

An Empirical Investigation of the Impacts of Sun-Related Glare on Traffic Flow

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ABSTRACT

Visibility is one of the basic needs for safe driving. Any type of reduction in visibility can lead drivers to change driving behavior resulting in changes in flow or speed, disorder on the network as a result of braking or driver error, or in the worst case to an incident or a crash. Glare can be caused by sun, headlights of other vehicles or other light sources can cause substantial reductions in vision performance. For freeway operations, glare is primarily associated with headlights from vehicles traveling in the opposite direction at night, is often addressed with median barriers or glare screens. However, the effect of sun-related glare is similar to the impact of headlight glare—it can lead to degradation of drivers' vision and affect driving performance. The occurrence of glare will vary according to time (only on certain days and times when the sun is low in the sky) and location (only on particular combinations of roadway horizontal and vertical geometry). Rather than investigating any direct relationship that may exist between reported crashes and glare, the objective of this paper is to examine the potential impact between measured traffic flow characteristics and the potential for vehicles to be impacted by sun glare. A method based on multiple regression was used to test the effect of the glare issue caused by sunlight on freeway speed/flow and flow/occupancy relationship.

INTRODUCTION

According to the U.S. Federal Highway Administration (FHWA), approximately fifteen percent of congestion experienced by travelers is attributable to nonrecurrent weather-related causes (1). It is well known that traffic operations and highway safety are highly influenced by adverse weather such as rain, snow and fog (2-4). For many adverse weather events, limited driver visibility is a key factor that results in congestion. One study found that as visibility decreases the resulting vehicular delay increases by approximately twelve percent (5). On many east-west highways, sun-related glare during periods of the day can also result in a reduction in driver performance due to a decrease of visibility. As common as this event may be, there has been little or no research toward understanding the effect of sun-related glare on traffic flow.

Potential sources of glare include headlights from vehicles traveling in the opposite direction, reflections from wet or specific dry pavement, and direct sunlight. In the *Dictionary of Visual Science*, glare is defined as a "relatively bright light, or the dazzling sensation of relatively bright light, which produces unpleasantness or discomfort, or which interferes with optimal vision" (6). There are three different components of the glare effect: 1) the disability caused by it; 2) the sensation of discomfort; and 3) the recovery time. The disability caused by glare is a physiological effect that consists of a reduction in visibility caused by light scattered in the eye (7). This disability limits the drivers' vision for a short period. It is during this period that a speed reduction, increase in vehicle headways, crashes or an incident has a greater probability of occurrence. The discomfort aspect is a subjective measure of the impact of glare on a particular person and is influenced by factors such as illuminance from the glare source, task difficulty, and the ambient brightness angle from line of sight (8). It is important to note that people do not react homogeneously to this discomfort, but it depends on age and visual health. Lastly, the recovery period is the time that it takes for a person to return to his or her usual performance. During this period, a driver's visual performance is reduced. However, this phenomenon, which fluctuates with the age of the person, is poorly understood.

Rather than investigating any direct relationship that could exist between reported crashes and glare, the objective of this paper is to examine the potential impact between measured traffic flow characteristics such as flow, speed and occupancy, and the potential for vehicle's drivers to be impacted by sun glare. This was accomplished with a regression analysis to test the effect of sun-related glare on freeway speed/flow and flow/occupancy relations. Archived 5-minute traffic data, weather condition, and estimates of sun position relative to the driver's path for a single location on the Interstate-5 (I-5) freeway in Portland, Oregon where sun glare is known to occur were used.

SITE DESCRIPTION

The study location chosen was located on the northbound I-5 freeway near a loop detector surveillance station at Terwilliger Blvd. as shown in Figure 1. During certain periods throughout the year, traffic is facing directly into the sun during morning and evening periods. I-5 is a major north-south corridor in the western United States and in the Portland area, it is a major commute route for traffic traveling to and from the downtown core. In 2005, the reported average daily traffic at this location was more than 128,000 vehicles per day. The northbound cross-section consists of three twelve-foot lanes, a ten-foot right shoulder and a 5-foot left shoulder. A concrete median barrier with a glare screen separates traffic. There is also an on-ramp just downstream of the detection station that is metered during the morning peak hours. The study location is situated near horizontal

and vertical curvature and drivers are facing directly east in the northbound direction and directly west in the southbound direction. In the northbound direction, there is a +3% grade at the detector location. The surveillance station records vehicle flow (vehicles/hour), speed (miles/hour) and occupancy (percent of time that a detector is occupied by a vehicle) at 20-second intervals in each lane.



FIGURE 1 Vicinity map of the study site.

METHODOLOGY

The objective of this investigation was to observe empirically the apparent effect of sun glare on traffic flow using archived traffic surveillance and weather data. In order to make these observations, factors that make sun glare likely were used to select a suitable set of comparison data. Time periods with and without appropriate sun position, days with and without cloud cover, and days with congested and uncongested measured flows were used to assemble the data for analysis. The following sections describe how these data were assembled.

To determine which periods of the day had candidate sun positions likely to cause a glare effect for most drivers, the position of the sun relative to the position of the vehicle must be known. It was hypothesized that sun-related glare might interfere with traffic when it is low in the sky and when the vertical and horizontal roadway geometry is essentially aiming traffic directly into the sun. There are many unknowns related to this hypothesis, and for this reason, this project should be considered to be the first step of an exploratory research effort. For example, it is not known precisely when the sun begins and ends interfering with drivers' vision and, even if it does, it is not certain that there will be any interference with traffic flow. Some drivers might be able to continue driving even if confronted with a flash of bright sun, while other drivers would brake, alter their path or even depart their lane as markings become invisible. Further, different vehicle heights, windshield configurations, styles of sun visors, window tinting and drivers' use of sunglasses will also introduce heterogeneity in the traffic stream.

However, given all of these caveats (some of which could be addressed through future research), the first step was to attempt to determine the maximum sun angle for which drivers and hence traffic conditions could be influenced. Three main factors influence the maximum sun angle of that will likely cause glare: drivers' eye height, highway horizontal and vertical geometry, and the specific site location (latitude). No definitive reference could be found that identified the sun angles likely to cause glare in vehicles. Given the wide variation in vehicle and driver characteristics that could possibly cause glare issues sun angles between 0° (sunrise) and 15° were chosen as a reasonable range to demarcate possible glare time intervals. Glare potential will also vary by solar position so it was necessary to estimate the hourly time periods when the sun would be directly in driver's line of sight at the assumed angle. It is possible to approximate the location of sun relative to a known location for a particular date and time of day using several readily available algorithms knowing the latitude and azimuth (9, 10, 11). These algorithms provide characteristics such as solar declination, solar

azimuth, and solar elevation for a specific latitude and month. Figure 2 illustrates these parameters of solar geometry (11). The study location is at approximately 45.47° latitude and the faces approximately east (90°). A sun path diagram was used to determine which hours of particular months were likely to have sun angles below 15° that cross the 90° azimuth. Sun-path diagrams are projections showing the sun path, solar azimuth, and solar elevation for particular latitude, by time of day and month of the year (12). A sun path diagram for the months of December to June at the study location latitude is shown in Figure 3. Note that the sun path diagram for July to December is identical (replacing June with July and the subsequent months with August and so on). In Figure 3, it is clear that the months of March, April, and May generally meet the criteria of having a sun angle below 15° with an azimuth that crosses 90°. The months of August, September, October also meet this criteria. The sunrise time for each month was calculated with the National Oceanic and Atmospheric Administration (NOAA) solar calculator and the sun path diagram to determine the end time of likely glare causing sun (11). Obviously, this process gives a rough approximation of the time periods likely to receive glare-inducing sun at the study location. Nonetheless, Table 1 summarizes the time periods for each month where it was determined that there was a potential for sun glare.

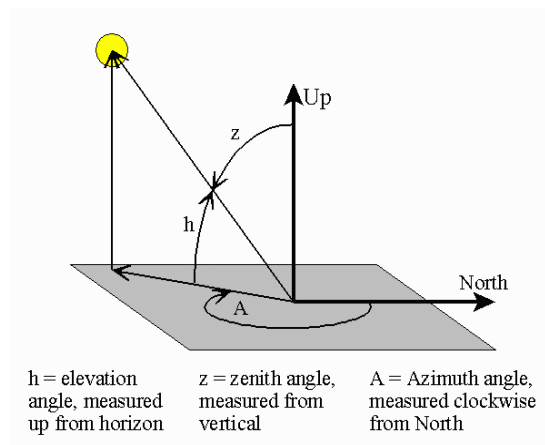


FIGURE 2 Astronomical geometry

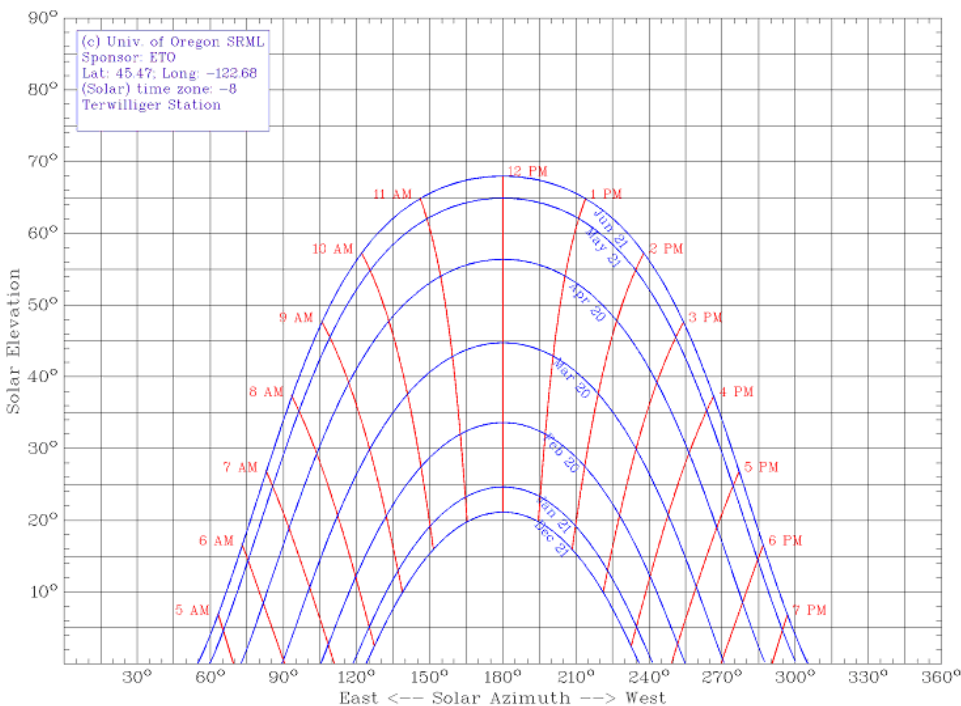


FIGURE 3 Solar elevation for Terwilliger Blvd location by time of day and month.

TABLE 1 Time of Day for Each Month with Potential Sun Glare, I-5 Northbound at Terwilliger Blvd.

Month	Start Time (AM)	End Time (AM)
March	6:45	7:30
April	5:50	7:00
May	4:55	6:30
August	4:55	7:00
September	5:30	7:30
October	6:00	8:30

To estimate the amount of cloud cover, hourly observational weather data were obtained from the NOAA. The data include temperature, precipitation, wind speed, visibility, sky coverage, cloud ceiling, pressure level and dew point. Data from five weather stations are available in the Portland metropolitan area with the closest station to study location being the Portland International Airport station (approximately 10 miles to the northeast from the study location). It was assumed that weather observations were comparable. The variable of interest, sky coverage, is defined as five states: clear, scattered (1/8 to 4/8 of the sky is covered by clouds), broken (between 5/8 and 7/8 covered), overcast and obscured. Within the daily time periods listed in Table 1, this study compares measured traffic parameters during two distinct periods: one with the potential for sun glare and one without. It is not possible to evaluate the percentage of glare present on cloudy days or to detect glare during days with scattered clouds. Therefore, only two time periods that were most likely to feature sun glare or not were used: clear days and overcast days. These two periods represent the extremes on the NOAA scale describing sky cover. This allows the investigation to focus somewhat more definitively on the sun glare issue comparing two set of data at the same location, with and without the phenomenon.

The traffic data used in this analysis were obtained from the Portland Oregon Regional Transportation Archive Listing (PORTAL) data archive (13). This database, developed by the Intelligent Transportation Systems Laboratory at Portland State University, archives data from the region's advanced traffic management system (ATMS). The Portland region's ATMS consists of a Traffic Management Operations Center (TMO), an extensive fiber-optic communication system, and a freeway surveillance system with 671 detectors, 198 stations, 185 ramp meters and 98 closed circuit television cameras (CCTV) as of July 2007. The primary data used in freeway management are from the inductive loop detectors, which generate count, occupancy and speed measures every 20 seconds. PORTAL is currently the Archived Data User Service (ADUS) for the region and also includes data on freeway traffic characteristics (flow, occupancy, and speed), weather, and incidents. At this specific location, the double loop detectors are implemented for directly measuring the velocity of vehicles in each lane. For this analysis, count, speed and occupancy data aggregated over 5 minute intervals are used.

The final parameter used in the selection of study days and times was the traffic state (congested or uncongested). The most appropriate way to distinguish between these two states is by using the measured values of speed and occupancy. During an uncongested period, the speed is high and the occupancy is low. During a congested period the occupancy becomes high and the speed low. These criteria were used to sort the data. For this exploratory study, an assumed occupancy greater than 33% and a speed under 50 mph were used to identify the congested periods.

The results of this data cleaning process are shown in Figure 4. The number of 5-minute periods of freeway data that were available at the study location for each of the categories are shown. Note that the total available time periods include all 5 minute intervals for the analysis years minus any inaccurate data readings (communication failure or calibration issues). The first division of the data defined those intervals with sun at the noted angles. The second division shows the weather classifications. Weather other than clear and overcast are not shown. Finally, the traffic state of each sun angle and weather classification is presented.

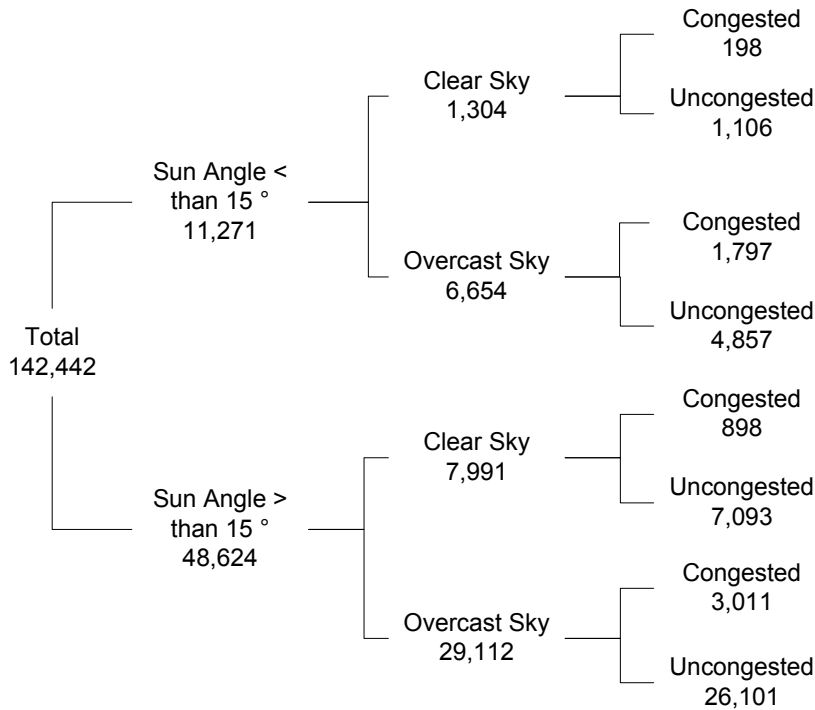


FIGURE 4 Results of the data cleaning process – the number of 5-minute periods in each category.

ANALYSIS

Although the PORTAL database began recording data in July 2004, this analysis focused mainly on the years 2005 and 2006. Three analyses were conducted using the assembled data. The first analysis compared two statistically similar days for evidence of the prospective sun glare effect on measured traffic flow characteristics. The second analysis compared a larger set of data from multiple days in 2005 and 2006. The third analysis focused on changes that occurred in the principal relationships describing the flow of vehicles, particularly the speed/flow relationship.

Two Day Comparison of Traffic Flow Parameters

Typically, it is thought that nonrecurrent weather events affect freeway traffic flow by degrading performance, measured by flow and speed along a particular corridor. Usually these events such as rain, snow or ice, also negatively impact travel reliability. When thinking about the impact of glare, intuitively one would expect the measured flow and speed to drop slightly while glare is occurring (and impacting drivers). During periods of bright sun striking drivers in the eyes, it is assumed that drivers will reduce their speed and increase their headways due to a tentative feeling and lack of visibility of other vehicles and lane markings.

In order to explore this intuition, two days were chosen for their statistical similarities, in terms of weather conditions and volume distribution, and measured speed has been compared during those days. For these days (September 28 and 29, 2005) the study times were the same and no incidents or other nonrecurrent disturbances were reported according to the archive. On September 28, during the time window when glare was expected, skies were clear. On September 29, skies were cloudy, so the clouds would have prevented glare from being an issue. A time series plot of these data, including the calculated sun angle is shown in Figure 5. In the plot, the flow data (expressed in terms of volume) appear similar while there is a difference in measured speed. Paired *t*-tests were used twice, first for checking the similarity in the flow and then for assessing whether there were significant differences in speed. The power of this test is greater than a simple test of means. The paired *t*-test considers the hypothesis that the average of the differences between each paired sample is zero (14). The *t*-test statistic is calculated as:

$$t^* = \frac{\bar{X}_d}{s_d / \sqrt{n_d}},$$

where:

\bar{X}_d = average of sample differences;

s_d = standard deviation of sample differences; and

n_d = sample size.

Further, the confidence interval for the average difference can also be calculated using:

$$\bar{X}_d \pm t_{\alpha/2} \left(\frac{s_d}{\sqrt{n_d}} \right)$$

The results of the paired t -test are displayed as p-values in Table 2. All tests and confidence intervals were calculated using a significance level of 95% ($\alpha = 0.05$). If the p-value is less than the test level α then the null hypothesis of equal means is rejected. In this comparison, p-value for flow difference is greater than 0.05. Thus, the null hypothesis of equal means is confirmed for flow. We can assume that on these days flows were statistically equal. Concerning the speed t -test, the p-value is equal to 0.009, which is less than the test level 0.05. Therefore, the hypothesis of equal means is rejected. Speeds were statistically different in these two different days. This exploratory investigation lends some possible empirical evidence of the influence of sun glare on traffic flow.

TABLE 2 Summary of Paired T -Test Results

Statistical Characteristics	Flow Difference	Speed Difference
Mean	-18.24	2.8
Standard Deviation	172.27	3.7
Number of data	25	25
p-value	0.601	0.009
Confidence Interval	(-89, 53)	(0.55, 3.61)

Multi-day Comparison of Traffic Flow Parameters

After finding some initial evidence of a potential sun glare impact on traffic conditions, further analyses were conducted to explore how potential sun glare can affect measured traffic flow parameters. Further traffic and weather data (during days and times when the sun angle was correct) were matched and sorted by sky cover characteristics and traffic state. Investigations focused on the recurrence of the glare phenomenon and its possible impact on the relationships that govern traffic flow. Weekdays from 2005 and 2006 without incidents, work zones or ramp metering issues were used for this analysis.

Some basic statistical measures were used to test for differences between the three data sets. Classic variables (speed and flow) were compared between periods with different types of sky cover and different traffic states, providing evidence of an interaction between weather and traffic. The speed variable was the most useful because it provided a good description of the vehicular travel quality. Because during free-flow periods flow is only the representation of the demand, the flow variable was only used during congested periods. The average, standard deviation and number of data points, which is also the number of 5-minute periods considered, for each comparison are summarized in Table 3.

Differences are noticeable in the mean values of speed and flow in Table 3. For the first comparison, the mean speed of 31.1 mph was slightly higher under potential glare conditions than the speed of 29.3 mph under the control (no glare) conditions (solar angle lower than 15° and overcast sky). Flow was higher during potential sun glare periods than during these control conditions. For the second comparison, the average speed of 31.1 mph was lower during potential sun glare conditions than the mean speed of 33.3 mph recorded during the control conditions (solar angle higher than 15° and clear sky). The average flow remained higher during the potential sun glare periods than during these control conditions. So the hypothesis that glare might induce lower speeds appears to be valid for the second comparison, but the higher flows observed here seem to contradict the notion that glare may reduce freeway capacity. Further analysis of the data is warranted.

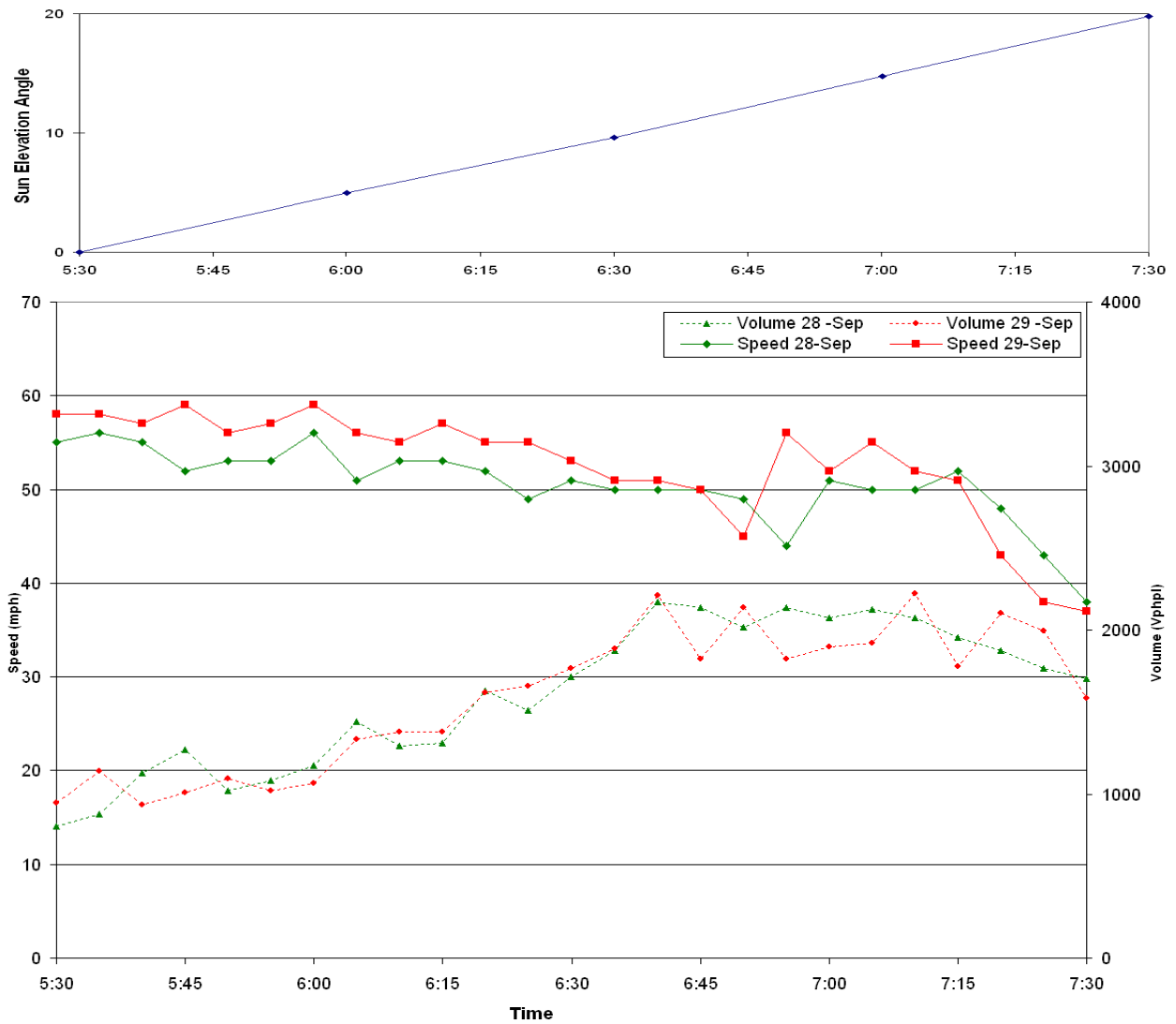


FIGURE 5 Time series plot of speed and flow and sun elevation, I-5 northbound at Terwilliger Blvd. on September 28 and 29, 2005.

TABLE 3 Comparisons Under Different Weather and Traffic Conditions

Traffic		Potential Glare	Control: No Potential Glare	
Parameter	State	Sun Angle < 15°	Sun Angle < 15°	Sun Angle > 15°
		Clear Sky mean (SD, n)	Overcast Sky mean (SD, n)	Clear Sky mean (SD, n)
Speed (mph)	Congested	31.1 (5.2, 200)	29.3 (5.7, 1797)	33.3 (5.9, 898)
Speed (mph)	Uncongested	57.9 (4.4, 1004)	57.3 (4.3, 4857)	55.9 (2.9, 7093)
Flow (vphpl)	Congested	1,719 (202, 200)	1,682 (195, 1797)	1,645 (249, 898)

Speed-Flow Relationship

The previous analyses provide some evidence that sun-related glare could influence traffic flow at this particular location. A less aggregate analysis of the data using multiple regression was used to attempt to understand whether changes in the fundamental traffic flow relationship were occurring.

There are several relationships that can be used to describe traffic flow using speed, flow and occupancy. For this analysis a scatter plot showing the relationship between speed and flow is provided in Figure 6. One plot (open circles) displays the data points from days with the solar angle higher than 15° and clear sky—this was the portion where the mean speed was lower than during the potential glare conditions. The data from the periods with potential sun glare area also shown in Figure 6 with solid circles. Points are shown during both uncongested (upper branch) and congested (lower branch) periods.

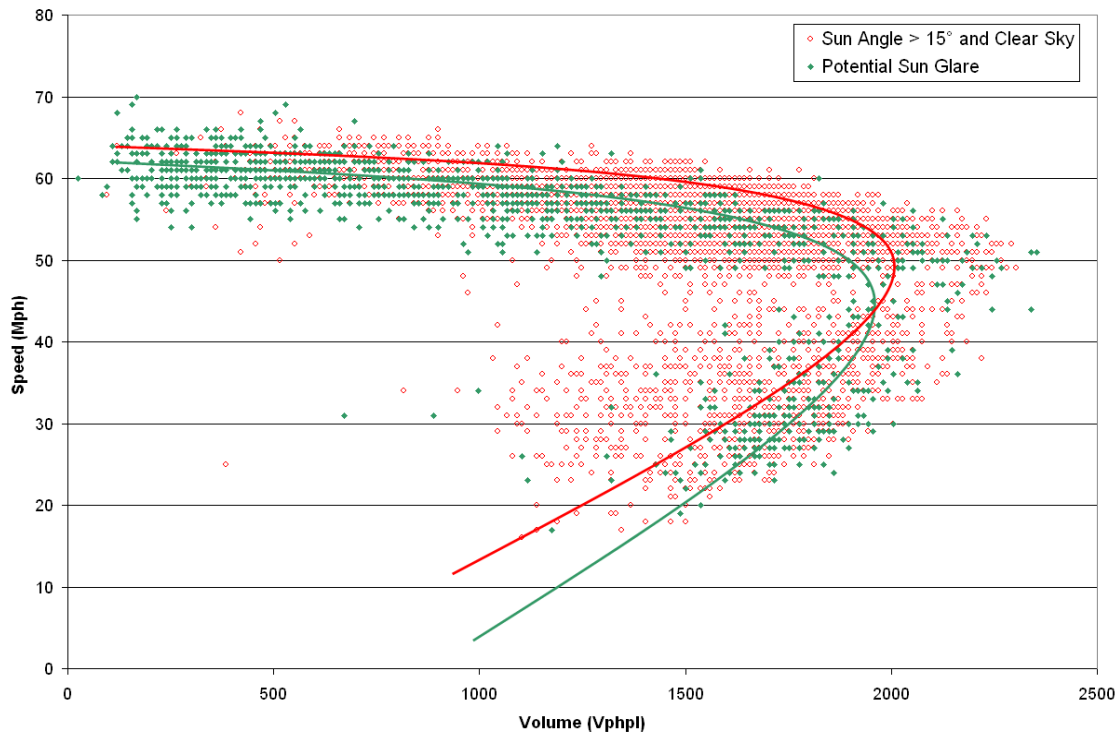


FIGURE 6 Scatter plot of the speed/flow relationship under different illumination conditions

The two curves represent estimated traffic flow relations calculated during the two different weather conditions—one during the control period (solar angle higher than 15° and clear sky) and the second during potential glare conditions. While not claiming to perfectly define a traffic flow fundamental diagram, for this example, a second-order polynomial curve was fitted to the raw data in order to illustrate a possible speed/flow relationship. The R^2 was 0.67 for the potential sun glare regression curve and 0.34 for the control conditions respectively.

If the global shape of the curve remains the same, a degradation of performance during periods with sun glare can be noticed by the gap between the two curves and the flatter top (lower speed) of the glare curve. The curve representative of potential sun glare lies below the control curve for uncongested conditions and above it for congested conditions. These regressions confirm the results found previously: higher speeds seem to prevail under sun glare conditions during congested periods and lower speeds under sun glare conditions during uncongested conditions. Thus, sun glare may induce a drop in driver speed and a small drop in the total capacity of the freeway. It is also necessary to understand that even if these results confirm what was expected, the exploratory and indirect nature of the findings certainly limit the ability to draw any firm conclusions.

DISCUSSION

The above analyses represent preliminary steps toward addressing the question of whether sun glare can have an affect on traffic flow, using data from one particular location over several years. However, the results of the analysis has had some conflicting results. If flow is always greater during periods of potential sun glare than during control periods, the results are not the same when focusing on speed. Indeed, in our hypothesis we expected that speed would decrease during periods of sun glare because of a new dynamic bottleneck created by the glare. The empirical data did not always show this glare effect. Due to the nature of the sun glare phenomenon, conclusions are difficult to draw. We attempted to use different comparisons to cover all aspects of the sun glare phenomenon. Speed fluctuations changed with the sets of data used for the comparison.

In actuality, the two data sets used for comparison represented different aspects of the phenomenon. If the first one focused on the same period of time and sky cover, the second one focused on the sun angle. It is difficult to draw solid conclusions because different data focused on different periods of the day. The change noticed in the results could be due to the fact that the data were measured during different periods of the day, inducing different kinds of traffic and hence different characteristics in the traffic measured patterns. Adding to that, weather data are collected hourly by an officer of the NOAA. Some uncertainty issues can be found in the methodology used for characterizing sky cover.

Concerning the regression on the speed/flow relationship, interpretations are somewhat limited. If differences can be seen on the scatter plot, these differences are principally due to the regression. Further analysis is necessary which could lead to different results.

CONCLUSIONS

This paper demonstrates that there is some potential that sun glare can have an impact on traffic flow. While far from conclusive, this study has revealed a potential for future research using archived data in the Portland, Oregon metropolitan area. The presence of potential for sun glare can apparently affect the speed and flow distributions during congested and uncongested periods. The possible sun glare when the sun is low in the sky and vehicles are aiming into the sun with particular horizontal and vertical geometry can create an additional dynamic bottleneck at a specific location. This restriction of capacity can lead to a decrease in flow, a drop in speed and a loss of homogeneity in the vehicular flow. However, it was difficult to quantify or describe this effect. The nature of this phenomenon, a combination of several factors, makes it difficult to uncover with precision. Hence, we can assume that sun glare may be the cause of changes in the measured traffic flow characteristics but it cannot yet be detected or quantified strictly. Further investigations are needed to see if the previous results are reasonable using different locations and different traffic patterns. Future research may also examine crash frequency data in order to investigate whether a direct impact on safety is revealed. Another issue that has been left for further research is the question of sun glare caused indirectly after reflection onto wet pavement.

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