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Feasibility of Simple Digital Photometric Techniques for Evaluating Headlamp Illumination

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Abstract

Methods for characterizing the performance of vehicle headlamps in field or in-use conditions from the literature were summarized, and overall, the review of the literature suggested that a simple digital photometric imaging technique could be a useful way to provide a preliminary characterization of headlamp beam patterns as they might be expected to perform in the field. The results of measurements made using a calibrated digital camera are summarized and discussed in terms of their potential strengths and weaknesses.

Keywords: .... headlamp, photometry, digital photography,
visual optical aim, visibility, glare

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ABSTRACT

Methods for characterizing the performance of vehicle headlamps in field or in-use conditions from the literature were summarized, and overall, the review of the literature suggested that a simple digital photometric imaging technique could be a useful way to provide a preliminary characterization of headlamp beam patterns as they might be expected to perform in the field. The results of measurements made using a calibrated digital camera are summarized and discussed in terms of their potential strengths and weaknesses.

INTRODUCTION

This report contains a review of the relevant literature on the photometric characterization and measurement of vehicle headlamps, and the results of several simple, preliminary measurements to develop and apply techniques for evaluating headlamp beam patterns. The literature review focuses on three main topics relating to the photometric study of headlamps: vehicle body dynamics, visual target locations and glare implications, and previous photometric headlamp performance evaluation techniques. Subsequent sections of the present report summarize the work done to investigate the feasibility of evaluating headlight beam patterns with the use of a digital single lens reflex (DSLR) camera. This work consisted of five main sections: experimental setup, data capture, camera calibration, data and results, and conclusions.

LITERATURE REVIEW

Headlamps with higher beam intensity and tighter light cut-offs are becoming increasingly common on motor vehicles due to their higher effectiveness when compared to older technology. These headlamp systems should not appear very glary because their cut-off design should prevent excessive amounts of light from entering an oncoming driver's visual field. However, the exceptional number of complaints to the government about glare from new headlamp types suggests that the cut-off design approach might be breaking down in practice. The purpose of this project is to develop an image-based approach to predicting when and how this breakdown might occur.

Vehicle Dynamics

One factor which may affect how much glare a headlamp set produces is the dynamics of the vehicle's body. The dynamics of a vehicle body may be characterized by velocity and rotation in three axes as shown below in Figure 1. Fukuba et al. (2003) used four GPS receivers (one on each corner of the vehicle) and three gyros (one for each roll axis) to characterize the attitude of the tested vehicles' bodies. The ultimate purpose of the Fukuba et al. work was to develop a system which characterizes and predicts vehicle body behavior.

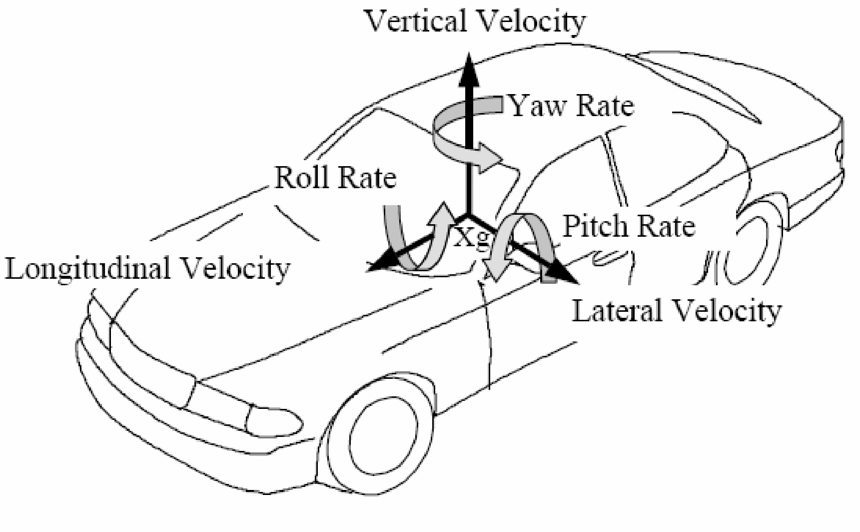


Figure 1. *Physical Descriptors of Vehicle Body Dynamics (Fukuba et al., 2003).*

While these researchers' work doesn't directly relate to this research topic, their approach to data collection is suitable for this topic. The headlight beam is affected most by pitch. Roll may also play a minor role. Yaw and the velocity in the three axes will have the least effect on the headlight beams' aim.

Visual Target Location and Glare Implications

Bhise et al. (1977) developed a statistical distribution for pedestrian position likelihood. To formulate the distribution the authors analyzed four years of vehicle/pedestrian collision data from King County, Washington. The nearly 140,000 incidents over the course of the four years included both rural (unlighted roadways) and urban (lighted roadways) accidents. Figures 2a and 2b, below, show the probability distributions for pedestrian locations. Figure 2a shows the probability of pedestrian presence across the width of the roadway (the roadway is assumed to be a two lane, 24 foot wide surface). Figure 2b shows the longitudinal position probability function for the same roadway. Both plots assume that impact occurs between vehicle and pedestrian, and are valid for the moment five seconds prior to impact.

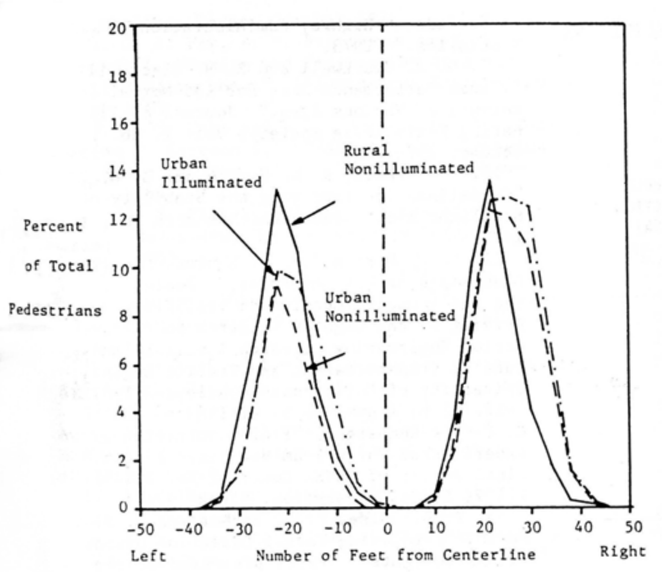


Figure 2a. *Pedestrian Location, 5 Sec. Prior to Impact (after Bhise et al., 1977).*

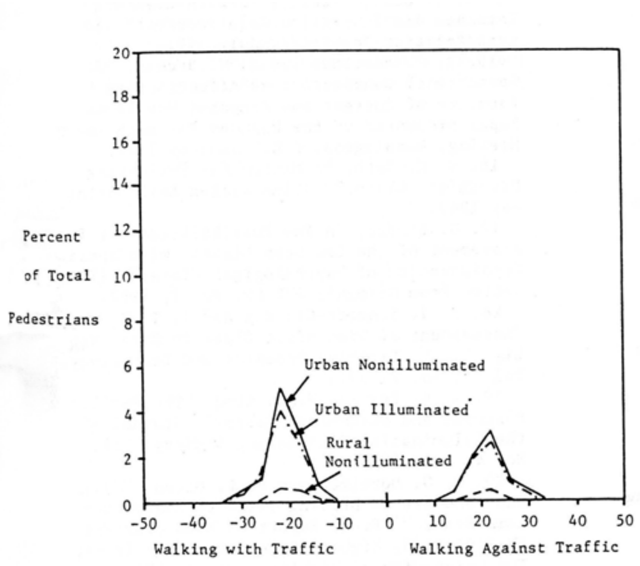
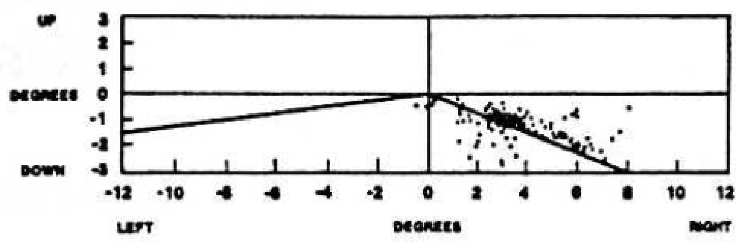
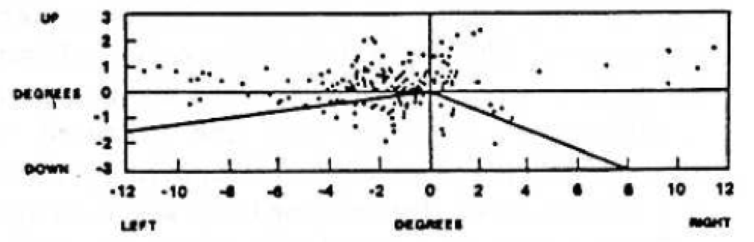


Figure 2b. *Pedestrian Location, 5 Sec. Prior to Impact (after Bhise et al., 1977).*

In a paper written by Perel (1985) additional visual targets are suggested. In addition to pedestrians, oncoming drivers, delineation lines, and road signs are suggested for visibility studies. Figure 3 shows the location probability density of delineation lines and oncoming drivers.



DELINEATION TARGETS



ONCOMING DRIVERS

Figure 3. *Target Location Probability Densities (after Perel, 1985).*

A study performed by Bacelar (2003) illustrates how serious the implications of glare can be for oncoming traffic. Bacelar investigated visibility levels for drivers on street lit and non street lit roads using high and low beams. He then repeated the experiments in the presence of oncoming glare. To evaluate visibility levels, the author used a square target with surface area of 400 cm2 and reflectance of 20%. The luminance of the target was measured from the driver's eyelevel, as was the illuminance from the oncoming glare (when present). The visibility level was then calculated with this information using the Adrian model (1989).

Bacelar found that, for targets at a distance of 40 meters from the observer, visibility levels ranged from 13 to 45 depending on where across the roadway the target was located. The author claims that a minimum visibility level of 25 needs to exist to maintain safety. The author found that for a target distance of 90 meters, the only configuration that resulted in a satisfactory visibility level ($3<VL<10$) was with high beams and no road lighting. In addition, he found that headlights in conjunction with street lighting performed worse than either by itself.

The addition of glare to these conditions produced results with very serious implications. Bacelar first tested the results of glare in the presence of street lighting. He found that if the driver looks into oncoming low-beam headlamps, the visibility level is degraded by at least 30% and as much as 50% if more than one set of oncoming headlamps is present. This is significant because it implies that the target would be invisible to the driver experiencing the glare. If the driver looks straight ahead visibility level is diminished by 15-20%. Bacelar then tested the impact of glare without the presence of street lighting. If the driver is looking into the oncoming glare, then the targets may be considered invisible for at least 35 m after passing the glare source. If the driver simply looks ahead, then visibility level is reduced by 40-50%.

Photometric Headlamp Performance Evaluation

In the 1970's, Ford developed a headlamp beam pattern assessment program called CHESS (Comprehensive Headlamp Environment Systems Simulation). Michael Perel (1985), of NHTSA, wrote a paper critiquing the function of this software. According to Perel the CHESS system evaluates beam performance based on three main factors (right side lane delineation, discomfort glare to oncoming traffic, and pedestrian visibility) and produces a "Figure of Merit" (FOM) for the beam being tested. Figure 4, below, shows the function of the CHESS Program.

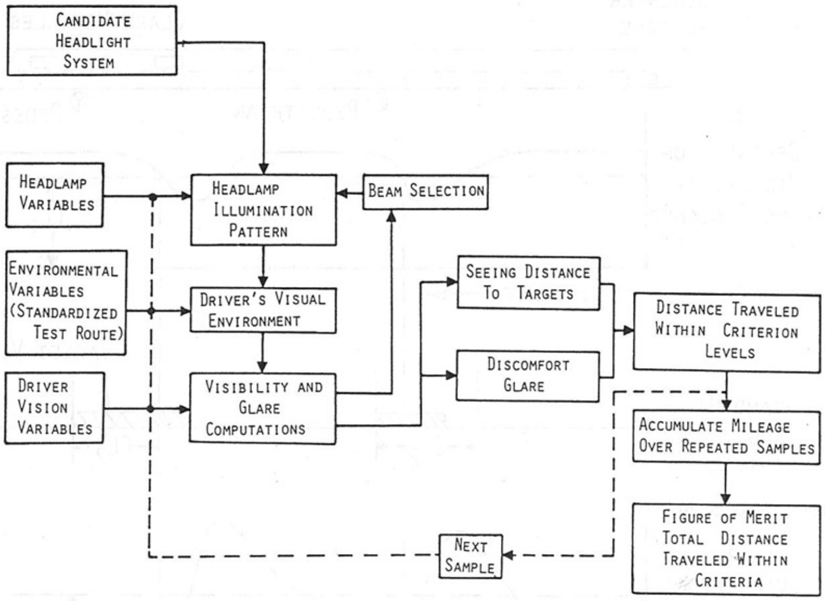


Figure 4. *Block Diagram of the CHESS Program (after Bhise et al., 1985).*

According to Perel, the CHESS Program measures the amount of time that the three criteria are simultaneously satisfied and compares it to the total amount of time to determine the figure of merit. The program requires the lane delineation to be visible for at least 2 seconds travel time, the detection distance of pedestrians must be greater than or equal to the stopping distance for the speed traveled, and that the deBoer comfort rating must have a value of 4 or better.

The lane delineation and pedestrian detection is positively correlated to the amount of forward light a headlamp system produces. However, glare comfort ratings are negatively correlated to the amount of front-light. Perel notes that the FOM for a headlamp system is highly dependant on how each of the three variables is weighted. Along this line of reasoning, drastically different headlamp systems can theoretically have the same figure of merit as a well designed headlamp system even if they contain serious deficiencies.

In his conclusion, Perel makes the following suggestions for improving the evaluation of systems: make the lane delineation evaluation more beam sensitive, factor in glare from other vehicles for visibility calculations, and make sign visibility a testing criterion. He also recommends the separate reporting of the systems' performance on the various criteria. By reporting the values separately, the pros and cons of the systems can be more readily evaluated.

Preliminary Conclusions from Literature Review

As was stated earlier, new headlight designs have produced massive amounts of complaints from the public about glare. As the literature review has shown, glare is a serious impairment for night time drivers. The development of a method of predicting the performance of headlamp systems through photometric measurements is a worthwhile endeavor. Important parameters, such the magnitude of vehicle body movements need to be more closely considered in such a model, as they may contribute significantly to headlamp misaim.

The literature review suggested that the following research activities would be useful to assess whether, and how, digital photometric techniques might be suitable in the preliminary evaluation of headlamp beam patterns:

- Identify the magnitude of vehicle body movements during steady state driving, acceleration, deceleration, and turning in both city and country driving environments.
- Photometrically characterize several headlamp systems using RAW format camera files.
- Develop a metric to computationally analyze the data collected to predict the performance of headlamp systems.

The subsequent sections of the report describe the methods, results and analysis methods developed to meet these objectives.

EXPERIMENTAL SETUP

The equipment used to collect the data from the headlamp patterns consisted of a screen, headlight system, and camera system. In describing the configuration of the experimental setup, the following axis conventions will be used: X – left to right along the length of the screen, Y – top to bottom of the screen, Z – through the axis of the camera's lens (orthogonal to the flat face of the screen)

Screen

The screen used consisted of plotter paper rolled out and taped to a wall. The plotter paper used is nominally 36 in. wide, so each course of paper was 36 in. high. Two courses of paper were used and taped together and to the wall using white gaffer's tape. The screen was positioned to be approximately 6 in. above floor level and measured nominally 20 ft in width. The screen was not adjusted to be plumb in the YZ plane due to the fact that it did not have any structure to hold it away from the wall (which was taken to be nominally plumb in the YZ plane).

A torpedo style level was used along with a carpenter's square to mark two perpendicular lines (12 in. in length) that were parallel to the X and Y axes. These were used as a level and length reference to calibrate the image dimensionally in during post processing.

Headlamps

The headlamps tested (VOL and VOR) were mounted to an aluminum plate with c-lamps. Both headlamps had a flat-bottomed housing, which was used to as the reference to align the assemblies with the aluminum plate. The square mounting bosses were used with machinist's square to align the headlamp housings with the aluminum plate secured to the tripod head. The pitch and roll controls of the tripod were used to level the headlamp along the X and Z axes. The third degree of freedom (rotation about the Y axis) was adjusted by eye such that the origin of the beam pattern fell approximately in the center of the screen. The headlamp filament was placed at a distance of 25 ft from the screen.

It is recognized that typically, headlamp photometry is performed at distances longer than 25 ft (25 m is typically recognized as the distance used for photometry in regulations of the Economic Commission on Europe [ECE]). Recognizing the limitation of making measurements at this closer distance, the present measurements were made in order to 1) test whether the camera technique used could provide accurate photometric measurements at all, and 2) to provide very preliminary, coarse looks at photometric beam performance that might be useful in characterizing these systems in field experiments without the necessity of relying on extensive photometric testing.

The headlamp was powered using a regulated laboratory DC power supply. The voltage was adjusted to 12.8 volts. The headlamps were allowed to stabilize for 10 minutes. After this time had elapsed, the voltage was checked and reset to 12.8 volts if necessary.

Camera

The lens/camera system consisted of a Canon 30D DSLR camera (serial number 1120807021) and Tamron 28-80mm F3.5-5.6 zoom lens (serial number A26897). The camera was placed on its own tripod over and immediately behind the headlamp. The lens was set to 28mm and the system was approximately leveled and aligned so that as much of the screen as possible was visible in the viewfinder.

DATA CAPTURE

In this section of the report, the process of data capture is described. Included in this topic is the procedure followed when photographing the beam patterns and post-processing procedure for extracting pixel information.

Image Capture

The camera was physically set up as described in the experimental setup section of this report. The camera settings were set up as shown in Table 1.

Mode	Aperture Priority (Av)
ISO	100
Exposure Compensation	-1 Stop
Exposure Bracketing	±1 Stop
Metering Mode	Evaluative

Table 1. *Camera Setup.*

The camera was allowed to meter its own exposure at aperture values from F3.8 – F8. Three exposures were taken at each aperture value through the use of exposure bracketing.

Image Processing

After visually examining the JPG images captured of the beam patterns, no appreciable difference could be found due to different aperture values. Therefore, images captured using F5.0 were chosen for analysis, due to the fact that F5.0 is generally considered to be relatively free from minor image defects caused by wider aperture use (smaller F numbers).

The steps involved in image processing were as follows:

- Import RAW file into PhotoShop as a 16-bit file
- Switch image mode to grayscale
- Level image, by rotating it an appropriate amount (1.5° clockwise for the images taken for this study)
- Crop image down to a usable size (done to reduce processor load)
- Apply test region overlay (A total of three: pedestrian visibility, delineator visibility, and oncoming glare)
- Use the Eye-Dropper tool along with the Color Pallet to identify the pixel’s numeric value. This was done to find the highest and lowest pixel values in the overlay region.

- Apply the remaining overlays.

Figure 5 shows the overlays used. The red crosses denote the location of the (0,0) coordinate in the overlay. Note that each of the three overlays is lined up vertically. Table 2 specifies the angular size of these regions as taken from Bhise et al. (1977) and Perel (1985).

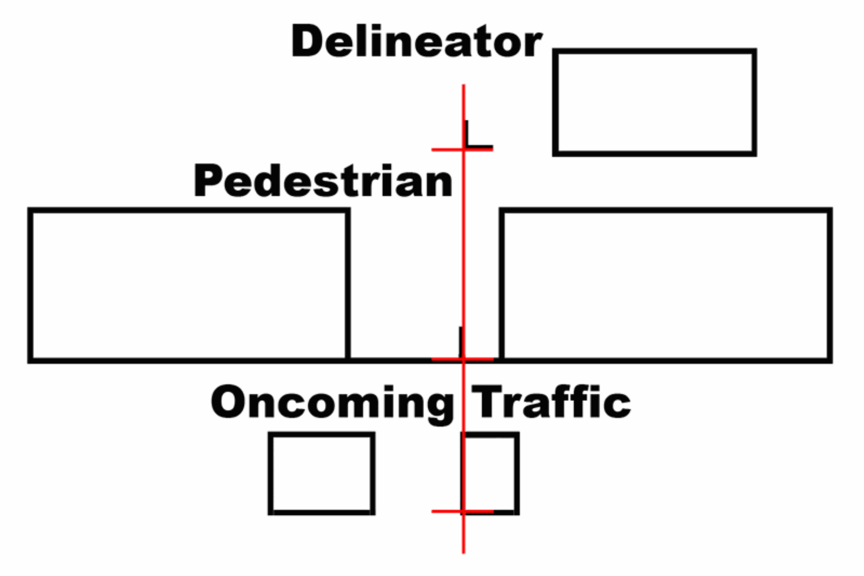


Figure 5. *Image Overlays.*

Figure 6 is an example of the delineator overlay as applied to the image of the VOL beam pattern.

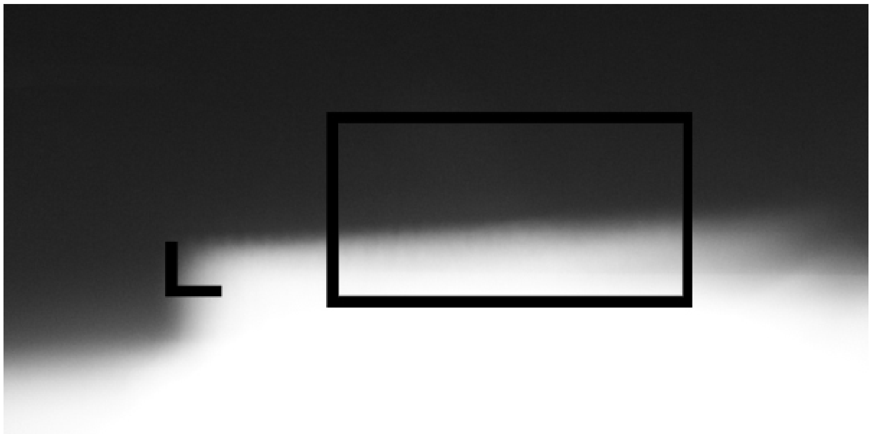


Figure 6. *Delineator Overlay Applied to VOL Beam.*

A second task was to determine the effect of loading on the headlight distribution in the regions defined by the overlays. To perform these measurements, the overlays were shifted down by an amount equivalent to the distance the beam pattern would have risen if it was shifted upward by 1.1°. The angle 1.1° was chosen because it represents the worst case of vehicle body shift due to the addition of passengers and weight loading to the trunk (Yokoi et al., 1997). Other than the overlay shift, the data extraction procedure is identical to that performed for a level car as outlined above.

Pedestrian Location Area

Left Side		*Right Side*	
Horizontal	Vertical	Horizontal	Vertical
-9.15	0	0.84	0
-2.74	3	7.51	3

Oncoming Traffic

Left Side		*Right Side*	
Horizontal	Vertical	Horizontal	Vertical
-4	0	0	0
-2	1.5	1	1.5

Delineation Targets

Right Side Only	
Horizontal	Vertical
2	0
6	2

Table 2. *Overlay Angular Sizes (degrees).*

CALIBRATION

Calibration of the photography system consisted of two steps: profiling the camera system's response to light and finding the camera system's physical constants (length/pixel ratio and angular deviation from level).

To profile the camera's response to light, an image of eight different gray levels was created in PhotoShop. The image was displayed on a laptop computer screen and each level of gray was measured and recorded using a Minolta LS-100 luminance meter (S/N 80313034). Images were then taken of the laptop screen at the aperture and exposure settings used for pixel value extraction of the beam pattern images. PhotoShop was then used to extract the pixel information for the calibration pattern. The result was an equation for each aperture/exposure combination used. Figure 7 shows the luminance pattern used for the calibration. The results of the calibration are shown in Figures 8 and 9.

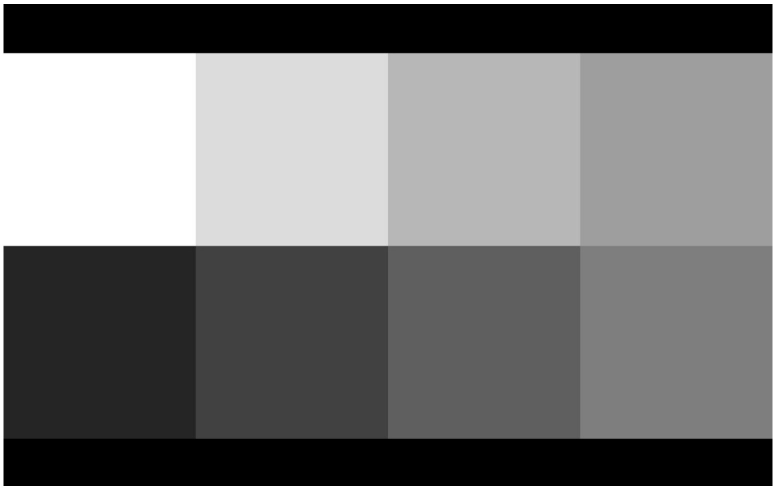


Figure 7. *Calibration Chart.*

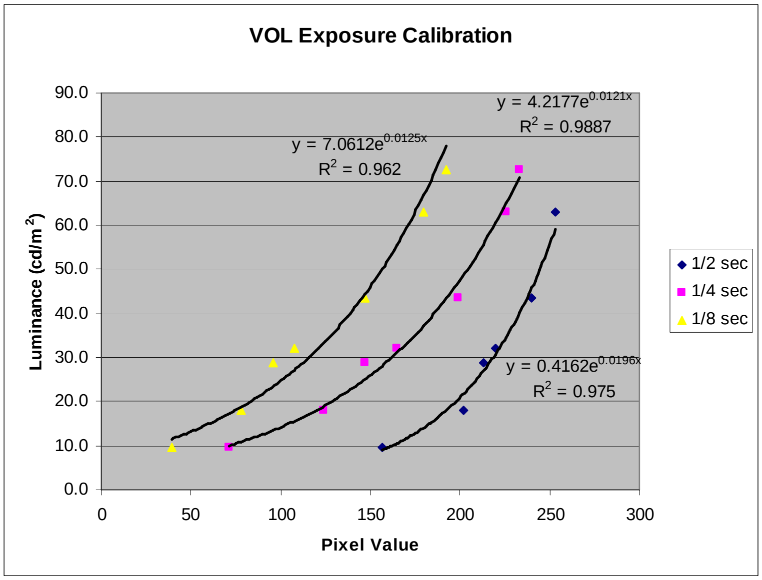


Figure 8. *VOL Exposure Calibration.*

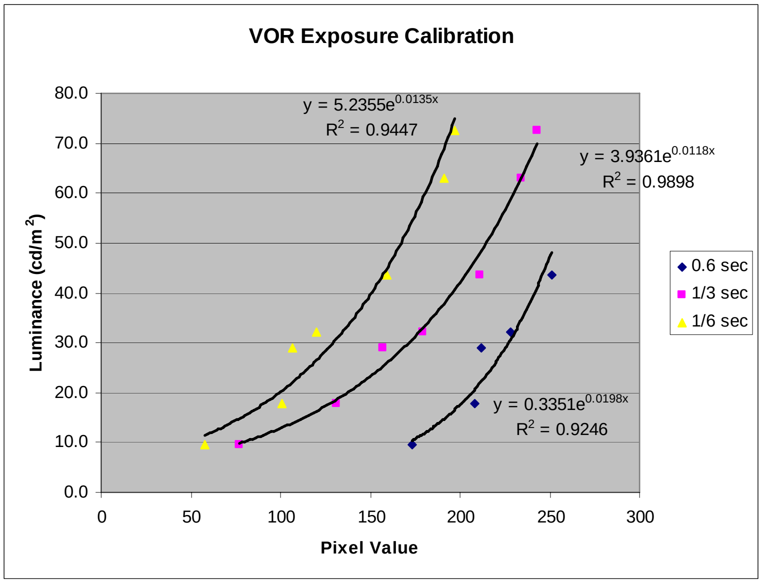


Figure 9. *VOR Exposure Calibration.*

RESULTS

The functions created in the calibration process were used to convert pixel values into luminance values. Through the use of photometry principles, the luminance values were converted into luminance values adjusted for the reflectivity of the paper used (taken to be 80%). The inverse square law was then applied to determine the intensity values. The numeric results for both a level car and 1.1° inclination are summarized graphically in Figure 10-19. The boxes represent the range of intensity values within the overlay regions.

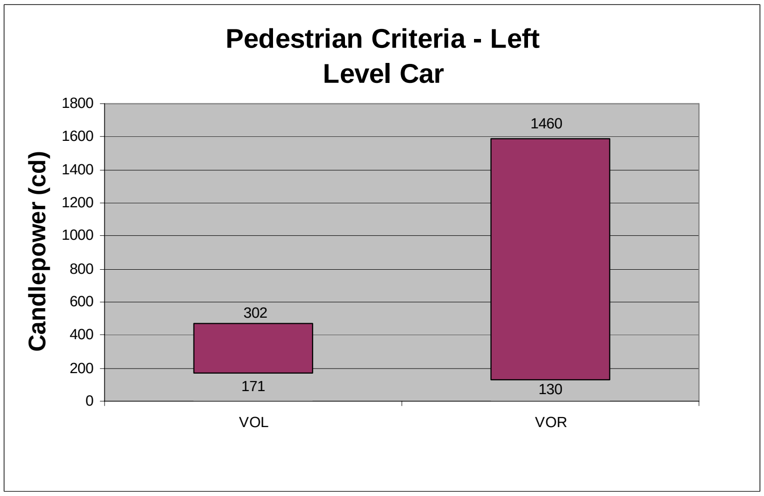


Figure 10. *Left-Side Pedestrian Overlay Results.*

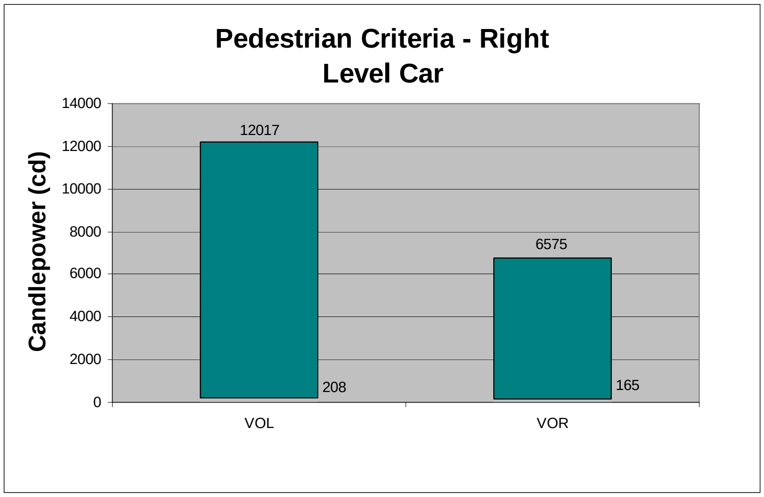


Figure 11. *Right-Side Pedestrian Overlay Results.*

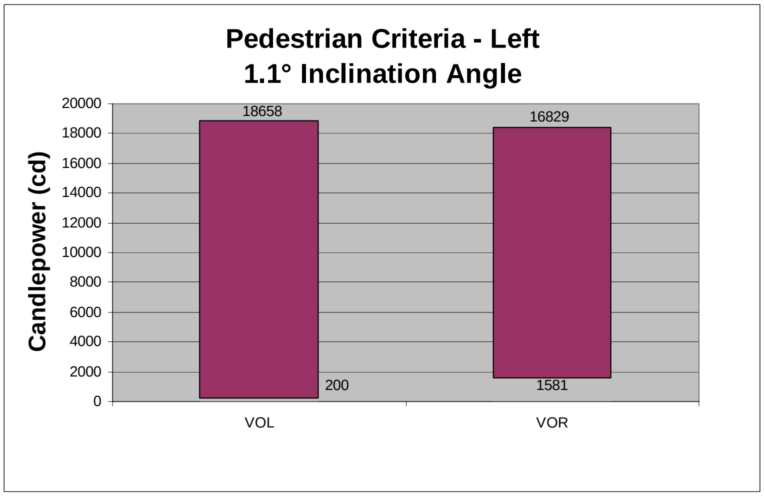


Figure 12. *Left-Side Pedestrian Overlay Results, 1.1˚ Inclination.*

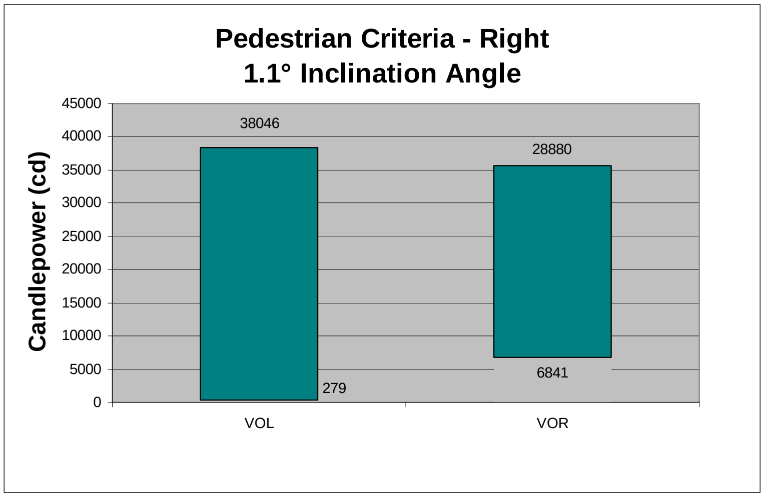


Figure 13. *Right-Side Pedestrian Overlay Results, 1.1˚ Inclination.*

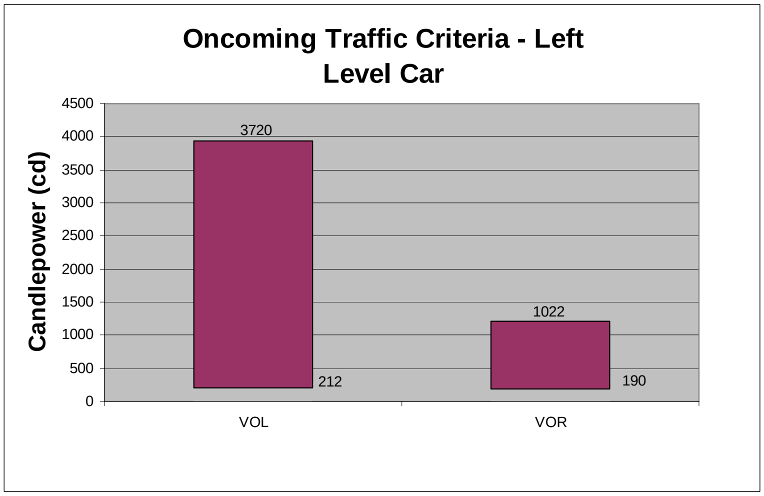


Figure 14. *Left-Side Oncoming Traffic Overlay Results.*

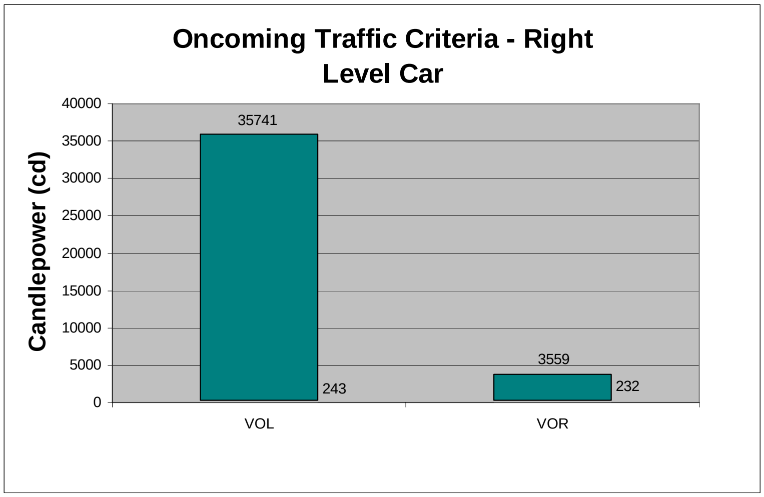


Figure 15. *Right-Side Oncoming Traffic Overlay Results.*

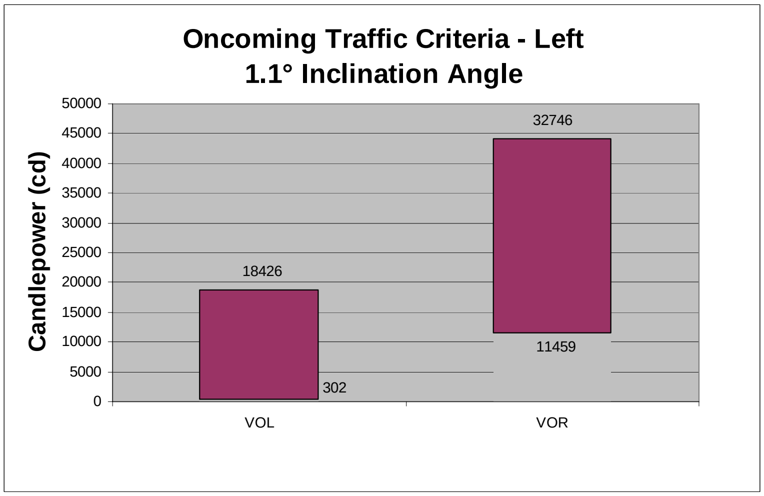


Figure 16. *Left-Side Oncoming Traffic Overlay Results, 1.1˚ Inclination.*

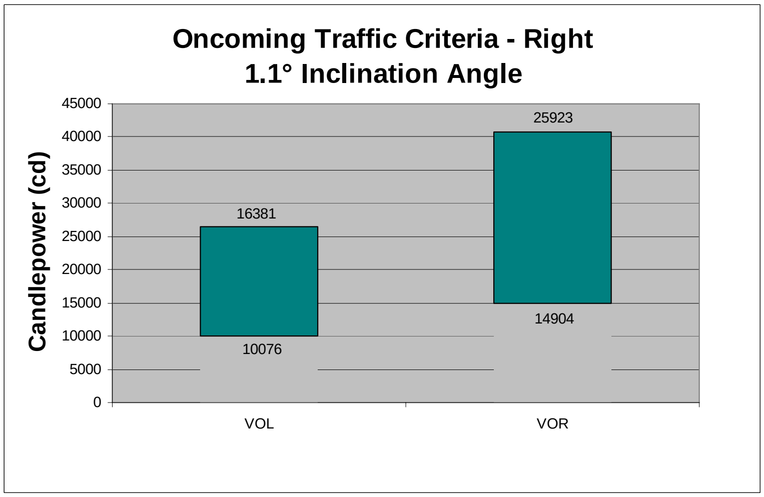


Figure 17. *Right-Side Oncoming Traffic Overlay Results, 1.1˚ Inclination.*

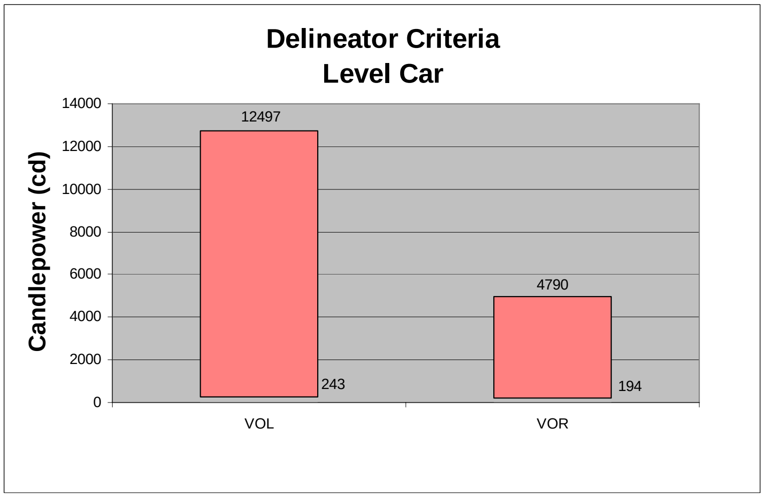


Figure 18. *Delineator Overlay Results.*

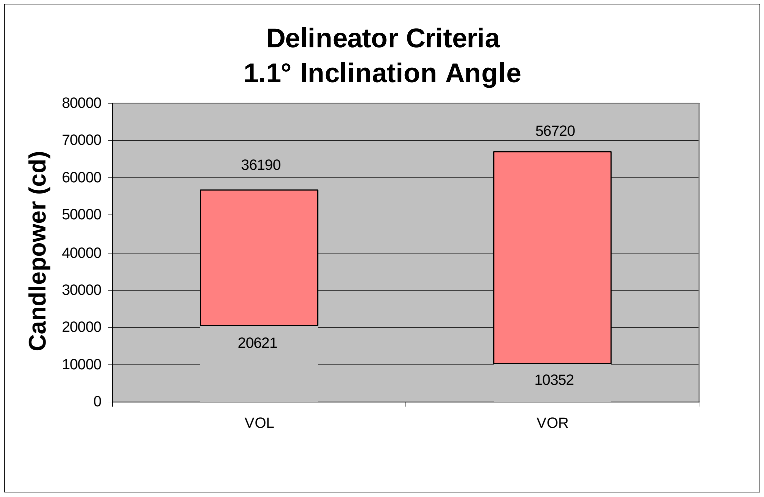


Figure 19. *Delineator Overlay Results, 1.1˚ Inclination.*

It is also useful to evaluate the headlamps tested to determine how much glare they would cause to oncoming drivers. To do this, the Schmidt-Clausen equation (NHTSA, 2005) was used to calibrate the deBoer ratings for the glare produced by the headlamps. The Schmidt-Clausen equation is expressed as:

$$W = 6.79 - 2LOG\left(\frac{E_{Max}}{0.003\left(1+\sqrt{L_a/.04}\right)\theta_{Max}^{0.46}} \right)$$

Where W is the deBoer glare rating, E_{Max} is the maximum possible illuminance, L_a is the background luminance (assumed to be 2 cd/m^2), and θ_{Max} is the angle to the light source in min-arc. The deBoer ratings for both headlamp types at level and 1.1˚ inclination were calculated based on two times the worst-case candle power (for two headlamps) at distances ranging from 120m to 5m to determine where the acceptability threshold of 4 was exceeded. Figure 20 shows the results of these calculations.

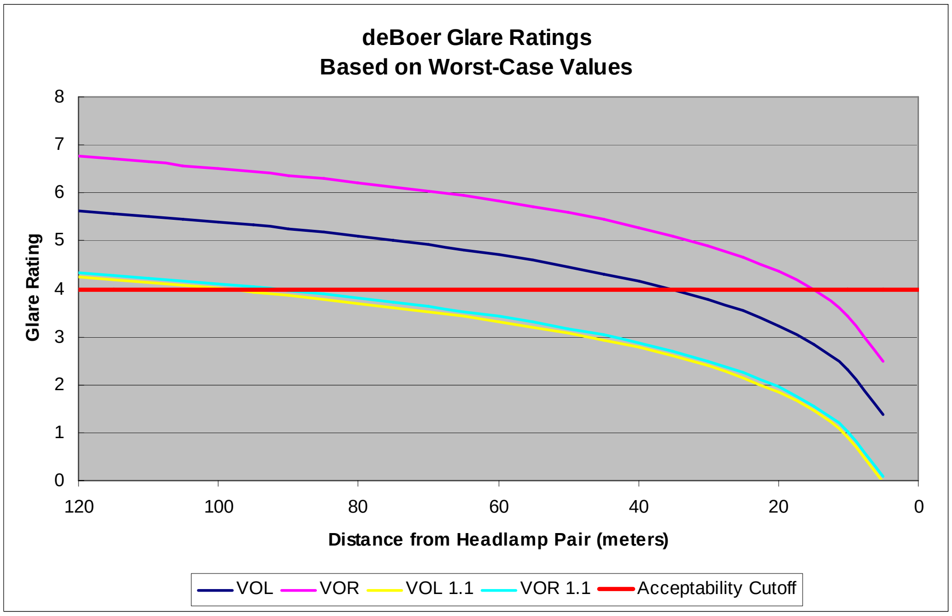


Figure 20. *deBoer Glare Ratings*

Summary

It can be seen that the angular regions where targets of interest may be located range greatly in illumination. This is due predominately to where the beam cut-off falls with respect to the target region. If the cutoff line runs through the target regions (as it did in most cases) then the region will have a very wide range of intensity values. If the region falls completely over the cutoff line, the intensity values will be comparatively low and more uniform. If the region falls completely under the cutoff line (like in the case of 1.1° inclination) then the intensity numbers will be comparatively high and uniform.

The figures above show that vehicle loading will alter the headlight beam aim enough to improve pedestrian and delineator visibility. However, as the glare calculations have shown in Figure 20, this inclination has devastating results for oncoming drivers – for whom glare was no longer at an acceptable level at a distance of more than 90 meters (300 feet) from the source.

To Perel's point (1985), the targets occupying a region will determine whether a high or low intensity distribution is desired, and the two often conflict. For example, to see pedestrians well, a high intensity distribution is desired for both sides of the origin. However, if a high intensity region exists on the left side of the origin then it will glare oncoming drivers. Therefore an overall rating based on these criteria isn't very practical.

DISCUSSION AND CONCLUSIONS

The experimental process used had both strong and weak points. One thing that worked well was the use of a tripod mount for the headlamp. This offered great flexibility in the mounting and positioning of the source, and is highly recommended.

The use of a level and length reference on the screen which was visible in the photographs was helpful in verifying the image leveling and the length of the overlay regions. The use of 16 bit RAW files, converted to grayscale, worked very well from within PhotoShop for the extraction of pixel information. One aspect of the experiment that needs reconsideration was adjusting the headlamp's Z axis so that it is orthogonal to the surface of the screen. Using a laser aligned to the Z axis along with a square on the screen's surface could be used to align the assembly.

During the data collection, images were taken at many different aperture/exposure combinations. Inspection of the images proved this to be unnecessary. Instead, a single aperture setting should be used and the exposure time should be varied to achieve different range.

The metering used was evaluative. This mode divides the image into 35 zones, and adjusts exposure to achieve middle gray in as many of the zones as possible. A better choice is spot metering, which only polls the area around the central focus point of the image. Spot metering of the headlamp's hotspot, using +1 stop of exposure compensation, and applying ±1 stop of exposure bracketing will capture three images: one metered to produce proper exposure for the hotspot, one a stop brighter (twice as bright), and one which is two stops brighter (4 times as bright). Doing so will offer more than enough range in the images to properly evaluate the beam pattern.

The calibration pattern was photographed on a laptop computer screen; however the uniformity of the screen could be improved. One way of doing this is using a cathode-ray tube (CRT) or projector in lieu of the LCD. A more reliable calibration could be attained this way.

If these issues are addressed, this method of evaluating headlamp beams offers great promise as a simple and effective technique. The true beauty of the approach is that once a camera is calibrated, no specialized equipment is necessary. In addition, this approach offers great promise as a rapid method for characterizing all types of beam patterns and is worthy of further development.

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