 a.m. to 4 p.m. All of the collected data were entered in statistical sheet of Excel 2007 software and regression models were applied to develop a model



between calculated and measured illumination variables. Measured data is presented as follows:

- First the results obtained from the equations for average vertical illuminance on south facing surface for every month in the full working year.
- Second, the probability to exceed a given illuminance level during two seasons: summer and winter, from 9:00 to 16:00 (typical office working hours in Tehran).
- Third, drawing Iso-Klx lines to display the variations of illuminance levels averaged according to working hours and months in Tehran.

CLIMATIC FEATURES of TEHRAN

Tehran is located on the slope of Alborz mountains and stretches towards the flat plains on the south, with latitude of 35.7 degrees and longitude of 51.3 degree. It has a hot and dry climate. Based on meteorological statistics reported by Mehrabad Weather Station, the sky of Tehran

is 64% clear, 27% partly cloudy and 9% cloudy during a year. Considering the significant percentage of clear sky, all calculations are based on a clear sky condition and direct solar radiation.

DATA ANALYSIS

With regards to 64% clear sky during the year in Tehran, properties of clear sky in IESNA equations for vertical illuminance calculation were used. Comparison of mean measured and mean calculated hourly illuminance on the south facing surfaces is shown in table 2. Maximum mean value of measured illuminance is 43.86 Klx at 12 a.m. while this is 48.11Klx for calculated illuminance at the same hour. The minimum value for measured illuminance is 18.95 Klx and 19.46 Klx for calculated illuminance at 4 p.m. If 3 p.m. is considered to be the last hour on a working day, then the minimum value of measured illuminance is at 9 a.m.

Table 2. Mean hourly values of measured and calculated vertical illuminance on south facing surface

Mean hourly south facing vertical illuminance at standard time (Klx)								
	9	10	11	12	13	14	15	16
Mean measured illuminance	23.07	32.42	40.22	43.86	42.48	36.58	27.88	18.95
Mean calculated illuminance	24.21	35.71	44.50	48.11	45.54	37.50	26.25	19.46

Patterns of comparative curves of mean measured and mean calculated hourly illuminances on the south facing surfaces illustrate that IESNA equations do not estimate vertical illuminances exactly as the measured values at corresponding standard times. For this reason a description for linear equation has been made between measured values and calculated values. Considering the obtained coefficient regression ($r^2 = 0.9535$) for this linear equation (Fig. 1), this equation could be used as complimentary for IESNA equations for the purpose of determining vertical illuminance on south facing surfaces in Tehran.

$$[18], E_{vs_m} = 0.9022 \cdot E_{vs_c} + 0.9845$$

Where E_{vs_m} is measured south facing vertical illuminance in Klx and E_{vs_c} is calculated south facing vertical illuminance in Klx. Figure 2 illustrates comparative curves of measured and calculated mean hourly values on the south facing surfaces. According to

measuring equipment, the vertical illuminance on south facing surface calculated for full working year from 9 a.m. to 4 p.m. mean hourly values for every month, is shown in Table 3.

According to table 3, maximum mean monthly vertical illuminance is in January with 70.23 Klx and the minimum is in June, 33.85. The maximum illuminance is in January at 12 a.m., 90.88 Klx. Minimum mean monthly vertical illuminance is 18.2 Klx at 4 p.m. in July. Figure 3 shows probability of daylight availability on south facing vertical surface in Tehran. In this figure vertical illuminance on south surface for winter and summer is illustrated. These curves show the percentage of working days at which the illumination level exceeds a certain level.

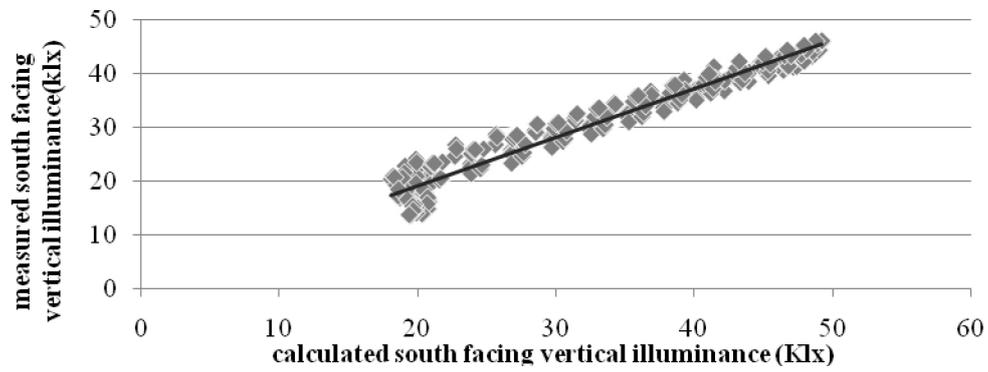


Fig. 1. Relation between measured and calculated values of south facing vertical illuminance ($r^2=0.9535$).

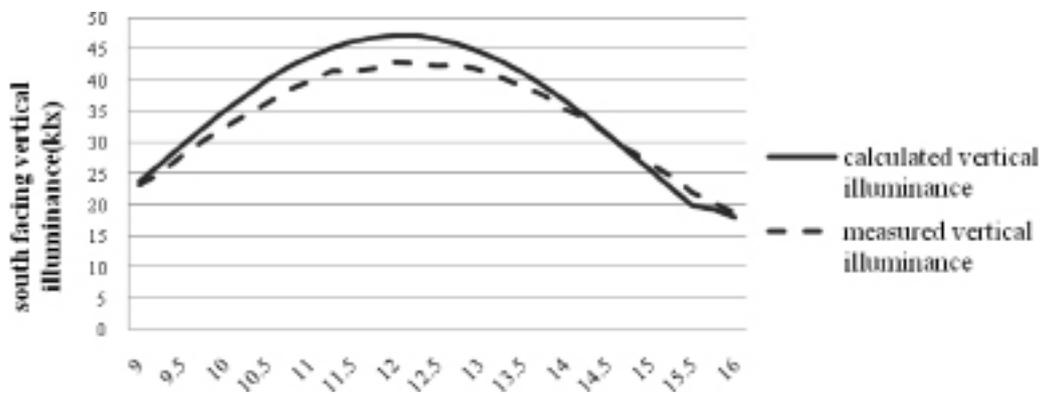


Fig. 2. Comparison of mean measured and mean calculated values on the south facing vertical surface.



Table 3. Mean hourly and monthly illuminance on a south facing vertical surface for a whole working year in Tehran

Mean hourly south facing vertical illuminance (KLx)									
Month	9	10	11	12	13	14	15	16	Mean Monthly Illuminance (KLx)
January	65.12	79.89	88.60	90.38	85.19	73.08	53.57	26.01	70.23
February	64.22	78.38	86.43	88.07	83.21	72.08	54.99	29.03	69.55
March	57.13	70.03	77.67	79.44	75.20	65.29	50.47	30.12	63.17
April	44.15	56.07	63.14	65.45	62.01	53.40	40.50	24.88	51.20
May	31.25	42.35	49.45	51.79	49.12	41.71	30.39	21.32	39.22
June	24.34	35.10	42.19	44.80	42.68	36.03	25.59	20.10	33.85
July	25.99	37.12	44.57	47.48	45.57	39.02	28.56	18.20	35.81
August	35.40	47.54	55.62	58.80	56.76	49.70	38.34	24.08	45.78
September	48.11	61.48	70.18	73.43	70.94	62.92	50.10	33.74	58.86
October	58.09	72.76	81.87	84.91	81.69	68.14	57.58	37.69	67.84
November	61.01	75.10	87.07	89.72	85.60	69.01	52.10	31.34	68.87
December	61.94	78.70	88.01	90.19	85.26	73.15	53.14	24.02	69.30

Considering the climatic calendar of Tehran, to decrease energy consumption in buildings, the use of solar energy and direct solar radiation is necessary for five months of the year (November to March) while in other months of the year, preventing direct solar radiation into interior spaces of buildings is recommended (Tabbaz, 2008, p.95). Consequently applying shading devices for transparent southern surfaces of buildings is required. At this stage the illuminance on southern vertical surface is only indirect, which includes diffuse solar and ground reflected illuminance. Direct solar illuminance cannot be used in seven months of the year. It is given by

$$[19], E_{v_{indirect}} = E_{vs_m} - E_{dv}$$

Where $E_{v_{indirect}}$ is vertical indirect illuminance on south facing surface in Klx, E_{vs_m} is measured vertical illuminance on south facing surface in Klx. Based on the above equation, the values of vertical illuminance obtained for hot months of the year (April to October) and the daylight availability curve for these months is shown in Figure 4.

According to Figure 4, 60% of working days exceed 18 Klx in hot months of the year (April to October). Maximum and minimum vertical illuminances in this condition (without any direct solar illuminance) are 22.70 Klx and 11.43 Klx respectively. In Figure 5 Iso-Klx lines are shown for each month of the year from 9:00 a.m. to 16:00 p.m. standard time in Tehran. In November, December, January and February from 10:00 a.m. to approximately 13:30, vertical illuminance is between 80 to 90 Klx, although in December and January at 12:00 p.m. it exceeds 90 Klx. Approximately In the whole working days vertical illuminance exceeds 30 Klx at 9:00 a.m. to 3:00 p.m.

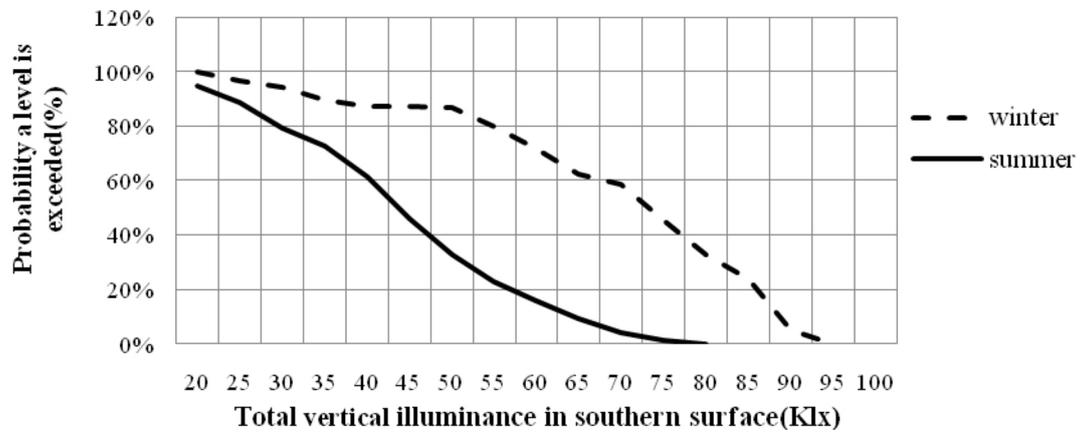


Fig. 3. Frequency curves for total vertical illuminance on south facing surface in Tehran

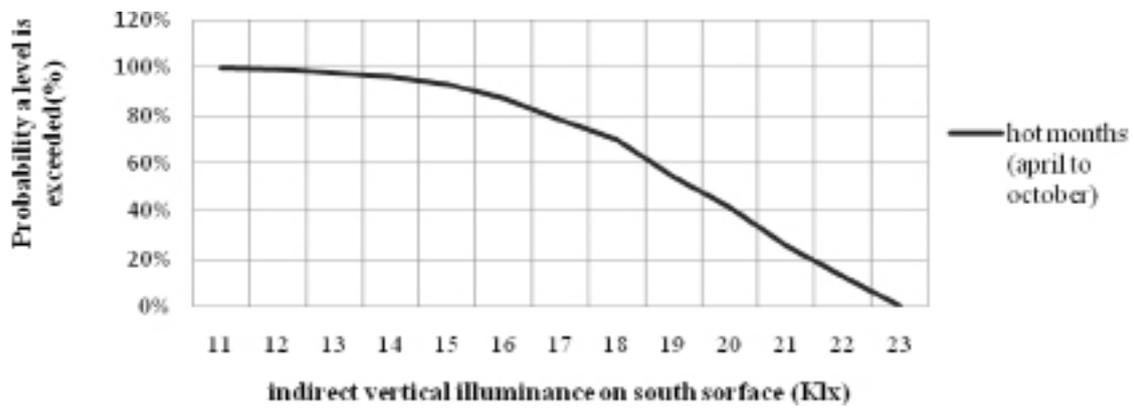


Fig. 4. Frequency curves for indirect vertical illuminance on south facing surface in Tehran

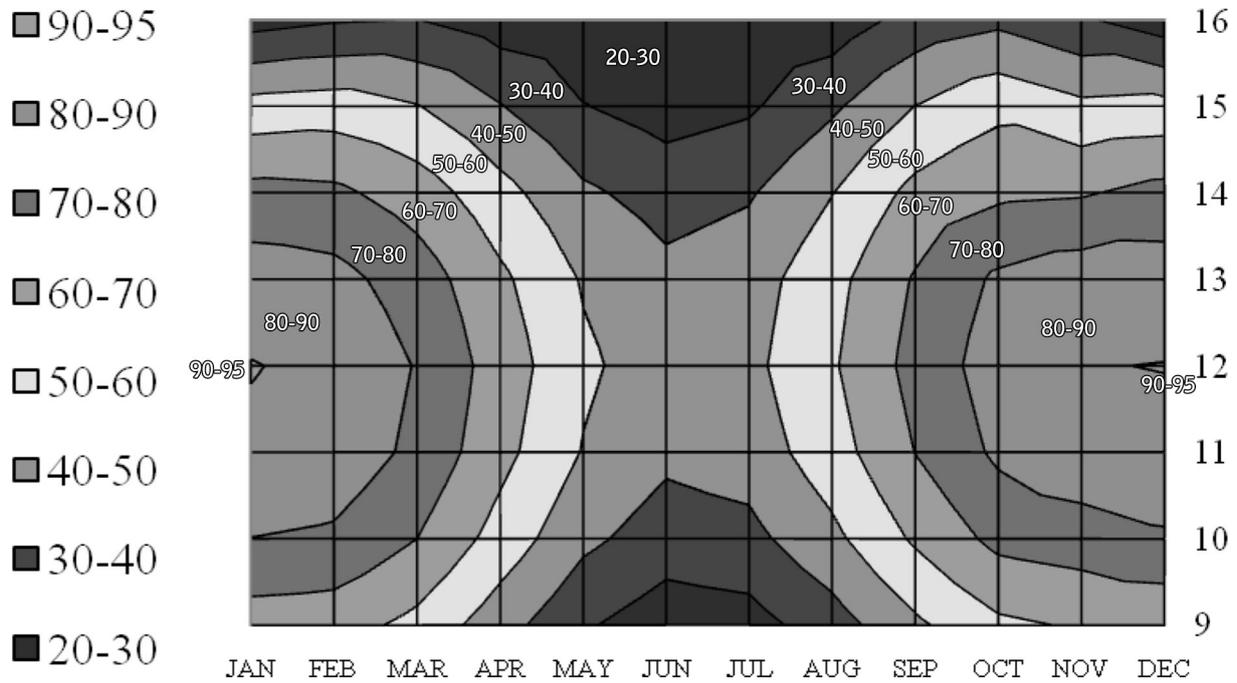


Fig. 5. Iso- Klx lines for varying vertical illuminance levels averaged according to working hours and months

CONCLUSION

In this paper the illuminance on south facing vertical surface was estimated using the IESNA method in order to obtain a developed regression model and daylight availability in Tehran. A regression model was developed using measured and calculated data of south facing vertical illuminance. This model, shows a good linear correlation between measured and calculated values ($r^2=0.9535$). The suggested model can effectively predict south facing illuminance in Tehran for a full year with clear sky conditions. To prevent direct solar radiation entering buildings in hot periods of the year, vertical illuminance on south facing surface was considered as indirect vertical illuminance, which consists of ground reflected illuminance and diffuse solar illuminance. By using these data, frequency curves for vertical illuminance and indirect solar illuminance were obtained which show daylight availability in Tehran for hot and cold months in a working year. It is evident that in cold months of the year direct solar radiation is necessary for passive heating of interior spaces and there is a high level of vertical illuminance on south facing surfaces that will cause glare

problems. During the hot months of the year, the use of shading devices on south facing transparent surfaces will result in acceptable levels of vertical illuminance. Therefore, it is recommended to choose materials with high reflectance coefficient for ground cover in order to increase the level of vertical illuminance from ground without generating too much undesired heat during hot months of year.



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