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Adaptive Driving Beam Headlights: Visibility, Glare and Measurement Considerations

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Abstract

Recent developments in solid-state lighting, sensor and control technologies are making new configurations for vehicle forward lighting feasible. Building on systems that automatically switch from high- to low-beam headlights in the presence of oncoming vehicles, adaptive driving beam (ADB) systems can detect both oncoming headlights and preceding taillights and reduce their intensity only in the direction of the other lights while maintaining higher levels of illumination throughout the remainder of the field of view. The nominal benefit of ADB systems is the provision of high-beam levels of illumination in the forward scene while reducing glare to oncoming and preceding drivers, who perceive low-beam illumination levels. Two dynamic field experiments were conducted; one experiment measured the ability of observers to identify the walking direction of roadside pedestrian targets with and without using the ADB system, and the other experiment evaluated the discomfort glare elicited by the ADB system in comparison to conventional low- and high-beam headlights. The findings from both experiments are consistent with previous analytical and static field tests and suggest that ADB systems can offer safety benefits compared to conventional headlight systems. Despite these potential benefits, ADB systems are not presently defined in North American headlighting standards. Field measurements of the photometric performance of an adaptive driving bean system were made in response to simulated headlight and tail light conditions. Roadway geometries were varied and multiple measurements for many conditions were made to assess repeatability of measurements. The results of the testing are summarized in the context of validating the likely safety impacts of these systems and of providing recommendations for standardized measurement conditions to ensure reliability.

Keywords: ....adaptive headlights, safety, visibility, glare, photometric measurement, standards and regulations

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ABSTRACT

Recent developments in solid-state lighting, sensor and control technologies are making new configurations for vehicle forward lighting feasible. Building on systems that automatically switch from high- to low-beam headlights in the presence of oncoming vehicles, adaptive driving beam (ADB) systems can detect both oncoming headlights and preceding taillights and reduce their intensity only in the direction of the other lights while maintaining higher levels of illumination throughout the remainder of the field of view. The nominal benefit of ADB systems is the provision of high-beam levels of illumination in the forward scene while reducing glare to oncoming and preceding drivers, who perceive low-beam illumination levels. Two dynamic field experiments were conducted; one experiment measured the ability of observers to identify the walking direction of roadside pedestrian targets with and without using the ADB system, and the other experiment evaluated the discomfort glare elicited by the ADB system in comparison to conventional low- and high-beam headlights. The findings from both experiments are consistent with previous analytical and static field tests and suggest that ADB systems can offer safety benefits compared to conventional headlight systems. Despite these potential benefits, ADB systems are not presently defined in North American headlighting standards. Field measurements of the photometric performance of an adaptive driving bean system were made in response to simulated headlight and tail light conditions. Roadway geometries were varied and multiple measurements for many conditions were made to assess repeatability of measurements. The results of the testing are summarized in the context of validating the likely safety impacts of these systems and of providing recommendations for standardized measurement conditions to ensure reliability.

INTRODUCTION

Automotive headlights are critically important elements of nighttime driving safety, especially since the majority of U.S. roads is unlighted (NHTSA, 2007). Developments in headlight technologies and performance specifications have been very gradual until the past two decades, when high intensity discharge (HID) and light emitting diode (LED) headlight sources started to displace filament sources in vehicle headlights. Additionally, dynamic or adaptive headlight control has become more common. While concepts such as steerable headlamps (Schneider and Duryea, 1913) and automated headlight dimming (Onksen, 1953) are not new, the combined use of solid state sources such as LEDs, which can be configured into arrays where each element produces a particular individual portion of an entire beam pattern, and developments in sensor, camera and image processing technology, have made adaptive headlight systems feasible. For these reasons, they are increasing in use (Wordenweber et al., 2007).

However, merely because new lighting functions *can* be realized does not necessarily justify the conclusion that they *should* be realized. Some of the functions that have begun to emerge result in beam patterns that do not meet the current requirements of the U.S. Federal Motor Vehicle Safety Standard (FMVSS) No. 108 for either low or high beam performance. The National Highway Traffic Safety Administration (NHTSA) has judged that steerable (curve lighting) headlights meet existing requirements as long as the entire beam distribution is swiveled when driving through a curve. Previous studies of the benefits of these systems (McLaughlin et al., 2004a; Sivak et al., 2005; Bullough et al., 2007; Bullough, 2009; Reagan et al., 2015) have supported the idea that they improve forward visibility and detection of potential roadway hazards in curves, although as reported by McLaughlin et al. (2004b) and Sivak et al. (2005), these systems can potentially increase glare to other drivers in certain curve scenarios.

Because it has been demonstrated that nighttime crash frequency reductions associated with nighttime lighting were correlated with visual performance increments from the same lighting conditions (Bullough et al., 2013), Bullough (2013) estimated the potential for nighttime crash reduction for visibility-related crashes that might be associated with adaptive curve headlights. These analyses took into account both the potential for improvement in forward visibility and the possibility of increased glare to other drivers, and found that overall these headlighting systems might reduce visibility-related nighttime crashes in small-radius curves by 3%-4%, and in larger-radius curves by 1%-2%. These nighttime crash reduction estimates were generally consistent with findings of insurance claim frequency reductions found in several vehicle models equipped with adaptive curve headlights compared to the same vehicle models without these systems (HLDI, 2011a, 2011b, 2012a, 2012b).

Adaptive driving beam (ADB) systems are a conceptual extension of automated high beam dimming systems that switch from high to low beams when oncoming vehicles are detected. ADB systems provide, essentially, high beam forward illumination levels along the roadway while selectively reducing their intensity just in the direction of oncoming headlamps or preceding taillights. As a result, other drivers perceive the appearance of low beam headlights while the driver using them has the benefit of the increased light levels throughout the remainder of the forward scene. However, by doing this, the resulting beam patterns conform neither to the low beam nor the high beam requirements of FMVSS No. 108. As part of a study commissioned by NHTSA (Skinner and Bullough, 2009) a prototype ADB system using mechanical shields to block portions of the headlighting beam pattern in specific directions was developed and evaluated. Field experiments confirmed that the prototype system provided forward visibility equivalent to high beam headlights, but elicited levels of discomfort and disability glare that were similar to levels from conventional low beam headlights.

Similar reports have been made regarding ADB systems in Europe (Neumann, 2014), and a recent field experiment in the U.S. was conducted of the discomfort glare perceived by drivers when facing ADB systems (Reagan and Brumbelow, 2015), showing that they resulted in similar levels of glare as low beam headlight systems. Furthermore, using a similar method as that developed by Bullough (2013) to assess the potential safety impacts of adaptive curve lighting systems, Bullough (2014) used previous field study results (Skinner and Bullough, 2009) to estimate the visual performance impacts of the ADB system for participants in that study, and estimated that ADB systems could reduce visibility-related nighttime crashes by 6%-7% compared to conventional low beam headlighting systems, which are the headlight beam patterns most frequently used in the U.S. when driving at night (Mefford et al., 2006).

Despite the potential benefits for safety, a challenge remains in specifying the performance of ADB systems, because by definition, they dynamically adapt the resulting overall pattern of illumination based on the presence and location(s) of other vehicles along the road. In contrast to ADB systems, fixed high and low beam headlights produce a static pattern of illumination that can be measured in a laboratory setting. The specific performance of an ADB system depends on the type and number of light source elements used, the method for controlling the beam pattern (mechanical or solid-state switching), the types of sensors and/or cameras that provide input to the control mechanisms, and the software or algorithms used to operate the control mechanisms. Because of this complexity, a static photometric test method similar to those used for fixed low beam and high beam headlights is impractical. As of June 2016, the Society of Automotive Engineers (SAE) is developing a test procedure for ADB systems (J3069™, see http://standards.sae.org/wip/j3069; accessed 9 June 2016), which utilizes the performance-based conceptual approach described by Flannagan and Sullivan (2011) and incorporated into field measurements by Mazzae et al. (2015). In short, J3069™ uses a road test to determine the illuminances produced by the ADB system at distances and locations representing drivers' eyes and rear view mirrors. To control glare, the illuminances at these locations should be no more than values representative of those that could be encountered in the presence of low beam headlights that conform to FMVSS No. 108. The information on the SAE website mentioned above, which describes work in progress on J3069™, stated the following:

- The ADB vehicle should drive along a straight, flat road past a stationary test fixture containing lights and measurement sensors located between two lanes to the left and two lanes to the right of the fixture
- Locations of lights on the text fixture should be representative of the locations of headlights and tail lights on passenger cars and motorcycles
- Locations of the illuminance sensor(s) should be representative of driver eye and mirror locations for oncoming and preceding passenger cars and motorcycles

- The test fixture lamps used to simulate headlights should produce a luminous intensity of 150 cd; lamps simulating tail lights should produce a luminous intensity of 13.5 cd

- The ADB system response time to the onset of test fixture headlights or tail lights should be no longer than 2.5 s

In the present report, two nighttime dynamic field experiments are described, which both used a passenger vehicle equipped with an ADB system, to extend the findings from Skinner and Bullough (2009) and other researchers regarding forward visibility under ADB illumination compared to that under low beam headlights, and to confirm and extend the findings from Reagan and Brumbelow (2015) regarding the amount of discomfort glare produced by the ADB system compared to fixed low beam and high beam headlights. In addition, the present report summarizes activities undertaken using the same ADB-equipped passenger vehicle, in order to evaluate the feasibility of making field measurements to characterize the performance of the ADB system, and to evaluate the repeatability of measurement results, using the information from SAE listed above as a guideline for testing.

METHOD: FIELD EXPERIMENTS

The field experiments were conducted along a dead-end, two-lane road in the Town of East Greenbush, Rensselaer County, New York (see Figure 1). This roadway has a long, straight, flat portion greater than 800 ft long. The roadway was closed during all experimental sessions with the cooperation of the town supervisor and police department. All of the sessions were carried out after the end of civil twilight (at least 30 minutes after sunset) in clear, dry weather conditions.

Figure 1. Section of test road used for the field experiments.

The test car (Audi A7) was equipped with an ADB headlighting system commercially available in Europe, which used a matrix of LEDs in both headlight compartments. The system used cameras and image processing algorithms in order to detect and identify oncoming headlights or preceding tail lights. The test car's headlighting system could be manually controlled to produce a low beam or a high beam pattern that conformed to the Economic Commission on Europe (ECE) specifications, or the headlights could be set to ADB mode (see Figure 2 for the appearance of each headlighting mode). In this mode, the low beam pattern would be used up to a driving speed of about 30 mph, and above this speed, the high beam pattern would be used. When oncoming headlights or preceding taillights from another vehicle were detected, the ADB system would reduce the headlight intensity only in the direction of those lights, and would maintain high beam levels of illumination elsewhere throughout the forward scene.

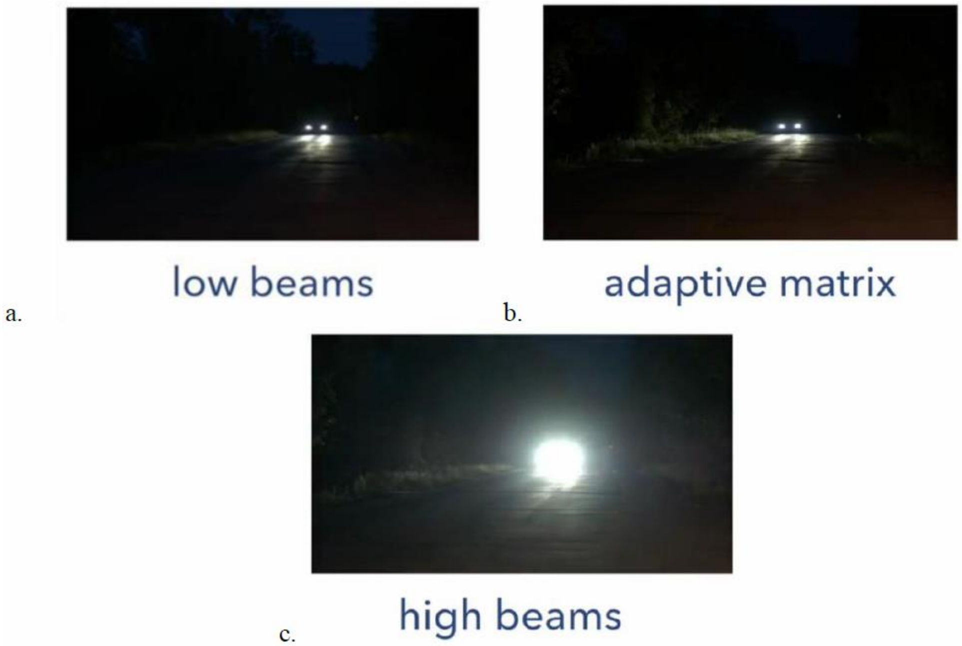


Figure 2. Appearance of the test car's oncoming headlights in each mode: a. low beam, b. ADB system, c. high beam. There is increased illumination along the edge of the road from the ADB system compared to the low beam headlights.

Pedestrian Target Identification Experiment

A total of 10 subjects (7 male/3 female, age 26 to 68 years, mean 46, s.d. 16) participated in the pedestrian target identification experiment. All subjects were licensed drivers. After they arrived at the test location, subjects practiced the visibility task. A black-painted (Lambertian reflectance = 0.05) matte plywood silhouette cutout (Figure 3) of a child (39 in. tall, approximately 8 in. wide) was located along the right-hand side of the straight portion of the roadway for traffic traveling in the northwestbound direction. Ahead of each trial, the walking direction of the pedestrian target was randomly adjusted to be either toward the road, or away from the road. An experimenter drove the test vehicle from beyond the curve to the southeast of the straight section, toward the target at a constant speed of approximately 40 mph.

Figure 3. Pedestrian silhouette target used in the visibility experiment.

Subjects rode as passengers in the test car and were asked to search for the pedestrian target; at the instant they could unambiguously identify the walking direction of the pedestrian (either toward the road or away from the road), they were instructed to drop a beanbag out of the open vehicle window (from a height of approximately 3 ft). The beanbag took about 0.4 s to drop 3 ft to the ground, so at a speed of 20 mph, both the vehicle and the beanbag would have moved approximately 23 ft during the time the beanbag took to fall to the ground. The distance between the location where the beanbag was dropped and the location of the pedestrian target, plus 23 ft, was used as an approximation of the subject's identification distance for the pedestrian target. Subjects also verbally reported which direction the pedestrian target was facing after dropping the beanbag.

After they practiced the visibility task, subjects performed the task once under each of two headlighting conditions: low beam headlights and using the ADB system. High beam headlights were not included in this experiment because they would be expected to be the same as the ADB system under the conditions of the test, and many published findings have already demonstrated the advantages of high beam headlights over low beams for forward visibility [see Perel et al. (1983) for a summary of research on low beam and high beam visibility]. The order of the headlighting conditions and the walking direction of the pedestrian target was randomized for each subject.

Discomfort Glare Experiment

In the discomfort glare experiment, a total of 12 subjects (9 male/3 female, age 23 to 68 years, mean 42, s.d. 16) participated. All subjects were licensed drivers. After they arrived at the test location, subjects were asked to sit in a passenger vehicle parked in the southeastbound traffic lane near the northwestern end of the straight section of the test road. The low beam headlights of the vehicle in which subjects sat were energized. The test car was driven from beyond the curve southeast of the subjects' viewing location, at a speed of approximately 40 mph, until it drove past the subjects. Subjects were asked to look toward the oncoming test car during this time and then after it had passed by, to rate the overall level of discomfort glare from the headlights during the approach using the following nine-point scale (De Boer, 1967):

9: just noticeable glare
8
7: satisfactory
6
5: just permissible
4
3: disturbing
2
1: unbearable

During each trial, the headlights on the test car were either low beam headlights, high beam headlights, or the ADB system. The order of the headlighting condition was randomized for all subjects, who viewed each lighting condition once.

RESULTS: FIELD EXPERIMENTS

Pedestrian Target Identification Experiment

Figure 4 shows the average pedestrian target identification distances under each forward headlight system in the pedestrian target experiment. The average identification distance was more than double under the ADB system than it was under the low beam headlights. A paired Student's t-test was used to compare each subject's identification distance under low beam and under ADB illumination; it confirmed that the mean identification distance was statistically significantly longer ($t_9=7.44$, $p<0.05$) under the ADB system. Subjects did not make any errors when reporting the walking direction of the pedestrian targets. It should be emphasized that subjects in the present study were aware of the type of target used in the study. Perel et al. (1983) reported that when subjects were unaware of the nature of the detection target, they had shorter visibility distances than subjects who were aware of the target in their particular studies. Despite these differences, the relative rank order of different headlighting systems (e.g., low vs. high beams) did not change regardless of the awareness of subjects.

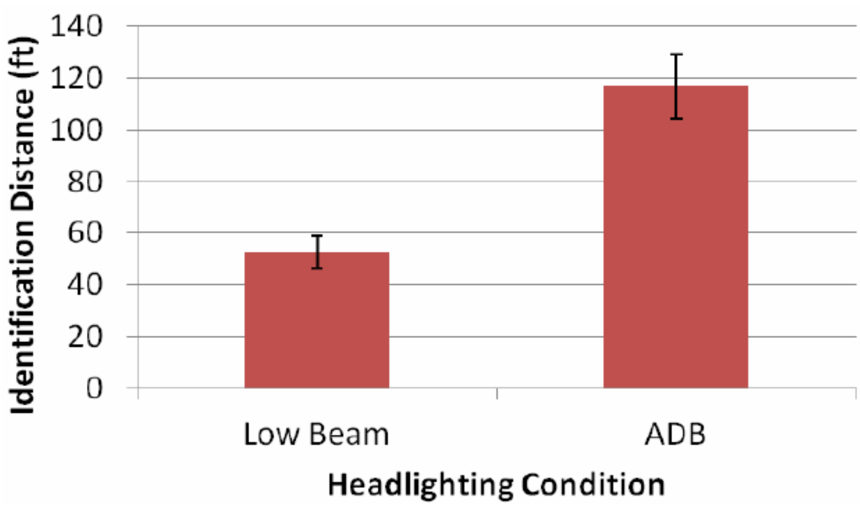


Figure 4. Average (±standard error of the mean) pedestrian identification distances under low beam headlights and under the ADB headlighting system.

Discomfort Glare Experiment

Figure 5 illustrates the average discomfort glare ratings for each of the oncoming headlighting conditions used in the discomfort glare experiment. A repeated-measured analysis of variance (ANOVA) on these ratings confirmed that there was a statistically significant ($F_{2,22}=61.4$, $p<0.05$) main effect of the headlight condition. Follow-up paired Student's t-tests between each subjects' glare ratings under different pairs of conditions, using the Bonferroni correction to adjust for multiple *post hoc* statistical comparisons (Sheskin, 1997), showed that there were statistically significant differences in the glare ratings between the low beams and high beams ($t_{11}=9.53$, $p<0.05$) and between the ADB system and high beams ($t_{11}=9.80$, $p<0.05$), but there was not a significant difference between the glare from the ADB system and from the low beams ($t_{11}=0.54$, $p>0.05$).

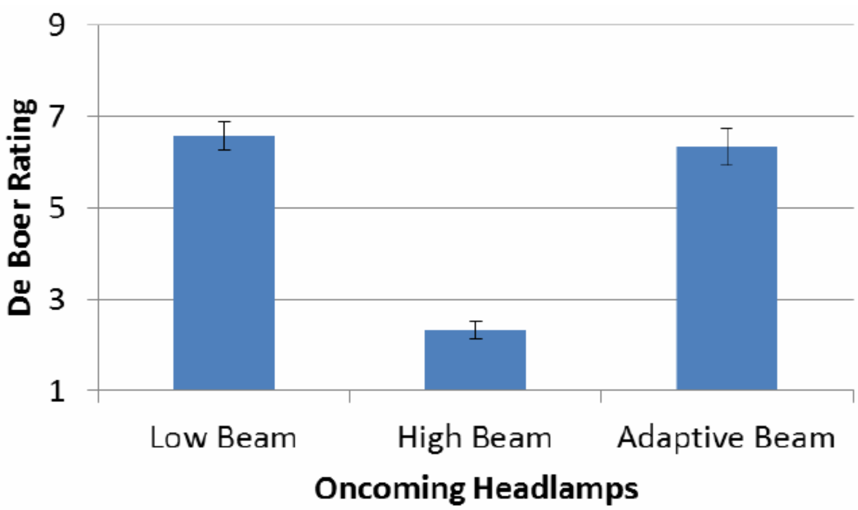


Figure 5. Average (±standard error of the mean) discomfort glare ratings given in response to each of the oncoming headlight conditions.

DISCUSSION: FIELD EXPERIMENTS

The results of the field experiments described in this report suggest that ADB functionality does have the potential to increase levels of forward visibility beyond those provided by fixed low beam headlights, without producing more discomfort glare to oncoming drivers. Subjective ratings of discomfort in response to the ADB headlighting condition were almost identical to those under the low beam headlights, which suggests that in terms of discomfort glare, the ADB system was unable to be distinguished from the low beam headlights, at least for the conditions under which they were tested in this study. These findings are consistent with those reported by Skinner and Bullough (2009), by Neumann (2014) and by Reagan and Brumbelow (2015).

It has commonly been assumed regarding vehicle headlights that there is an inherent tradeoff between forward visibility and glare (Perel et al., 1983). In other words, increasing the intensity of headlights improves visibility, but will increase the amount of glare other drivers experience. Reducing intensity will reduce glare, but would also reduce forward visibility to the point where sufficient stopping distance is not likely to be provided at speeds exceeding 35 to 40 mph (Bullough et al., 2008). When temporal control of vehicle lighting, which tailors intensity reductions only in the direction of oncoming and preceding drivers in order to mitigate glare, ADB systems may offer a way to escape the otherwise inherent tradeoff between visibility and glare from headlighting systems.

Of course, the results of the present study and of previous research need to be extended to additional conditions before an iron-clad statement can be made regarding the benefits of ADB headlighting systems such as the one used in these experiments. Only one single ADB system was tested under one single roadway geometry, and with one single pedestrian target location, with relatively few subjects and observations. Additional data for additional roadway geometries, such as those started by Reagan and Brumbelow (2015) for discomfort glare, and including preceding drivers, who experience glare through their rear-view mirrors, would also be needed. The temporal profiles of switching ADB systems among beam patterns also should be considered, to make sure that intensity changes will not be judged as distracting or disturbing.

Additionally, every ADB system from different manufacturers and for different vehicle models is almost certain to perform differently, and objective methods for characterizing their performance are needed. Mazzae et al. (2015) conducted extensive field photometric measurements of the illuminances produced by ADB systems under different roadway scenarios, and found that measurements could be conducted repeatably and consistently. The results of these measurements could permit quantitative assessment of disability glare from ADB systems. To the extent that objective and repeatable measurement methods for assessing the performance of ADB headlighting systems can be developed (a topic considered in the subsequent sections of this report), the experimental findings presented here suggest that ADB headlighting systems could offer substantial promise for improving nighttime driving safety.

METHOD: TEST MEASUREMENTS

The same test car used in the field experiments, equipped with an ADB system, was used for the test measurements. Testing was conducted along the same closed two-lane road (Town of East Greenbush, Rensselaer County, NY) and along the same flat, straight section (see Figure 1). A test fixture rack (Figure 6) was constructed using adjustable sliding pieces that could be moved around. The fixture included Edison screwbase sockets for the simulated test headlights and tail lights, and a mounting screw for a calibrated illuminance sensor. The test lamps and the illuminance sensor were mounted in the same vertical plane. The sockets were filled with LED A19 lamps, which produced white illumination having a luminous intensity of approximately 150 cd (±10%) within a 10° cone to simulate oncoming headlights. The lamps would be covered with gel filters (red and neutral) to simulate preceding tail lights having a luminous intensity of approximately 6 cd (±10%) within a 10° cone (this intensity seemed more representative than 13.5 cd suggested in the work-in-progress website for SAE J3069™, since the minimum required tail light intensity in FMVSS No. 108 is only 2 cd). The light from the unfiltered and filtered lamps conformed to SAE J578™ color requirements for white and red, respectively.

Figure 6. The test fixture where the illuminance sensor and the simulated headlights and tail lights were mounted for the test measurements.

All of the measurements were conducted following the end of civil twilight. During each measurement, the test car was driven by an experimenter at approximately 40 mph along the right lane (when the test fixture was either in the left lane or in a position one lane width to the left of the left lane) or along the left lane (when the test fixture was either in the right lane or in a position one lane width to the right of the right lane). At all times throughout the 250 m (800 ft) section of straight road, there was a clear line of sight between the ADB headlighting system and the test fixture rack.

Traffic sensors were located along the straight section of road at several distances in front of the test fixture rack; these distances are listed in Table 1. The distances of 30, 60 and 120 m were among several distances recommended by Flannagan and Sullivan (2011) in the assessment of glare from headlights. The longest distance, 155 m, was recommended by Rumar (2000) as the minimum distance within which high beam headlights should be dimmed to low beams (e.g., beyond this distance it would not be unreasonable to keep high beam headlights on when facing oncoming traffic). The traffic sensors were linked to a computer that in turn was linked to the illuminance meter and stored continuous measurements at approximately 50 Hz. The traffic sensor status was also stored at the same frequency so that illuminances at the time the vehicle passed each traffic sensor could be identified.

Also listed in Table 1 are the maximum illuminances that would be expected to be produced at oncoming drivers' eyes and at the mirrors of preceding vehicles by low beam headlights conforming to FMVSS No. 108, based on photometric analyses from Flannagan and Sullivan (2011). These illuminance values were also used by Mazzae et al. (2015) in their field measurements of ADB systems. It is important to note, however, that the test car (a European market model) was not designed to conform to FMVSS No. 108 requirements, nor to J3069™ requirements under development. However, since the ADB system on this vehicle was found in the field experiment described earlier in this report to elicit discomfort glare similar to that from low beam headlights meeting ECE requirements, which are recognized as having slightly stricter controls to prevent glare (Moore, 1998), the values based on the work by Flannagan and Sullivan (2011) were used as preliminary performance criteria in the present test measurements. Still, any differences between the measured performance and these preliminary criteria should not be interpreted as deficiencies in the design of the ADB headlighting system, since it is reasonable to expect that the beam patterns in a vehicle for the U.S. market would differ from those used in the European-market test car.

Distance (m)	**Driver Eye Illuminance (lx)**	**Mirror Illuminance (lx)**
30	1.776	18.854
60	0.634	4.041
120	0.281	4.041
155	0.281	4.041

Table 1. Test measurement distances and preliminary illuminance criteria for drivers' eyes and mirrors, based on Flannagan and Sullivan (2011) and also used by Mazzae et al. (2015).

The simulated passenger car headlights in the test fixture rack were positioned 0.6 m above ground and 1.1 m apart; the passenger car driver eye location was 1.1 m above ground and 0.4 m to the inside of the driver side headlight. The simulated passenger car tail lights were mounted 0.6 m above ground and 1.4 m apart. The passenger car rear view mirror location was centered between the tail lights and positioned 1.2 m above the ground. The driver-side and passenger-side mirror locations were positioned 0.2 m outside and 0.3 m above the tail light locations. The simulated motorcycle headlight was positioned 0.6 m above ground, and the motorcycle driver eye location was 0.7 m above the simulated headlight position. The simulated motorcycle tail light was 0.6 m above ground and the motorcycle driver-side and passenger-side mirror locations were 0.6 m above and 0.2 m to each side of the tail light position.

While all of the measurements were made during darkness in an otherwise unlighted area, all of the measurements experienced additional ambient light from the simulated headlight and tail light sources, either directly or indirectly, from illumination reflected off the pavement directly in front of the test fixture rack. In order to isolate the test car's headlight illumination, the average illuminance from the last several seconds of each measurement run, occurring after the test car had passed by the test fixture, was subtracted from all of the measurement values in a given run.

Overall, a total of 25 scenarios involving oncoming or preceding passenger cars or motorcycles were evaluated, measuring illuminances at driver eye locations or rear view mirror locations. In one of these scenarios, the simulated headlights on the test fixture rack were switched off at the start of the run, and then were energized during the run, in order to evaluate the ADB system's response time.

RESULTS: TEST MEASUREMENTS

System Response Time

To test the system response time, two runs were conducted with the test fixture located one lane to the left of the approaching test car equipped with the ADB system. The illuminance sensor was in the passenger drive eye location. At the start of each measurement run, the simulated headlights were turned off, and the test vehicle began to approach. As soon as experimenters verified that the test vehicle had passed the 120 m distance location, the simulated headlights on the test vehicle were energized. Figure 7 shows the illuminance profile as a function of time, for one of these trials. The test vehicle passed the 120 m location at time=60.7 s, and the illuminance was sharply reduced by time=61.8 s, a difference of 1.1 s (this includes the experimenter's response time to turn the simulated headlights on). The second response time trial yielded the same response time of 1.1 s, including the experimenter's response time. Both of these trials confirmed that the ADB system responded within 2.5 s from the J3069™ work-in-progress website.

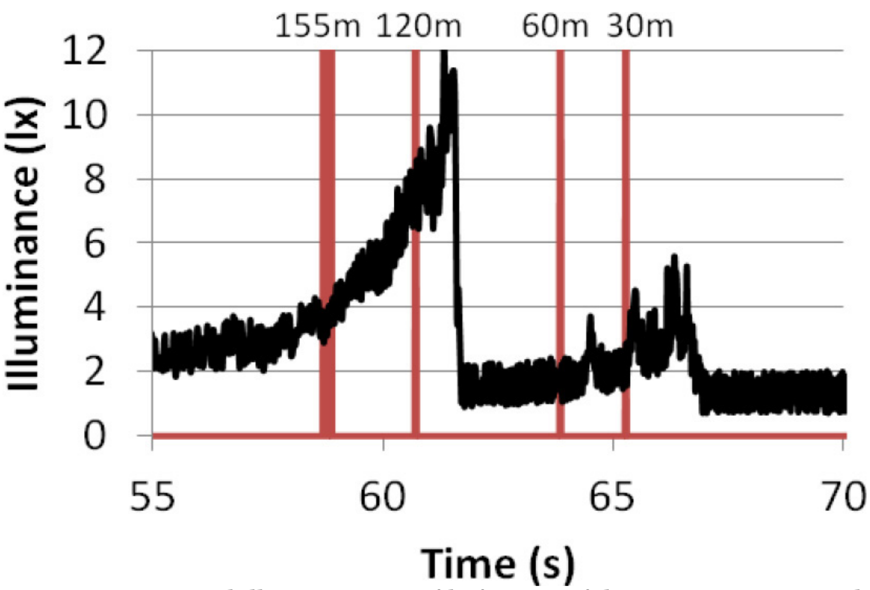


Figure 7. Temporal illuminance profile for one of the response time trials. The simulated headlights were switched on shortly after the test vehicle passed the 120 m distance, and the illuminance from the ADB system decreased shortly afterward (after no more than 1.1 s).

Measurement Artifacts

It was found that two factors could influence the individual illuminance measurement values: the light output modulation of the test car's headlights, and defects in the roadway pavement surface. Regarding light output modulation, Figure 8 shows the regular fluctuation in the illuminance measurements when they were sampled at 50 Hz. To reduce the impact of this modulation, the illuminances for the specific test distances in Table 1 were averaged together with the two preceding and two following measurements to smooth the data temporally.

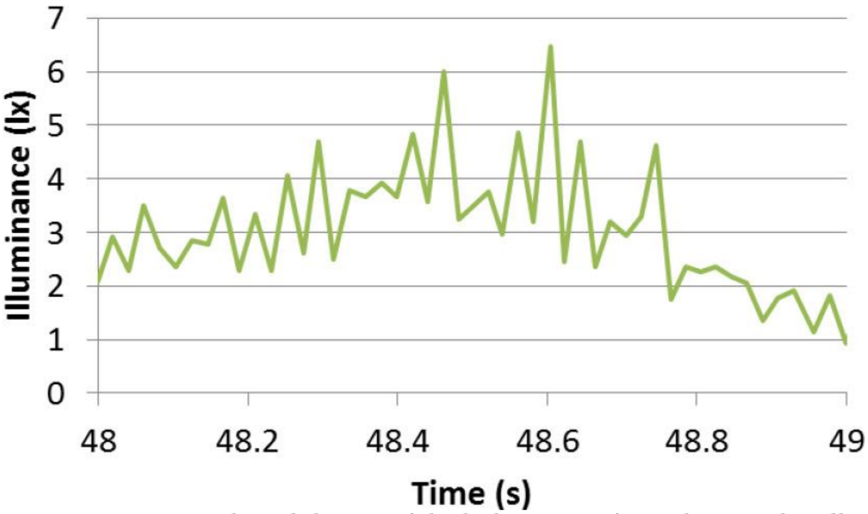


Figure 8. Temporal modulation of the light output from the ADB headlighting system for an illuminance sampling rate of 50 Hz. The data in this figure correspond to the driver eye illuminance for a passenger car driver located one lane to the right of the test car.

Related to the impact of roadway surface defects, Figure 9 shows the measured illuminances during one measurement run along with the times that the test vehicle passed each of the traffic sensors. "Spikes" in the illuminance values can be seen near 45 m, between the 30 m and 60 m locations, and near the 30 m location. The latter spike would strongly impact the resulting illuminance for the 30 m test distance. These two spikes were consistently found for measurement runs made with the test vehicle in the same lane, and in the same locations. After verifying visually that the test vehicle headlighting system did not exhibit sharp temporary increases in illuminance while approaching when it was 45 m or 30 m away along other sections of the road, inspection of the nominally flat roadway surface revealed that there were paving defects in one lane that temporarily changed the test vehicle's pitch when it was about 45 m and 30 m in front of the test fixture. Since the illuminance from the test car's headlights would be expected to gradually increase as the car approached the test fixture within this distance range, the illuminance measurements for the 30 m distance were interpolated from the smoother illuminance data sections both before and after the spike that occurred near 30 m.

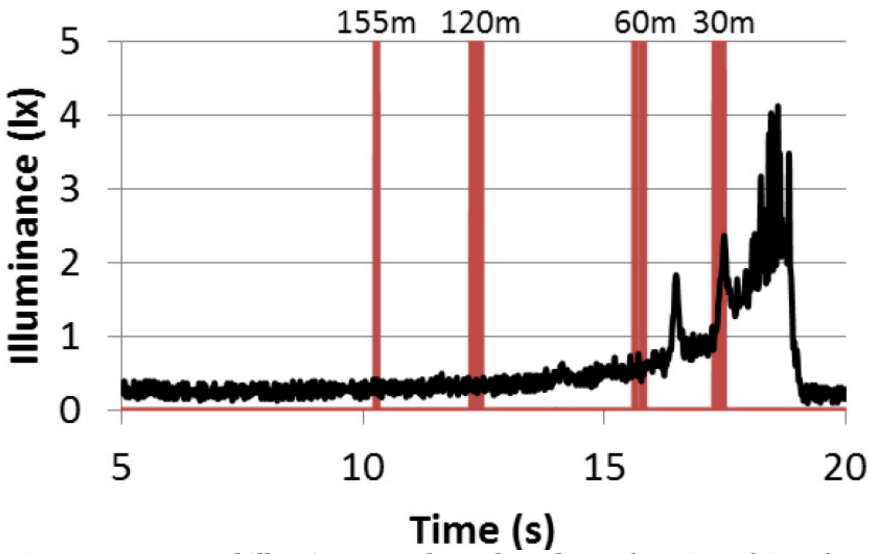
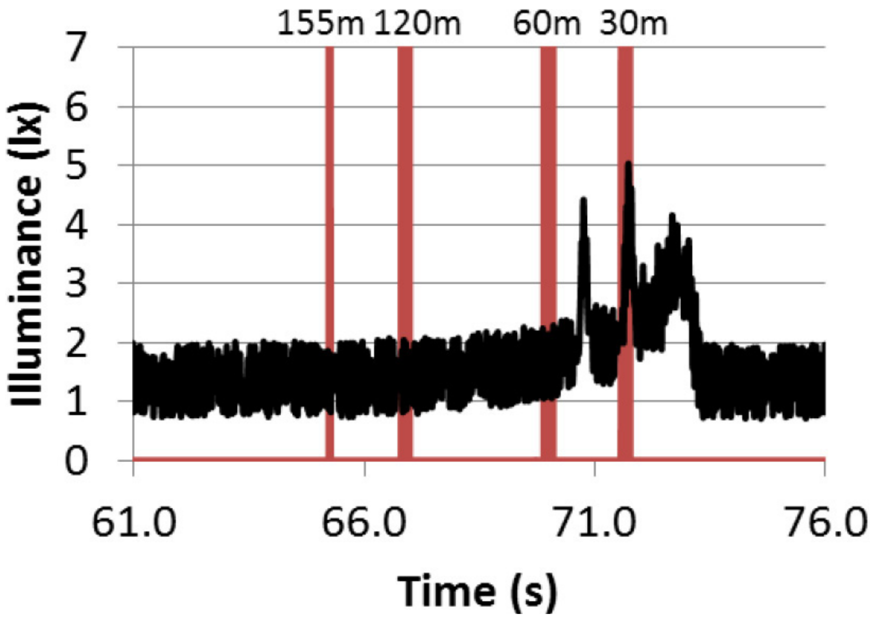


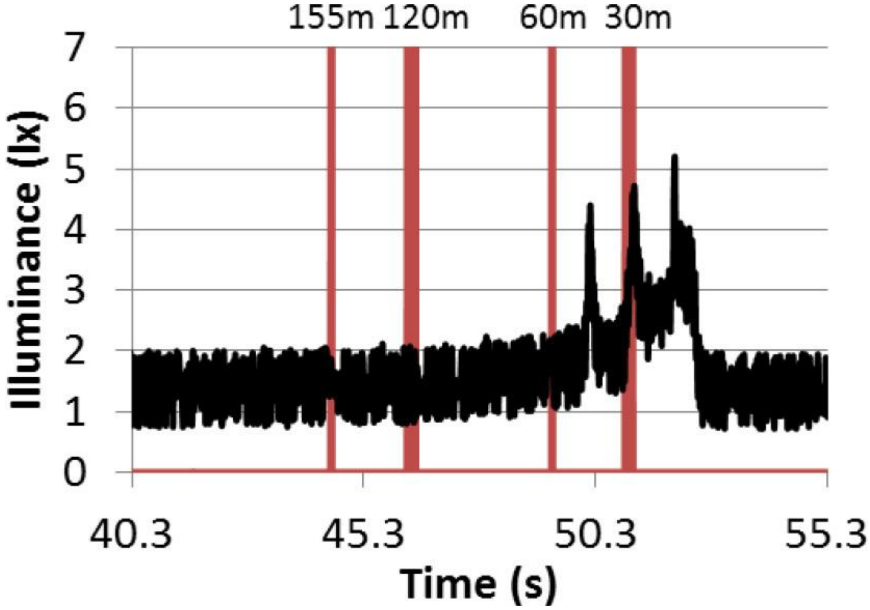
Figure 9. Measured illuminance values plotted as a function of time for one measurement run (with the ADB system approaching simulated tail lights located one lane to the left, and with illuminance measurements made at the rear view mirror location). The vertical bars show when the test vehicle passed each traffic sensor location.

Measurement Consistency

For most of the scenarios (17 out of 25), multiple measurement runs (from n=2 to n=5) were conducted to account for the potential effect of minor variations in lane position, vehicle speed/acceleration, and other factors on the measured illuminances. In some of the motorcycle scenarios the ADB system decreased its high beam illumination mode in some of the runs before reaching a particular distance (such as 120 m or 155 m), while in other runs the ADB system did not do so until after reaching a closer distance. This tended to result in larger variations in the measured illuminances for the 120 m or 155 m distances for some of the motorcycle scenarios. Aside from this issue, different individual temporal illuminance measurement profiles for the same scenarios were generally consistent. Figures 10a and 10b show two runs that were made when the test car's ADB system approached a passenger car located one lane to the left, for the driver eye location. The time scales for these runs were adjusted to facilitate comparisons, and the overall slopes and absolute values are very similar, including the presence of the spikes near 45 m and 30 m, as mentioned previously. The strong similarity between the curves indicates that it is possible to achieve relatively repeatable measurement data.



a.



b.

Figure 10. Temporal illuminance measurement profiles for two runs using the same scenario, in which the ADB headlight system approached simulated passenger car headlights located one lane to the left, and illuminances were measured at the driver eye location.

Scenario Results

Tables 2 and 3 summarize the average illuminance measurements for passenger car driver eye (Table 2) and mirror (Table 3) measurement locations. Some of the runs summarized in Table 2 used fixed low beam and high beam conditions on the test car; for all of the runs summarized in Table 3, the test car utilized its ADB system.

Tables 4 and 5 show the average illuminance measurements for the motorcycle driver eye (Table 4) and mirror (Table 5) measurement locations. In all of the runs summarized in these tables, the test car utilized its ADB system.

Test Car Headlights	Test Fixture Location	Distance from Test Fixture			
		30 m	60 m	120 m	155 m
Low beam (n=3)	Left 1 lane	0.99 lx (±0.09)	0.15 lx (±0.08)	0.11 lx (±0.06)	0.17 lx (±0.08)
High beam (n=3)	Left 1 lane	17.31 lx (±0.93)	17.35 lx (±2.38)	6.80 lx (±0.25)	4.10 lx (±0.34)
ADB (n=3)	Left 1 lane	1.24 lx (±0.09)	0.37 lx (±0.01)	0.04 lx (±0.02)	0.08 lx (±0.04)
ADB (n=2)	Left 2 lanes	0.55 lx (±0.19)	0.36 lx (±0.12)	0.14 lx (±0.11)	0.04 lx (±0.04)
ADB (n=4)	Right 1 lane	0.87 lx (±0.12)	0.50 lx (±0.11)	0.25 lx (±0.08)	0.17 lx (±0.06)
ADB (n=2)	Right 2 lanes	0.69 lx (±0.15)	0.85 lx (±0.01)	0.34 lx (±0.07)	0.37 lx (±0.04)

Table 2. Average (±s.e.m.) illuminances at passenger car driver eye locations for several scenarios and test fixture locations. Shaded cells indicate values that exceed the preliminary criteria in Table 1.

Sensor Location	Test Fixture Location	Distance from Test Fixture			
		30 m	60 m	120 m	155 m
Rear view mirror (n=3)	Left 1 lane	1.22 lx (±0.03)	0.34 lx (±0.02)	0.12 lx (±0.01)	0.11 lx (±0.02)
Rear view mirror (n=1)	Left 2 lanes	0.59 lx	0.27 lx	0.15 lx	0.14 lx
Rear view mirror (n=2)	Right 1 lane	0.95 lx (±0.01)	0.44 lx (±0.01)	0.19 lx (±0.07)	0.09 lx (±0.02)
Rear view mirror (n=1)	Right 2 lanes	0.53 lx	0.50 lx	0.17 lx	0.26 lx
Driver side mirror (n=3)	Left 1 lane	1.12 lx (±0.08)	0.33 lx (±0.01)	0.10 lx (±0.00)	0.12 lx (±0.03)
Driver side mirror (n=2)	Right 1 lane	1.32 lx (±0.12)	0.93 lx (±0.25)	0.08 lx (±0.03)	0.05 lx (±0.04)
Driver side mirror (n=1)	Right 2 lanes	0.84 lx	1.59 lx	0.59 lx	0.44 lx
Passenger side mirror (n=5)	Left 1 lane	1.83 lx (±0.05)	0.42 lx (±0.05)	0.14 lx (±0.07)	0.06 lx (±0.02)
Passenger side mirror (n=1)	Left 2 lanes	0.83 lx	0.43 lx	0.35 lx	0.37 lx

Table 3. Average (±s.e.m.) illuminances from the ADB system at passenger car mirror locations for several test fixture locations. None of the values exceed the preliminary criteria in Table 1.

Test Fixture Location	Distance from Test Fixture			
	30 m	60 m	120 m	155 m
Left 1 lane (n=3)	0.89 lx (±0.03)	0.25 lx (±0.02)	2.30 lx (±2.25)	2.95 lx (±1.48)
Left 2 lanes (n=2)	0.75 lx (±0.22)	0.48 lx (±0.17)	4.09 lx (±4.06)	2.85 lx (±2.73)
Right 1 lane (n=3)	1.07 lx (±0.05)	0.44 lx (±0.08)	0.18 lx (±0.09)	3.30 lx (±1.59)
Right 2 lanes (n=2)	0.51 lx (±0.08)	0.53 lx (±0.08)	3.90 lx (±3.66)	5.15 lx (±0.51)

Table 4. Average (±s.e.m.) illuminances from the ADB system at motorcycle driver eye locations for several test fixture locations. Shaded cells indicate values that exceed the preliminary criteria in Table 1.

Sensor Location	Test Fixture Location	Distance from Test Fixture			
		30 m	60 m	120 m	155 m
Driver side mirror (n=1)	Left 1 lane	1.30 lx	0.33 lx	0.10 lx	0.07 lx
Driver side mirror (n=2)	Right 1 lane	1.17 lx (±0.03)	0.44 lx (±0.03)	0.13 lx (±0.01)	0.08 lx (±0.01)
Driver side mirror (n=1)	Right 2 lanes	0.65 lx	0.47 lx	0.23 lx	0.21 lx
Passenger side mirror (n=1)	Left 1 lane	1.31 lx	0.47 lx	0.12 lx	0.08 lx
Passenger side mirror (n=1)	Left 2 lanes	0.44 lx	0.30 lx	0.11 lx	0.11 lx

Table 5. Average (±s.e.m.) illuminances from the ADB system at motorcycle mirror locations for several test fixture locations. None of the values exceed the preliminary criteria in Table 1.

DISCUSSION: TEST MEASUREMENTS

The test measurement data summarized in this report demonstrate that conducting road trials to assess the performance of ADB systems is practical and can yield repeatable results. While the measurements were underway, several issues were identified that could be of assistance in devising test protocols for ADB system evaluation.

Because ADB lighting systems might use temporal modulation to adjust the intensity of the headlights in various directions, particularly when they use solid-state (LED) light sources, it is recommended that when fast illuminance measurement sampling rates (such as the approximately 50 Hz rate in the present study) are used, the average of multiple measurements be used to determine the central tendency of the light output. In the present study, averaging a given measurement value with the two preceding and two following measurement values appeared to work reasonably well at temporal smoothing of the data.

Additionally, while it is important that the test measurements be conducted along a smooth, flat surface, it should also be noted that even apparently minor defects in the pavement can introduce substantial artifacts into the temporal measurement data. Fortunately, as identified in this study, these artifacts are highly repeatable, and in conjunction with verification that specific temporal artifacts are caused by the pavement surface and not by the lighting system, it is possible to interpolate measurement values to exclude the impact of these artifacts.

Regarding the specific performance of the ADB system on the test car that was evaluated in this study, it was found to have a relatively short response time, perhaps as short as 1 second, given the likely motor response times of the experimenters that were also part of the measured times. This is well within the 2.5 s recommended in J3069™ according to the SAE work-in-progress website described previously.

The ADB system that was tested had very few problems responding to the passenger car scenarios, and dimmed the headlights at all of the measurement distances evaluated. When the test fixture rack was located two lanes to the right of the test vehicle, the average illuminances at the passenger car driver eye location and at the three farthest distances were slightly greater than the preliminary criteria in Table 1. This may be related to the fact that this system was not designed to conform to the FMVSS No. 108 requirements underlying the criteria in Table 1. During some of the measurement runs when approaching a simulated motorcycle headlight, the ADB system did not always reduce its intensity by the time the test vehicle reached the 155 m or 120 m distances. This is expressed in terms of the increased variability in the measured values for these scenarios. The ADB system, however, always decreased its intensity in response to the simulated motorcycle headlight by the time it passed the 60 m measurement distance.

Overall, the measurement data for this vehicle's ADB system, particularly those in Table 2, are consistent with the visibility and glare evaluations summarized earlier in this report, which showed that ADB systems approaching passenger vehicles generally produce discomfort glare levels similar to those produced by low beam systems within the range of measurement distances used in this study (30 m to 155 m).

OVERALL DISCUSSION

Taken together, the findings from the experiments and test measurements summarized in this report suggest that ADB headlighting systems offer substantial promise for safety improvements, compared to the use of fixed low beam headlights, when driving at night. The test measurement data gathered in the present study, in combination with data from Mazzae et al. (2015), indicate that consistent and repeatable results can be obtained using a field measurement procedure involving the entire ADB system including headlight sources, cameras/sensors, image processing and control algorithms, and the vehicle itself. This in turn leads to the conclusion that objective criteria for performance can be developed and used to define ADB system performance.

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