A METHODOLOGY TO ASSESS THE ROAD ACCIDENT RISK AS A RESULT OF DIRECT SUNLIGHT EXPOSURE: A CASE STUDY IN CAPE TOWN

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ABSTRACT

The sun is most hazardous to drivers when it is close to the horizon, particularly within an hour time frame after sunrise (dawn) and before sunset (dusk). The position of the sun and the angle of the rays during this period can render sun visors inadequate. As a result, the risk of having an accident is increased, due to the interference with a driver's ability to see the road ahead. This paper discusses a Geographic Information Systems-based methodology, which was used to determine the areas of the City of Cape Town road network that are exposed to direct sunlight (sun glare); thus creating a road safety risk. For an arbitrary position in the roadway alignment of the study area, the amount of sun glare risk for drivers was analysed for the 2014 equinox and solstice days. The results revealed that approximately 14.7% of the road network in the autumnal equinox and spring equinox is exposed to direct sunlight (sun glare risk), while 12.2% and 15.2% are exposed in the winter solstice and summer solstice, respectively. A case study carried out in one of the Cape Town streets proved that the methodology produces valid and reliable results. Therefore, results from this procedure can be an informative dimension to consider when evaluating existing roads or layout and alignment alternatives for new roads. In addition, the methodology can also be incorporated into car navigation systems to provide automated real-time sun glare risk information to drivers.

Keywords: Direct Sunlight Exposure; GIS Tool; Sun Glare Risk; Road Safety

1 INTRODUCTION

Traffic crashes can be attributed to numerous potential explanations, and it is not surprising that so many dimensions appear important, since driving is such a complex task (Plainis et al., 2006). Visibility conditions have been identified by various authors as being an important environmental factor. In most cases, visibility refers to night and rainy conditions, both influencing the severity and the rate of crashes (Clarke et al., 2006; Konstantopoulos et al., 2010). Sun glare is mentioned in the literature as a visibility factor (Pande and Abdel-Aty, 2009; Mitra and Washington, 2012; Dozzaa and Paneda González, 2013). Staubach (2009) evaluated factors correlated with traffic accidents as a basis for evaluating Advanced Driver Assistance Systems

(ADAS). Sun glare is a temporary dazzling sensation of relatively bright light from the sun which produces unpleasantness, discomfort or interferes with optimal vision (Knott, 1983). Sun glare was identified as a factor correlated with causation of crossroad accidents for the driver, in over half of all cases (52%).

According to the National Highway Traffic Safety Administration (NHTSA) of the U.S. Department of Transportation, sun glare is the official cause of a fraction of fatal crashes across the country, which is 195 in 56 793 (0.34%) (Hastings, 2012). Data compiled by the Abu Dhabi Traffic Department showed that sun glare was blamed for 22 minor crashes in the capital during the first eight months of the year 2010 (Salama, 2010). Furthermore, a number of accident cases were reported in the USA where sun glare was identified as the cause of the accident. One of these occurred in Colorado Springs, where four Coronado High School students landed in hospital in the month of September after they were hit by a van while crossing the street on the cross walk (Stone, 2007). The driver, who was going into an easterly direction into the sun, claimed to have been blinded by the sun. In a different case, a truck driver in Syracuse New York struck a female pedestrian while she was crossing the streets, causing her death (Ha, 2011).

Research by Hagita and Mori (2013) indicates that the angle of the sun is most potent to drivers during the times when the sun is closest to the horizon, which is dawn and dusk; typically between 07h30-09h30 and 17h00-18h30, respectively. In agreement, Mitra (2008) also disclosed that the traffic accident rates at dusk and dawn are higher than the rates at other times. This was concluded in an analysis of traffic accident data, sunset and sunrise time, and road travel directions in Arizona, America. In addition, in an analysis of sun glare as a contributing factor to traffic accidents, Hagita and Mori (2013) also found that traffic accidents tend to be higher when the sun was in front of the vehicle. This is an expected conclusion, because, at the right angle, the sun is highly likely to impair visual acuity when it is in front of the driver.

Several investigations have shown that high traffic volume is linked with an increase of collision rate and a decrease of fatality number (Auffray, 2007; Abdel-Aty and Radwan, 2000). As such, it is highly likely that roads with low traffic volumes have considerably less sun glare risk, compared to roads that carry peak traffic at volumes that produce higher speeds. Although this is debatable considering that the vehicle speeds in a congested road are lower compared to those of a free flowing road. In slower moving traffic, drivers experiencing sudden blinding, as a result of sun glare, have a relatively longer reaction time and a lower crash/impact severity as a result of the low speeds, compared to free-flowing traffic; meaning the risk is greater in the latter. Glare resulting from direct sunlight exposure can be painful to the eye of the observer and potentially very distracting to the driver in terms of visibility (Auffray, 2007). Consequently, this distraction to the driver has well under-stood adverse effects, not only on the safety of the driver but on adjacent drivers as well.

Literature does provide proof that sun glare is a hazard that increases road safety risk, and that the danger of the sun is even more potent/hazardous at dusk and dawn. The key objective of this study was to identify and develop a method that can quantify, geographically, where and when sun glare occurs on a road network. Essentially, the method determines which areas in a geographic setting’s road network, i.e. the City of Cape Town, are exposed to direct sunlight, thus making them vulnerable to road accident risk as a result of impaired vision. It should be noted that the terms ‘sun glare’ and ‘direct sunlight exposure’ will be used interchangeably in this paper. Essentially, the presence of direct sunlight exposure implies that there is sun glare risk. Based on the assumptions and limitations, the outcome of this methodology gives an overview of the vulnerability of road network segments, in the City of Cape Town, to accidents as a result of sun glare.

2 METHODOLOGY

The occurrence of sun glare conditions is influenced by a number of factors. Three factors were identified in this study as key influences to sun glare occurrence. These are road network (geometric design), physical environment (topography and terrain profile), and sun position (azimuth and altitude). The wrong combination of these factors could result in hazardous conditions due to increased sun glare risk, which is actually, to a larger extent, a road safety risk.

2.1 Research Tool

Taking into account the need for a tool with the ability to combine spatial data and sun position data, ArcGIS (Geographical Information Systems (GIS) technology) was considered the most suitable tool for this study. Simple modules for computing sunlight exposure, which require only the surface data and the sun position angles, are available in GIS programs. Such modules include the hillshade tool in ArcGIS, which was utilised here. The tool identified road segments exposed to direct sunlight in the Cape Town road network.

Hillshade is an ArcGIS tool that was employed to model the effects of sunlight exposure. Hillshade is a shaded relief technique where a lighting effect is added to a map based on elevation variations within the landscape (http://landtrustgis.org/). The hillshade function intends to mimic the sun’s effects – illumination, shading and shadows – on hills and canyons, thus, obtaining hypothetical illumination of a surface by determining illumination values for each cell in a raster (Hegazy and Effat, 2011). In this context, illumination refers to hypothetical sunlight exposure produced by the hillshade model. This function uses the latitude and azimuth properties to specify the sun’s position, which are the function’s inputs including a Digital Elevation Model (DEM) and a z-factor. A DEM is the presentation of continuous elevation values over topographic surface by a regular array of z-values, referenced to a common datum, DEMs are typically used to represent terrain relief (http://support.esri.com/). A hillshade model is a derivative of a DEM that stimulates relative sun illumination for each grid cell based on its slope, aspect and the position of the sun (as defined by elevation and azimuth angle) (Bricher et al., 2008). The azimuth is the sun’s relative positions along the horizon, and is expressed in positive degrees ranging from 0 to 360, measured clockwise from north. The altitude is the sun’s angle of elevation above the horizon, and is expressed in positive degrees ranging from 0 to 90˚ - with 0° at the horizon and 90° directly overhead (http://www.esri.com/).

2.2 Case Study

The chosen study area for this research was the City of Cape Town (CoCT), in South Africa, which occupies the south-western most point of Africa. Cape Town is a legislative capital of South Africa and capital of the Western Cape Province, and is located at 33°55'31"S latitude and 18°25'26"E longitude in the Southern Hemisphere. The city is the second largest city in South Africa based on population, and is the largest in land area at 2 455km^2 (http://www.britannica.com/). The City Centre lies embedded between Table Mountain, Devils Peak, Lions Head and Signal Hill on the one side and borders on the Table Bay and the Atlantic Ocean on the other side.

2.3 The Data

The data used in this study was categorised into spatial data (DEM, road network and topography), sun position data (azimuth and altitude) and sun cone data. The study area DEM, obtained from the University of Cape Town GIS laboratory, was derived from 10m-interval (spatial resolution) contour lines. The slope and aspect of the DEM played a key role in the creation of hillshade layers. The road network layer was derived from the topographical map.

A study by Jurado-Pina and Pardillo-Mayora (2009), analysing driver impairment situations as a result of sun glare, identified two values of the angle of glare to characterise problem situations - 19° and 25° (altitude). After some tests, this study adopted the same values to use for the altitude values of the sun cone.

The analysis instruments provided by the ArcGIS Spatial Analyst hillshade tool allow a map drawing and an analysis of the sun's effects on a geographical area during a certain specific time frame. Two astronomical events (solstice and equinox) each of which occur twice a year, and have the added benefit of seasonal variation, were selected for use in this research. The Autumnal Equinox (AE) and Spring Equinox (SE) occurred on the 20th of March and 22nd of September (2014) in the Southern Hemisphere, respectively. While the Winter Solstice (WS) and Summer Solstice (SS) occurred on the 22nd of June and 22nd of December.

Subsequently, Sun position data (azimuth and altitude) for these four days, for both the morning (AM) and afternoon (PM) snapshots, was obtained from the Astronomical Applications Department of the U.S. Naval Observatory server (aa.usno.navy.mil/). A decision was made to select time snapshots – for the four days – whose altitude values are defined by the vertical sun cone (19° and 25°). This means each scenario/time snapshot modelled in this study either had a 19° or 25° altitude value.

Overall, a total of 16 scenarios/time snapshots were formulated for this model. First and foremost, there are the four days which are split into 2 equinox days and 2 solstice days. For each of these four days, there is the morning (AM) and afternoon (PM) scenario. Each of the AM and PM scenarios are further split into two time snapshots each of which is for the 19° and 25° altitudes. Table I gives an example of the sun position data for equinox days, which has a total of 8 scenarios (time snapshots).

3 FINDINGS

The Cape Town road network was divided into small straight line road segments with constant geometry (polylines). The reason for doing was to get line elements that are manageable, with constant direction; thus, allowing for the establishment of the bearing for each segment. Several statistical tests were applied while analysing the results from the model. The data analysis and findings presented entail a discussion of the percentage of road segments exposed to direct sunlight (sun glare risk) during each day, as well as a discussion of the statistical analysis outcome.

In comparing the percentage values of road segments exposed to direct sunlight in the morning and afternoon period, the apparent trend is a decrease from the morning to the afternoon period in the AE and SE scenarios, and an increase for the same change in the WS and SS scenarios (see Table 1).

Table 1: Equinox and Solstice Sun Position

Date (2014)	Day	Time Period	Time	Altitude (°)	Azimuth (°)
20 March	AE	AM	08h30 08h55	19.9 24.8	76.2 72.1
		PM	16h55 17h20	24.4 19.4	287.7 283.6
23 September	SE	AM	08h15 08h40	19.8 24.8	76.1 72.0
		PM	16h40 17h05	24.4 19.5	287.5 283.4
21 June	WS	AM	09h55 10h35	19.4 24.5	41.9 33.7
		PM	15h00 15h40	24.7 19.7	326.8 318.5
22 December	SS	AM	07h20 07h45	19.8 24.8	105.5 102.6
		PM	17h45 18h10	24.8 19.8	257.5 254.5

For example, at 25° altitude, the percentage of road segments in the autumnal equinox changes from 21% in the morning to 15% in the afternoon. At the same altitude the percentage of roads at risk in the summer solstice increases from 16% in the morning period to 21% in the afternoon period. Presumably this implies that the sunlight exposure in the afternoon period of the winter and summer solstice has a relatively greater effect than the morning period, which means the opposite applies to the autumnal and spring equinox. The SE boasts the same percentage values as the AE, for both AM and PM. With 13% and 15% for the AM and PM period, it is not surprising to learn that the winter solstice has the least amount of road segments exposed to direct sunlight.

A statistical analysis comparing the morning and afternoon period was carried out using the Wilcoxon Signed Rank test as it is a non-parametric equivalent of the parametric t-test, which cannot be used if the data is not normally distributed, as is the case. The analysis produced a p-value of 0.0117 for the autumnal and spring equinox, implying there is a significant difference in the median amount of the average sunlight exposure between AM and PM. On the contrary, the WS data produced a p-value of 0.5779 which is greater than the 5% statistical significance level, implying there is no evidence for a statistically significant difference in the median amount of average sunlight between AM and PM. The significance level is a boundary at which to assume there is evidence to reject the null hypothesis, i.e. if $p \leq 5\%$. On the other hand, if $p > 5\%$, it implies there is insufficient evidence of a difference in the results and the null hypothesis is accepted, which is the case with the WS. The p-value for the SS is 0.0221. Similar to the AE and SE, it also implies a significant difference in the median amount of average sunlight between AM and PM. However, the AE and SE have relatively stronger evidence considering that the evidence against the null hypothesis in favour of the alternative increases with a decreasing p-value. An overall comparison of all the four days and times, using a linear mixed-effects model, revealed a number of findings. The streets were modelled as random effects as there are multiple measurements per street. The morning and afternoon for each individual day was also compared. The output revealed that, on average there is less sunlight in the afternoon compared to the morning, as the effect of PM is negative and statistically significant (see Table 2).

Table 2: Linear Mixed Effect Model Results

Percentage	Effect Size	Std. Error.	p-value
SE	-0.16	1.86	0.933
SS	-11.15	2.05	<0.001
WS	-10.10	2.22	<0.001
PM	-11.32	2.05	<0.001
SE:PM	0.16	2.72	0.954
SS:PM	22.32	3.06	<0.001
WS:PM	11.75	3.16	<0.001
Constant	53.90	3.04	<0.001
Between Street		0.32	
Within-street/error		0.17	

4 MODEL VALIDATION

On the 15th of August, 2014, a video footage of four Freeway and Primary arterial roads in the Cape Metropolitan CBD were taped for the morning and afternoon periods during the time periods when sun was considered to be at its worst – which in this case was defined by the 19º/25º sun cone. The investigation was carried out using a Road Eye JS-300 camera, which is an intelligent electronic device designed to record driving parameters using an advanced Wide Dynamic Range Function. The camera used is a 120 degree 0.3 MP Complementary Metal-Oxide Semiconductor and has a H.264 Video Graphics Array (VGA) resolution of 640 pixels wide by 480 pixels tall up to 30fbs. Footage was recorded while travelling at a speed approximately between 40 and 60km/h. The terrain around these four roads is relatively flat.

In the morning the 19º/25º sun cone occurred between 09h15 and 09h45, while in the afternoon it occurred between 15h55 and 16h30. Considering that these times were well within an hour or so after sunrise (07h24) and before sunset (18h16), a decision was made to record sun glare footage between these periods. The clear weather condition on this day also made for a suitable recording environment. Figure 1 provides an example of the footage collected. While the image on the left clearly indicates a sun glare challenge, the image on the right indicates that high buildings can influence sun glare exposure in practice.

The calculations from the ArcGIS-Hillshade tool, applied for the same day, time and area, provided the same results as the field investigation, as can be seen in the video-snapshot of Buitenkant Street in Figure 1 and the map in Figure 2. According to the map in Figure 2, the street segments affected by direct sunlight exposure at this time of day are northeast-orientated, as indicated by the light-blue coloured lines (streets). For instance, northeast-bound traffic in the Buitenkant segment between Roeland Street and Darling Street is exposed to direct sunlight.

Figure 1: Buitenkant Street Snapshop (NE bound)

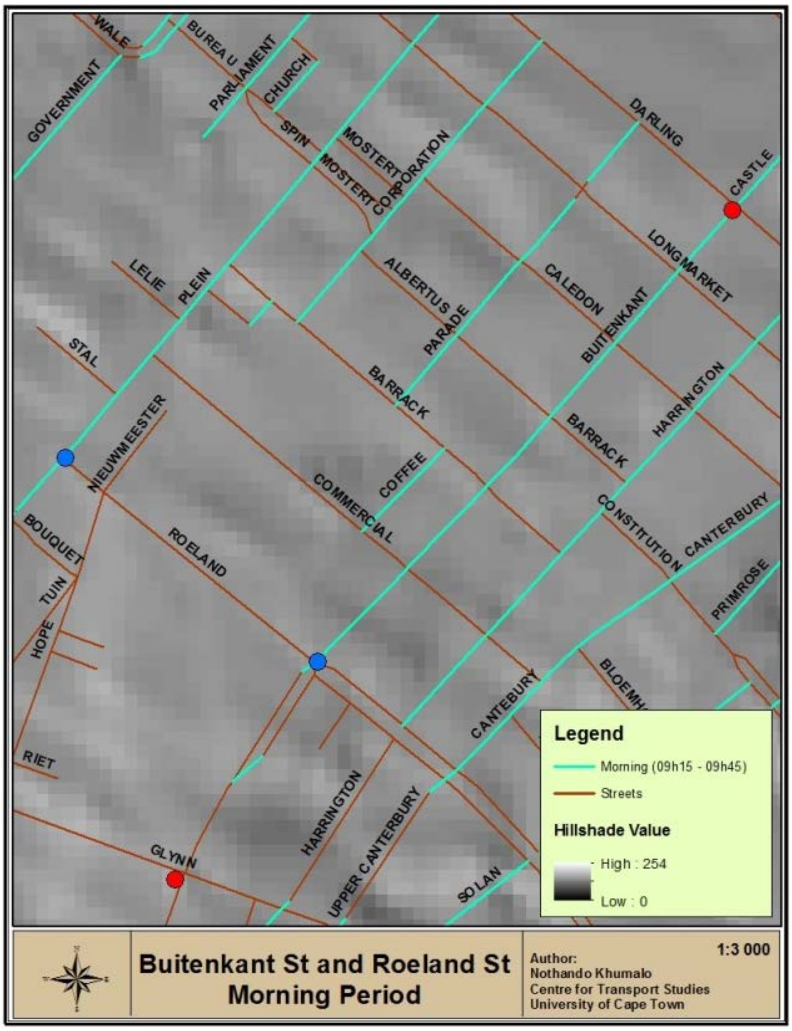

Figure 2: Morning Period Segment Distribution Map for Buitenkant Street

5 CONCLUSIONS

Sun glare can be a nuisance and increase the road safety risk. The position of the sun and the angle of the rays may render sun visors useless. Accordingly, terrain analysis using DEM-based hill shading has led to the discovery of a method to identify roads vulnerable to sun glare conditions. The identification of road segments at risk is useful information with regards to the implementation of mitigation measures, such as visual barriers or warning signs, to prevent accidents.

The implementation of this method to the Cape Metropolitan road network showed that the AE and SE both have approximately 14.7% of road network exposed to direct sunlight (sun glare risk). The WS and SS, on the other hand, have approximately 12.2% and 15.2% of the road network at sun glare risk, respectively. With the exception of the WS, statistical analysis of the results revealed that there is a significant difference in the amount of sunlight exposure between the morning and afternoon time periods. According to these results, on average, there is less sunlight in the afternoon, compared to the morning. Looking at the individual days, the AE and SE are in accord with this outcome – they have less sunlight in the afternoon.

However, the WS and SE actually have more sunlight exposure in the afternoon than the morning. Overall, the AE and SE have the most sunlight exposure, while the WS has the least.

The main assumption of the study was whether increased exposure to sun glare entails an increased risk of accidents. Various authors have proven the relationship. Another assumption in the study was the identification of a sun cone ranging between 19º and 25º altitude, which, according to Jurado-Piña and Pardillo-Mayora (2009), characterises vision impairment. The validation has proven that this assumption was valid. Furthermore, a horizontal sun cone threshold (±15º) was adopted for azimuth and slope filtering.

The model does not allow for atmospheric effects (cloud, rainfall etc.) and the presence of buildings or trees affecting the direct sunlight. It is, however, important to note that in the case of real implementation systems, these limitations would have to be factored in. All the assumptions and omissions influence the results and provide opportunities to extend the study. On a different note, with respect to future research, a 24-hour calculation of sunlight exposure can be carried out, whereby the duration of direct sunlight exposure per “spot” can be used to evaluate the sun glare risk. Additionally, further investigation of the sun cones could be carried out to determine ones that are more appropriate and suitable for SA conditions.

Outcomes from the proposed methodology can be applied to both existing and new road designs. With respect to the design process for new roads, it would be an informative dimension to consider, particularly when evaluating different layout and alignment alternatives. Aside from the use of mitigation measures, such as visual barriers (e.g. row of trees), Intelligent Transport Systems (ITS) could be employed. Considering that the model produces results for a specific time, automated real time warning systems could be implemented for the identification of high risk conditions and road segments in terms of direct sunlight exposure. In a similar study, Chalkias et al. (2013) proposed incorporating a methodology like this in car navigation systems, in order to provide additional real-time information to drivers. The incorporation of GIS technology with Global Positioning Systems could enable the development of optimal automated real time warning systems. All in all, ITS research could potentially provide endless opportunities for the mitigation of sun glare conditions in line with this methodology.

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