Window shades: selecting optical properties for visual comfort

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Abstract

Currently, there is no methodical procedure for selecting solar-optical properties of roller shades, which affect the energy and indoor environmental performance of perimeter building zones. This paper presents a new systematic methodology for identifying the range of shading properties (openness factor and visible transmittance) that can significantly reduce the risk of glare. A model that calculates angular beam-beam and beam-diffuse shading optical properties using minimum inputs is used within a hybrid ray-tracing and radiosity daylighting model, validated with full-scale experiments. The temporal variation of beam and total vertical illuminance is used to define the annual visual discomfort frequency and establish a process for selecting the range of acceptable shading properties for each set of external parameters (location, orientation, glazing visible transmittance, and buffer zone). Recommendations for openness factors and visible transmittance values are made for different scenarios. Selecting the upper limits of suggested ranges can provide more daylight into the space and reduce the probability of high contrast. These guidelines may be used for selection of shading products, followed by considerations about energy savings and provision of outside view.

1. Introduction

Interior roller shades, commonly used in North America, allow occupants to control daylight, solar heat gain, visual connection to the outdoors, as well as visual comfort. Several studies have shown the lighting energy saving potential of shading control (Hviid et al., 2008; Shen and Tzempelikos, 2012). However, there is no systematic procedure for selecting solar-optical properties of roller shades, to assist engineers, building scientists and designers in their decisions that affect the energy and indoor environmental performance of perimeter building zones (Tzempelikos, 2008).

In the fenestration and shading selection and decision-making process, visual comfort should be a priority for any manual or automated shading system. Nevertheless, roller shade selection lacks widely adopted guidelines addressing visual comfort concerns. In this paper, a new systematic methodology is proposed for identifying the range of shading optical properties (openness factor and visible transmittance) that can significantly reduce daylight glare issues. A hybrid ray-tracing and radiosity daylighting model, using adjusted solar-optical properties is used to analyze the temporal frequency of two vertical illuminance criteria violations (annual visual discomfort frequency) and determine a range of acceptable openness factors and visible transmittance values. Finally, guidelines for selecting properties of shading fabrics are provided for different scenarios. Using these recommendations as a basis, designers and engineers can consider other factors such as energy savings, outside view and daylight availability for selecting shading products.

2. Solar optical properties of roller shades

Roller shades come in a wide variety of colors and patterns with varying degrees of shading and weave construction that result in different degrees of openness and transmission/reflection characteristics. Visible transmittance, openness and color have a direct impact on indoor daylight conditions and discomfort glare. Other factors, such as reflectance and absorptance, are more important for controlling solar heat gain. When direct radiation strikes the shade surface, it is split into two portions: the unobstructed portion, directly transmitted through the openings (beam-beam portion), and the interrupted portion –part of which will be scattered in the forward direction (transmitted), another part scattered in the reverse direction (reflected), and the rest is absorbed by the fabric material. As a result, except for the angular dependence, the beam-diffuse split of solar radiation (or illuminance) through roller shades needs to be considered.

However, detailed property measurements are rarely conducted for most available products since they are expensive and time-consuming. Usually, shading fabric manufacturers provide a single value of (average) visible and solar total transmittance and reflectance at normal incidence when demonstrating or specifying their products, together with openness factor and color. Even these properties are often not properly measured (Chan et al., 2014). Therefore, a reliable approach to estimate the detailed (off-normal and beam-to-diffuse) properties from such limited information, such as the method proposed by Kotey et al. (2009), is desired for more accurate thermal and daylighting modeling. Other methods (EnergyPlus, 2013) are either inaccurate (using constant values or ignoring angular characteristics) or too complex, such as the geometrical radiosity method to estimate BSDFs of woven shades (Carli Inc., 2014).

2.1 Visible transmittance (VT), openness factor (OF) and color

The term "openness factor" refers to the "open" or "see-through" percentage of the shading fabric. Openness allows a visual connection to the outside, as well as direct light transmission. Different solar shading fabrics have different degrees of weave density and therefore different openness factors. Beam-diffuse transmission was often ignored in simplified daylighting calculations (i.e., in EnergyPlus shading module); consequently, the error in daylight autonomy and annual glare risk predictions could reach 60% (Chan et al., 2014). VT describes the percentage of visible light transmitted through the fabric and is related to the color and openness factor of the fabric, However, the relationship between openness factor, color, and visible transmittance cannot be simply formulized.

2.2 Semi-empirical model by Kotey et al. (2009)

Kotey et al. (2009) developed a semi-empirical model for direct-direct, direct-diffuse and angular shade properties. The model was extracted from detailed integrated sphere measurements (Collins et al., 2012) of the spectral beam-beam transmittance, beam-diffuse transmittance, and beam-diffuse reflectance of different shading fabrics at incident angles ranging from 0° to 60°. The spectral data was converted to solar optical properties according to ASTM standards, and a cosine power function was fitted to the measured properties at different incident angles. This method seems to be reliable and useful, since it is based on physical quantities and allows to extract the necessary shade properties (for straightforward use in detailed models) using only beam-total transmittance at normal incidence, usually provided by manufacturers. Therefore, for all typical cases when limited fabric properties information is available, this model is preferred and is used in the methodology described later.

3. Daylighting model

To understand the impact of fabric properties on visual comfort and daylight availability, the semi-empirical properties model was embedded in a hybrid ray-tracing and radiosity model that maintains satisfactory levels of efficiency and accuracy. The model was then used to run a series of simulations to study the role of different properties and establish a methodology for selecting appropriate values for glare protection.

The daylighting model (Chan and Tzempelikos, 2012) uses TMY3 weather data (or sub-hourly computed or measured data) and first calculates direct and diffuse daylight incident on a window using solar geometry and the Perez et al. model (1987). If field measured data is available, then these are used as inputs (e.g., for validation purposes or for real-time, model-based control).

Daylight transmission through any (simple or complex) fenestration system is next, and in this case, detailed beam-beam, beam-diffuse and off-normal properties of roller shades were calculated using the semi-empirical model (Kotey et al., 2009) described above. The glazing optical properties are determined using the WINDOW 7 software (LBNL, 2013). Direct sunlight transmitted and/or specular reflections in the room are tracked with the ray-tracing module, while the radiosity module computes interior diffuse reflections and final illuminance distributions. The daylight transmitted through the window is not uniformly distributed; the model corrects the sky and ground luminance according to sky and ground illuminance, occupant (or sensor) view direction, and then uses these values to further estimate work plane and vertical illuminances. Given the space geometry and interior reflectivities, the model finally calculates interior illuminance and luminance distributions, glare indices, as well as respective annual metrics. The model has been validated with full-scale experimental measurements, and comparison with Radiance and Daysim for various shading scenarios (Chan and Tzempelikos, 2012).

4. Methodology for selecting shade properties and visual comfort restrictions

4.1 Criteria for visual comfort

Several different criteria and metrics have been introduced to identify daylight discomfort glare. Illuminance-based criteria, such as work plane illuminance, are used in design guidelines. For example, IES Standard LM-83-12 (2012) recommends that no more than 10% of the work plane area should receive more than 1000 lux of direct sunlight for more than 250 hours per year (ASE metric). Useful daylight illuminances (*UDI*) were defined with an upper work plane illuminance limit of 2000 lux (Nabil and Mardaljevic, 2006) to identify conditions that might result in visual or thermal discomfort. However, field studies have showed significant differences in preferred illuminance levels (Van Den Wymelenberg and Inanici, 2014). Luminance-based criteria (luminance ratios or constant thresholds) are also widely used for glare (Konis, 2014) and are reported in IES lighting handbooks (Rea, 2000). Glare indices that combine the illuminance- and luminance-based criteria, also using the position index and glare source size, are forward-looking approaches. However, due to their complexity, they have not been extensively used in design guidelines. Daylight Glare Probability (Wienold and Christoffersen, 2006) considers both the vertical (eye) illuminance and glare source luminance, while DGI focuses on the impact of luminance contrast. Several studies have shown that DGP performs better (Vincent, 2012; Van Den Wymelenberg and Inanici, 2014) while others reported the opposite (Hirning, 2014). Researchers hardly reproduce the same results when applying the same metrics to different spaces and different fenestration systems. The different methods have their advantages and limitations. The authors of this paper agree with the statement by Jakubiec and Reinhart (2013) that multiple criteria are required for an integrated visual discomfort evaluation, especially if direct sunlight is somehow transmitted into the space. The exact metrics and criteria need to be further studied.

The situation is more complex for the case of roller shades, which transmit direct and diffuse light into the space and allow a view of the sun through the fabrics. Discomfort glare studies in spaces with roller shades are scarce. A recent study (Konstantzos and Tzempelikos, 2014) pointed out the issue of seeing the sun through a shading fabric has not been studied. Even for fabrics with very low openness (1%), when the sun is within the field of view, its contributed luminance could be greater than 10^6 cd/m^2, but at the same time the direct-direct illuminance received by occupants' eyes can be very low –less than 300 lux. Although this usual scenario will fail all luminance-based glare criteria (absolute luminance, luminance ratio, DGI, DGP), most 1% open fabrics are not expected to result in significant glare problems (Fernandes and Lee, 2014). More occupant-based studies are needed in spaces with roller shades to reach solid conclusions.

Based on the above, illuminance-based criteria are used in this study. Vertical illuminance on the eye (E_v) is selected as a more appropriate parameter (compared to work plane light levels) since recent findings support that it outperforms all commonly used visual comfort metrics (Van Den Wymelenberg and Inanici, 2014). In addition, the original DGP study also demonstrates a good correlation between E_v and glare probability.

The proposed method utilizes two vertical illuminance criteria to evaluate the risk of visual discomfort:

- $E_{v,\ beam}$ < 1000 lux
- $E_{v,\ total}$ < 2670 lux

The first criterion is used to check if the occupant (virtual sensor in the simulation model) receives more than 1000 lux of beam illuminance (sunlight) on the eye –a modification of IES LM-83-12. The second criterion checks for total vertical illuminance on the eye and is derived from the simplified version of daylight glare probability, DGPs:

$$DGPs = 6.22 \times 10^{-5} E_v + 0.184 \quad (1)$$

When E_v exceeds 2670 lux, glare probability reaches 0.35, which is considered the (lower) limit of acceptable values. This criterion addresses the overall impact of vertical illuminance, including transmitted direct, direct-diffuse and diffuse light and contribution from interior reflections. The only limitation of this method is that it cannot adequately capture all contrast effects (Wienold, 2009) as discussed later. The two criteria *and the temporal frequency of violations* are used in the annual simulation as described below to determine acceptable openness factors and visible transmittance values respectively.

4.2 Selection of shade properties based on annual visual discomfort frequency

Fig. 2 presents the process of identifying an acceptable range of roller shade properties. For any scenario (location, orientation, window properties, room configuration), the developed model runs a series of annual parametric simulations containing fabrics with variable openness factors and visible transmittance values (from 1% to 20%). Vertical illuminance on the eye level is calculated at different distances from the window (buffer zone limit), but always for the case facing the window, to determine maximum property values for the worst case scenario (highest risk of glare). The logic consists of three steps:

- The annual simulation results are first used to calculate the percentage of working hours in the year (8am – 6pm) during which the first criterion (direct vertical illuminance >1000 lux) is not satisfied. These results are used to determine the acceptable range of fabric openness factors based on a strict and a more flexible constraint (0% and 5% frequency).
- The next step is to calculate the percentage of working time in the year during which none of the two criteria are satisfied. This value is defined as the **annual visual discomfort frequency** and is used to determine the range of maximum visible transmittance in a similar way.
- In most cases, the selected openness factor is smaller than the selected visible transmittance values (OF < VT). However, for some scenarios with few sunlight hours, diffuse illuminance dominates in annual-based considerations, resulting in more restricted visible transmittance values, sometimes smaller than the openness factors determined in the first step. In such cases, the acceptable range of openness factors is adjusted to match (equal) the selected VT values.

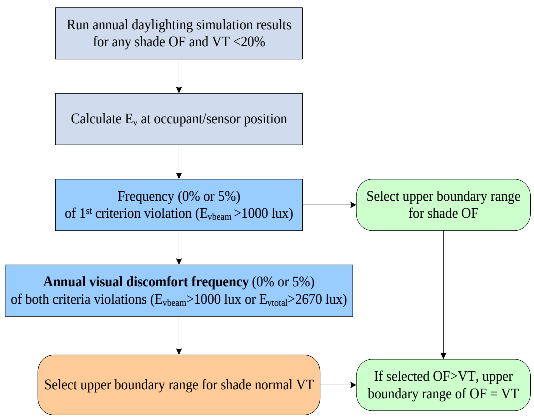

Fig. 2 – Process for selecting acceptable ranges of shade openness factor and visible transmittance based on annual temporal frequency of vertical illuminance restriction violations

5. Results

Following the above methodology, simulation results and shade selection guidelines are presented for different locations, orientations, window properties and occupant positions (buffer zones) as shown in Table 1. The analysis was done for a medium-size perimeter office space (12 m × 12 m × 3 m high) having one exterior façade with 70% window-to-wall ratio. The reflectances of ceiling, vertical walls and floor are 80%, 50% and 20% respectively. Continuous daylight autonomy is also presented as a design reference (work plane illuminance set point is 500 lux). Tables 2 and 3 in section 5.2 show the overall results and recommendations for selecting shading properties for every studied scenario.

Table 11 – Variable simulation parameters

Parameter	Range
Shade Visible Transmittance	1% - 20%
Openness Factor	1% - 20%
Location	Phoenix, New York
Orientation	South, Southwest, West, Northwest, North
Glazing Visible Transmittance	65%, 50%, 35%
Buffer Zone (occupant distance from window)	0.91m, 1.83m, 2.74m

5.1 Impact of shade Openness Factor and Visible Transmittance

While one would expect higher OF and VT to result in higher risk of glare, the combined impact of visible transmittance and openness factor on annual discomfort frequency is non-linear and complex, since it involves the implications of simultaneous beam-to-beam and beam-to-diffuse daylight transmission. Higher differences between *VT* and *OF* values indicate light-colored fabrics with more diffuse characteristics. Fig. 3 presents annual visual discomfort frequency results for Phoenix, with 0.91m buffer zone and 65% glazing visible transmittance, for a south and a northwest façade. For the south facade, there is no significant discomfort for shades with *OF*< 3% and *VT*< 6-7%, thus these would be the upper boundary ranges for this case. Higher *OF* or *VT* values will result in unacceptable discomfort values; for higher openness factors, the two criteria overlap and the *VT* lines converge. For the northwest façade, smaller variations are observed (due to less hours of sunlight) and shades with *VT*< 10% satisfy the 5% discomfort frequency limit for almost any *OF* value. The 0% restriction is never satisfied because the sun is low for several hours in the year for this orientation.

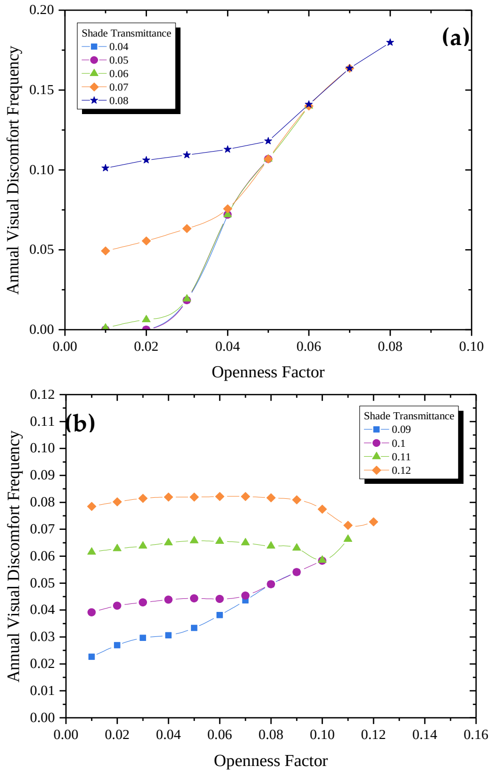

Fig. 3 – Combined impact of openness factor and visible transmittance on annual visual discomfort frequency for (a) south and (b) northwest orientation in Phoenix (0.91m buffer zone, 65% glazing normal VT)

The significance of the two vertical illuminance criteria and their overlap with respect to selection of shade properties are presented in Fig. 4, showing temporal graphs with violation frequency of each criterion and their combination for the same space facing south (Fig. 3a), using three fabrics with different properties. The first criterion restricts OF and direct sunlight transmission; using the first fabric (3% OF, 6% VT) that has a minimum discomfort frequency as a baseline, increasing OF to 4% (2nd set of graphs), causes $E_{v,beam}$ to exceed 1000 lux for more hours. The second criterion restricts VT and total light transmission; when VT increases to

7% (3rd set of graphs), $E_{v,total}$ exceeds 2670 lux for more hours. Their combined effect on annual visual discomfort frequency (last graph in every set) is used to restrict both OF and VT as shown in Fig. 2.

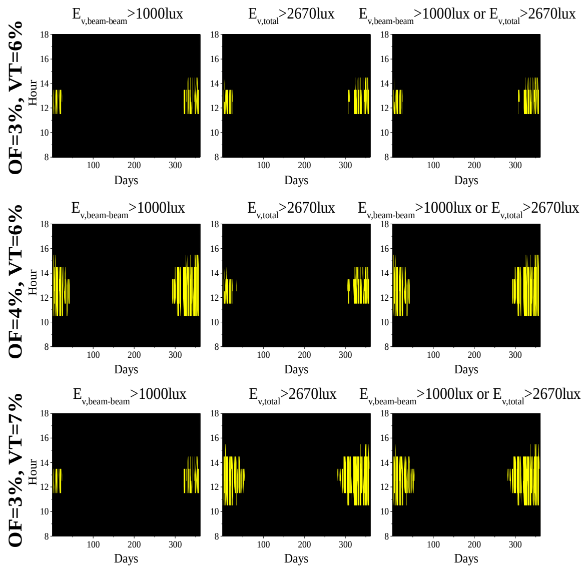

Fig. 4 – Temporal graphs of violation frequency of each vertical illuminance criterion and their combination (annual visual discomfort frequency) for three shading properties

5.2 "Glare-safe" boundaries of shade properties

A graphical representation of utilizing simulation results to select shading properties is presented in Fig. 5. Annual discomfort frequency values are shown in contour plots for every set of external parameters, with shade *OF* on the y-axis and shade *VT* on the x-axis. The curved shape of contours indicates the non-linear effects of both properties (for higher, non-recommended values, *VT* becomes the dominant factor). For the case presented here, values within the 0% or within the 5% area in Fig. 12(a) are considered acceptable for visual comfort. This allows for the selection of different combinations of shade *OF* and *VT* values within these boundaries, resulting in the same effect on visual discomfort. However, the impact of these acceptable combinations on daylight autonomy are quite different, as shown in Fig. 5(b), with dashed lines showing the upper boundary limits. Products with higher *VT* and smaller *OF* within these "glare-safe" boundaries provide more daylighting benefits. The results for all studied scenarios with recommended shading *OF* and *VT* (maximum acceptable values) are summarized in Tables 2 and 3, for annual visual discomfort frequency of 0% and 5% respectively. These results are consistent with the previous sections findings and contain the impact of orientation, location, glazing properties and buffer zone limit on the selection process. The 5% frequency results of Table 3 are presented because visual discomfort is always subjective and occupants might tolerate slightly higher values of vertical illuminance for 5% of the working time (and higher shading property values allowing more daylight and outside view). Note that, in that case, Phoenix has stricter limitations than New York, because of more sunlight hours. North-facing facades are not bounded by any *OF* limit for most cases.

Table 12 – Recommended maximum values of shade OF (and VT in parenthesis) for 0% annual visual discomfort frequency

Buffer Zone	**Orientation**	***New York***			***Phoenix***		
		Glazing Visible Transmittance			***Glazing Visible Transmittance***		
		0.65	***0.5***	***0.35***	***0.65***	***0.5***	***0.35***
0.91m	**S**	2% (5%)	3% (7%)	4% (9%)	2% (5%)	3% (6%)	4% (6%)
	SW	2% (5%)	2% (6%)	4% (8%)	2% (4%)	2% (6%)	3% (8%)
	W	2% (5%)	3% (7%)	4% (9%)	2% (5%)	2% (6%)	4% (7%)
	NW	3% (7%)	5% (9%)	7% (11%)	3% (6%)	4% (8%)	6% (10%)
	N	-	-	-	-	-	-
2.74m	**S**	2% (9%)	3% (10%)	4% (13%)	3% (9%)	4% (12%)	6% (15%)
	SW	2% (7%)	2% (10%)	4% (12%)	2% (7%)	2% (9%)	3% (12%)
	W	2% (9%)	3% (10%)	4% (13%)	2% (8%)	2% (10%)	4% (12%)
	NW	3% (12%)	5% (14%)	7% (17%)	3% (10%)	4% (12%)	6% (15%)
	N	-	-	-	-	-	-

Table 3 – Recommended maximum values of shade OF (and VT in parenthesis) for 5% annual visual discomfort frequency

Buffer Zone	Orientation	*New York*			*Phoenix*		
		Glazing Visible Transmittance			*Glazing Visible Transmittance*		
		0.65	***0.5***	***0.35***	***0.65***	***0.5***	***0.35***
0.91m	**S**	4% (7%)	6% (8%)	8% (10%)	3% (6%)	4% (8%)	6% (9%)
	SW	4% (7%)	5% (8%)	7% (10%)	3% (6%)	4% (7%)	5% (9%)
	W	4% (7%)	5% (8%)	8% (10%)	3% (6%)	4% (7%)	5% (9%)
	NW	13% (13%)	15% (15%)	16% (16%)	8% (10%)	10% (11%)	13% (13%)
	N	-	-	-	-	-	-
2.74m	**S**	7% (14%)	10% (16%)	14% (19%)	12% (12%)	15% (15%)	18% (18%)
	SW	4% (12%)	6% (14%)	9% (16%)	3% (10%)	4% (12%)	6% (14%)
	W	5% (12%)	6% (15%)	9% (17%)	3% (9%)	4% (11%)	5% (15%)
	NW	-	-	-	17% (17%)	-	-
	N	-	-	-	-	-	-

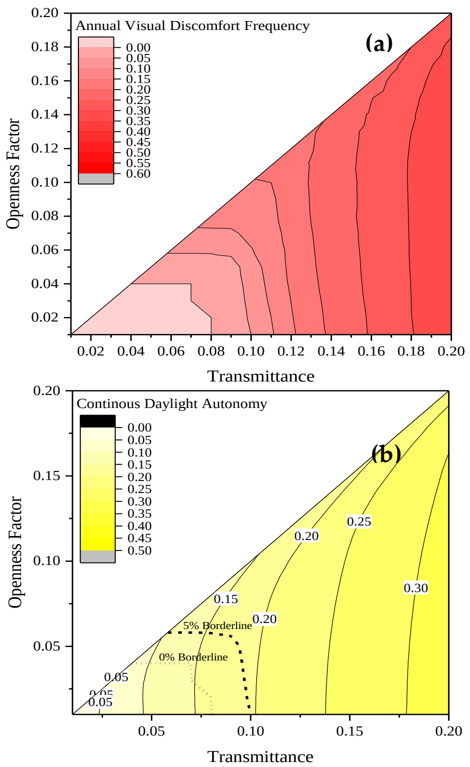

Fig. 5 – Selection of "glare-safe" boundaries of shade OF and VT based on annual visual discomfort frequency (a) and impact on continuous daylight autonomy (b), for the case of a west facing office in Phoenix, 0.91m buffer zone, 35% glazing normal VT)

6. Conclusion

This paper presents a new systematic methodology for identifying the range of shading optical properties (openness factor and visible transmittance) that can significantly reduce the risk of daylight glare. A semi-empirical model that calculates angular beam-beam and beam-diffuse shading optical properties using minimum inputs provided by shading manufacturers is used in a hybrid ray-tracing and radiosity daylighting model. Two vertical illuminance criteria, for beam and total illuminance on the eye, are used to establish visual comfort restrictions. The temporal variation of the two criteria is used to calculate the annual visual discomfort frequency, which is used to define a process for selecting the range of acceptable shading properties for each set of external parameters (location, orientation, glazing visible transmittance, and buffer zone).

The combined impact of visible transmittance and openness factor on annual discomfort frequency is complex. Following the proposed methodology, recommendations for roller shade properties are provided for different scenarios. Different openness factors and visible transmittance values are recommended for different locations, orientations and glazing properties. Smaller values are required for orientations between south and west, while north facing facades have essentially negligible restrictions. The upper limits of suggested ranges of these properties are recommended to provide more daylight into the space and reduce the possibility of higher contrast. Using these recommendations as a basis, designers and engineers can consider other factors such as energy savings, outside view and daylight availability for selecting shading products. Further research is needed towards a glare index applicable to cases with direct sunlight transmitted into the building, and towards overall fenestration system optimization including related system controls.

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