2019-01-1005 Published 02 Apr 2019

Nighttime Visibility in Varying Moonlight Conditions

William Neale, James Marr, and Nathan McKelvey Kineticorp LLC

Michael Kuzel 4M Safety

Citation: Neale, W., Marr, J., McKelvey, N., and Kuzel, M., "Nighttime Visibility in Varying Moonlight Conditions," SAE Technical Paper 2019-01-1005, 2019, doi:10.4271/2019-01-1005.

Abstract

When the visibility of an object or person in the roadway from a driver's perspective is an issue, the potential effect of moonlight is sometimes questioned. To assess this potential effect, methods typically used to quantify visibility were performed during conditions with no moon and with a full moon. In the full moon condition, measurements were collected from initial moon rise until the moon reached peak azimuth. Baseline ambient light measurements of illumination at the test surface were measured in both no moon and full moon scenarios. Additionally, a vehicle with activated low beam headlamps was positioned in the testing area and the change in illumination at two locations forward of the vehicle was recorded at thirty-minute intervals as the moon rose to the highest position in the sky. Also, two separate luminance readings were recorded during the test intervals, one location 75 feet in front and to the left of the vehicle, and another 150 feet forward of the vehicle. These luminance readings yielding the change in reflected light attributable to the moon. In addition to the quantitative measurement of light contributed by the moon, documentation to the change in visibility of objects and pedestrians located on the roadway were documented through photographs. Calibrated nighttime photographs were taken from the driver's perspective inside the vehicle with low beam headlamps activated. The photographs were analyzed after testing to determine how the light intensity of the pixels in the photographs changed at each thirty-minute interval due to the additional light contribution from the moon. The results of this testing indicate that the quantifiable change in visibility distance attributable to added moonlight was negligible, and in real-world driving situations, the effect of additional illumination from a full moon would be unlikely to affect the detection of an object or pedestrian in or near the travel lane of the roadway.

Introduction

The moon, with a remarkable ability to provide natural light during the night, has been the subject of books, songs, art and folklore. The light producing power of the moon provides the background for legendary stories, such as the account by the Royal Air Force pilot Hugh Verity, who in his book "We Landed by Moonlight", provides accounts of British RAF pilots entering occupied France without external lighting, guided during takeoff and landing by only the light of the moon [1]. Other books, such as Kristin Henderson's memoir about war and faith "Driving by Moonlight", features a cover photograph of a moonlit roadway with visibility stretching into the horizon [2]. In music, the mysterious ability of the moon to light one's way has been expressed in Led Zeppelin's 1969 ballad "Ramble On" and The Doors 1967 single "Moonlight Drive".

The pervasive perception of the moon's illuminating power extends to macabre and the extreme. In the May 1946 issue of The Lion, a featured piece called "Moonlight for Headlights" [3] tells the story of two teenage drivers who collided head-on at night due to driving with their headlamps off, being so convinced that the light from the moon was sufficient to illuminate the road ahead. Australia's Safe Drive Training company performs driver education in over 20 Asia-Pacific and African Countries. The instructors in Egypt found that "*Egyptian drivers do not use any headlights when driving on the remote desert highways late at night*". The apparent theory behind this behavior being that moonlight can be sufficient for driving, and through adaptation, the driver develops a keen nighttime awareness [4].

However, the folklore, music and art about the powers of moonlight does not provide basis for scientific analysis. In addition to the potential misperceptions that emerge from the aforementioned texts and recounted observations, numerous publications have provided values for the additive illuminance of moonlight that could lead a person to expect significant differences in visibility during new moon versus full moon conditions. For example, prior publications have reported the ambient sky illuminance at night varying from 0.001 lux for an overcast night to 0.01 lux to 0.03 lux for a clear sky with no moon, to a very wide range of 0.1 lux to 2.2 lux for a full moon [5, 6, 7, 8], though most studies report and accept that at most, the illuminance from the moon would likely be in the mid to high 0.3 lux range under optimum conditions [7]. While the moonlight can assist in tasks such as walking at night or reading text of sufficient size and proximity to the viewer, [5, 9], performing driving tasks are entirely different due to the speed of travel, reduced light transmission through the windshield, and the relative size of objects that might be present on the roadway, such as pedestrians, animals, or other vehicles.

Some studies have reported an association of lunar cycle (new moon versus full moon) to the occurrence of crashes [10, 11, 12]. Redelmeier and Shafir [10] performed a double control cross sectional analysis of 13 029 motorcycle fatalities in the United States between 1974 and 2014 to "*test whether a full moon contributes to motorcycle related deaths*", concluding that there was a relative risk of 1.05 associated with being involved in a fatal crash during a full moon, a contradiction to the idea the moonlight increases visibility [10]. The authors also found an accentuated increase risk of fatal crashes during a super moon. Similarly, Onozuka et al. [11] conducted a time-stratified case-crossover analysis of road traffic crashes in 47 precincts Japan in the years 2010 to 2104, reporting a 1.042 adjusted relative risk of being in a crash that required emergency transport when there was a full moon [11]. Although the authors of these studies accept that there is a potential for confounding, they propose that the effect of the full moon in these crashes may be related to factors such as: (a) distraction by the moon; (b) an increase in contrast of luminance; (c) optical illusions during the early rise period; and (d) increased outdoor activity, which may lead to increased travel, higher travel speeds, longer travel distances, or selection of unfamiliar routes. Nonetheless, findings that indicate an increase in crash risk during a full moon contradicts the idea that moon increases visibility.

An earlier study by Sivak et al. [12] found a converse association between pedestrian crashes and the presence of the moon. In their study, the researchers compared fatal pedestrian crashes occurring on nights with a new and full moon in the United States in the 10-year period of 1996 to 2005 [12]. After excluding days that may have high pedestrian activity, they found a 22% mean increase in fatal crashes when there was a new moon, *i.e.*, no moon light contribution. The authors concluded that the findings were "*unlikely to be correlated with any other factors*" and instead offer that the results "*imply that the amount of moonlight has substantial influence on pedestrian crashes*," yet offer no further explanation.

A search of published studies did not identify laboratory or field studies that have attempted to evaluate or demonstrate the potential contribution moonlight has on visibility. Thus, the objective of this study involved isolating the contribution from moonlight and the potential effect on visibility, using two general methods. The first method employed two common visibility metrics of illuminance and luminance to measure light with and without contribution of moonlight. The second method involved visually recording any change in visibility from the moonlight using nighttime photographic documentation. Given that pedestrian crashes and impacts with disabled vehicles in the roadway are commonly related to visibility and the amount of available light, the focus of the study was to evaluate if measurable changes of these metrics could be related in a meaningful way to a change in detection or recognition distance by a driver.

Determining the Testing Date

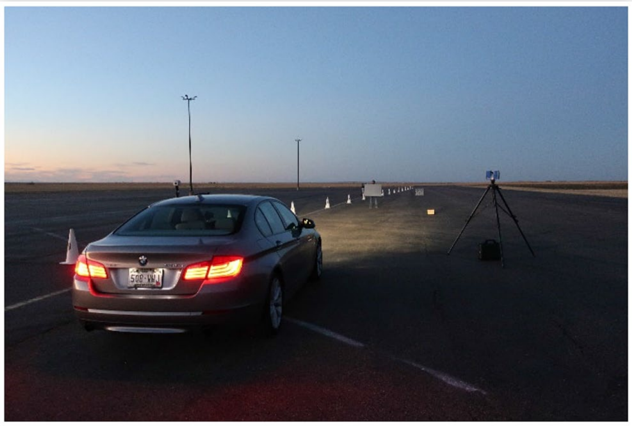
Testing was performed in Denver, Colorado, with two dates selected to document and record moonlight contribution. The first date was December 3, 2017, chosen because of the occurrence of a super moon, when the moon would be closest to the Earth and brightest in the night sky. According to NASA [13], at the farthest distance, the moon will be approximately 252,800 miles away, while the average distance from Earth to the moon is 238,855 miles. When closest to the Earth, the moon could be 221,800 miles away. This difference is significant enough that the far and near distances have their own names: a micro moon when full and located at the apogee of the ellipse; a super moon when full and located at the perigee of the ellipse. December 3, 2017 marked the last super moon of 2017, when the moon was approximately 222,317 miles from the Earth [14]. A super moon condition is a rare event and represents an extreme condition of moonlighting. Most comparable full moon nights would provide significantly less illumination. To evaluate the likely maximum contribution of moonlight, illuminance was collected from moonrise to midnight, when the moon was at its brightest and highest in the sky.

The second date, October 26, 2018 was chosen to coincide with an average full moon condition. On this date, the moon was 96.7% illuminated and 234,950 miles from Earth. On this night, measurements were collected during two relevant phases of the moon to evaluate the potential effect of illuminance from the moon to aide a driver's ability to detect objects in the roadway: 1) no moon, prior to the rise of the moon, yet during conditions of nighttime darkness, *i.e.*, after astronomical twilight; 2) during moon rise to full moon. The timing of moon phases was obtained from sunrisesunset.com.

Testing Procedure and Setup

The testing was performed at a controlled location on an asphalt lot at Front Range Airport outside of Denver, Colorado. A 600' long section of the roadway was chosen, which was flat and offered a straight line of sight for the entirety of the testing area. Sixteen (16) numbered cones, "0" to "15", were placed in 25-foot intervals in front of a vehicle beginning at 25 feet and extending to 375 feet. The cones were staggered left to right to allow an un-occluded view from the driver's perspective and to generally follow the vehicles low beam pattern, which provides illumination oriented slightly down and to the right. While the results of the testing and summary of conclusions would not be expected to be dependent on the vehicle used, or style of headlamp, nonetheless, the make and model was a 2011 BMW 335i x-drive equipped with projector optics style headlamps. Figure 1 shows a photograph of the testing setup including the calibration charts, calibration luminance panels, and cones.

FIGURE 1 Photograph of testing setup and numbered cone configuration



In addition to the numbered cones, calibration charts were utilized in the setup for calibrating nighttime visibility through photographs. Two charts were placed at 150 feet from in front of the headlamps of the vehicle, and 10 feet to the right and left of center. The calibration chart placed 150 feet forward and to the left of the vehicle, measured 2 feet wide by 10 feet tall and contains ten Landolt C's [15]. The second chart placed to the right was a contrast and spatial frequency panel has been validated for calibrating nighttime imagery [16, 17]. This chart, measuring 3.3 feet wide by 2.6 feet tall, contains 24 circles with varying gradients of light to dark and varying size and visual frequency. A LED light panel was also used in the photographic calibration process [20]. The luminance meter was mounted on a tripod outside the vehicle, just to the side of the driver's door, and used to take luminance readings throughout the night from this location. Luminance measurements were taken on two surfaces. At 150' in front of and centered on the vehicle was a solid gray card 30 inches tall and 40 inches wide. This card is 40% reflective, and uniform across its surface for accurate luminance readings. The card was rigidly fixed to a tripod base and did not move during the course of the study. The second luminance measuring surface was Cone 3, located 75 feet from the front of the vehicle and 10 feet to the left of center. Figure 2 shows the general setup of the testing including the location of the luminance meter, the nighttime photography calibration charts and LED panel, and luminance target surfaces of Cone #3 and the gray card. Figure 3 is a photograph of the equipment used in the testing.

FIGURE 2 Top down diagram of the testing layout

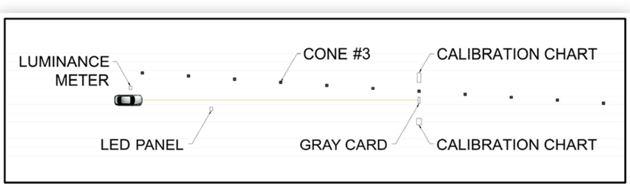


FIGURE 3 Equipment Used in the Testing

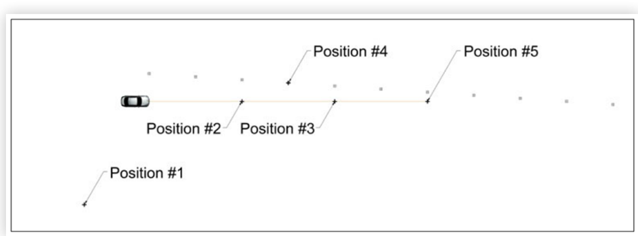
Measurements and Documentation

Illuminance was measured with a Konica Minolta T-10 Illuminance meter with NIST traceability and a factory reported accuracy of ±3%. The meter was calibrated on-site prior to each measurement. Luminance was measured with a Minolta LS-110 Luminance Meter, certified with NIST traceability, last calibrated on October 19, 2017, and having a manufacturer reported accuracy of ±2%. Both devices were recalibrated after the testing on November 1, 2018.

On October 26, 2018, measurements began 30 minutes prior to moon rise, but after astronomical twilight, and continued at 30-minute intervals as the moon started to rise from 8pm until 3am when the moon was 68 degrees altitude and 180 degrees south heading, perpendicular to the center line of the testing setup. This represented a baseline, no moon condition, as well as a maximum moon light contribution condition on the same date. During the testing, data was collected at 5 different positions, which are shown in Figure 4 and labeled Positions #1 through #5.

Position #1 was away from all light sources except for the moon and at this location the change in illumination that results from moonlight contribution only was measured.

FIGURE 4 Top down diagram of the measurement positions

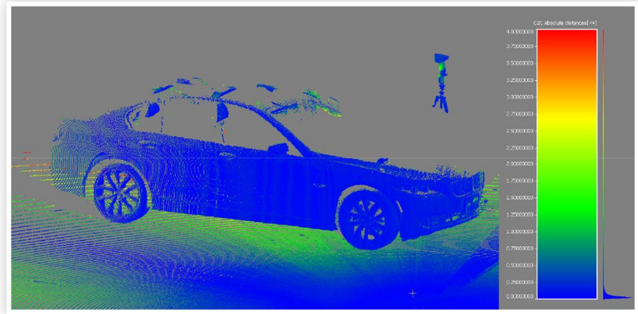


Horizontal measurements were made on the ground, and vertical measurements of moon illuminance were made with the meter held at facing directly at the moon to yield the maximum possible value, rather than placing the meter probe perpendicular to the ground and facing a cardinal direction or location. Positions #2 and #3 were on the centerline of the vehicle at 50 and 100 feet. Illuminance measurements both vertical and horizontal were recorded at these two positions. Horizontal measurements were made with the illuminance meter on the surface of the ground, and the vertical measurements were made with the meter probe at 90-degrees to the surface and facing the vehicle. Measurements at Position #4 were made with the luminance meter mounted on a tripod and taken at the front surface of Cone #3, which was 75 feet in front and 10 feet to the left of center of the vehicle. Luminance measurements made at Position #5 were on the surface of the solid 40% reflective gray card located 150 feet directly in front of the vehicle.

Documentation of visibility for calibrated nighttime photography consisted of taking three photographs from the driver's perspective at each 30-minute interval. The first photograph included the view through the windshield, with a 60-degree field of view, and with a pedestrian, dressed in medium gray clothing, standing 10 feet to the right of centerline at 75 feet from the vehicle. The second photograph had the pedestrian was positioned 150 feet in front of and 10 feet to the right of center of the vehicle. The third photograph did not include the pedestrian in the photograph. A photograph of the surrogate pedestrian used in the testing is shown in Figure 5, including a color calibration chart for assessing the reflectivity and color of the clothing [18].

FIGURE 5 Surrogate pedestrian in medium gray clothing

FIGURE 6 Image analyzing alignment comparison of point cloud data



The vehicle headlamps were set on low beam for all measurements and photographs. A voltage meter was attached to the battery to ensure consistent output of the headlamps due to extended idling. In addition to ensuring consistent voltage, an analysis was performed to ensure there was no shift in the vehicle during the testing. The vehicle was scanned before and after testing, using the same scanner in the same position. The scans were aligned using features of the environment and analyzed for any differences in the distances between separate point clouds using an open-source software [19]. Any change between the positions of points in the scan data can be shown through color variance, *i.e.*, the vehicle would be shown in different colors. Figure 6 shows the results of this comparison, demonstrating that the location of the vehicle is unchanged between the scans, since the vehicle is shown only in blue.

Based on observations made during the December 3, 2017 pilot testing, the sensitivity of the meters for the field study was identified as a potential factor in the results. Accordingly, each instrument was used to make repeated measurements before and after testing. A short break was taken between each reading. For example, during the before (7:30 PM) and after (2:30 AM) periods, ten (10) measurements of illuminance at the road surface were made at each target distance and for each orientation. Similarly, there were fifteen (15) repeated measurements of the luminance of a pedestrian and Cone #3. The same person obtained all measurements throughout the testing. As shown and discussed in the Results section of this paper, the variation in measurements reported by the instrumentation, even when taken back to back and under the same conditions, was significant relative to the potential contribution from the moonlight.

Results

Baseline Measurements

The horizontal and vertical illuminance attributable solely to the moon was measured on December 3, 2017 (super moon) and October 26, 2018 (average full moon). The sky was clear on both nights. The measurements were obtained at an area away from any possible contribution of vehicle headlights. On December 3, 2017, with the moon at less than 8-degrees above the horizon, the horizontal and vertical illuminance was 0.02 lux and 0.06 lux, respectively. On October 26, 2018, with the moon less than 8 degrees-degrees above the horizon, the readings were 0.01 lux and 0.05 lux, respectively. These values are consistent with the reported ranges from other studies for both normal and super moon conditions [5, 6, 7]. The measurements for illuminance from the moon, as measured in the field throughout the night, were consistent with predicted light levels from the moon using computer modeling software designed to estimate illuminance at the Earth's surface for a specific date and weather condition [20].

Baseline measurements were also taken at the beginning of the testing, prior to the moon rising at positions #2-#5 to record the light values at these location prior to any contribution from the moonlight. These values are provided in Table 1.

30-Minute Interval Measurements

The data collection on December 3, 2017 started at 6:30pm and continued until 12:00am, yielding 12 readings, while data collection began at 7:30pm on October 26, 2018 and ended at 3:00am, yielding 15 measurements. Figures 7 and 8 depict the 30-minute interval measurements of horizontal and vertical illuminance attributable to moonlight alone. The altitude of the moon for each date is overlaid on the graph, which shows the increase in illumination following the trend of the rise in altitude. The super moon is denoted in orange bars while the average moon is denoted in blue bars. The notable outlier in December 3, 2017 data is at 11:30pm, when clouds partially occluded the moon. This provides an interesting data point, in that the cloud cover reduced the ambient illumination by one-half, even in the vertical plane, with the probe pointed directly at the moon.

When comparing the ambient illuminance conditions during the super moon and average full moon, the illumination notably doubled due to the super moon. Compared to the horizontal measurements, the vertical ambient illuminance was generally greater, although the method of aiming the probe at the moon likely contributed to the increased values and variability in measurements.

FIGURE 7 Horizontal ambient illumination readings.

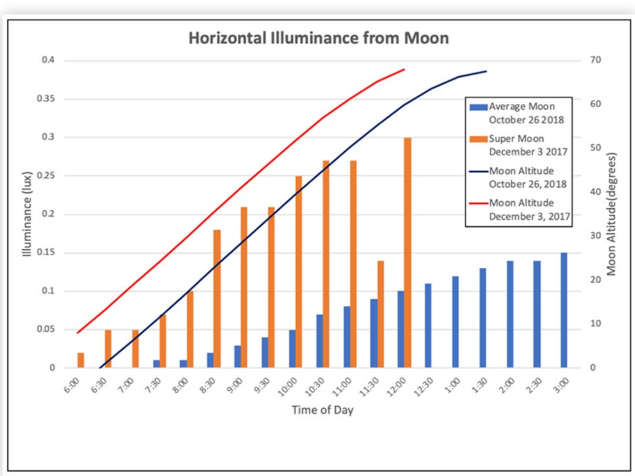
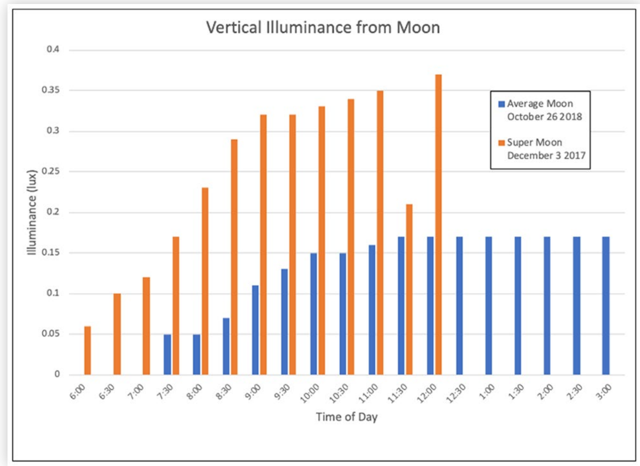


FIGURE 8 Vertical ambient illumination readings.



Given the measurable addition of moonlight, with the values approaching the peak in the last four or five readings, a similar trend may be expected in the readings of illuminance at the road surface and luminance of the target objects. Table 1 shows the measurements obtained during baseline measurements and the readings from the final four 30-min intervals leading to the peak altitude of full moon.

Figure 9 depicts a graph of the 30-minute interval measurements of illuminance with a line overlaid showing the change in ambient illumination. When comparing the baseline value (grey line) to the values of the last four illuminance measurements at the surface in front of the vehicle at 50 feet (blue bars) and 100 feet (orange bars), the variability in the readings appears to have a greater effect than the expected additional illuminance. For example, at 50 feet in the horizontal plane, there was a 0.15 lux increase in illumination between the baseline and peak full moon condition, which roughly corresponds to the change in illuminance between those times, yet the illuminance from the moon increased only 0.02 lux during the preceding three measurements while the change in illuminance at the ground level increased 0.16 lux. Similarly, at 100 feet, where smaller amounts of additional illuminance may be expected to be measurable in comparison to the headlights, the measured changes do not correspond to the absolute measured increase of illuminance from the moon alone. Notably, at both locations, the vertical change was even more variable – a 0.5 lux change at 50 feet between baseline and peak full moon, yet the same value at 100 feet across these periods.

The luminance measurements showed a similar trend, or lack thereof. Figure 10 depicts a plot of the interval measurements of luminance of the Cone #3 and solid gray card and an overlay of the ambient illuminance attributable to the rising moon. As shown, the measured luminance did not follow any type of trend that could be attributed to a clear increase in ambient illuminance.

Sensitivity Measurements

As described in the previous section, a series of repeated measurements were collected at the beginning and end of the

TABLE 1 Measurements obtained prior to moon rise and at full moon.

	Baseline	Full Moon			
Ambient Illuminance due to Moon (lux)					
Horizontal					
10/26/2018	0.01	0.13	0.14	0.14	0.15
12/3/17	0.02	0.27	0.27	0.14	0.30
Vertical					
10/26/18	0.05	0.17	0.17	0.17	0.17
12/3/17	0.06	0.34	0.35	0.21	0.37
Illuminance at Road Surface (lux)					
50 feet					
Horizontal	7.55	7.44	7.49	7.72	7.70
Vertical	99.4	99.10	99.20	99.80	99.90
100 feet					
Horizontal	2.56	2.65	2.60	2.71	2.69
Vertical	37.70	37.30	37.20	37.70	37.70
Lumiannce of targets (cd/m2)					
cone 3	6.58	6.6	6.76	6.71	6.72
Pedestrian Chart at 150 feet	1.53	1.67	1.68	1.69	1.71

FIGURE 9 Depicting measurements of horizontal illuminance in front of test vehicle at 50 feet and 100 feet (columns, left axis) and the corresponding measured ambient illuminance (line, right axis).

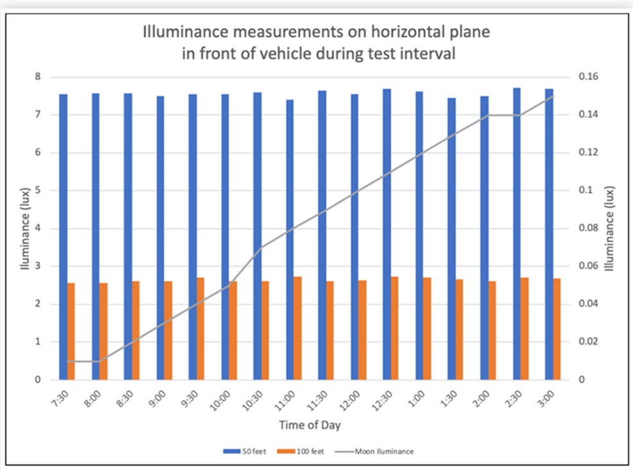
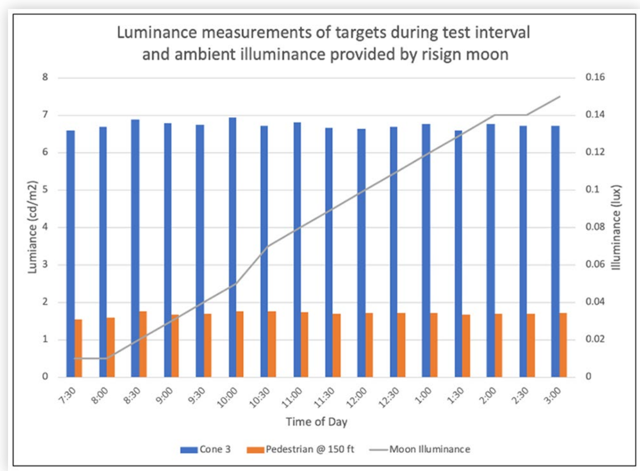


FIGURE 10 Depicting luminance of cone and pedestrian targets (columns, left axis) and an overlay of the measured ambient illuminance (line, right axis).



evening. This was done to assess the variation in measurements that may result from the use of the light measuring devices in a field study. Table 2 provides the descriptive statistics for the readings. As shown, the repeated measurements indicate a decrease in the mean illuminance at the road surface at 50 feet in both the horizontal and vertical plane. This simply could not occur, given the known increase in ambient illuminance. Similarly, even though the luminance meter was mounted on a tripod and the same spot was measured on the target, the mean values of the 7:30pm and 2:30am measurements indicate a decrease in the luminance of Cone #3 located 75 feet away from the vehicle, but a small increase in the luminance of the solid gray card target located 150 feet from the vehicle. While the variation in measurements was small, there was nonetheless a difference, demonstrating that even taking the same measurement at the same location under the same conditions can result in small differences in the field.

Adjusted Position to Match Baseline Measurements

One of the planned goals of this study was to determine an adjusted position for the illuminance meter on the roadway, or for the distance of the solid gray card from the vehicle when adjusted to match the baseline measurements, *i.e.*, move the meter or target away from the vehicle at peak full moon to a distance when the new location would result in the same measurements as baseline. However, as the 30-minute interval and repeated measurements both demonstrated significant

TABLE 2 Descriptive statistics of repeated readings

	7:30				2:30			
	Mean	S.D.	Min	Max	Mean	S.D.	Min	Max
Illuminance at Road Surface (lux)								
50 feet								
Horizontal	7.80	0.09	7.68	7.92	7.69	0.12	7.52	7.87
Vertical	102.78	0.35	102.30	103.20	98.63	0.91	97.60	99.90
100 feet								
Horizontal	2.64	0.04	2.55	2.71	2.70	0.04	2.66	2.66
Vertical	38.62	0.16	38.30	38.80	37.23	0.25	36.90	37.80
Luminance of targets (cd/m2)								
cone 3	6.69	0.05	6.61	6.75	6.61	0.04	6.54	6.69
Pedestrian Chart at 150 feet	1.54	0.04	1.48	1.63	1.62	0.03	1.56	1.67

variability in readings, making meaningful assessment of an added distance no longer feasible.

Photographic Documentation

Lacking a consistent increase in visibility attributable to the increase in moonlight using common light measuring instruments, this study included an alternative means of measuring moonlights contribution through calibrated nighttime photography. To document the visibility during this testing and evaluate the effect moonlight has on calibrated images that record nighttime visibility, analysis was performed throughout the night using accepted methodologies for calibrated photography [21, 22, 23]. Inside the vehicle, and from the driver's perspective, a Sony a7s camera was rigidly mounted at the driver's eye position with suction mounts and stabilizing arms. An Atomos Shogun field monitor was used to calibrate the camera and adjust camera settings to match the view available from the driver's perspective. Figure 11 shows the calibration equipment utilized in the study.

Photographic documentation began at 7:30pm when there was no moon, hence recording the driver's visibility for only the light contribution from the vehicle headlamps. This established a visual baseline in the photographs. As the moon began to rise and continuing until the moon was at full height in the sky, photographs were taken at 30-minute intervals using the same calibration settings, so that the subsequent recorded images would reflect any increase in visibility attributable to the moonlight. In other words, as the moon rose and contributed light, the photographs should appear brighter if there is any measurable increase in light since the camera's setting were unchanged. These images can then be compared to each other to determine the effect that moonlight has on visibility over each 30-minute time interval from 7:30pm to 2:30am.

Since the first calibrated image was taken with no moon present, the subsequent images, where moonlight began to add to the total light recorded by the camera, would provide a visual record of the light contribution for visibility. Figure 12 shows an image from the driver's perspective showing the 7:30pm testing time with no moon contribution. Figure 13 shows the last photograph taken, when the moon contributing is at a maximum. When comparing the no moon photograph to the full moon photograph, there was no observable difference of the visibility of the pedestrian at either the 75-foot or 150-foot positions. Even when the photographs were analyzed in RAW format, at pixel level, in photo editing software there

FIGURE 11 Setup of the nighttime photography equipment

FIGURE 12 Photograph documenting contribution from no moon (7:30pm), pedestrian at 75 feet

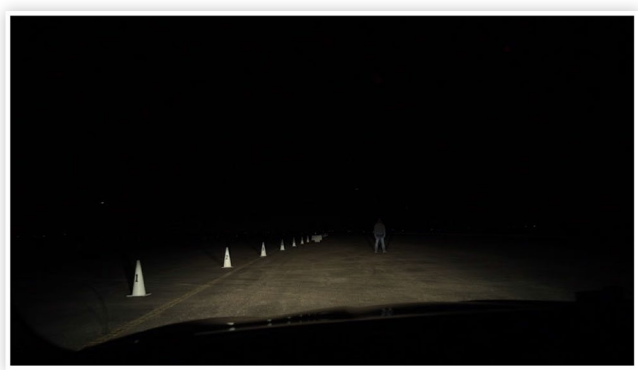


FIGURE 13 Photograph documenting contribution from full moon (2:30), pedestrian at 75 feet

was no visible difference in the visibility of the pedestrian between any of the photographs taken throughout the night.

To further analyze if the sensors on the camera recorded a change in luminance, the raw images were analyzed in Adobe Photoshop and selections averaged to determine the change of luminance intensity between the first photograph taken and the last photograph. These luminance intensity values were compared between photographs to numerically evaluate the effect that the moon light has on the visibility of the pedestrian. Figures 14 and 15 show the two photographs analyzed with the locations denoted where intensity values were obtained.

FIGURE 14 Photograph at 7:30pm with light intensity measurements

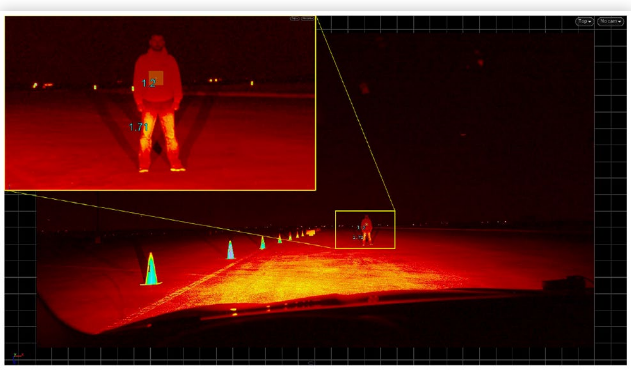


FIGURE 15 Photograph at 2:30am with light intensity measurements

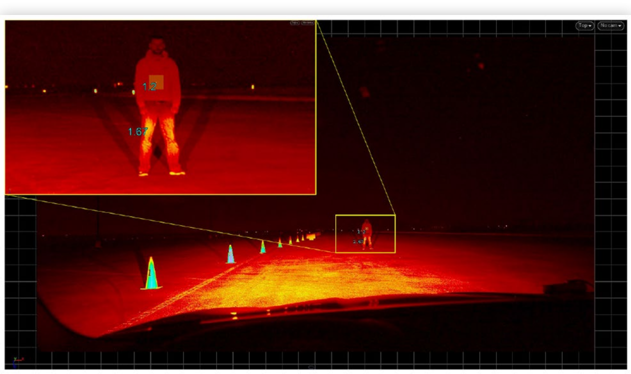


TABLE 4 Numerical results of intensity measurements

Photograph	Luminance Intensity (shirt)	Luminance Intensity (pants)
7:30 PM	1.2	1.71
2:00 AM	1.2	1.67

Table 4 shows the results of the pixel analysis. The luminance intensity for the pants at 2:30am is actually lower than at 7:30pm, likely a result of a small shift in the surface of the fabric of the jeans between the two photographs.

Discussion

Measurement of the Contribution of Moonlight

The change in ambient illumination with the rise of the moon was measured on two occasions, one of which was an average full moon and the other a rarer event, a super moon. When the illuminance meter was positioned to read the most favorable value during the super moon, the maximum illuminance was 0.37 lux. A more likely expected change of illuminance between a full and new moon would be approximately half this value, or 0.17 lux, as measured at the peak altitude on an average full moon night.

While the ambient illumination associated with these lunar contributions is measurable, whether the increase can be consistently and accurately measured in association with other sources of lighting is another question. In the testing that coincided with the December 2017 super moon, horizontal and vertical illuminance was collected at 50 feet and 100 feet, as were luminance readings from live pedestrians dressed in grey sweat shirts and jeans. However, upon processing the data, very unexpected and unexplainable results were found. This led to a thorough examination of the testing process, which found that controls were likely too lax with regard to monitoring vehicle power, handling of the test equipment, consistency in measuring location on the ground and target, and consistent positioning of the live targets. Hence, a second test was conducted, with greater process controls. Yet, even with much more stringent controls, the variability associated with making measurements in the field overwhelmed the ability to measure the minute addition of light from the full moon.

This is consistent with the findings of studies that have evaluated visibility of objects and pedestrians in relation to the illuminance from low beam headlights. Consider, for example that the reported necessary levels for detection of dark objects at 15 to 20 lux, gray colored objects at 3.2 to 5 lux, and white or lighter colored objects at 1 to 2 lux [24, 25, 26, 27], potentially a magnitude of order greater than the contribution from the moon. Even the addition of 0.3 lux, which would on only very rare conditions and occasions, is not likely to lead to a corresponding shift between established demarcations of target visibility, *i.e.*, the light from the moon will not be sufficient to make at dark object, needing 15 to 20 lux and predicted visibility at less than 155 feet, now visible at 185 feet or more. Rather, the potential contribution could be for white or lighter color objects, and even then, any expected increase in lighting would not be significant enough to lead to a difference in detection distance.

Adjusting Photographs to Account for Moonlight Contribution

In review of the calibrated photographs, there was not an observable difference in visibility between no moon and a full moon condition, despite the increase in ambient light recorded, as demonstrated in Figures 7 and 8. Since there was no noticeable difference in the visibility of the photographs, an analysis was performed to determine if adjusting settings on the camera, even at the lowest settings, resulted in noticeable visibility differences in the photographs. In other words, when the camera settings are adjusted to brighten or darken the images at the smallest increment, would this change be observable and measurable? If this were the case, then adjusting for moon conditions by changing the camera settings would not be applicable, since the increase in visibility by the moon would be less than the increase in visibility by the camera setting adjustment. To perform this analysis, the exposure settings were adjusted in the raw files of the 7:30pm testing image and the 2:30am testing images to increase their intensity values and visual appearance by 1/3rd of one f-stop – the smallest increment adjustment to the aperture in the camera. Since the photographs were recorded in high definition raw format, adjustments to the exposure in the digital editing program has the same effect as adjusting the actual camera settings in situ. In the 7:30 pm photograph the exposure was change from 5.6 aperture to 5.0 aperture, an increase in 1/3rd of one f-stop. This same increase was performed on the photograph from 2:30am. Review of the images show a discernible difference in just 1/3rd of one f-stop adjustment, both visually and numerically when measured. Hence, any adjustment to the camera settings, even for the lowest increment, yielded a greater change in visibility than the effect from the moon, *i.e.*, adjusting camera settings for any moonlight contribution would not be reasonable, since the increment of change in the camera would have a greater effect on the image that the moonlight. Table 5 shows the results in luminance intensity comparison that results from a 1/3rd increment adjustment in aperture for the photograph from 7:30pm. Results for the photograph at 2:30am were the same offset - an increase in 1/3rd of one f-stop resulted in the intensity of the shirt increasing from 1.2 to 1.22, whereas there was no measurable difference in intensity between the 7:30pm shirt value and 2:30am shirt value. Similarly, the change in intensity for the pants was greater when adjusting 1/3rd of a f-stop than between the two time frames of photographs.

TABLE 5 Numerical results of intensity measurements for 7:30pm

Reading Location	Original Intensity	Adjusted by 1/3 f-stop
Shirt	1.2	1.22
Pants	1.71	1.95

Contribution of Moonlight to Detection of Objects and Pedestrians

Sivak et al. concluded "*pedestrian crashes are sensitive to differences within low levels of ambient illumination*," yet provided no explanation for why or how this could be. The measurements of changes in target luminance, especially the pedestrian target at 150 feet, do not provide an explanation or basis that full moon leads to significantly improved visibly and finding that pedestrian fatalities on nights with a new moon would be 22% higher than on nights with a full moon.

While the current findings support that the addition of moonlight could have a maximum of 0.3 to .4 lux from the super moon, this does not explain why such minimal levels of illumination from the moon would enable drivers to detect and recognize pedestrians at sufficiently greater distances to lead to avoidance on a night with a full moon as compared to a new moon. One potential explanation would be that the full moon provides ambient lighting for the pedestrians, assisting in the pedestrian maintaining a safe position out of the travel path of vehicles.

One notable, albeit subjective finding from the current testing was that the dark-adapted experimenters found that the full moon, even in early stages with the moon lower in the sky, provided more than ample illumination to move about in areas not illuminated by headlights. This is not an uncommon experience. Therefore, from the pedestrian's perspective, movements at a walking speed in an environment illuminated by additional light from the moon can and likely does make a difference in visibility. This is especially so if the pedestrian had visually adapted to the dark conditions. This also likely lends to the belief that the moon can significantly contribute to detection of pedestrians by drivers, *i.e.*, I can see well enough to walk, the driver should be able to see me walking here.

To put aside at least one other potential explanation for the findings of Sivak et al., numerous studies have reported that there is no association of lunar cycle to attempted or successful suicide [28, 29]. Yet, to further add confusion to the findings of Sivak et al., aggressive human behaviors that lead to robbery and assault, burglary and theft, offenses against family and children, drunkenness, and disorderly conduct have been reported to occur significantly more frequently during the full moon phase [30].

Theoretical Increase of Visibility Assuming Moonlight is Additive

The research conducted in this testing sought determine if an adjustment factor could be established to account for a visibility study conducted on a moonless night when the collision occurred under a full or partial moon. The findings of Sivak et al. cannot be supported by the field study and are generally inconsistent with the findings of more recently published studies, which would indicate that pedestrians crashes should increase during a full moon rather than a new moon, especially if the explanation for the increase motorcycle and vehicle crashes includes factors such as distraction by the moon and a greater increase in movement during full moon condition. Nonetheless, the study did not find a measurable increase in characteristics related to visibility due to the contribution of moonlight, either through commonly utilized instruments for measuring the contribution of light or through analysis of nighttime photographic taken using published techniques. Despite the resulting conclusion that moonlight would not likely increase visibility for a driver encountering typical roadway hazards, the physical principles of light suggest that there could be some additional light, however small. To explore this concept, a mathematical estimate for the increase in visibility was performed.

To determine the additional distance beyond the 50-foot and 100-foot markers that the lower lux values would be located under the full moon light condition, a lux to distance relationship was created based on the testing from that night. Given the additive nature of light, and assuming an increase in maximum illuminance provided by a full moon of 0.2 lux along with the 5 lux decrease in illuminance from 50 feet to 100 feet readings, a linear relationship can be determined from the collected data. This linear relationship resulted in the low lux reading at 50 feet increasing to a distance of 51.2 feet under the full moon condition. For the low lux reading at 100 feet, in the full moon condition this same reading would be shifted to 101.2 feet. Thus, an increase of approximately 1.2 feet may be expected to occur from a no moon condition to a full moon condition when using a linear relationship. Figure 16 shows the distance shift from no moon to a full moon in illuminance measurements at 50 and 100 feet.

Since the falloff of light from headlamps is not linear, an additional analysis was performed where a non-linear average falloff and lux to distance relationship was calculated. This

FIGURE 16 Distance shift for illuminance values (no moon and full moon)

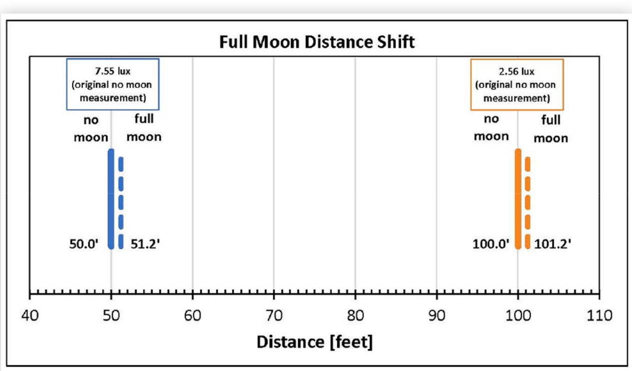
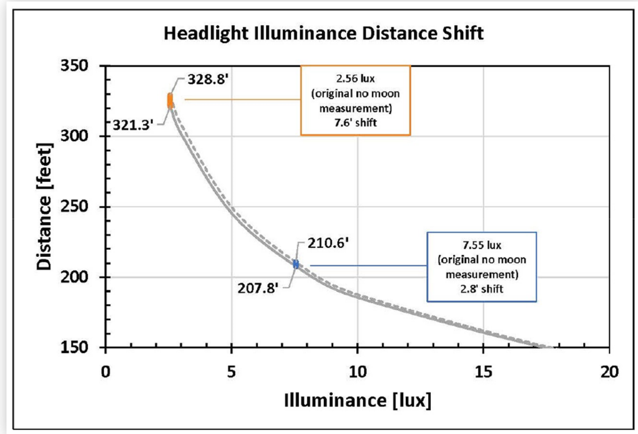


FIGURE 17 Distance shift for headlight illuminance values (no moon and full moon)



nonlinear relationship was based on the iso-illuminance diagram of median U.S. low beam headlamps [31]. By plotting the distance versus lux relationship established by this diagram, a more accurate estimate for how the lux level would shift was established. Using the average additive illumination from moonlight of 0.2 lux found during the study, the effect of the addition of 0.2 lux to headlight beam illuminance measurements was analyzed. The addition of moonlight illuminance resulted in a non-linear increase in distance from the headlamps for a given lux reading. Figure 17 shows the original headlamp illuminance readings plotted against distance (solid grey line) and the adjusted readings including additive moonlight illuminance (dashed grey line). The distance shifts at 2.56 lux and 7.55 lux are highlighted for comparison to the linear relationship from moonlight study results.

As shown in Figure 17, the distance shift was not linear. At 7.55 lux, the distance shifted 2.8 feet, which adds 1.4% to the original distance measurement for headlamp illuminance at 7.55 lux. At 2.56 lux, the shift increased to 7.6 feet, adding 2.4% to the original distance measurement for headlamp illuminance of 2.56 lux. Using this non-linear relationship resulted in the low lux reading at 50 feet increasing to a distance of 50.7 feet under the full moon condition, while the low lux reading at 100 feet, under the full moon condition this same reading would be shifted to 102.4 feet. A conservative 'rule of thumb' can be provided from the estimated shift in headlamp illuminance illustrated above: if the illuminance measurement is recorded on no moon between 50-250 feet from the headlamps, the distance that this same value will exist on a full moon might increase by a maximum of 1.5%; when measurements are made on no moon conditions from 250-350 feet, the distance might increase a maximum of 3% to account for full moon conditions. Adjusting visibility according to this mathematical model is only theoretical, however, as the in-field testing shows that no adjustment in visibility would be needed between a no moon and full moon condition.

Conclusions

The findings of the present study are that while the contribution of light from a full moon is measurable, the additional light is unlikely to be meaningful when assessing visibility of a driver using headlights. The sensitivity of commonly utilized equipment, which was utilized in a test protocol designed to minimize the influence of the human user, was unable to demonstrate a consistently measurable change in two metrics most commonly associated with visibility assessments. Even calibrated photographs taken in accordance with published methods did not demonstrate a difference in visibility due to the contribution of the moon. Hence, the main conclusion is that the additionally illuminance from the moon would be unlikely to affect assessments of visibility conducted on nights with moon phases that might differ from the subject collision for typical hazards encountered in the roadway.

References

1. Verity, H., *We Landed by Moonlight* Second Revised Edition (Crecy Publishing, 1995).
2. Henderson, K., *Driving by Moonlight* (Seal Press, 2003).
3. “Moonlight for Headlights”, The Lion, May 1946
4. Safe Drive Training Company, Brisbane Australia, “Safe Drive Directory”, Chapter 25, 1.
5. Biberman, L.M., Dunkelman, L., Fickett, M.L., and Finke, R.G., “Levels of Nocturnal Illumination,” No. IDA/HQ-66-4569, Institute for Defense Analyses Alexandria VA Research and Engineering Support Div, 1966.
6. Brown, D.R.E., “Natural Illuminance Charts,” Report No. 374-1, Department of the Navy, Bureau of Ships, Washington, DC, 1952.
7. Kyba, C., Mohar, A., and Posch, T., “How Bright Is Moonlight? - A&G,” *Astronomy and Geophysics* 58(1):1.31-1.32, 2017.
8. Leibowitz, H.W. "Ambient Illuminance during Twilight and from the Moon," in *Night Vision: Current Research and Future Directions. Symposium Proceedings*, 1987, 19-22.
9. Rea, M.S., editor, *The IESNA Lighting Handbook* 9th Edition (New York: IESNA, 2000).
10. Redelmeier, D.A. and Shafir, E., “The Full Moon and Motorcycle Related Mortality: Population Based Double Control Study,” *BMJ* 359:j5367, 2017.
11. Onozuka, D., Nishimura, K., and Hagihara, A., “Full Moon and Traffic Accident-Related Emergency Ambulance Transport: A Nationwide Case-Crossover Study,” *Science of the Total Environment* 644:801-805, 2018.
12. Sivak, M., Schoettle, B., and Tsimhoni, O., “Moon Phases and Nighttime Road Crashes Involving Pedestrians,” *Leukos* 4(2):129-131, 2007.
13. Williams, D., “Moon Fact Sheet,” NASA Space Science Data Coordinated Archive, National Aeronautics and Space Administration, 23 Dec. 2016. Web. 13 Apr 2017.
14. Denver, C., “USA - Moonrise, Moonset, and Moon Phases,” December 2017, https://www.timeanddate.com/moon/usa/denver.
15. Muttart, J.W., *Driver’s Responses in Emergency Situations* (Crash Safety Solutions, February 2017), 103.
16. Ayres, T.J., “Psychophysical Validation of Photographic Representations,” Safety Engineering and Risk Analysis 1996, SERA-Vol. 6 American Society of Mechanical Engineers.
17. Ayres, T.J and Kubose, T., “Calibrating a Contrast Sensitivity Test Chart for Validating Visual Representations,” Human Factors and Ergonomics Society, 59th Annual Meeting, 2015.
18. KODAK Color Card/R-27, “KODAK,” Eastman Kodak Company, Oct. 19, 2009. Web: June 27, 2017.
19. CloudCompare (Version 2.10 Alpha), [GPL software], http://www.danielgm.net/cc/.
20. US Naval Observatory, “Computer Program for Sun and Moon Illuminance with Contingent Tables and Diagrams,” Sun Moon.exe Windows Application, February 19, 1987, P.M. Janiczek and J.A. DeYoung.
21. Neale, W.T.C., Marr, J., and Hessel, D., “Nighttime Videographic Projection Mapping to Generate Photo-Realistic Simulation Environments,” SAE Technical Paper 2016-01-1415, 2016, doi:10.4271/2016-01-1415.
22. Ayres, T.J. and Kayfetz, P., *Calibration and Validation of Videographic Visibility Presentations* (Seattle: American Academy of Forensic Sciences, 2010).
23. Holohan, R.D., Billing, A.M., and Murray, S.D., “Nighttime Photography - Show It Like It Is,” SAE Technical Paper 890730, 1989, doi:10.4271/890730.
24. Edwards, C.J. and Gibbons, R.B., “The Relationship of Vertical Illuminance to Pedestrian Visibility in Crosswalks,” Transportation Research Board of the National Academies, 2009.
25. Kosmatka, W., “UDC - Uniform Detection Characteristic for Detecting Roadway Obstacles,” SAE Technical Paper 2006-01-0948, 2006, doi:10.4271/2006-01-0948.
26. Muttart, J. W. and Romoser, M., “Evaluating Driver Response and Ability to Avoid a Crash at Night,” in *Proceedings of the 1st Joint ITAI-EVU Conference*, Hinckley, Leicestershire, England, 2009.
27. Kledus, R., Bradac, A., and Semela, M., “Comparative Perception of Objects by Drivers from Stationary and Moving Vehicles in Regular Road Traffic”, European Association for Accident Research and Analysis [EVU], 2010.
28. Martin, S.J., Kelly, I.W., and Saklofske, D.H., “Suicide and Lunar Cycles: A Critical Review Over 28 Years,” *Psychological Reports* 71(3):787-795, 1992.
29. Gutierrez-Garcia, J.M. and Tusell, F., “Suicides and the Lunar Cycle,” *Psychological Reports* 80(1):243-250, 1997.

30. Tasso, J. and Miller, E., "The Effects of the Full Moon on Human Behavior," *The Journal of Psychology* 93(1):81-83, 1976.
31. Schoettle, B., Sivak, M., and Flannagan, M.J., "High-Beam and Low-Beam Headlighting Patterns in the U.S. and Europe at the Turn of the Millennium," UMTRI-2001-19, May 2001.

Acknowledgments

The authors of this paper would like to thank Drew Donaldson and David Hessel for their contribution in helping analyze the data collected during this study, and for their insight and ideas that helped improve the veracity and clarity of this research. Thanks to you both.

Contact Information

William Neale, M. Arch.
Kineticorp, LLC
(303) 733-1888
wneale@kineticorp.com
www.kineticorp.com

ISSN 0148-7191