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Driving Impairment Detection Due to Sun Exposure and Contrasting Shadow of Surface Objects: An Urban Case Study

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22

23 **Abstract**

24 A change in drivers' vision quality might result in the deterioration of their perception and
25 their effectiveness. The lack of an integrated algorithm to distinguish the location of
26 drivers' vision impairment motivates this study. The proposed model benefits from a
27 combination of several sub-algorithms, such as sun positioning, glare detection, and
28 contrasting shadow illustrator derived from raw geospatial data. The methodology is
29 implemented through a case study involving a large-size metropolitan area road network, a
30 Digital Elevation Model, the associated hillshade geographic data, and weather data from
31 Montreal, Canada. The methodology and corresponding data analysis are implemented in
32 Python. The result revealed a geospatial model to estimate the boundaries of transition
33 points between the glare and contrasting shadows created by changes in roadway
34 surroundings. The results provided by the model can be used as a tool to aid decision-
35 makers in the new road construction and urban planning by creating safety countermeasure
36 strategies and design review of road geometry.

37 **Keywords:** sun glare, contrasting shadow, geospatial data processing, road environment
38 mapping

39 Introduction

40 Road environment and driving perception are hidden tips on queue forming and safety
41 degradation. The shining of the direct sunlight in the drivers' eyes effects on driving perception.
42 It has a tremendous impact in reducing driver's vision performance and in creating a low safety
43 situation. Considerable work has been undertaken by researchers to demonstrate the
44 consequences of losing concentration while drivers lost their ability to see surrounding objects
45 (Faure, Lobjois and Benguigui 2016; Whitlock, Pethick and Mills 2017; Chen *et al.* 2019; Liang
46 *et al.* 2019). Review of scientific literature on the impact of vision deficiency on traffic operation
47 and safety indicated that crash odds increase nearly 18.5 % due to the occurrence of vision
48 impairment (Andrey, Mills and Vandermole 2001). Regardless the impact of intensive lights
49 from artificial sources, sunlight has been recognized as the primary cause of the reduction in
50 vision performance during daytime. When sun is positioned at low angle in front of drivers, the
51 sun glare phenomenon occurs and might cause deterioration of driving performance (Auffray
52 2007).

53 The apparent trajectory of the Sun through the sky changes throughout a year, so the sun glare
54 can occur at different times and different locations during the year. Prior studies investigated sun
55 glare from different aspects such as time and location of occurrence, impact on vision disability,
56 traffic operation and road safety (Andrey, Mills and Vandermolen 2001; Yingkui and Ke 2012).
57 However, high contrast points on roadways, defined as sensitivity of eyes on adapting abrupt
58 change in received light along the sightline, have not been adequately studied. Terrain and
59 topography of environment account for a change in the spatial and temporal of sun glare for any
60 point on the roadway. The importance of considering the condition of building shadows on

roadway has not been considered in prior studies. A study of the entrance and exit of tunnels has recently illustrated that the sudden entry into the shadow and vice versa causes physiological and psychological impacts on drivers' performance (Yingkui and Ke 2012). The physiological and psychological impact of transition between sun glare and shadow causes dazzling and blindness effect on drivers, respectively. Thus, vision impairments have an important impact on the health of drivers' eyes and safety of road users.

Evaluation of time and location of sun glare and contrasting shadow occurrence can be helpful to recognize critical road segments and establish an appropriate safety measure. Obtaining an analytical tool for this purpose not only provide an assessment tools for new roadways, but also significantly improve both efficiency and the correctness of accident analysis. In this study, the spatial analysis of geographical road data is combined with astronomical algorithms to predict the sun glare occurrence based on drivers' location on the roadway. The study also describes the impact of buildings height on road safety due to sun glare exposure.

Background

Poor visibility and challenging weather conditions cause numerous collisions each year (Pisano, Goodwin and Rossetti 2008). A Canadian study on weather hazards (Andreescu and Frost 1998) indicated that 16% of fatal and 18.5% of personal injury collisions occurred during adverse weather conditions, i.e., rain, snow, hail, and fog (Andrey, Mills and Vandermolen 2001). There is a limited number of studies that investigated collisions under clear sky. For example, one study found that vision is the most influential input channel for maneuvering a vehicle even in clear sky (Tonnis, Broy and Klinker 2006). The main issue of the study illustrated that shining of intensive light into the drivers' eyes is a probable cause of crashes. Glint (a short flash of light)

and glare (a continuous source of extreme brightness corresponding to the ambient lighting) are recognized as two causes of vision impairment for any driver on a given road (Ho, Ghanbari and Diver 2011).

Glare is principally associated with intense spotlights at night or shining of the Sun in the low elevation on the opposite of driving course. Sun glare is the most influential environmental parameter on occurring road accidents during days. Among the studies on sun glare, a few of them indicated on four prominent types of vision deficiency on drivers' eyes: disability glare, sun blindness, veiling glare, and dazzle (Faal *et al.* 1989; Gallace, Tan and Spence 2006; Erdoğan *et al.* 2011; Ho, Ghanbari and Diver 2011; Verma *et al.* 2016; Liang *et al.* 2019; Santos *et al.* 2019).

The Sun blindness phenomenon arises when the Sun presents in the low altitude such as after sunrise or before the sunset. According to a study by the Institute for Road Safety Research (SWOV), the direct shining of sun at acute angles has the most physical harm for drivers' eyes (Schreuder 1968). Veiling glare occurs in bright sunny days when the sun ray reflection on the top of the dashboard and windshield appears in the field of vision and obscures the view (Schreuder 1968; Auffray 2007). Dazzling is the most painful and harmful impact of sunlight that occurs when an intense sun ray shines directly into the centre of eyes while eyes try to recognize an object in the same alignment of the sun ray (Santos *et al.* 2019). Dazzle sunlight also has a destructive impact on central vision and causes a permanent blind spot in the driver's eyes (Reidenbach 2009).

The dazzling affects discrepancies in receiving visual data and may hinders ahead traffic states such as the lateral movement of the surrounding vehicle or road users (e.g., lane changing,

turning movement) and longitudinal change of ahead vehicle (e.g., braking light, red light violation). Drivers need to be concerned with all surrounding objects for a safer driving. Consequences of vision deficiencies, particularly dazzle, would be extreme and inescapable in transition locations where a driver moves between a road segment in a shadow, and the next segment is under the sun glare condition.

On the other hand, the reverse situation of dazzle effect has been identified as blindness in such as tunnel entrance (Zhigang *et al.* 2014; Yan *et al.* 2017). In comparison with dazzle conditions, driving the vehicle in longitudinal alignment of the road in blindness situation has no harm for drivers' eyes but cause an obvious threat for other road users located under the contrasting shadow area ahead of the vehicle. Further research has been centred on what type and degrees of vision impairment reduce the road safety and driving performance. While some previous researches revealed the impact of sun glare on traffic operation of freeways (Auffray 2007), one of the recent studies investigated the effect of sun glare on overall intersection crashes (Mitra and Washington 2012). These studies only focused on evaluation of driving behaviours and road safety under the sun glare condition at a specific segment of the roadway. Another study proposed a novel method to estimate the location of sun glare on the roadway segment (Churchill, Tripodis and Lovell 2012). Authors chose a recognized point under the sun glare phenomenon in a specified time interval within a year where the sun glare threat the visibility of drivers. In the most recent study, drivers' vulnerability for driving under the sun glare was evaluated, including the impact of cloudiness on results (Redweik *et al.* 2019). The study concluded the adverse effect of sun glare; however, the impact of surface object shadows was not considered.

A recent study considered the impact of surface objects to detect the most accurate sun glare on roadways by using API with google street view (Li *et al.* 2019). The study relied on the availability of the street-level images and require heavy image processing computation to have the precise occurrence of sun glare. In addition to the lack of considering the impact of cloudiness, the study did not contribute to the influence of blindness and dazzling impacts on visibility. The accumulative number of vision impairment occurrences on any road segments for an entire year has not been studied yet. In this regard, a geographical tool can identify the influence of sun glare faster, including the impact of the surface objects, without relying on the availability of street-images or high-quality data.

This study proposes an integrated macro model of sun glare detection using recent astronomical algorithms of sun position. The novelty of identifying transition locations from shadow to sun glare and vice versa, provides a suitable substrate for additional studies to improve road safety at predetermined locations. The proposed analytical method to recognize critical locations on roadways within a specific timeframe is described next.

Methodology

This section presents a step-by-step method for systematically identifying vision impairment locations on roadways caused by sun glare under different built environment. The proposed methodology can be applied to any study area with suitable geographical information data. The development of a suitable glare-detection algorithm at a network level relies on a complex analytical procedure built on a geographical information system. The algorithm's input data consists of a complete 3-D road network geometric alignment (including elevations) as well as hillshade data and solar radiation information for the study area. Figure 1 represents the core of

the proposed methodology in four stages. First, robust sun position algorithms are used on each analysis period for a given road segment. Second, geometry model analyses the visibility reduction of drivers based on the visible sun trajectory and situation of the vehicle on the road segment. Third, the projection of buildings' elevation on the road segment identifies shadows as a different cause of vision impairment. Finally, the impact of cloudiness considers providing the most accurate results for vision impairment analysis.

Sun positioning algorithm

The occurrence of sun glare is directly related to the position of the Sun with respect to the observer's sightline. The apparent path of the Sun changes over the course of a year. The algorithm used NOAA Global Monitoring Division of the National Oceanic and Atmospheric Administration in this study to detect the position of the Sun with respect to a given location on the earth surface (Cornwall, C., Horiuchi, A., Lehman 2011). This algorithm requires the GIS coordinates and the timestamp of the location to be analyzed.

Additionally, the solar path is bent due to refraction effect from the earth's atmosphere. The refraction effect displays unrealistic sun elevation when it is close to the horizontal surface of the Earth (sunrise and sunset). The refraction analysis outlined in this study needs to be considered to identify the apparent position of the Sun, particularly the critical time of sunrise, when drivers might be affected by potentially devastating eye damage from the sunshine parallel to the sight line. Saemundsson proposed a refraction correction model when the actual angle elevation is known (Saemundsson 1986). In addition, the change in pressure and temperature has been accounted for by Meeus (Meeus 1988) with an algorithm that provided an updated formula in NOAA algorithm [1].

$$\theta_{s,r} = \theta_s + (P/1010) \times [283/(273 + T)] \times \left[1.02 / \tan \left(\theta_s + (10.3/\theta_s + 5.11) \right) \right] \quad [1]$$

171 Where θ_s is the actual elevation of the Sun, $\theta_{s,r}$ is the corrected (i.e., apparent) elevation of the
 172 Sun, P is the atmospheric pressure and T is temperature.

173 In addition to analyzing the position of the Sun at a specific time, the location of the observer
 174 point is required in order to identify the effects of the position of the Sun. The proposed model
 175 assumes a homogeneous vertical/horizontal alignment of each road segment of a study area.
 176 Thus, the road segments are divided into the longitudinal five-meter long subsegments, the
 177 average length of a typical passenger vehicles. The movement of vehicles on the road is similar
 178 to changing their positions between five-meter-long cells or subsegments. The driver position in
 179 a passenger car is assumed to be located nearly in the middle of each subsegment, regardless of
 180 the vehicle type. In addition, AASHTO safety design guidelines assumes an average car driver's
 181 eye equal to 1.08 m for passenger cars (AASHTO 2011). The position of the Sun is calculated
 182 through the modified algorithm of sun position for any points on the road within the analyzed
 183 period. The results of sun position are represented as azimuth and elevation angles and are the
 184 preliminary input into the sun glare detection algorithm (Figure 2).

185 ***Sun glare detection algorithm***

186 In order to detect the sun glare phenomenon, it is very important to accurately evaluate the
 187 alignment of driver sightline. The occurrence of sun glare is identified in the horizontal and
 188 vertical plane of the driver's vision towards the sun position. The glare angle is obtained from
 189 the angular distance function between the line of sight and the sun position. Several studies were

conducted to quantify the angular distance at which glare causes distraction on vehicle control. One of these studies provided a review of the disability due to the sun-glare phenomenon (Vos 2003).

A study analyzed the visibility of different driver's age based on the external and road surface illuminances and determined that the vertical angle of 25 degrees or less has the most vision impairment on older driving population (Zwahlen 1989, Jurado-Piña and Mayora 2009). Also, according to another study, the vision impairment of drivers are limited horizontally within the 30 degrees of drivers' vision apex which are represented as acute vision angle (Gong *et al.* 1990). Regardless of the threshold values used, the assessment of the position of the sun relative to the observer's location on roadways requires an accurate position identification in a three-dimensional coordinate system.

The sun azimuth is an angular measurement in a spherical coordinate system (Figure 2). The most common conventional method of measuring azimuth for analyzing solar position is clockwise from due north, according to National Renewable Energy Laboratory (2013). The azimuth of sun position can be converted to a Cartesian system using [2-4]. First, the azimuth angle is converted into the polar coordinate system, where φ represents an angle from the east, and r is the distance between observer point and sun, and to have a unit vector ($r = 1$), u represents the direction vector [4] in the cartesian system (i.e., x, y, z).

$$x = r * \cos(\varphi) \quad [2]$$

$$y = r * \sin(\varphi) \quad [3]$$

$$u = [\cos(\varphi), \sin(\varphi)] \quad [4]$$

208 The sun position and sun glare detection algorithms are coded using Python to eliminate the use
 209 of Geographical Information System (GIS) software and analyze the combination of algorithms.
 210 The evaluation of sun glare occurrence needs to be considered for every subsegment of the road
 211 network. GIS software is very limited in analysis and working in real-time conditions along with
 212 other applications. The compiled GIS data into the Python script is used to simulate movement of
 213 vehicles on roadways and analyze the position of the Sun from any observer points. In our
 214 experiment, road segments are divided into 5-meter discrete subsegments (average vehicle
 215 length) and are examined based on corresponding road IDs. It is the most straightforward method
 216 by which the tangent vector can be estimated to calculate the slope of each subsegment as
 217 defined in [5].

$$\delta = \tan^{-1} \left(\frac{z_e - z_s}{\sqrt{(x_e - x_s)^2 + (y_e - y_s)^2}} \right) \quad [5]$$

218 where,

219 δ - represents the slope of a segment, it is calculated based on the tangential difference
 220 between x_s, y_s, z_s coordinates of start point of a segment and x_e, y_e, z_e at the end of
 221 segment.

222 Amount of $\varphi_{driving}$ has to be defined as a positive angle from the east on the horizon tangent
 223 surface; therefore, since $atan2$ in [6] returns values between $-\pi$ to π , the angle is modified by
 224 adding 2π when negative values are returned.

$$\varphi_{driving} = atan2(y_s, y_e) \quad [6]$$

In this study, the range of drivers' sightline that might be affected by sun glare is represented by a cone with the apex on driver's eyes. In principle, the direction of driving is defined according to the direction of driver's vision (i.e., the windshield and front side windows). Consequently, the formulation in [7] represents a limitation in detecting the sightline under the vision impairment condition.

$$abs|\delta - \theta| < 25, \text{ AND }, abs|\varphi_{driving} - \varphi_{sun}| < 30 \quad [7]$$

where,

θ – represents the elevation of the Sun,

φ_{sun} – is the conversion of sun azimuth to measure from the east direction (Figure 2).

The slope of a road segment, δ , is identified from the elevation values at the ends of the road segment, while the driving direction, $\varphi_{driving}$, is evaluated based on the x, y coordinates at the two ends of the road segment.

Optimization

Various surface structures (e.g., buildings, overpasses, etc.) may temporarily block solar radiation and create contrasting shadows on specific roadway segments. The coverage of this type of shadows has a variety of length and shape on the road surface based on the building dimensions, road geometry, time of day, and the season. Therefore, a road user is exposed to sun

glare at different locations along the road depending on the date and time of day, the coordinates of user's location, the azimuth and elevation angles of the Sun. The height of the shadow generating structure and terrain data analysis are required to consider impact of shadows on roadway. However, highly detailed resolution of this kind of analysis is a computationally intensive task. To demonstrate the feasibility of the proposed methodology with a computationally efficient approach, a fishnet of highest elevation points is generated with 5 by 5 meters 2D dimension to represent the maximum elevation of terrain and buildings roofs within each grid cell. Each cell is represented by its centre point and corresponding coordinates of x , y , and the maximum elevation of cell. Figure 3a provides an example of how the defined grid can be utilized to evaluate the position of the observer with respect to the Sun.

Identifying a restricted influential area of grid cells provides an efficient algorithm for the occlusion test. Figure 3a illustrates that the rectangular investigation area (i.e., occlusion area) is extended from the location of drivers on the roadway, O , to the farthest length of locating maximum elevation point, E , to obstacle the sun ray. The coordinates of observer vector ($\overrightarrow{OE}$) are calculated as the center line of the rectangular area. Coordinates of occlusion area corners use to diagnose and recover the centre of cells under the influence area by fitness functions [8-10]. The horizontal angle of the Sun, φ_{sun} , is modified to represents an angle from east-west axes.

$$x_i = x_{observer} \pm abs |5 * \sin \varphi_{sun - modified}| \quad [8]$$

$$y_i = y_{observer} \pm abs |5 * \cos \varphi_{sun - modified}| \quad [9]$$

$$x_i = x_{occluded} \pm abs |5 * \sin \varphi_{sun - modified}| \quad [10]$$

$$y_i = y_{\text{occluded}} \pm \text{abs} |5 * \cos \varphi_{\text{sun} - \text{modified}}| \quad [11]$$

For the purpose of the occlusion test, a ray detection algorithm figures out which centre points inside the tangent rectangle locate inside the occlusion area. The optimization algorithm provides a direct link between each centre point and the observer point to evaluate the number of intersections with sides of the inner rectangle. If a centre point has no intersection with the sides of the rectangle, it will be considered as a point inside the occlusion area.

The centre points identified inside the occlusion area are examined for the occlusion test (i.e., shaded cells in Figure 3a). The distance between the observer point and each centre point is calculated to identify the corresponding sun elevation and investigate the situation of receiving sunray at this angle on the observer point (Figure 3b & 3c).

Weather conditions

In addition to the occlusion of sunlight caused by buildings and terrain shape, clouds are another cause of the shadow. Cloud coverage has a bright shadow; thus, cloudiness alone is not likely to create vision deficiency and it does not affect road safety. However, clouds may avoid the occurrence of sun glare within a specific time. The occurrence of sun glare is sensitive to atmospheric conditions and specific locations. Historical atmospheric data from weather stations does not provide reliable or accurate cloud coverage information for specific locations on the roadway. Also, the heterogeneous displacement of clouds adds to the complexity of evaluating the percentage of glare occurring on partially cloudy days. Therefore, except the overcast weather (i.e., cloudy, snowy, foggy, rainy atmospheric conditions) all other conditions will be categorized as clear sky, and this is the data used for testing the sun glare detection algorithm.

278 **Analysis and Results**

279 The occurrence of dazzling or blindness at critical locations negatively affects road safety of
280 vulnerable road users, particularly on the most hazardous locations close to junctions and mid-
281 blocks with pedestrian crossings. Conducting an empirical study examines the theory based on
282 the real-world data and validates the modelling approach. Montreal is the second largest city in
283 Canada and was used to evaluate drivers' vision impairment due to the variety of high-rise
284 buildings in the downtown area (Figure 4).

285 *Montreal Case Study*

286 The proposed methodology requires the GIS of roadways in triple coordinates, grid cells of
287 building elevation, historical weather data, and analysis period to reveal locations under vision
288 impairments. The roadway GIS for downtown Montreal (Montreal 2014) is discretized into
289 smaller road segments (i.e., average 100 meters), but it misses the elevation information, and this
290 is a primary parameter used in the methodology. The analysis period of 6:30 am to 8:30 am was
291 selected in this study to identify locations of vision impairment. In addition to the geometric
292 alignment data described above, pressure and temperature weather data at YUL airport
293 (Gouvernement of Canada 2019) was used in the preliminary stage of the methodology to identify
294 the refraction factor of the apparent sun elevation and the cloudiness for the posterior analysis of
295 critical points.

296 The algorithms and data processing methodology described in the previous section were
297 implemented via a Python programming script. The prepared sources of data were utilized as
298 inputs into the algorithm in the requested form. In the input stage, the developed scripts used
299 tabular data format of the roadways network, the building's elevations grid cells, the historical

weather data, and integrated the analysis peak period to prepare them for the evaluation algorithms.

In the evaluation stage, the coordinates of the driver were considered at the centre of each subsegment to evaluate the critical angular position of the Sun according to the NOAA algorithm (Laboratories of Global Monitoring Division) and the corresponding refraction factor. Also, the occlusion role of the building's elevation was evaluated through the grid cell data. The solar vector was constructed from each subsegment to the Sun position, every 5 minutes, for the entire analysis period, and the optimization method chose the most influential elevation cells along this vector. In this regard, corners of the occlusion area were identified with a buffer of 5-meter from the solar vector, and the ray crossing method chose the best fit of cells within the occlusion area. The occlusion test evaluated the condition of influential building's elevation cells on driver's visibility by connecting the centre of the cell and driver's location and comparing the elevation angle of the Sun with an elevation angle of each cell within the occlusion area.

The execution of the sun glare detection algorithm revealed the location of critical points by comparing the occlusion conditions on every two successive subsegments. Drivers' transition from a shadowed zone – caused by buildings or other infrastructure, into a sun glare zone may lead to a dazzling effect, hence negatively affecting traffic safety. Similarly, another significant critical zone was identified for the drivers that approach a contrasting shadowed zone as the travel from bright sunny conditions, leading to temporary blindness.

Results

This section summarizes the predicted results obtained by the algorithm for downtown Montreal, in particular the identification of the zones with potential dazzling and blindness occurrences.

Figure 5 shows the duration of sun glare and contrasting shadows in downtown Montreal for each month of the year, during the morning peak period. It can be seen that there is a relative mirroring of the January to May months versus the July to November ones, and this can be explained by fact that June and December are solstice months and the period of rotation of the Earth around the Sun. Moreover, the grid-like pattern of roadways in Montreal caused neither sun glare nor contrasting shadow within the analysis period between May and July. On the contrary, Montreal drivers experienced the highest amount of sun glare and shadows (i.e., 6000 minutes and 13500 minutes, respectively) during each February and October. Thus, the apparent position of Sun on these months caused more minutes of vision impairment and need particular safety countermeasures on the analysis network.

The best confidence level of detecting critical points was considered by eliminating the cloudiness period from outcomes. The weather data including cloud coverage and precipitations collected from the nearest weather station at YUL airport for the period of 2005 to 2015 to determine the clear sky and overcast weather conditions. The impact of cloudiness on annual glare occurrence was investigated on two arbitrarily selected sections of roads with same driving direction but with different gradient (i.e., gradient 4.5% - Simpson St. and level road approx. 1% - Mackay St, respectively). Figure 6 shows the accumulated time of sun glare occurrence in the division of occluded condition (blue bars) and the visible sun glare (yellow bars) for the selected roads. The event of visible sun glare was high in the approach of the vast junction with René Lévesque Blvd on the right bottom corner of the Mackey street (Figure 6, b and d) while the most length of the street was under the event of invisible sun glare (i.e., shadow of high-rise building). On the other hand, drivers on the Simpson Street (Figure 6, a and c) might experience intermittent sun glare and contrasting shadow along the road. This is the main purpose of

deterioration in road safety due to the blindness, as an impact of the transition from the visible sun glare to the contrasting shadow. Although the distinction of the clear sky based on the weather data reduced total minutes of vision impairment to half, the pattern of sun glare occurrence was consistent.

Deteriorated vision may also be the cause of early congestion onset – explained by the fact that a pre-emptive driving behaviour leads to bigger gaps and reduced speeds. Therefore, queues are forming sooner, and vehicular delay may increase during peak hours. Consequently, the algorithm was applied to wider area in downtown Montreal to reveal critical points of vision impairment in dazzling due to the sun glare or blindness due to the contrasting shadows. The algorithm evaluated the visibility situation of driver on morning peak hours (i.e., 6:30 am to 8:30 am) for the 20th of each month. The cloudiness was evaluated for any identified results of critical points from the 10 years record of weather data and only critical points under the clear sky are shown on the Google map open-source data visualization tool (Figure 7) and different months are shown in different colors (blue: February, orange: April, yellow: December). Although Figure 5 showed that drivers encountered comparatively less than a moderate amount of sun glare and shadow in April (i.e., approximately 1200 and 2800 minutes, respectively), the number of critical points in April was significantly higher in comparison to February and December. Figure 7 illustrates a relative comparison of critical point occurrence (i.e., sun glare to contrasting shadow and vice versa) in three seasonal day samples for the selected range in Downtown Montreal.

This study included an empirical validation of the application outcomes by studying glare-conditions along an arbitrarily selected arterial road of Montreal. This arterial in the proximity of downtown Montreal (i.e., street of Chemins de la Côte-Sainte-Catherine) was selected for an analysis of the sun exposure footprint. The application of this study evaluated the occurrence of

the sun glare and critical points for the morning periods during the peak hour to identify the period and location that the Sun is considered to be at its worst angular position along the road. A segment under sun exposure and two types of critical points were identified in the potential section of the road. The application revealed the occurrence of sun glare between junctions with Mc Eachran Ave. and Boulevard Saint Joseph during 6:30 to 7:15 morning time interval on July 18, 2020. Additionally, another occurrence of critical points is near Ave. McCulloch and Ave. Laurier. Figure 8a shows the outcome of the application on the Google map open-source data visualization tool.

The field investigation was carried out using a Sigma camera to validate the accuracy of the application on detecting vision impairment locations. The camera was adjusted on the mode of taking the best photo shot in different exposure. Figure 8 shows the captured photos for each identified critical points including: 8b) driving under direct sun exposure, 8c & 8d) transition points between sun glare and contrasting shadow (blindness), and 8e) location of transition from shadow to sun glare (dazzling).

An accurate glare evaluation of photos in real scenes of contrasting shadows via luminance level requires the use of a wide view of fisheye lens (Inanici, 2006; Wienold and Christoffersen, 2006; Jacobs, 2007). In this study, a Sigma 4,5mm F2,8 EX DC HSM Circular Fisheye lens was used for the investigation of luminance of objects in sun exposure when driver approach to contrasting shadows. The luminance and visual comfort of photos have been analyzed by the Pintools online method. Identification of the blindness impact of sun glare needs to assess the exposure level (i.e., luminance) in the shadow and in the brightness area. A captured photo from a critical point (i.e., blindness situation) using the fisheye lens is illustrated in Figure 9a, while the

corresponding minimum and maximum exposure of photos are shown in Figure 9b & 9c, respectively. Both bounds of the exposure level revealed the high saturation of sunlight in photos and impairment of the vision in detecting the front of overtaking bus on the left side of the photo. The comparison of the clearance between the centre of the vision and surrounding environment vividly proved that overexposure of the sunlight disables eyes on detecting objects under the contrasting shadow in front of the driver.

Summary and Concluding Remarks

In order to reveal critical points with respect to sun glare occurrence on a road network this study combined geographical road network data, an astronomical algorithm, specific trigonometric formulation, and data analysis in Python. The methodology has two steps, the sun glare detection algorithm and sun glare occurrence identification on the given network. The workflow of sun glare detection comprises of processing of data sources, the sun positioning algorithm, and identifying the critical angular location of the Sun for driving sightline. The methodology processes the GIS road data for a specific sub-segment of road and calculates the annual sun position by considering refraction factor for the analysis period. The angular position of the Sun was evaluated within the critical sightline of the driver on horizontal and vertical plan.

The result indicated the appearance of contrasting shadows on roads during sun glare time for having precision in identifying critical points (i.e., dazzling and blindness). The implementation of occlusion test revealed the occurrence of most important case of vision disability at the middle of mid-block sections or wide intersections.

The algorithm developed in this study could be employed on many different procedures to reduce the effect of sun glare as a road safety audit tool for existing or future roads. Potential

412 road safety issues such as sun glare or critical points occurrence defines opportunities for
413 improvement in safety for all road users. Future investigation for assessing the impact of vision
414 impairment on road safety should be considered using robust real-world data or advanced driving
415 simulators and conflict analysis.

416 In order to eliminate deteriorated safety segments on roadways in the road design phase, the
417 designated widget in this study can be used to identify the location and density of sun glare
418 occurrence based on the ending coordinates of each road segment. The algorithm evaluates the
419 given alignment of road to select the optimal safe design scenario. However, it might be
420 financially unreasonable to change road geometry to skip the impact of sun glare on drivers.
421 Thus, the use of this application needs further study to consider it as an input to the design of
422 automated highway system where safety issues have to be addresses.

423 On the other hand, planned roads, which are highly exposed to sun glare, needs additional
424 facility of traffic management, such as variable message signs or providing a driving-assistance
425 application to decrease the risk of vision deficiency. Therefore, in the future, by employing the
426 proposed algorithm in this study, the definition of the optimal speed limit for any part of the
427 roadways is merely achievable.

428 **Competing interests' statement**

429 The authors declare there are no competing interests.

430 **Contributors' statement**

431 **HE:** Conceptualization, Methodology, Software, Data Curation, Validation, Writing - Original

432 Draft

433 **RE:** Software, Data Curation, Visualization

434 **MK:** Investigation, Validation

435 **CA:** Resources, Writing - Review & Editing, Supervision

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438 **Data availability statement**

439 All data and models used during the study are either directly downloadable from the websites
440 listed in the References section or available from the corresponding author by reasonable request
441 (GIS, DEM, and hillshade data from the open data portal of city Montreal, Weather data from
442 Government of Canada). The authors did not have any special access privileges.

443 All code generated during the study are proprietary or confidential in nature and may only be
444 provided with restrictions. The component of the code includes apparent sun positioning
445 function, sun glare detection, occlusion test and related optimization methods.

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Figure captions

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Figure 2. Sun position coordinate system.

Figure 3. a) Plan view of the area for occlusion test. b) glare condition. c) occluded point.

Figure 4. Study area. a) Center of Montreal includes the solar path. b) Section of Downtown.

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Figure 6. Total time of sun glare (yellow) and shadow (blue) occurrence for Simpson St (a) and

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Figure 9. Captured sun exposure by fisheye lens

583 **Figures**

584

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