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ABSTRACT

An experimental field investigation is described that compares off-axis (peripheral) visual performance between high-intensity discharge (HID) forward lighting and halogen systems. The goal of the investigation is to determine if the higher off-axis intensity levels combined with the spectral properties of HID lamps provide any benefits to visual performance over conventional tungsten halogen lamps.

In this study three current production European headlamp systems, one HID and two halogen, are compared. These systems are used to illuminate a fixed scene. Subjects perform a visual tracking task, cognitively similar to driving, while simultaneously small targets located at various angles in the periphery are activated. Subjects release a switch upon detection and reaction times and missed signals are measured.

From the results, comparisons are made among the HID and halogen systems in terms of reaction time to signals at different peripheral angles, and in terms of numbers of missed signals. The results are compared to a model that predicts visibility at nighttime (mesopic) light levels. Potential implications of the results on driving safety and on the development or refinement of forward lighting standards are discussed.

INTRODUCTION

BACKGROUND

In the United States and in Europe, automotive forward lighting must adhere to specifications regarding the luminous intensity distribution along the forward direction of view. These specifications ensure that the vehicle forward lighting allows for safe, comfortable driving at night without causing glare to oncoming drivers. Historically, tungsten, and then tungsten halogen, filament lamps have been used in headlamp systems as the light source to achieve these lighting standards.

In the early 90's high-intensity discharge sources were developed for vehicle forward lighting systems. HID lamps employ gas discharge rather than an incandescent filament to produce light. They offer the advantages of greater light output, higher luminous efficacy, and longer life than conventional systems using halogen lamps.[1]

Typically HID lamps produce 2-3 times more luminous flux than comparable halogen lamps. In general, most of this extra flux is distributed at larger angles creating a wider beam. HID headlamps also have a different spectral power distribution (SPD), being discharge rather than graybody sources. These SPDs tend to be shifted more toward the shorter visible wavelengths compared to the SPDs of tungsten halogen headlamps.

Since their development discharge lamps have gained wide popularity in Europe and are being employed on an increasingly larger numbers of cars each year. HID lamps are also now beginning to emerge on vehicles in North America. However, because of the high system costs, these systems are still limited to options on high to mid range priced vehicles. As the technology develops the costs will decrease and more widespread application should be seen.

As HID headlamps increase in popularity so do questions on their relative benefits and drawbacks. While incidental reports from drivers may indicate increased glare from HID headlamps there is also evidence of increased visual performance and safety as well. Hamm and Steinhart recently reported on a static field experiment comparing visual detection thresholds of a small, low contrast target with halogen and HID headlamps.[2] From the study results Hamm and Steinhart calculated the relative benefit, in terms of detection time and distance, provided by the HID headlamps, because of their greater light output.

Until now the impact of HID headlamps on off-axis vision was still unknown. Off-axis vision is important for driving in detecting edge of roadway hazards, such as pedestrians and animals, as well as providing a feeling of comfort. As an illustration of this consider a thought experiment (not to be actually done!). One could block central or foveal vision by holding their thumbs out at arms length in the center of the field of view. It would not be comfortable to drive this way but it probably still could be done without too much difficulty. Now consider driving with two long tubes up to one's eyes allowing only central vision. Although the tubes could turn with your head it would still be extremely difficult, if not impossible, to drive this way.

The properties of HID lamps may make them ideal for improving off-axis vision. As stated above, the width of an HID beam typically exceeds the width of a halogen beam pattern. This results in more peripheral light. HID lamps also produce light with different spectra than halogen lamps. While driving at night, off-axis human vision is in the mesopic response range. The mesopic range lies in-between the photopic (high light levels) and scotopic (almost no light) ranges. In this response region the eye's sensitivity shifts towards shorter wavelengths. At mesopic light levels off-axis vision is enhanced (faster reaction times, larger detection range) by the use of a lamp more closely matched to the shorter wavelength sensitivity range.[3][4]

The combination, of these factors may endow HID headlamps with greater nighttime off-axis visual performance that may translate into greater driving safety.

SCOPE OF PAPER

The goal of this paper is to report the results of a field investigation exploring the relative off-axis visual performance of HID headlamps compared to standard tungsten halogen. It is divided into three main sections. The first reviews the experimental methods employed in this study. This includes a description of the experimental geometry, procedure, and subjects used.

The second section presents the experimental results. This includes both reaction time and number of missed signals as a function of target location and target contrast. The data are further analyzed and presented as a function of subject age.

The last section analyzes the presented data. Potential implications of the results on driving safety and on the development or refinement of forward lighting standards are discussed.

METHODS

EXPERIMENTAL GEOMETRY

This experiment was designed to measure off-axis visual performance under different vehicle frontlighting systems. Three headlamp systems were used, one HID system and two halogen systems, all considered relatively "high quality" lighting systems and all having beam patterns corresponding to European standards. In addition, two target contrast levels were used to examine the effect of contrast on visual performance under these conditions. Subjects were shown off-axis targets lit with the test headlamps and asked to respond as soon as the target was seen. If no response was given within 1 sec the target was considered missed. This process was repeated many times and the subject reaction times and numbers of missed signals were recorded.

In order to increase application validity this experiment was performed in the field. A disused runway at Schenectady County Airport in Scotia, NY was chosen as the study location. This location offered a straight, flat, paved surface with little stray light. The tarmac is asphalt and exhibited reflection characteristics similar to a typical roadway surface.

The experimental geometry, shown in Figure 1, is as follows. The subject sits in the driver position in a stationary test vehicle. A tracking task is placed 15m away from the front of the test vehicle directly in the subject's line of sight. Six targets are placed at a contestant distance of 60m from the vehicle. The targets have a 5^{o} angular separation, with four to the right of the driver and two to the left. In both directions the targets start at 2.5^{o} from the line of sight. This geometry results in targets at the angular positions shown in Figure 1, where negative angles indicate to the left of the driver and positive to the right.

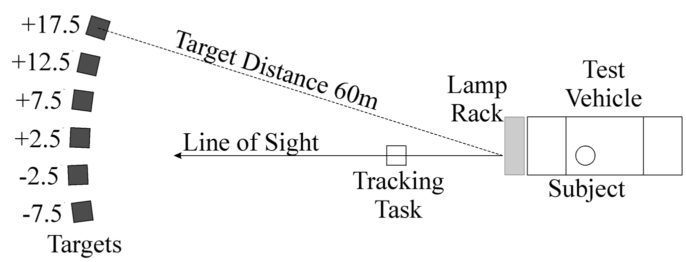

Figure 1. Schematic diagram of experimental geometry.

The headlamp systems were placed on a buck or rack in front of the car. The subject could not see the rack from the driver's position so it appeared the lighting was from the vehicle. Headlamps were mounted at the correct vehicle height and separation. The HID system was powered directly from the test vehicle battery. The halogen systems were powered by a DC power supply running from the test vehicle battery. A power supply was used to ensure the voltage remained constant. Care was taken to aim the headlamps to the line of sight every time they were mounted on the rack or adjusted. Since the headlamps produce European beam patterns aiming was performed visually using a screen 10m from the lamps.

The tracking task used consisted of an LED "bar graph". This was a linear series of LEDs that mimicked a moving bar graph. The LEDs start lit in the middle and light a random distance up or down. The subject has a knob controlling the LEDs and is instructed to turn them off till they reach the center again. Once the center is reached the LEDs light in a random direction again. The subject is asked to perform the tracking task throughout the experiment. This ensures that the subject's line of sight is fixed and targets are presented off-axis.

Figure 2 shows the targets used in this experiment. They are a 7"x7" grids of "flip dots". The flip dots are small 0.5" diameter electromagnetic disks that are white on one side and black on the other. When a current is applied the disks flip completely within 20ms, showing the white or black face. The dimensions and relative position on the targets were constructed to match other studies of roadway visibility. [5][6]

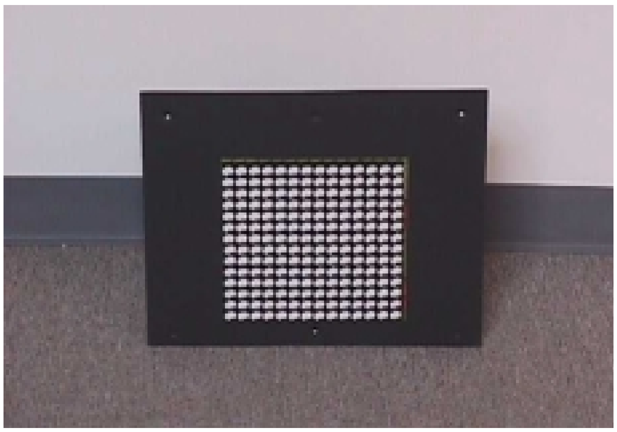

Figure 2. Flip dot target.

Changing the target contrast was accomplished by placing neutral density filters over the targets. Neutral density filters were used so the light spectrum would be minimally affected. For high contrast the target was used with no filter. The lower contrast condition was accomplished by placing a 0.15 optical density filter mounted on glass substrate over the target. This resulted in a contrast level of ~50%. The filters were placed over the target at an angle so that any light reflected from the filter would not return to the subject.

The illuminance levels were measured at the targets each time the headlamps were mounted. Figure 3 shows the average target illuminance as a function of angular target position. The study was performed over four sessions; each point represents the average of four illuminance measurements with the error bar length equal to twice the standard deviation. Note that at 2.5^o all three headlamps produce approximately the same illuminance. However, as the angle increases the HID lamp provides significantly more illuminance. At 17.5^o the illuminance from the HID headlamp is an order of magnitude greater than that produced by the halogen lamps. Also note that the halogen A headlamp produces less illuminance at larger angles than the halogen B headlamp. Visually, the halogen A appears to have a narrower beam than the HID and halogen B headlamps.

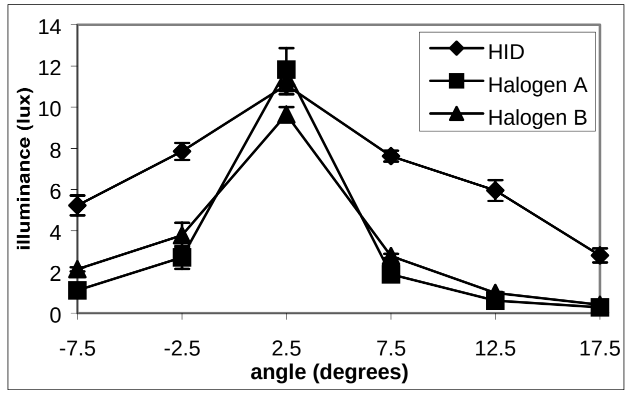

Figure 3. Plot of average target illuminance.

PROCEDURE

The experiment was conducted as follows. Subjects were asked to sit in the driver's position with the scene already illuminated. Subjects did not see which lamp system was being used. Once seated the subject was given a control box. It contained a knob to control the LED tracking task and a reaction time switch.

After a trial run to get acquainted with the controls the actual test was started. The subject held the reaction time button down while performing the tracking task. Targets were presented in a random order at random time intervals. Subjects were asked to release the reaction time button when a target was seen. If the subject did not respond in one second to the target presentation it was considered missed. The reaction time and number of missed signals was automatically recorder by a computer. In one data collection period each target was presented to the subject four times.

The data collection periods were repeated within groups of approximately three subjects. Each subject performed the experiment with one headlamp type and the targets at one contrast level. The contrast level was then changed, either higher or lower, and each subject performed the experiment again. After each subject in the group performed the experiment for one headlamp type at both contrast levels the headlamp system was changed and the process repeated.

Care was taken to randomize the order of headlamps and target contrast levels presented. This was done to counterbalance any order effects. Therefore, in total, six data collection periods were completed by each subject, three headlamp types and two target contrast levels. In each data collection period 24 data points were collected (4 for each target). So, for each subject 144 data points were collected.

SUBJECTS

Twelve subjects were used in total. Six subject were less than 30 years old and six were over 50 years old. This age grouping ensured a relative sample of the driving population and allowed analysis of age related effects. Each subject was tested to ensure they had at least 20/20 corrected acuity and no color blindness.

RESULTS

REACTION TIMES

<u>Target Contrast</u>

Figure 4 shows reaction time versus target location for the high contrast target case. The y-axis shows reaction time in cycles. 1 cycle is approximately equal to 1ms. The x-axis shows target location in degrees. Each reaction time data point is the average of all subjects and the errors bar length corresponds to twice the standard deviation. Reaction times are shown for all three headlamp types. Reaction times that exceed the scale correspond to targets where no reaction time data points were collected (all targets were missed). The impact of target location on reaction time was found to be statically significant for these data ($p<0.01$).

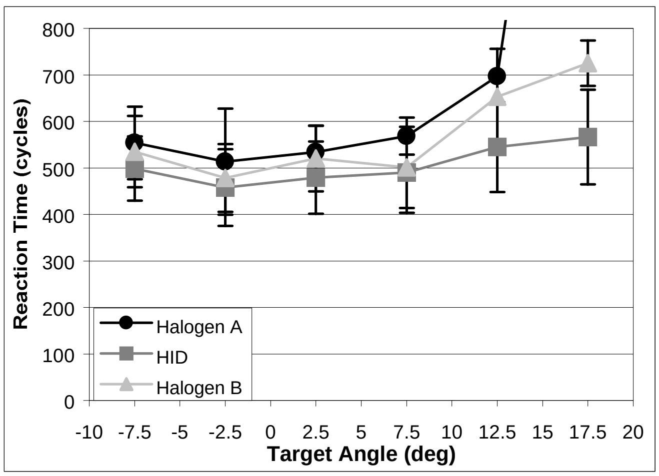

Figure 4. Average reaction times for high contrast targets.

Several things are evident from the graph in Figure 4. Generally, reaction time is lowest at the small angle targets where illuminance is highest. Reaction time increases as the target angle increases and the illuminance decreases.

For the high contrast condition, reaction times for all three headlamps are statistically similar at small target angles. As the target angle increases the reaction times for each headlamp type begin to separate. This is particularly evident at the 12.5^o and 17.5^o target locations. The halogen A headlamp produces the longest reaction times at these target locations and the HID headlamp system produces the shortest reaction times. In fact at 17.5^o all target presentations were missed for the halogen A system and the HID system produced reaction times that are ~150ms less than that produce by the halogen B system.

Figure 5 shows a plot of reaction time vs. target location for the 50% contrast target case. Each reaction time data point is the average of all subjects and the errors bar length corresponds to twice the standard deviation. Reaction times are shown for all three headlamp types. Reaction times that exceed the scale correspond to targets where no reaction time data points were collected (all targets were missed). The impact of target location on reaction time was found to be statically significant for these data ($p<0.01$).

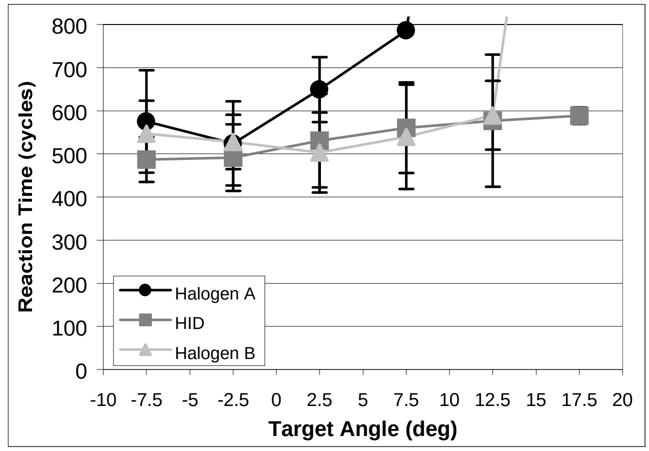

Figure 5. Average reaction times for 50% contrast targets.

Overall reaction times have increased compared to the high contrast case. However, once again the same general trends are seen as in Figure 4. Reaction time increases with target angle and decreasing target illuminance. However, for the lower contrast case, this trending is more severe and the separation between reaction times produced by the different headlamp types is larger.

At only 2.5^o there is a significant separation between reaction times for the Halogen A lamp and the other headlamp systems. By 12.5^o all signals are missed for the halogen A headlamp. This is consistent with the narrow beam pattern observed for the halogen A headlamp.

The halogen B and HID headlamps produce similar reaction times through 12.5^o. However, as seen in the next section, the halogen B lamp is producing significantly more missed signals so the variation and error of the remaining reaction time data is greater (fewer samples). At 17.5^o the there is significant separation with the halogen B system producing only missed signals and the HID headlamps still resulting in reaction times under 1 second.

<u>Subject Age</u>

Figure 6 shows the reaction time for the high contrast target case correlated as a function of subject age. For illustration, only the HID and halogen B headlamps are compared. Similar results are seen for the halogen A headlamp and the 50% target contrast case. Each reaction time data point is the average of all subjects in that age group and the errors bar length corresponds to twice the standard deviation. The correlation between target location and reaction time was found to be statically significant for these data ($p<0.01$).

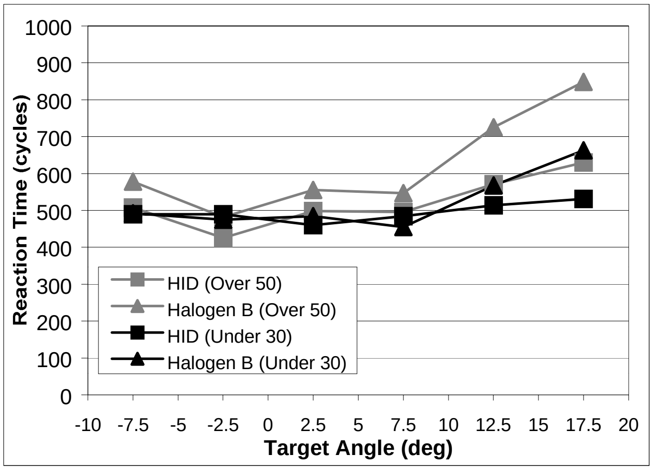

Figure 6. Age correlated reaction times for high contrast targets.

In Figure 6 several expected features can be seen. The general trending is as described for the averaged reaction times. The subjects over 50 years old do have higher reaction times than subjects less than 30 years old, particularly at high angles. This is true for both headlamp systems.

The reduced reaction times under HID illumination at high target angles are still seen in the age-correlated data. However, the relative magnitude of change between the HID illuminated targets and the halogen B illuminated targets in reaction time is approximately the same for both age groups. This is the case for the halogen A headlamp as well as the 50% target contrast conditions.

MISSED SIGNALS

<u>Target Contrast</u>

Figure 7 shows a plot of missed signals vs. target location for the high contrast target case. The y-axis corresponds to the percentage number of totals targets missed. Each target is presented 4 times to the 12 subjects for a total of 48 possible target presentations to miss. The x-axis shows target location in degrees.

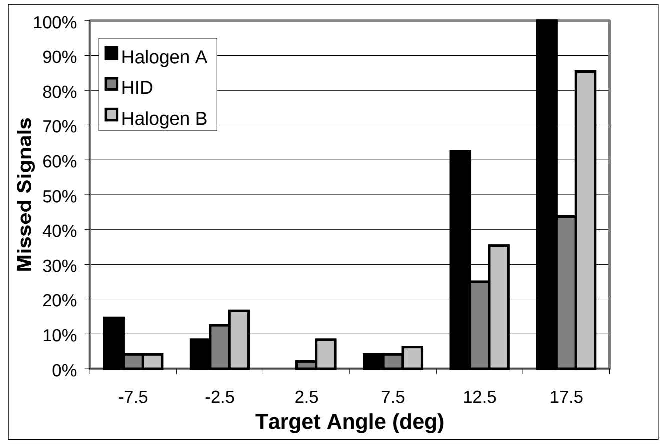

Figure 7. Percent missed signals for high contrast targets.

The same general trends as seen in the above reaction time graphs are present In Figure 7. For all headlamps, at small angles few targets are missed. The missed targets shown in Figure 7 from -7.5^o to 7.5^o are experimental noise. As the target angle increases, and the target luminance decreases, the number of missed signals increases.

The increase in missed signals does vary between the headlamps used. The HID lamps show the least amount and the slowest increase of missed signals. Halogen A headlamps produce a significant number of missed signals at only 12.5^o. More than twice as much as the HID headlamps produce. At 17.5^o the halogen A lamps results in all of the signals being missed. Missed signals also increase rapidly, more than double, for the halogen B headlamp between 12.5^o and 17.5^o.

Figure 8 shows a plot of missed signals vs. target location for the 50% contrast target case. The y-axis corresponds to the percentage number of totals targets missed. Each target is presented 4 times to the 12 subjects for a total of 48 possible target presentations to miss. The x-axis shows target location in degrees.

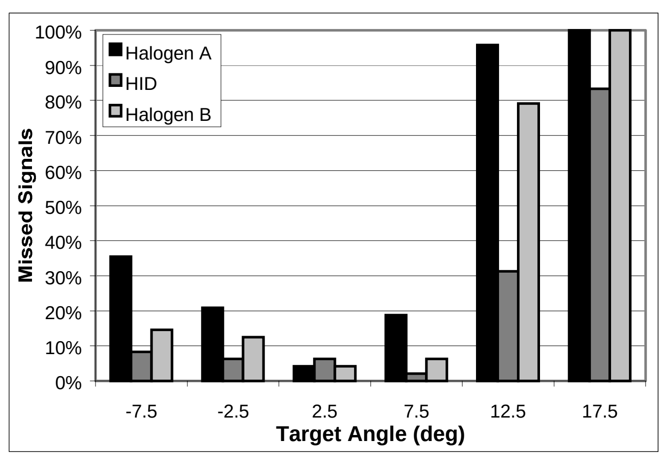

Figure 8. Percent missed signals for 50% contrast targets.

The total numbers of missed signals have increased over the high contrast case. However, the same general trends are seen again. As with reaction time, the trending is more severe with the 50% contrast targets than with the high contrast case. The numbers of missed signals increases more rapidly as the target angle increases and the target illuminance decreases. At only 2.5^o in both directions the number of miss signals start to significantly increase. By 17.5^o degrees all the signals are missed for all of the headlamps except for the HID.

Once again the increase in missed signals is not equal for the three headlamp types. The HID lamps show the least amount and the slowest increase of missed signals. This is particularly true at 12.5^o, where the halogen A lamps produce almost three times as many missed signals and the halogen B produce more than twice as many missed signals.

Subject Age

Figure 9 shows the percent missed signals for the high contrast target case correlated as a function of subject age. For illustration, only the HID and halogen B headlamps are compared. Similar results are seen for the halogen A headlamp and the 50% target contrast case.

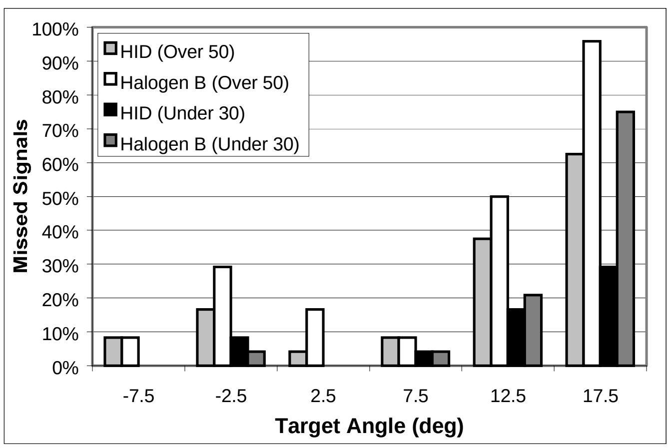

Figure 9. Age correlated missed signals for the high contrast targets.

In Figure 9 several expected features can be seen. The general trending is as described for the averaged missed signals. The subjects over 50 years old do have more missed signals than subjects under 30 years old, particularly at high angles. This is true for both headlamp systems.

The reduced number of missed signals under HID illumination at high target angles is still seen in the age-correlated data. However, the relative magnitude of change in number of missed signals between the HID illuminated targets and the halogen B illuminated targets is approximately the same for both age groups. This is the case for the halogen A headlamp as well as the 50% target contrast conditions.

DISCUSSION

The results of this study indicate that for these representative headlamps the HID system provides relative visual benefits for off-axis vision. The increase in visual performance is seen in both reaction time and number of targets seen. Under HID illumination, subjects had shorter reaction times and fewer missed signals at larger angle targets. This trend occurs regardless of subject age.

Lowering target contrast increases the total reaction time and the total number of missed signals at all visual angles. This effectively narrows the visual performance beam pattern. Although the HID headlamps result in performance that also decreases with contrast level, this decrease is not as rapid as with the halogen systems tested. Therefore the magnitude of difference between the HID system performance and the halogen system performance increases as the contrast decreases. In other words the relative visual benefits of the HID system increases for lower contrast targets.

Effects of age were seen in visual performance. The older subjects had increased overall reaction times and increased numbers of overall missed signals, as would be expected. However, there was no significant difference in relative subject performance between the HID and halogen systems. In other words, the older subjects performed worse overall but the relative difference between HID and halogen performance was the same for both age groups.

It is important to note that in this experiment there are two factors that may be responsible for the increased off-axis visual performance produced by the HID system: higher target illuminance and different light spectra. Since the test beam patterns were not controlled, the illuminance at the targets were as they would be in practice, there is no way to distinguish between the two effects. Further research would need to be done.

CONCLUSION

This study was performed to determined if there was any relative benefit for off-axis vision for HID forward lighting systems over standard tungsten halogen systems. In as closely as these systems are representative of typical headlamp systems, it can be generalized from this study that HID headlamps do produce greater off-axis visual performance than traditional halogen systems due to their increased light output and SPD. The magnitude of the difference in performance depends on the off-axis angle and the beam pattern.

It is important to note however that the same properties that allow HID systems to produce greater visual performance may cause them to produce more glare. Further study needs to be performed to further quantify the glare aspects of HID systems and weight them against the visual benefits shown here and elsewhere. Only then can decisions on regulations and standards be informatively made on the use of HID forward lighting systems.

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