Methodology to Analyze Sun Glare Related Safety Problems at Highway Tunnel Exits

R. Jurado-Piña[1]; J. M. Pardillo-Mayora[2]; and R. Jiménez[3]

Abstract: Good visibility of the road and its surroundings is a basic requirement for safe driving. Glare caused by direct sunlight interferes with drivers' vision performance. In high-glare conditions the visibility of objects is reduced thus increasing the probability of occurrence of incidents and crashes. Critical sections of existing or newly designed roads need to be analyzed in order to prevent these problems. The research presented in this paper provides a practical method to evaluate potential driver vision impairment situations caused by sun glare at tunnel exits. The methodology is based on the projection of the solar paths on a cylindrical chart; other geometrical variables involves in the model are also represented on the same projection. An application to an existing Spanish motorway tunnel is presented. Results show that the methodology can be successfully employed (1) to identify possible sun glare related problems; (2) to analyze different mitigation alternatives; and (3) to design physical countermeasures to avoid driver exposure to sun glare inside the tunnel and at its exit.

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Introduction

Good visibility of the road and its surroundings is a basic requirement for safe driving. Glare caused by direct sunlight interferes with drivers' vision performance. In high-glare conditions the visibility of objects is reduced and low-contrast objects may be rendered invisible thus increasing the probability of occurrence of incidents and crashes. Although this fact has been discussed in several previous studies, a causal link between laboratory or field measurements of an individual's glare susceptibility and the probability for accidents in sun-glare conditions is lacking. However, there exists evidence that during the glare period a speed reduction in the traffic flow and an increase in vehicle headway occurs, and also crashes or incidents have a greater probability of occurrence.

In a recent study Mitra (2008) analyzed the characteristics of glare related studies by comparing and contrasting crashes that were supposed to be affected by morning and evening sun-glare with those that were unaffected by glare, finding that sun-glare has strong influence on crash occurrence. This study was focused at signalized intersections and only estimated the effect of glare on crash occurrence by a fairly simple consideration of sun position (i.e., time of day and direction of crash). The conclusion were meant to serve as entry point for further inquiry rather than representing the final word on the effect of sun glare on intersection safety.

Gray and Regan (2007) used a simulator to study driving performance at an intersection in the absence and presence of low sun. Glare caused by low sun was found to increase the risk of collisions not only with pedestrians and cyclists, but also with other vehicles. They concluded that older drivers had a significantly greater reduction in safety margin than younger drivers. They suggested that drivers tend to overestimate the time to collision with the approaching vehicle during a left turn.

Auffray et al. (2008) examined the effect of sun glare on measured traffic flow. They found that sun glare affects the speed and flow distributions during congested and uncongested periods, and can even create dynamic bottlenecks at specific locations.

The eyes require some time to adjust from darkness to daylight. This process is called light adaptation. As a consequence sun glare is particularly hazardous at tunnel exits. A value of about three seconds can be adopted as representative for the disappearance of the difficulty in perceiving areas of low contrast (Wolfson and Graham 2000; Tasman and Jaeger 2004). Therefore it is advisable that drivers be protected from glare while light adaptation takes place.

In a recent paper, Jurado-Piña and Pardillo-Mayora (2009) presented a methodology to determine the days and times of the year when sun glare may impair drivers' vision on a particular road section depending on its geographical location, the geometric design of the road, and the physical characteristics of its environment.

This article presents an extension to the previous methodology to analyze sun glare related problems at tunnel exits. The new methodology can be used to study in detail the problem at existing tunnels and to analyze newly designed road tunnels. It may also be used as a tool when designing sun glare countermeasures.

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Factors of Glare Vision Impairment Situations

Three main factors determine the occurrence of sun glare in a particular road segment at a given time: the position of the sun relative to the driver's eyes, the direction of the driver's line of sight, and the configuration of the terrain (Jurado-Piña and Pardillo-Mayora 2009). As a driver travels through a tunnel, the geometry of the tunnel intervenes as a fourth factor.

Sun Position

The sun position at a given time and location is defined in local coordinates by the local azimuth angle and the elevation angle. These coordinates can be determined by applying the simplified algorithms developed by Michalsky (1988). The successive sun positions throughout a day define the solar path.

Direction of the Line of Sight and Angle of Glare

The driver's line of sight is usually directed to the segment of road ahead of him. For the analysis, it has been assumed that it is fixed on a point of the road axis located 90 m ahead of the driver's position. The equations for disability glare published in CIE report Number 146 [Commission Internationale de l'Èclairage (CIE) 2002] are the result of almost a century of scientific discussion and research on disability glare. These equations express glare as a function of the angle between the line of sight and the glare source, the age of the drivers and the ocular pigmentation. Based on the equations, it can be assumed that the visual nuisance for drivers of a given age is similar for all the solar positions that make a constant angular value around the line of sight. These solar positions define the base of a cone with the apex at the driver's eye that is referred to as glare cone in this article.

The angle made by the line of sight of the driver and a line directed to the sun is referred to as angle of glare. Based on the equations for disability glare, it may be shown that angle of glare values of 19° and 25° characterize glare vision impairment situations for drivers aged 40 and 60 years, respectively. Jurado-Piña and Pardillo-Mayora (2009) selected these specific values to characterize the range of sun glare effects on a great percentage of the driving population.

Terrain Profile

At certain angles the driver's eyes may be shielded from the sun by the terrain. For this reason, the profile defined by the terrain within the driver's visual field has to be considered when analyzing sun glare situations. This profile is referred to as the terrain profile.

Tunnel Geometry

When drivers travel though a tunnel and approach its exit, the configuration of the tunnel has to be taken into account as the sunbeams can only reach the drivers eyes through the tunnel exit. The portion of the tunnel exit portal that can be seen while driving inside the tunnel is referred to as tunnel exit view.

Methodology

Identification of Times of Glare Occurrence at a Highway Section

To determine the sun position in any location at a given time Michalsky's algorithms were implemented in a computer program. The error in the solar azimuth and elevation computed by the program is less than 0.01° for the period covering from 1950 to 2050.

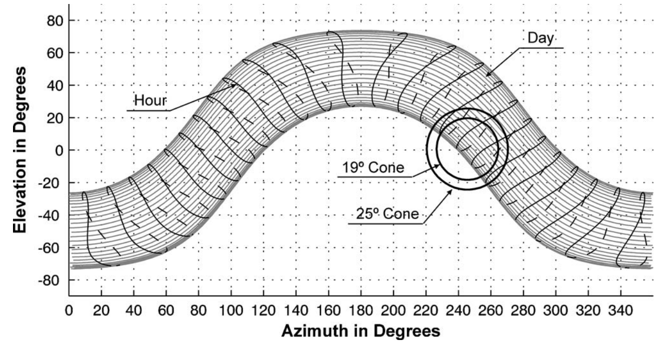

Fig. 1. Sun path and glare cones at km 217+920 National Motorway A-5 (Spain)

The solar paths throughout a year at any specific position can be plotted on a cylindrical solar chart (Fig. 1). This graph is based on the projection of the solar trajectory in a cylinder surrounding the observer. The sun position at a specific time is represented by a point on the chart, by means of its azimuth as the abscissa value and its elevation as the ordinate value. On the cylindrical chart, the curves from east to west (labeled as days) show the sun paths for different days of the year. The transverse curves (labeled as hours) represent the civil time, from sunrise (east) to sunset (west). A uniform scale for the solar elevation (−90° to 90°) is used.

To analyze the impact that the sun has on the visual conditions on the road, the driver's field of view has to be represented on the solar chart. For a specific driver position, the direction of the line of sight is determined by its azimuth and elevation. On the cylindrical chart, the direction of the line of sight will therefore be represented by a point. Around this point, different glare cones can be plotted, reflecting all the positions at which the sun has a similar effect on the drivers' visual performance. In Fig. 1, the glare cones for the characteristic values of 19° and 25° are shown.

For a specific position, the terrain profile is defined by pairs of azimuth-elevation values defining the outline of any topographic element within the visual field which may block the sun beams from the driver's eyes. These are obtained from a digital terrain model. An independent modulus of highway design software was developed to obtain the terrain profile and other variables related to road design that are required in the analysis for each position of the driver along the road.

As well as the terrain profile, the pairs of azimuth-elevation values defining the border of the area seen by the driver from each position inside the tunnel needs to be determined. For this calculation, both the road plan and profile and the tunnel cross section are considered, since the tube walls can shield the driver's eyes from the sun. The set of points obtained in this way forms a closed outline which has been previously referred to as the tunnel exit view (Fig. 2).

In order to detect the time periods during which visual impairment conditions occur at a specific road section, the solar paths are displayed on the cylindrical chart jointly with the driver's line of sight, the glare cones around it, the terrain profile and the tunnel exit view. Fig. 3 shows in detail the section of the cylindrical chart plotted in Fig. 1 including all the factors that intervene in the problem.

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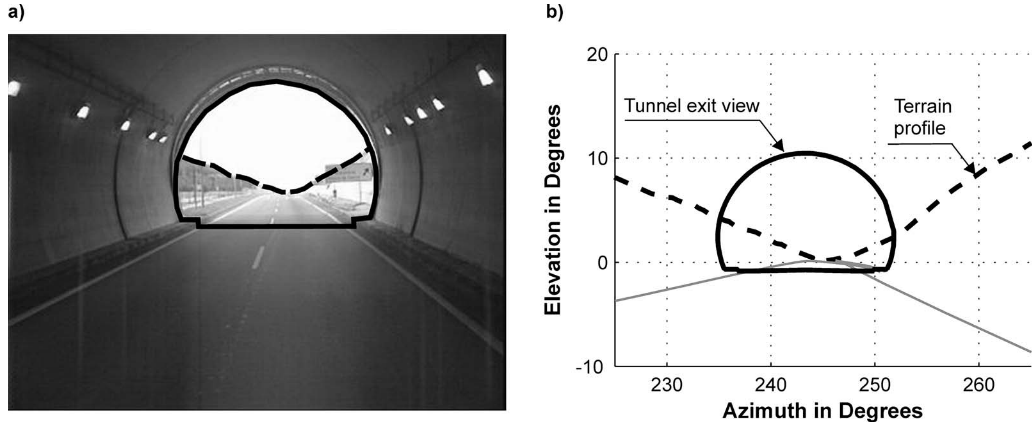

Fig. 2. Problem factors: terrain profile and tunnel exit view (a) reality; (b) representation in a cylindrical chart

The cylindrical chart is based on a geographic coordinate system. Since digital terrain models are usually referred to cartographic coordinates the data obtained from them must be converted into geographic coordinates taking into account the meridian convergence for the transformation.

Using the joint representation of the problem factors, the days and times of the year when sun glare may impair drivers' vision can be identified (Fig. 3) as the portions of the solar paths within the area delimited by the glare cones, the terrain profile and the tunnel exit view.

In addition to the graphical identification procedure based on the solar charts, the time intervals at which glare problems arise can also be determined numerically using the same methodology. For each glare cone, an indicator of the total yearly glare exposure at a particular position has been defined. It is referred to as the local glare exposure index (LGEI). Its value is the total time during which sun glare occurs for each position of the driver. Its units are hours of glare/year.

Segment Glare Exposure Analysis

Glare analysis can be performed systematically for every position along a particular section of a road to determine the values of LGEI for different glare cones. LGEI values along the segment axis are then plotted to obtain a glare exposure profile.

Fig. 4 shows the LGEI profile between km 217+600 and 218+600 of National Motorway A-5 (Spain).

The first section inside the tunnel in which sun glare occurs during some period of the year is noted as the tunnel glare starting point. In the example shown in Fig. 4, the tunnel glare starting point is located at km 217+625, about 340 m before the exit of the tunnel at km 217+965.

Countermeasure Design

To prevent glare problems until the drivers' vision is adapted to the external luminosity, it is necessary to minimize exposure to

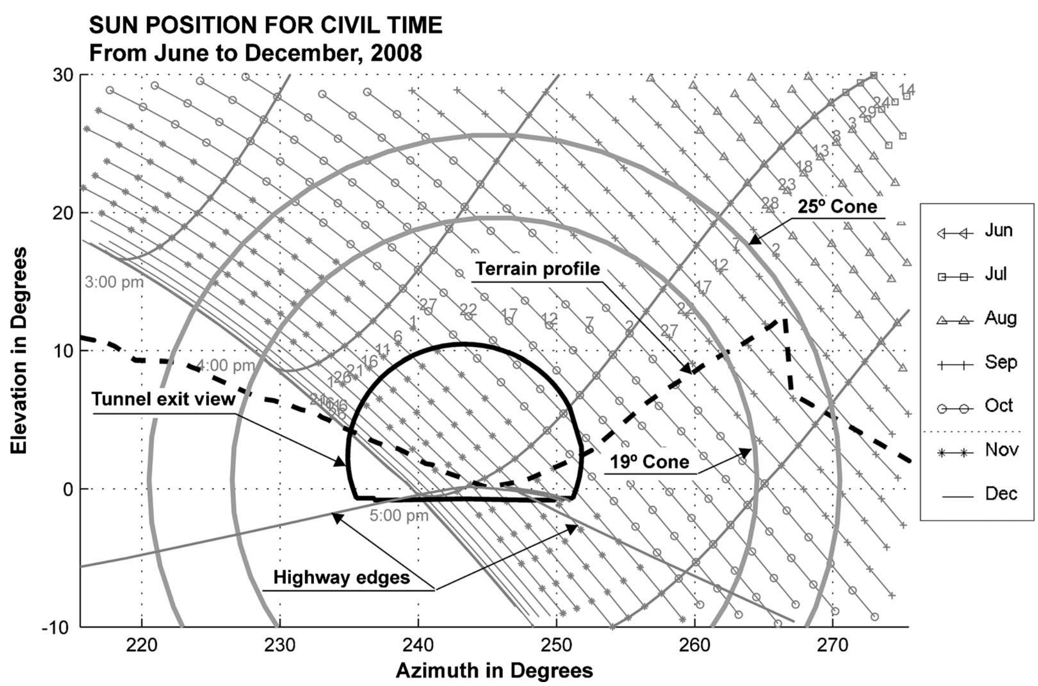

Fig. 3. Local glare analysis at km 217+920 National Motorway A-5 (Spain)

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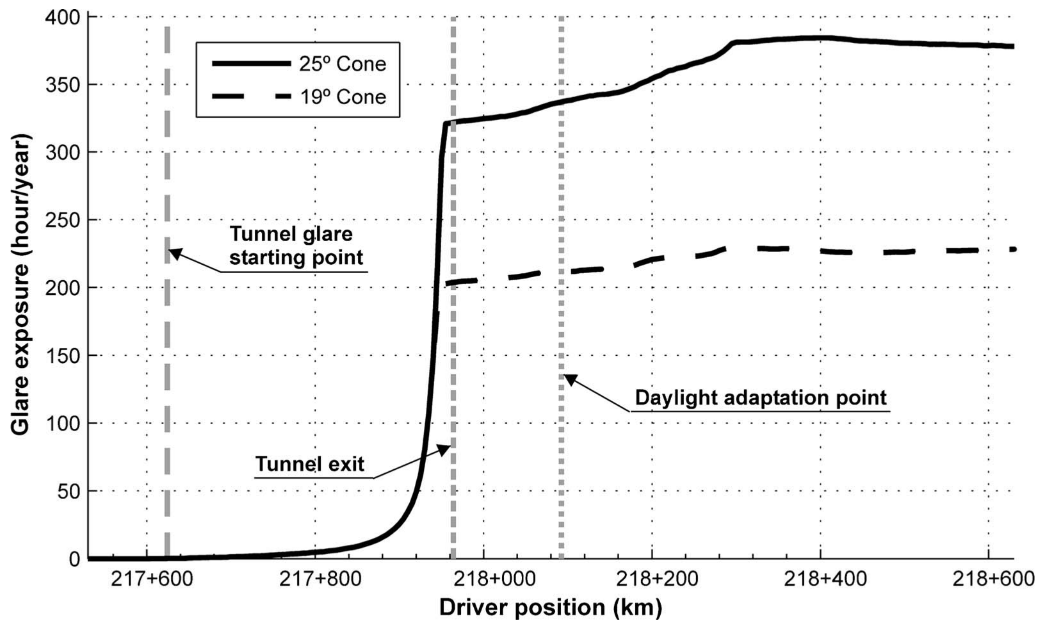

Fig. 4. Local glare exposure profile between km 217+600 and 218+600 of the National Motorway A-5 (Spain)

sun glare between the tunnel glare starting point and the eye adaptation point. In existing tunnels, the road plan cannot be modified, and therefore the countermeasures usually consist of the installation of sunlight shielding screens in the vicinity of the tunnel exit.

The potential measures that may be considered in order to minimize these sun glare problems are: overhead sunlight screens. Overhead screens can be designed to protect drivers' eyes from the sunbeams along a certain distance from the tunnel exit when the sun is located within a particular glare cone. An overhead screen does not need to be a continuous surface. It can also consist of a series of vertical plates or slats arranged perpendicularly to the road within a fixed distance of each other. These screens transmit some of the ambient light, but shield drivers eyes when the sun elevation is below a given design angle which corresponds to the reference angle of glare.

Fig. 5 shows the design of discontinuous overhead screen for an angle of glare α at a level road section. It consists of a series of vertical slats of a width w_1 at a distance s_1 of each other. The slats are fastened to longitudinal beams that are supported by a framework perpendicular to the roadway at a height h measured to the lower edge of the vertical slats. The distance between slats will vary depending on the assumed driver's eyes height h_1, the roadway gradient, the size of the slats, the height of the support, and the reference angle of glare.

As an example, for $\alpha=25°$ on a level section the distance between slats s_1 should be 0.89 m for $h_1=1.1$ m, $w_1=0.4$ m, and $h=5.7$ m.

Roadside sunlight barriers. Lateral screens placed on certain areas of the terrain can contribute to reduce sun glare. They are usually constituted by rows of trees. Screens made of artificial materials can be also be used for this purpose. They may be placed on vertical supports near the highway edges or hanging from the overhead screen.

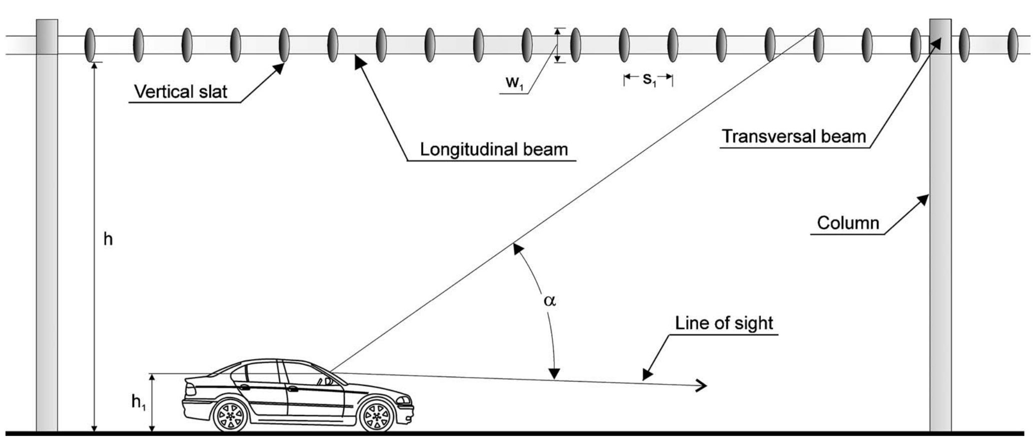

Fig. 5. Example of discontinuous overhead screen design on level terrain

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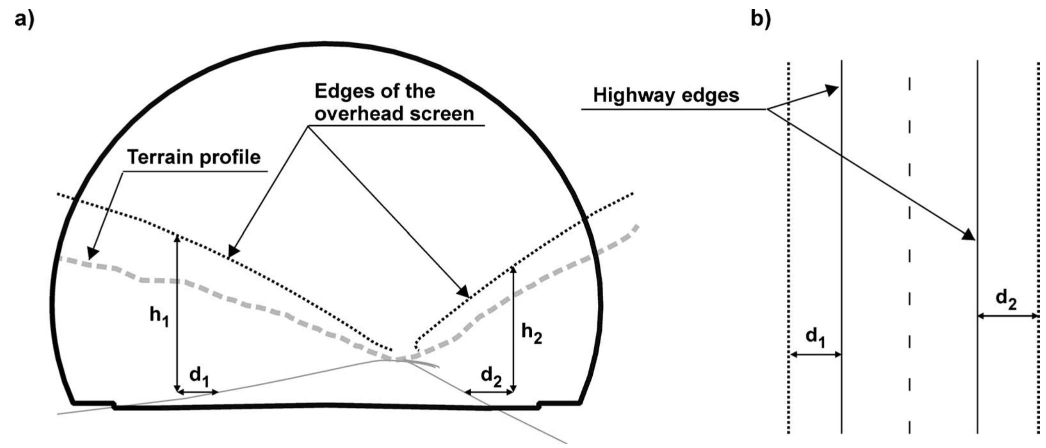

Fig. 6. Geometric definition of an overhead screen (a) perspective; (b) plan

Geometric Definition

Overhead Screens

Fig. 6 shows the geometric definition of an overhead screen. It is defined by the curves representing its external edges. The right and left borders of the screen are defined at each section by the height above the roadway (h_1 and h_2) and by the horizontal distance to the right and left edges of the roadway (d_1 and d_2, respectively).

Once the geometry of the curves which define the overhead screen has been obtained, they are approximated to two polygonal lines with a fixed distance between vertices. The universal transverse mercator (UTM) spatial coordinates UTM_x, UTM_y, and UTM_z of these two polygonal lines are used to define the screen.

Roadside Screens at a Fixed Distance from the Edge of the Road

Similarly to the definition of overhead screens, roadside screens can also be systematically defined by the curve which represents the upper border of the screen. For example, right roadside screens are defined by the horizontal distance to the right edge of the road and by its height.

If the screen does not start from the ground, its lower height in relation to the edge of the road will also be defined. In this way, the screen will be defined by two curves which represent its lower and upper borders.

Freely Defined Vertical Screens Adapted to the Terrain

In order to be able to define screens freely on a digital model, polygonal lines defined in plan view by the coordinates of their vertices (UTM_x and UTM_y) were used. Each of these vertices has to be assigned a height in relation to the elevation of the digital model of the terrain in the same point in plan view. The geometry of the screen is so defined by means of the three-dimensional polygonal line which represents the upper edge of the screen.

Graphical Representation

A graphical procedure based on the representation on cylindrical charts has been developed to analyze sun glare countermeasures. For each road section, the cartographic coordinates of the polygonal lines defining the countermeasures are transformed into local coordinates in relation to the position of the driver, that is, into pairs of azimuth-elevation coordinates. Once these local coordinates for a particular position have been obtained, the measures can be represented on a cylindrical chart (Fig. 7).

Countermeasure Effectiveness Analysis

Depending on the configuration of a tunnel and its roadside, it may not be technically possible to prevent exposure to sun glare completely. If this is the case, exposure should be reduced as much as possible.

At the design stage, road alignment in the proximity of the tunnel exit should be chosen to avoid any exposure to sun glare until drivers reach the daylight adaptation point. When this is not possible, it is important that the geometric design of the road and roadside area is carried out simultaneously to the design of measures against sun glare.

To analyze the effectiveness of sun glare countermeasures at tunnel exits all the variables that intervene in the problem are represented in a cylindrical chart for each position of the driver between the tunnel glare starting point and the daylight adaptation point (Fig. 7). Alternative countermeasures designs may be assessed this way to identify the solution that minimizes driver exposure to sun glare throughout the year.

The driver will be shielded from the sun by an overhead screen for all the sun positions corresponding to the segments of the solar paths that are located within the area delimited by the two curves representing the edges of the screen (Fig. 8). Roadside screens are defined by its upper border. When the upper border is below the terrain profile, the screen will have zero efficiency, since in those cases the driver is already shielded by the terrain itself. However, when the upper border is above the terrain profile the driver will be shielded by the screen when the sun is at the positions corresponding to the segments of the solar paths within the area delimited by the screen border and the terrain.

In the example shown in Figs. 7 and 8, the exposure intervals are the same for the glare cones of 19° and 25°. Fig. 8 shows the glare reduction achieved with the installation of an overhead screen and a roadside screen. In this example a residual sun glare exposure zone remains unshielded.

The analysis can be repeated for the successive positions of the drivers along the segment of the road between the tunnel glare starting point and the daylight adaptation point. The results allow obtaining the LGEI profiles for alternative countermeasure designs against sun glare and for different glare cones. By compar-

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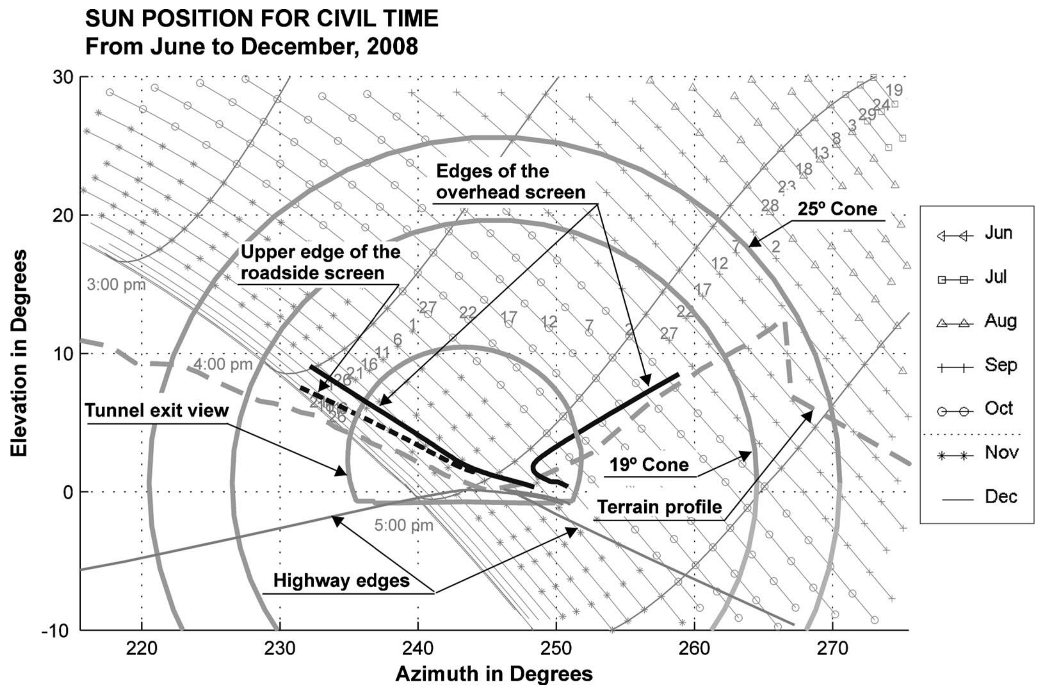

Fig. 7. Cylindrical chart with all the variables involved in local glare countermeasure effectiveness analysis

ing these profiles with those obtained in the initial situation in which no countermeasures are implemented, the efficiency of the measures along the said segment of the road is assessed. The efficiency is obtained as a percentage (%) of reduction in glare exposure in relation to the initial situation.

Fig. 9 shows the reductions in glare exposure for a 25° glare cone that would be achieved if a tree screen on the left roadside and a 465-m-long 6.7-m-high overhead screen at the exit of the tunnel were installed. Reductions are shown both in absolute values (left axis) and in percentages in relation to the original situation (right axis).

Case Study

The methodology has been applied to an existing tunnel in which sun glare problems occur during the months from November to

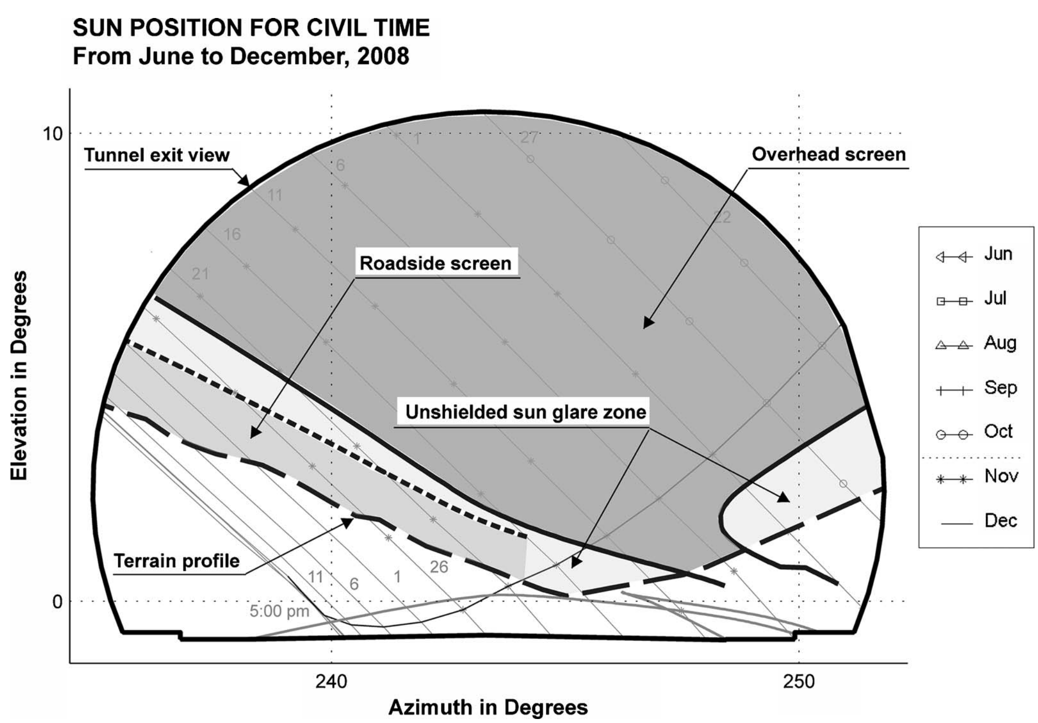

Fig. 8. Glare reduction achieved with an overhead screen and a roadside tree screen

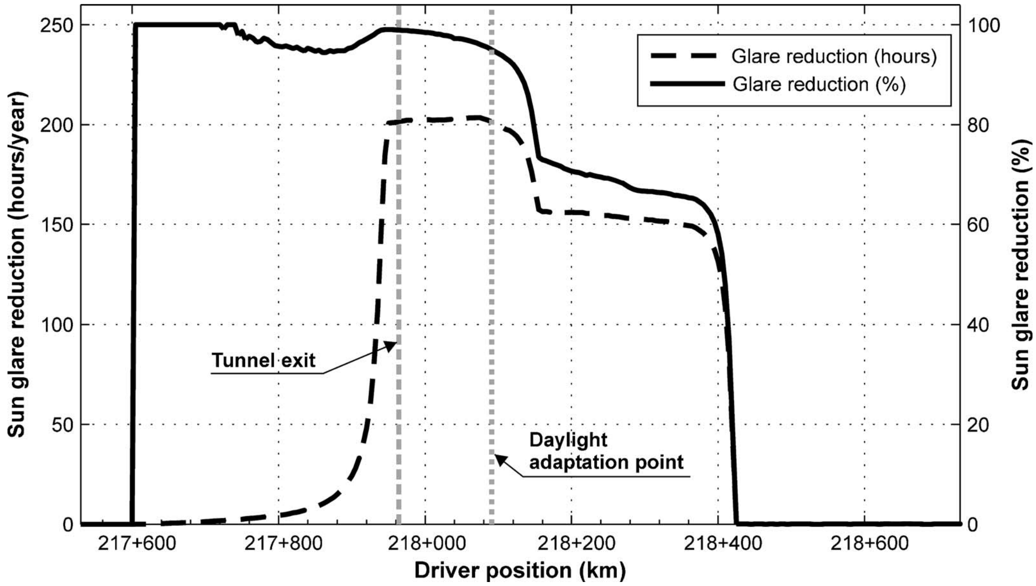

Fig. 9. Example of countermeasure efficiency analysis for a 25° glare cone

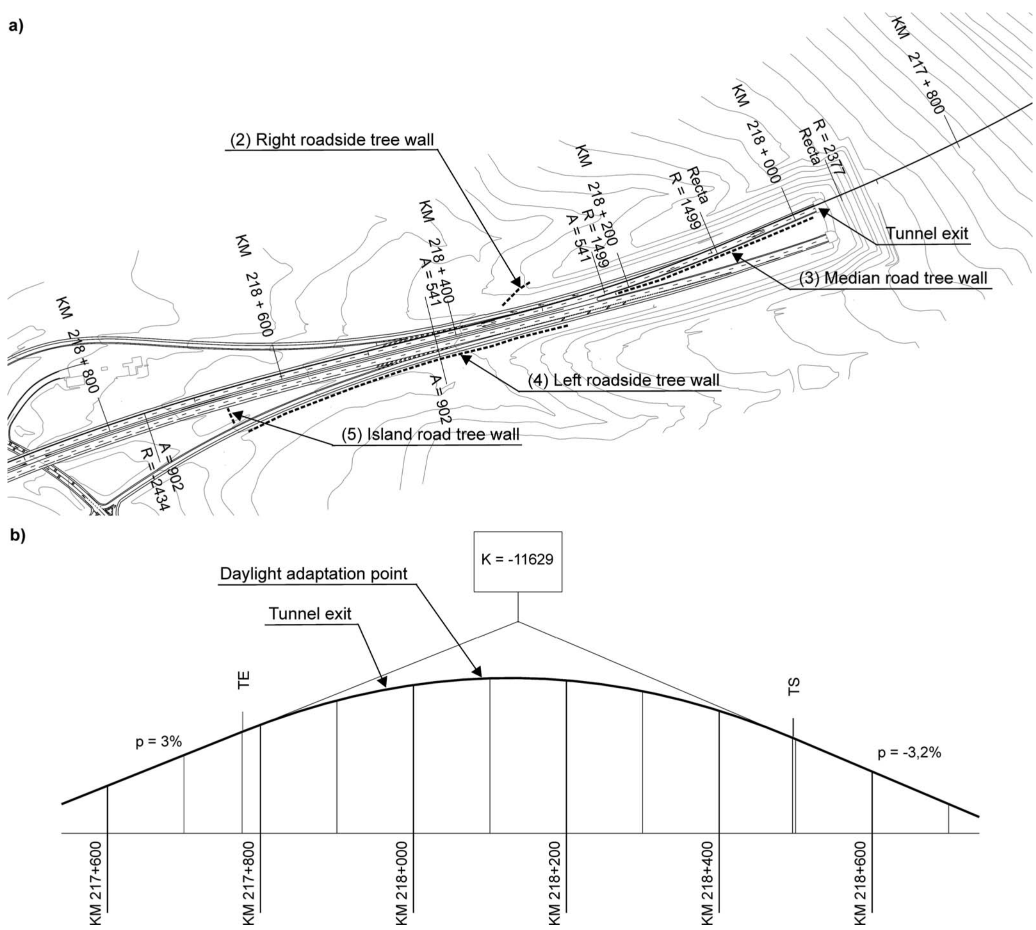

Fig. 10. (a) Road plan showing location of sun glare countermeasures layout; (b) road profile

February, both inside the tunnel and near its exit. The tunnel is located between km 217+020 and 217+965 National Motorway A-5 (Spain). At the tunnel exit, the road is oriented to the southwest with an upward gradient and a crest 150 m beyond the exit (Fig. 10).

Fig. 3 shows the initial situation at km 217+920, and Fig. 4 shows the LGEI profiles. The goal when designing the countermeasures against sun glare was to eliminate as much as possible of the existing glare exposure from the tunnel glare starting point to the daylight adaptation point.

To achieve this reduction, different combinations of measures against sun glare were tried. As an example, Fig. 9 presents the efficiency analysis of one of these combinations including a tree screen on the left roadside together with a 465-m-long overhead screen.

The solution that was finally adopted included the installation of the following elements:

1. 6.7-m-high overhead screen, between the exit section of the tunnel and km 218+340;
2. 15-m-high tree screen on the right roadside;
3. 8-m-high tree screen on the freeway median;
4. 15-m-high tree screen on the left roadside;
5. 15-m-high tree screen located on a traffic island at the road exit; and
6. 3-m-high side screen fastened to the right-hand edge of the overhead screen.

Fig. 10 shows the tree screens layout in plan view. Measure 6, consisting in a roadside screen, has the same layout in plan view as the right edge of the overhead screen, that is, Measure 1. Measure 6 is defined by two curves, the lower representing the lower edge of the screen and located at a height of 3.7 m from the right edge of the roadway, and the upper which coincides with the right edge of the overhead screen, and therefore is at a height of 6.7 m in relation to the right edge of the roadway. For simplicity, Measures 1 and 6 have not been represented in Fig. 10.

Figs. 11(a and b) show the cylindrical charts resulting from the analysis for two characteristic points of the road segment: km 217+920, before the tunnel exit, and km 218+090, at the daylight adaptation point. Fig. 11(a) shows that exposure inside the tunnel is almost entirely eliminated. However, a complete elimination of glare exposure was not possible at the daylight adaptation point due to the road geometric design and to the existence of a junction in the vicinity of the tunnel exit. In order to completely eliminate any exposure it would have been necessary to plant trees on the freeway ramp of the junction, for which the junction would have to be moved further from the tunnel exit. This situation could have been avoided if, during the planning stage, the road design had been performed together with the design of the measures against sun glare. A computer generated image illustrating the final solution at the exit of the tunnel is shown in Fig. 12.

Conclusion

The research presented in this paper provides a practical method to evaluate potential driver vision impairment caused by sun glare at tunnel exits. The results may be used to study in detail the problem at existing tunnels or to analyze newly designed road tunnels.

During the planning stage, this methodology can allow to make decisions on the designing of a road tunnel so as to avoid drivers' exposure to glare both inside the tunnel and at its exit, at least until their vision has adapted to external lighting conditions.

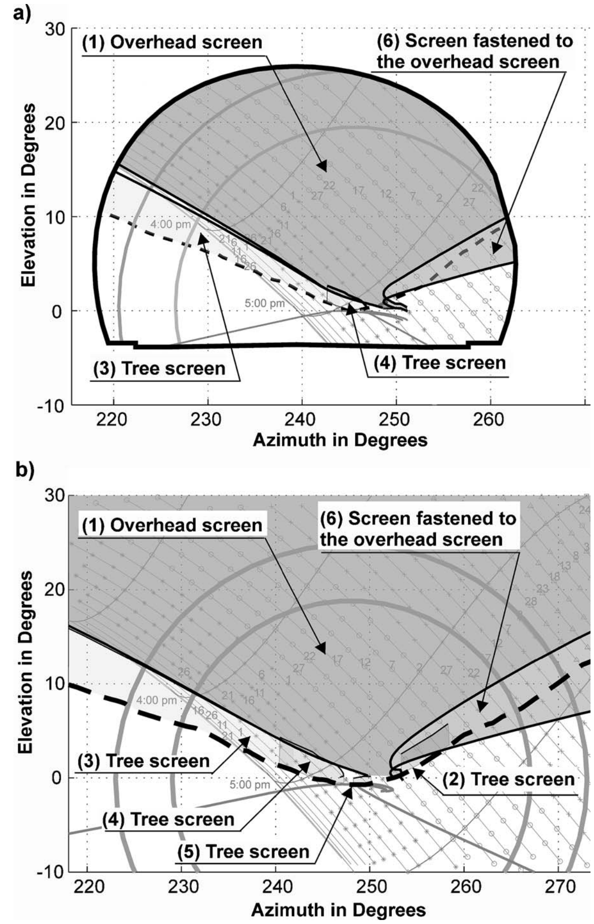

Fig. 11. Glare protection measures (a) inside the tunnel; (b) at the daylight adaptation point

When this is not possible, the methodology developed allows analyzing the geometric design of the road together with that of the measures against sun glare, so that a total reduction of glare exposure between the tunnel glare starting point and the daylight adaptation point can be achieved.

This methodology can also be used by highway departments to analyze existing glare problems at in-service tunnels, as well as the possible connections between road accidents and sun-related

Fig. 12. Computer generated image at km 218+100 National Motorway A-5 (Spain)

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glare. Once the problems have been identified, the methodology provides a procedure to analyze the design of measures against sun glare.

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