A procedure for auditing highway alignments for the effects of sun glare

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ABSTRACT

We propose a geometric method to evaluate three dimensional highway alignments, either existing or proposed, for possible deleterious effects due to sun glare. Depending on the time of day and the position of the sun, serious traffic congestion and safety degradation can occur as a result of the blinding effect of the sun. The horizontal and vertical geometry of the roadway contribute directly to placing the viewing angle of the driver in a situation to be susceptible to these effects. The trajectory of the sun through the sky changes over the course of the year as a result of the axial tilt of the Earth, so these problems can occur at different times and at different locations during the year.

The problem is most prevalent when the sun is low in the sky, either setting or rising, as roadway grades tend to be quite slight from a geometric perspective. In such conditions, however, the atmosphere plays a significant role in refracting the sunlight, causing the sun's apparent position to be different than its actual position.

We develop a mathematical method to determine, for a given geometrical description of a highway alignment, what locations, and at what times, that alignment might be susceptible to these problems. This information can then be used to develop alternative alignments that would not suffer so much from this potential safety hazard.

Our calculations include astronomical algorithms to determine the vector direction of the sun from a given location on the highway, at any time during the year, as well as the optical refinements necessary to account for atmospheric refraction. Essentially, the output of the model is a list of locations and times that are expected to suffer from sun glare effects. Such an algorithm could serve as one of a number of road safety audits conducted in a safety review for a given alignment, or it could serve as an input to an automated highway design process whose objective function accounted for safety deficiencies of candidate alignments. The algorithm is motivated and developed in detail, and is tested against highway alignment data.

1. INTRODUCTION

Humans have long understood the difficulties involved when the sun is low in the sky, and located in a direction they would like to look. Clearly this posed a problem for hunters eons ago, but it continues to pose a particular problem for anyone directing a vehicle, be it a car, truck, airplane, or boat. The glare caused by looking in the general direction of the sun can be painful and potentially very distracting. The consequences of losing concentration while managing a vehicle are well understood, and considerable work has been undertaken to avoid these.

Although the patterns of the rising and setting sun have been well understood for a very long time, detailed analyses using these patterns have been conducted only in the computer era, because of the computational complexity involved. In this study, the principles of modern transportation engineering are combined with these astronomical algorithms to produce reports on the potential impact sunglare may have. Here, the focus is on highway operations, but similar analyses may be useful for other modes as well. This problem was recently addressed in [1] to develop visual aids to identify potential times of glare impact. This study focuses on the development of an automated procedure.

An increasingly common practice in the highway design community is the road safety audit, or RSA [2]. In general, this is a comprehensive review of an existing or proposed highway alignment to test its suitability in a number of critical performance areas, all related to safety. Specific components that can be reviewed include horizontal and vertical geometry, signing and striping, traffic control devices, sight distance, etc. Some of these elements that are strictly geometrical in nature can be evaluated computationally. The purpose of this paper is to demonstrate a computational method by which the issue of potential sun glare can be addressed for any existing or hypothetical roadway alignment. The method will identify what sections of the highway, in which direction, at what time of year, are susceptible to potential safety and congestion issues stemming from sunlight glare affecting drivers. The practical uses of the method include advising signing and control plans for existing alignments, measuring benefits and safety impacts for competing hypothetical alignments, and possibly helping to discriminate between candidate alignments. Because the methods are computerized and efficient, they can be incorporated into automated alignment design/evaluation tools as well.

This paper is organized into four sections. First was the introduction and motivation behind the study. Following this, in §2 is a detailed description of the mathematics underlying the analysis. Then, a case study of applying this model to real highway geometry data is shown in §3. Finally, some conclusions and continuing work are presented in §4.

2. ALGORITHM DESCRIPTION

In this section, the algorithm for determining at which locations and at which times drivers on a particular highway alignment will experience sunglare is outlined. A flow chart summarizing this process is shown in Figure 1.

The first step in this process is to process the traditional specification of highway geometry into a format which is more easily processed by a computer. Once completed, this data must be projected onto a map to locate the various stations in traditional geographic coordinates.

In addition, the processed highway alignment data is used to calculate the estimated viewing direction of a driver. The tangent vector along the road is used to represent this.

Once the highway location has been identified geographically, the relative position of the sun for each station is calculated. Several algorithms have been proposed in other research for this general process, and one of these is outlined here.

Once the viewing direction and solar position have been identified, a test is conducted to determine if the sun lies in a cone surrounding the viewing vector. If so, the driver's gaze will likely be affected by the glare.

In this section, each of these processes is described mathematically.

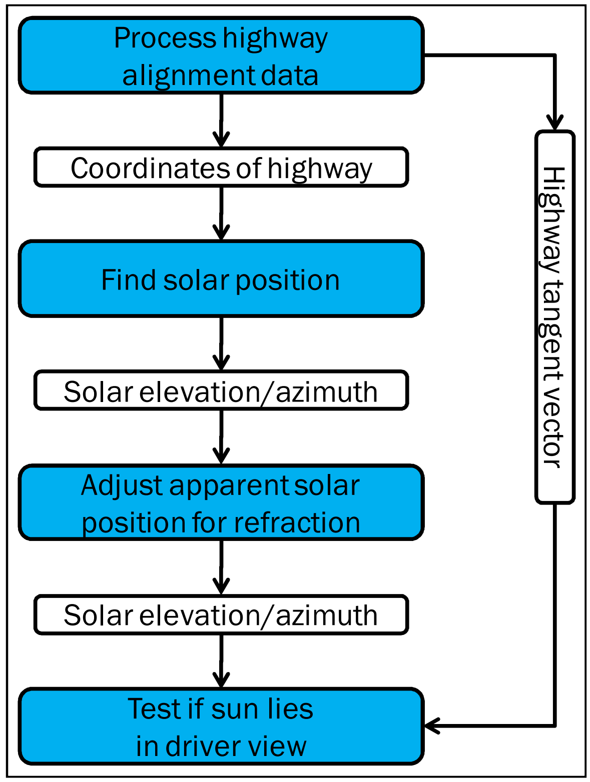

Figure 1 – Sun glare algorithm flow chart

Highway data requirements

The model described here has an obvious need for highly precise data concerning the location of the highway centerline. Such data is typically available as part of technical drawings created in building or improving the alignment. However, such drawings are intended for use by highway engineers and surveyors, and as a result do not describe the alignment geometry in terms generally compatible with this model.

Typically, the horizontal and vertical geometry of an alignment consist of several types of curves. The horizontal geometry comprises tangent sections, circular curves, and Euler spirals, while the vertical geometry comprises tangent sections and parabolic curves. Given these sets of curves and a starting point, it is necessary to identify the rectangular coordinates $\{x_i, y_i, z_i\}$ of many points along the alignment. The sunglare test may then be performed at each of these control points.

In principle, finding the discrete points lying on each of these types of curves is straightforward, but in some cases the mathematics are rather involved. For the horizontal geometry, this process is described in detail in [3] and [4]. For the vertical geometry, the procedures are quite similar, with the exception that only two types of sections are possible and the mathematics of these sections are somewhat simpler.

Thus, the result of this step is a complete description of the position of the highway by coordinate pairs $\{x_i, y_i, z_i\}$ at some spacing along the centerline.

Finding highway tangent vector

To approximate the viewing direction of the driver, the tangent vector along the surface of the highway centerline is calculated.

Because the highway alignment comprises many discrete line segments, the most straightforward method by which the tangent vector can be estimated is simply to calculate the slope of each segment. Given the sequences of points $\{x_i, y_i, z_i\}$ defining the curve, the vector of line segment slopes $\hat{u}$ is calculated as shown in (1).

$$\hat{u} = [x_i - x_{i-1}, y_i - y_{i-1}, z_i - z_{i-1}] \quad (1)$$

The segment lengths are then normalized to produce a vector of unit length, as shown in (2).

$$u = \frac{\hat{u}}{\|\hat{u}\|} \tag{2}$$

Inverting projections

Because the processed highway alignment data is specified in units of distance from a base point, the next step of this process is to identify the latitude and longitude coordinates of each station along the highway. That is, the planar coordinates must be projected onto the elliptical surface of the earth.

For this work, the well-known Universal Transverse Mercator (UTM) family of projections is used. In principle, any projection for which a unique transformation exists could be applied, likely with very similar results. For convenience, the functions included with the MATLAB Mapping Toolbox were applied to perform this transformation.

Solar position algorithm

The crux of this work lies in identifying the position of the sun in the sky.

It is important to consider the frame of reference required for this algorithm. It is desirable that the position of the sun be described relative to a specific position at a specific time. This consideration rules out some of the more traditional astronomical coordinate systems which rely on either the Earth's equator or the solar ecliptic as their fundamental plane. Rather, the position of the sun should be described relative to what is visible from a point on the surface of the earth.

Several algorithms have been proposed to efficiently determine the position of the sun. Often, these were developed to support solar energy research, but the algorithms are sufficiently general to be used for any other purpose as well. Many authors have approached the problem, each typically reporting an improved error percentage or decreased computational effort. One of the early modern approaches was Spencer [5], followed by Walraven [6], which saw many subsequent authors provide enhancements. Michalsky [7] provided an important update, but the gold standard for accuracy is Meeus [8], and as enhanced, Reda & Andreas [9]. Two more recent approaches, each of which took a systematic approach to comparing errors of these various models, were Blanco-Muriel, et al. [10] and Grena [11].

The steps outlined here for the solar position algorithm are taken, with few modifications, from the work of Blanco-Muriel, et al. [10]. This procedure was chosen over others because of its good combination of computational performance and predictive accuracy. The remainder of this subsection is attributed to Blanco-Muriel, et al. Any of the others mentioned here or elsewhere in the literature could be used interchangeably if there were some compelling reason to do so.

Three types of input data are required to determine the solar position using this algorithm. First, the position relative to which the solar position is determined must be identified. This is specified as a coordinate pair of latitude (positive north) and longitude (positive east). Also, the time at which the solar position is calculated must be specified as a date and time. The date is described with year y, month m, and day d. Time must be specified according to Universal Time (rather than local) as hours after midnight, including minutes and seconds as fractions of an hour.

Finally, the atmospheric conditions of temperature T and pressure p must be specified to accurately model refraction.

The output of this algorithm is the apparent solar position, relative to the position specified as input. The horizontal coordinate system of elevation angle and azimuth angle is used because it most accurately represents the needs created by this problem.

Compute Julian Day

The first step in this algorithm is to compute the Julian Day of the time being considered. The Julian Day represents the number of days, and fractions of a day, elapsed since March 1, 4800 BCE. This formula is shown in (3).

$$jd = \frac{1461}{4}\left[y + 4800 + \frac{m-14}{12} \right] - \frac{3}{400}\left[y + 4900 + \frac{m-14}{12} \right] + d + \frac{h}{24} - 31708.5 \tag{3}$$

For ease of computation, the value of the Julian Day jd shown above is normalized in (4) so that zero now corresponds with the J2000.0 epoch (noon on January 1, 2000).

$$n = jd - 2451545 \tag{4}$$

Compute location of sun in ecliptic coordinates

The ecliptic coordinates of the sun are calculated simply as a function of the Julian Day. The ecliptic coordinate system uses the ecliptic as its fundamental plane. The ecliptic is the path that the sun appears to follow across the sky over the course of a year. First, an auxiliary variable Ω is calculated in (5).

$$\Omega = 2.1429 - 0.0010394594n \tag{5}$$

Then, the mean longitude and mean anomaly are calculated as shown in (6) and (7), respectively.

$$L = 4.8950630 + 0.017202791698n \tag{6}$$

$$g = 6.2400600 + 0.0172019699n \tag{7}$$

Finally, the ecliptic longitude l is calculated as shown in (8) and the obliquity of the ecliptic in (9).

$$l = L + 0.03341607\sin(g) + 0.00034894\sin(2g) - 0.0000203\sin(\Omega) - 0.0001134 \tag{8}$$

$$ep = 0.4090928 - 6.2140310\times10^{-9}n + 0.0000396\cos(\Omega) \tag{9}$$

Convert ecliptic to celestial coordinates

Once the position of the sun has been determined in ecliptic coordinates, the following transformations are applied to describe this location in equatorial coordinates. The equatorial coordinate system uses as its fundamental the projection of the Earth's equator onto the celestial sphere. The equations for calculating right ascension (10) and declination (11) are simply transformations of the ecliptic coordinates.

$$ra = \tan^{-1}\left[\frac{\cos(ep)\sin(l)}{\cos(l)} \right] \tag{10}$$

$$\delta = \sin^{-1}\left[\sin(ep)\sin(l)\right] \tag{11}$$

Convert celestial to horizontal coordinates

The final step of this algorithm is to convert the solar position from equatorial into horizontal coordinates. In this system, the horizon, relative to a single position on the curved surface of the earth, is used as the fundamental plane. This completes the process, in that the position of the sun will now be expressed relative the location of an observer.

The first step in this process is to calculate the Greenwich Mean Sidereal Time (GMST), as shown in (12).

$$gmst = 6.6974243242 + 0.0657098283n + h \tag{12}$$

Then, the GMST is then adjusted to the Local Mean Sidereal Time (LMST), as shown in (13).

$$lmst = 15gmst + \lambda \tag{13}$$

Next, the hour angle is calculated as a function of the LMST and the right ascension, as in (14).

$$\omega = lmst - ra \tag{14}$$

At this point, all of the transformations are complete to allow for the direct calculation of the relative position of the sun. The azimuth angle is calculated according to the formula shown in (15). This is a function of the hour angle, declination, and latitude.

$$\gamma = \tan^{-1}\left[\frac{-\sin(\omega)}{\tan(\delta)\cos(\phi) - \sin(\phi)\cos(\omega)}\right] \tag{15}$$

Finally, the zenith angle $\theta_{z,n}$ is computed as shown in (16).

$$\theta_{z,n} = \cos^{-1}\left[\cos(\phi)\cos(\omega)\cos(\delta) + \sin(\delta)\sin(\phi)\right] \tag{16}$$

However, the zenith angle is measured relative down from the zenith (the point on the celestial sphere furthest from the fundamental plane), rather than up from the fundamental plane itself. As a result, the transformation shown in (17) is applied along with a slight correction for parallax to arrive at the solar elevation angle.

$$\theta_s = \frac{\pi}{2} - \left[\theta_{z,n} + \frac{6371.01}{149597890}\sin(\theta_{z,n})\right] \tag{17}$$

A set of example outputs are shown in Figure 2 and Figure 3 for several days in 2008.

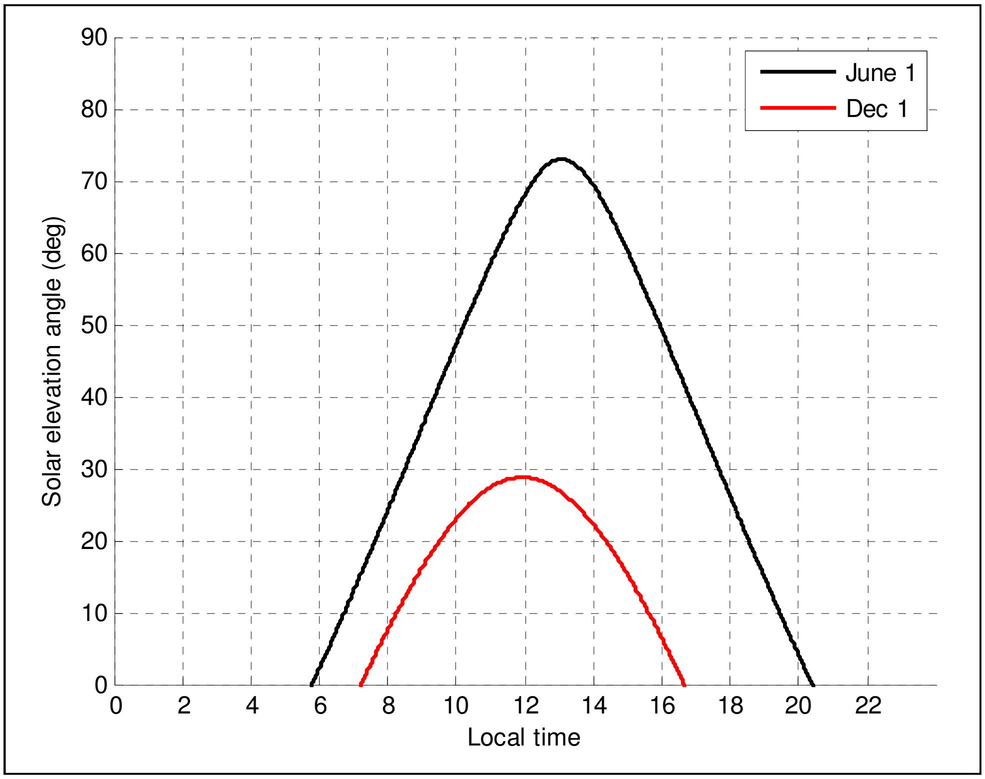

Figure 2 – Solar elevation angle for several days

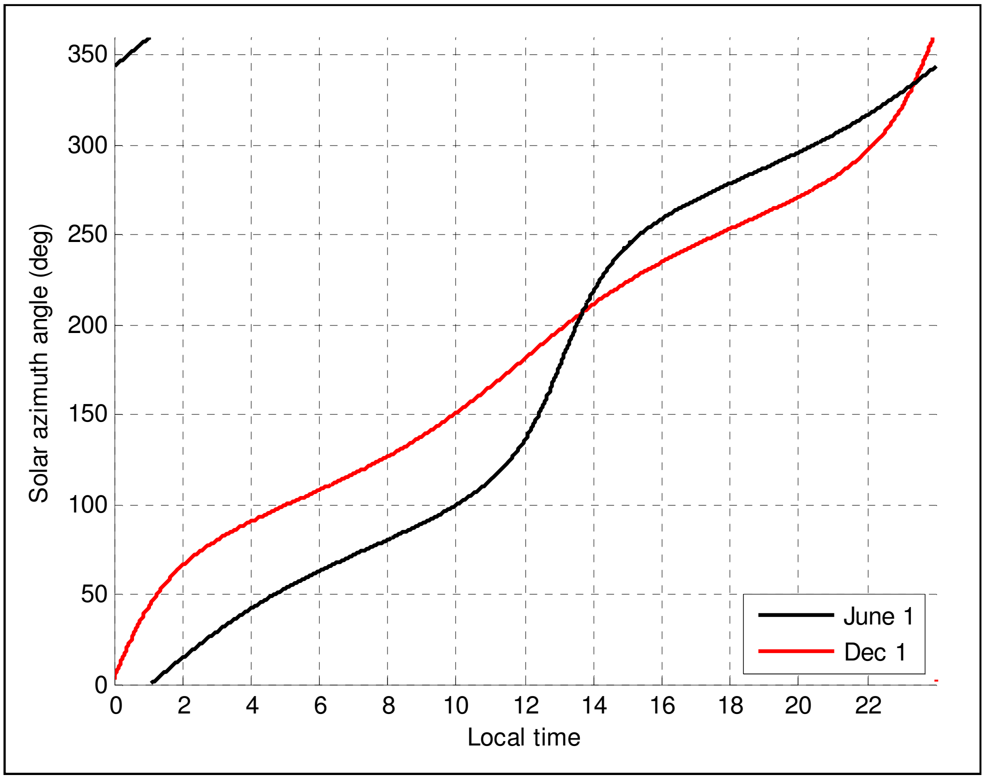

Figure 3 – Solar azimuth angle for several days

Adjust apparent solar position for atmospheric refraction

Light waves change direction when passing from one medium to another. This effect is particularly apparent when the angle of incidence is particularly shallow. This phenomenon is known as refraction. The effect of this on the analysis outlined in this research is that the apparent position of the sun to an observer differs from the actual position. The algorithm described previously calculates the actual position, and the procedure outlined here adjusts that position to that which is seen by the observer.

Sæmundsson proposed in [12] the following formula for a refraction correction when the true elevation angle of a star is known. This is shown in (18). This formula assumes atmospheric pressure of 1010 millibar and air temperature of 10° Celsius.

$$\theta_{s,r} = \theta_s + \frac{1.02}{\tan\left(\theta_s + \frac{10.3}{\theta_s + 5.11}\right)} \quad (18)$$

Meeus [7] points out that refraction will increase with increased pressure or decreased temperature, and provides the following update to the refraction formula shown in (19). The symbol *P* represents atmospheric pressure and *T* temperature.

$$\theta_{s,r} = \theta_s + \frac{P}{1010}\frac{283}{273+T}\frac{1.02}{\tan\left(\theta_s + \frac{10.3}{\theta_s + 5.11}\right)} \quad (19)$$

Change coordinate systems

For numerical convenience, the spherical coordinates in reference to the horizon, calculated during the solar position algorithm, are converted to rectangular coordinates. This is shown in (20).

$$\hat{s} = \left[\sin\gamma, \cos\gamma, \tan\theta_{s,r}\right] \quad (20)$$

Once again, this vector is normalized to unit length, as in (21).

$$s = \frac{\hat{s}}{\|\hat{s}\|} \quad (21)$$

Test highway tangent vector in cone of solar influence

The final step in identifying glare conditions is to test if the view of the driver will approach the sun. A diagram illustrating the horizontal geometry of this test is shown in Figure 4.

Research to quantify the angular distance at which glare causes distraction has a long history. See Vos [13] for a review of the disability glare phenomenon, and Boulos et al. [14] for a discussion of identifying glare angles in automotive applications. The problem is related to identifying the appropriate angular displacement of a sign from a driver's view. For that problem, [15] suggests the use of a 20° maximum aperture for visibility.

In this work, the viewing region of the driver of the driver which might be affected by sunglare is represented by a cone with a circular base whose apex lies at the driver's position.

The aperture α of the cone may be estimated experimentally, but values from previous studies on driver vision are used in this work.

In principle, it is possible to vary the shape of the base of the cone. For example, if research showed that drivers had a larger range of sensitivity laterally than vertically, then the base of the cone could be an ellipsis with a horizontal major axis. Further, it is possible to change the perspective of this test, so that the sun is treated as impacted a region of sky (which then forms the base of the cone) and the viewing direction as simply a vector. In this case, the test remains exactly the same as that which is shown here.

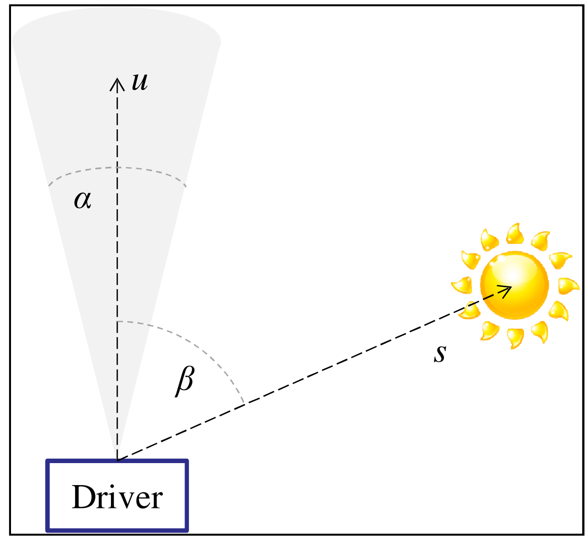

Figure 4 – Horizontal geometry of sunglare test

To determine if the sun lays in the driver's view, first the cosine of angle between the axis of the cone and the solar vector (β) is calculated as the inner product of these two vectors. This is shown in (22). Having normalized both vectors earlier simplifies this equation.

$$u \bullet s = \cos\beta \tag{22}$$

Because the base of the cone is a circle, if the angle β is less than the half angle of the cone $\left(\alpha/2\right)$, then the solar vector must lie within the cone. This test is conducted in (23) using the cosine of the angles to limit computational operations. If the indicator variable I takes a value of one, then glare is expected at that location and time under consideration. Otherwise, I takes a value of zero, and glare is not expected.

$$I = \begin{cases} 1 \text{ if } \cos\beta \geq \cos\dfrac{\alpha}{2} \\ 0 \text{ otherwise} \end{cases} \tag{23}$$

3. CASE STUDY RESULTS

To evaluate the efficacy of this procedure, a study was undertaken to examine a stretch of highway already in use. In this section, the section of highway examined is described, and then results indicating periods of expected glare are described.

Study region

A portion of the McKeldin Beltway (I-695) surrounding Baltimore, Maryland was selected for analysis. The southwest section of this circumferential road was selected, with the general boundaries for the study area being I-95 on the southern end, and MD-144 on the northern end. A map of the horizontal geometry is shown in Figure 5, and a diagram of the elevation is shown in Figure 6. The values to the right of the line in Figure 5 indicate station numbers.

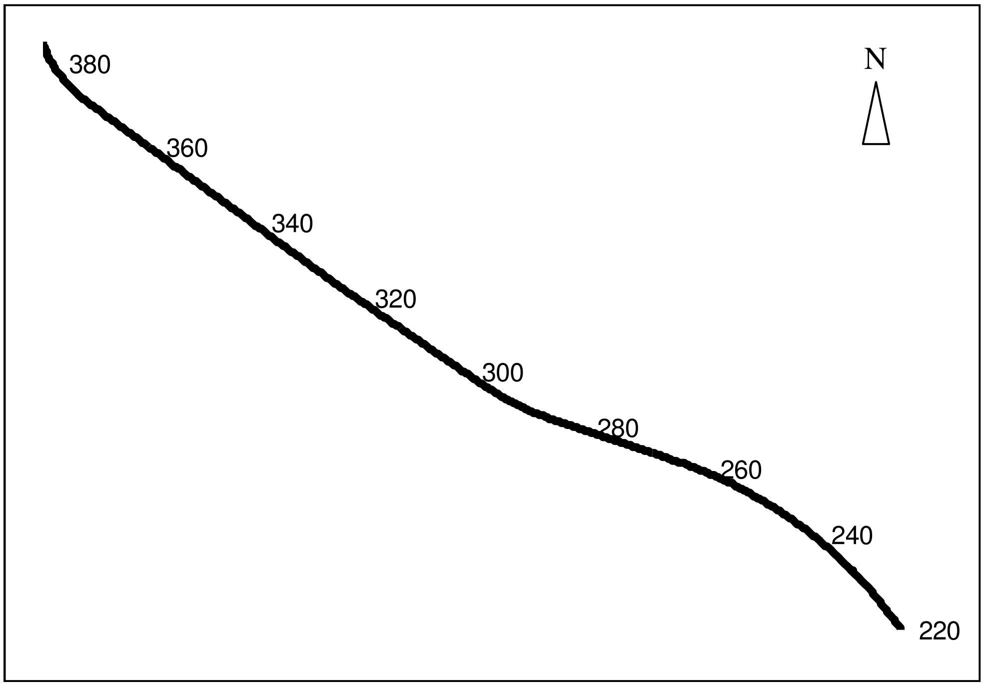

Figure 5 – Horizontal geometry of section

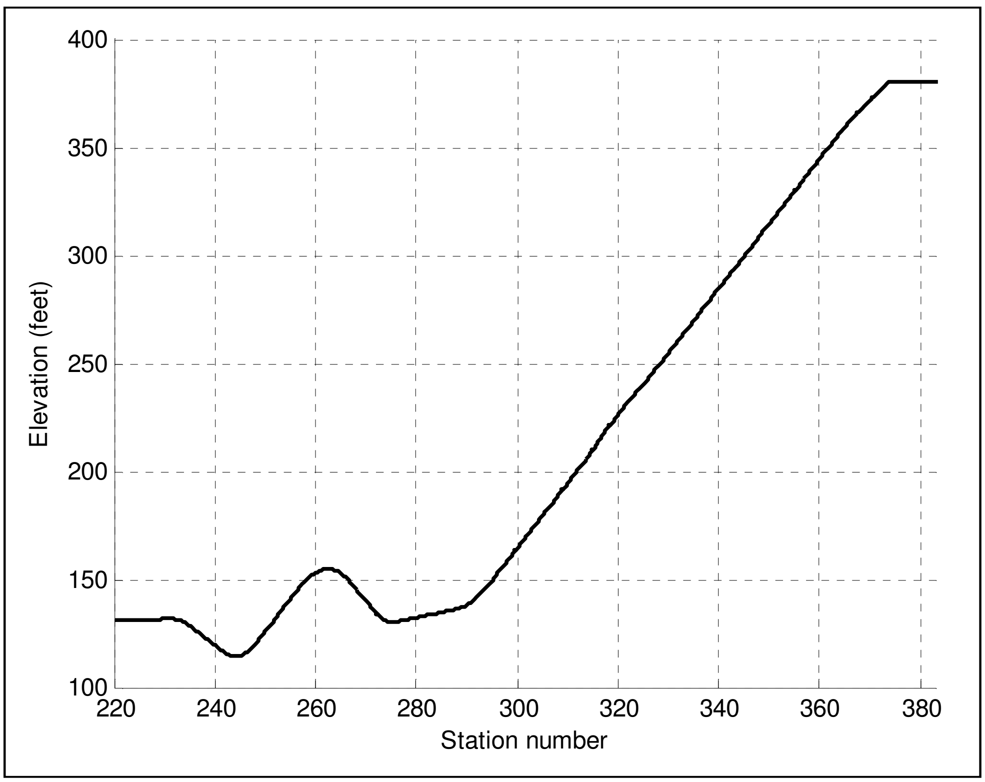

Figure 6 – Vertical geometry of section

Results

The section described above was examined for the calendar year 2008. Both directions of the roadway were considered, as impacts from rising and setting sun should affect only one direction at a time. A driver viewing angle of 20° was used, as suggested by Zwahlen in [15] for sign visibility.

Two visualizations of the case study results are shown. The first set of visualizations (Figure 7 and Figure 8) indicates the expected length of the glare period at each station on several individual days. These days were selected in Figure 2 and Figure 3 because they are six months apart and represent the seasonal changes in the solar positions.

In Figure 7, the northwest-bound direction (increasing station numbers) is shown for June 1 because the sun sets in the northwest during that time of year at that position. Because this direction of the alignment is oriented to the west, it should be affected by the setting sun. This is confirmed by the results shown in Figure 7.

Likewise, in Figure 8, the southeast-bound traffic (decreasing station numbers) is shown. In this case, however, December 1 is examined because the sun rises in the southeast during that time of year at this position. Because this portion of the alignment is oriented to the east, it should be affected by the rising sun. This is confirmed by the results shown in Figure 8.

In this work, however, such an analysis is conducted automatically for every day. If the results for each day are aggregated, visualizations of the daily length of glare impact can be developed. This information can be used to identify critical times of year for awareness.

The second set of graphics (Figure 9 and Figure 10) demonstrates at which times of year glare is most prevalent, as measured by daily length of glare. The color intensity on these figures is used to indicate the length of the glare period. Figure 9 shows the daily length of glare throughout the year at each station in the northwest-bound direction. As a result, these glare durations occur with the setting sun, typically during the evening traffic. Figure 10 again shows the daily length of glare throughout the year, but now for the southeast-bound direction. These glare durations occur with the rising sun.

The hole in the center of the strong glare region occurs not because of changes in the horizontal geometry, but because the vertical geometry of the road declines at that point. Thus, if the vehicle is pointed below the horizon, it is unlikely that the sun will be in view.

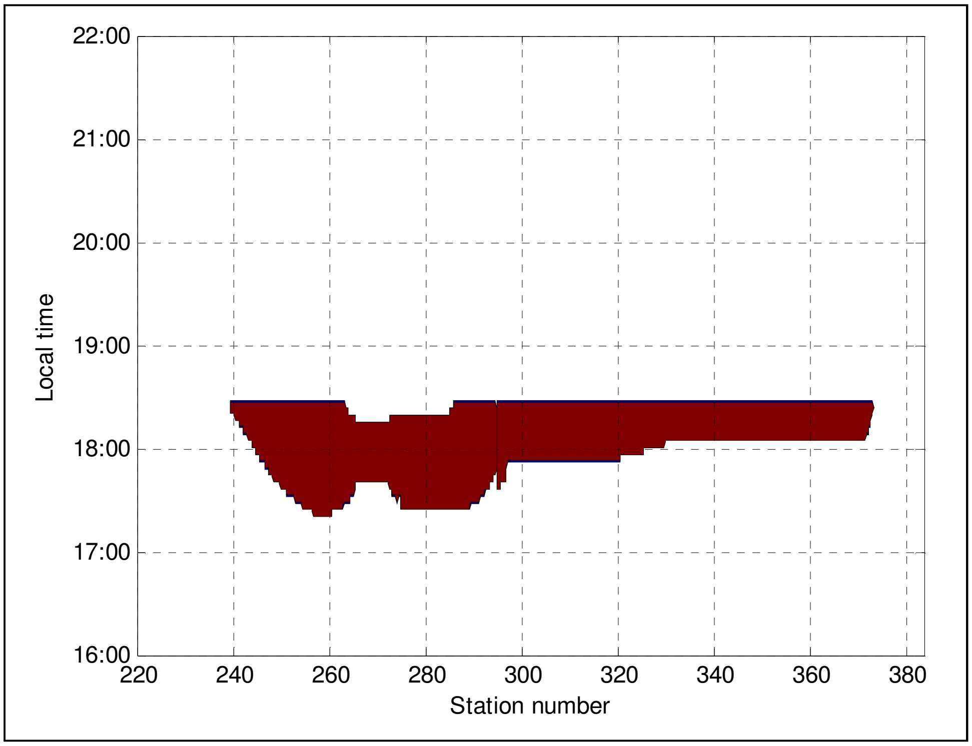

Figure 7 – Time of predicted glare occurrence on June 1, 2008

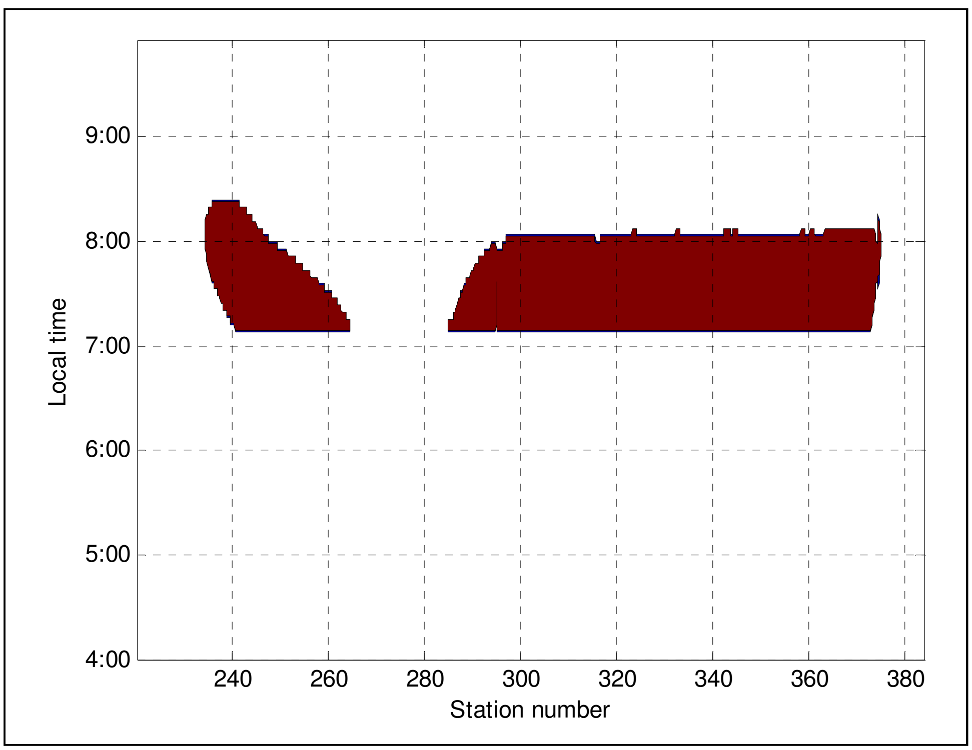

Figure 8 – Time of predicted glare occurrence on December 1, 2008

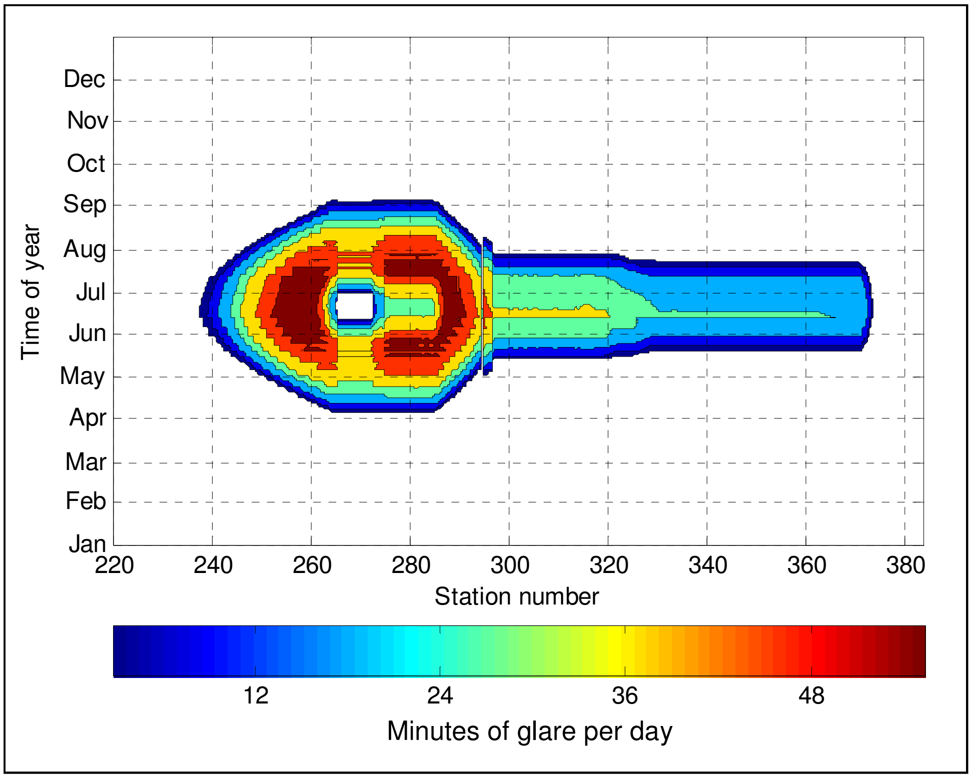

Figure 9 – Northbound daily glare occurrence

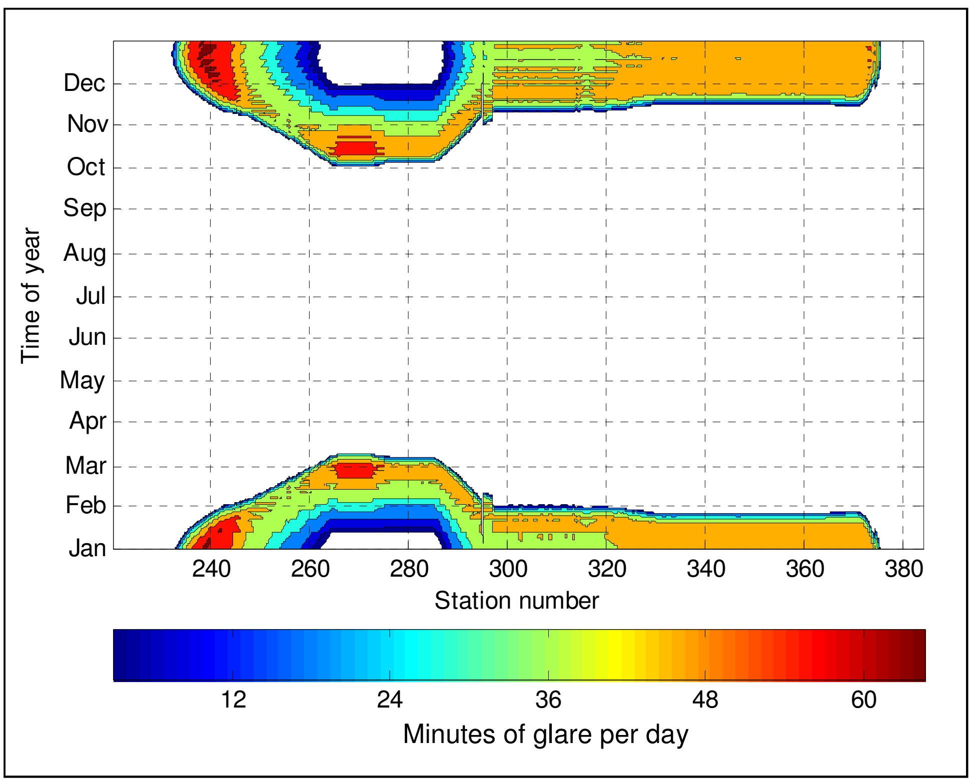

Figure 10 – Southbound daily glare occurrence

4. CONCLUSIONS

In this paper, a novel method for identifying glare conditions along a highway alignment was introduced. The method predicts, for an arbitrary position on an arbitrary three-dimensional roadway alignment, what times of year (if any) the traffic on that roadway could be faced with sun glare in drivers' eyes that could have adverse impacts on safety and traffic flow. This method would be a suitable and useful addition to the process of roadway safety audits for existing facilities. It would also be an informative dimension to consider in the design process, particularly when evaluating different candidate alignments that might otherwise be quite similar. Finally, it can be used to identify causal factors for recurring congestion on existing alignments.

Several extensions from this work could be readily examined. It will be necessary to have a more complete understanding of the incident angles at which sun glare really has an effect on driver visibility. These effects might differ in certain weather conditions, such as immediately after a rainstorm, when extra glare from the roadway surface or vehicle hoods might exacerbate the problem. The models described here do not take into account the surrounding topography, but some areas with mountains, for example, might be less susceptible than these methods would predict, because the sun is occluded when it might be most problematic. It would be informative to couple this work with empirical studies of traffic congestion to confirm the extent to which these geometric situations contribute to congestion. Finally, there may be extensions to other modes of travel, particularly rail and air. For these other modes, this model may provide a tool for planning new facilities, as well as for identifying performance degradations in operational data.

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