Rationale and Supporting Work for Headlight Test and Rating Protocol

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RATIONALE AND SUPPORTING WORK HEADLIGHT TEST AND RATING PROTOCOL

This document describes the justification and supporting research for specific components of the Insurance Institute for Highway Safety (IIHS) headlight test and rating protocol. It is available from the technical protocols section of the IIHS website (http://www.iihs.org/iihs/ratings/technical-information/technical-protocols).

SUMMARY

This IIHS headlight evaluation assesses the on-road illumination provided by passenger vehicle headlight systems. The evaluation is based on illumination measurements on road sections with various horizontal curvature (straightaway, 150 m radius left and right curves, and 250 m radius left and right curves). Visibility illumination distances are assessed for low and high beams, with additional credit given for systems that automatically switch between high and low beam. In the low beam tests, glare illumination for drivers of oncoming vehicles also is measured and related to thresholds developed from Federal Motor Vehicle Safety Standard (FMVSS) No. 108. Systems which create excessive levels of glare on specific road sections do not receive credit for visibility readings in that scenario.

The overall headlight rating is assigned based on a combination of the low and high beam performance in the five curvature scenarios. The 10 total test conditions are weighted differently to more closely reflect their representation of real-world scenarios.

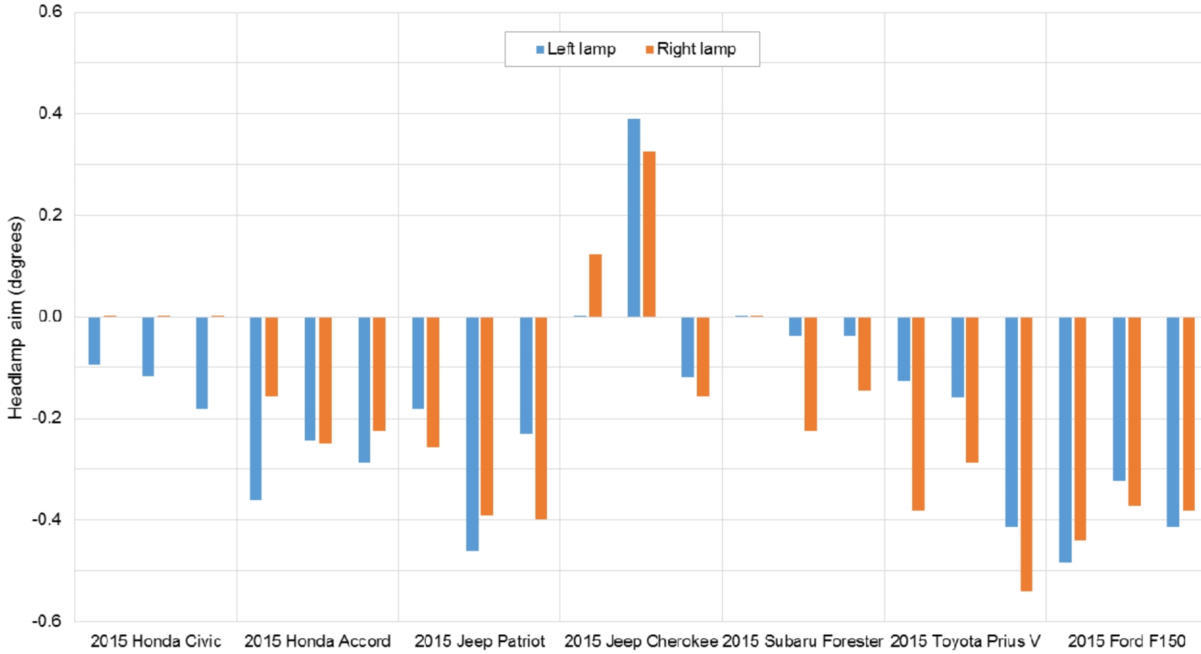
HEADLAMP AIM

In the United States, vehicle headlamps are certified to FMVSS 108. To comply with this standard, lamps must meet luminous intensity maxima and minima that are specified at fixed horizontal and vertical angles relative to the central axis of the headlamp. However, FMVSS 108 does not stipulate how the headlamp should be aimed when fitted to a vehicle. Most previous headlight-oriented research has involved reaiming the headlamps according to the vertical aim guidelines contained in the Society of Automotive Engineers (SAE) J599 Lighting Inspection Code, which calls for a vertical aim of 0 ± 0.76 degrees for lamps mounted at heights below 90 cm (SAE, 1997).

Because the IIHS headlight evaluation involves testing visibility at distances as great as 250 m (the beginning of the straightaway approach), even small headlamp aim angles can make a large difference. For example, the vertical angle between a headlamp mounted at 69 cm and the illuminance sensor placed 25 cm above the roadway is -0.25 degrees at 100 m. Downward aim of 0.25 degrees will result in the low beam cutoff falling below the sensor at any distance greater than 100 m.

IIHS measured aim for seven new vehicle models with VOR type headlamps, with measurements repeated on three unique vehicles for each model. All vehicles were measured with a full tank of gas and 77 kg of ballast in the driver seat. The aim measurements of both headlamps for all 21 vehicles are displayed in Figure 1. The 2015 Ford F150 was the only vehicle with lamps mounted above 90 cm, and the measured aim for all six lamps was close to the SAE recommended -0.38 degrees. All the other vehicles fell within the SAE J599 range of 0 ± 0.76 degrees, but most had aim values that would still be expected to have a substantial effect on the measured visibility distances in the IIHS evaluation. In addition, with the exception of one vehicle, the range of measured aim values for a given headlamp did not span 0 degrees. This indicates that conducting headlight evaluations with the lamps reaimed to SAE recommendations (i.e., 0 degrees for most vehicles) is likely to reduce the real-world relevance of the evaluation program. While some of the measured aim values may reflect variability in the aiming

Figure 1
Headlamp Aim Measurements



procedures during vehicle production, there are multiple reasons that some vehicle manufacturers may intentionally be aiming their headlamps at angles other than 0 degrees. To reflect their real-world performance, vehicles will be tested as received, with the headlamp aim unadjusted from its factory setting.

TEST CONDITIONS

Headlights are evaluated on a straightaway and on left and right curves of 150 and 250 m radii. An analysis of fatal nighttime crashes was conducted to support the selection of the curve conditions (Brumbelow, in press). For this analysis, satellite imagery was used to measure horizontal curve radius and length of 1,900 road sections on which fatal nighttime passenger vehicle crashes occurred in the 2012 Fatality Analysis Reporting System (FARS). Using a 500 m radius as the boundary between a curved and straight road, radii of 150 and 250 m represent approximately 30 and 60 percent, respectively, of the cumulative distribution of curve-related crashes (Figure 2).

Curve length and speed, in addition to radius, can be related to real-world driving scenarios. The 120 m test curve length is close to the measured median length of the FARS curves with radii below 500 m (Figure 2). The test speeds of 65 and 80 km/h are typical design speeds for rural roadways with curve radii of 150 and 250 m, respectively (American Association of State Highway and Transportation Officials, 2001). In addition, they fit within the speed limit range of 56-89 km/h (35-55 mi/h) in which 87 percent of the FARS curve crashes occurred (Figure 3). Curve length and speed are important mainly for dynamic curve adaptive systems that may have different sensitivities and response times upon entering a curve.

Figure 2
Curve Radii and Lengths for Fatal Nighttime Crashes

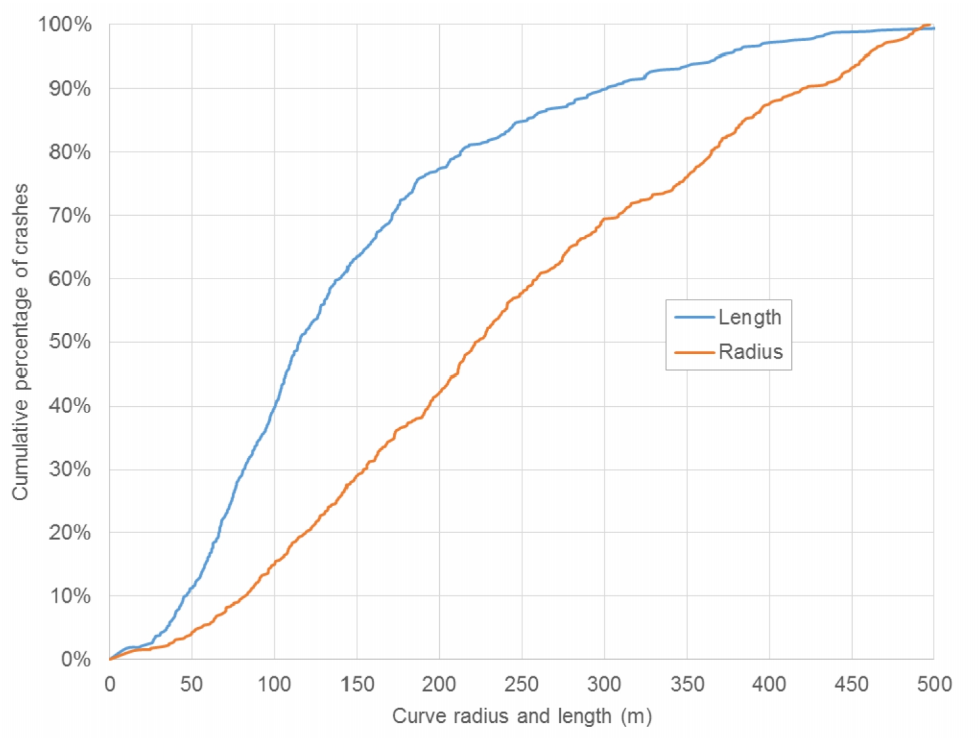
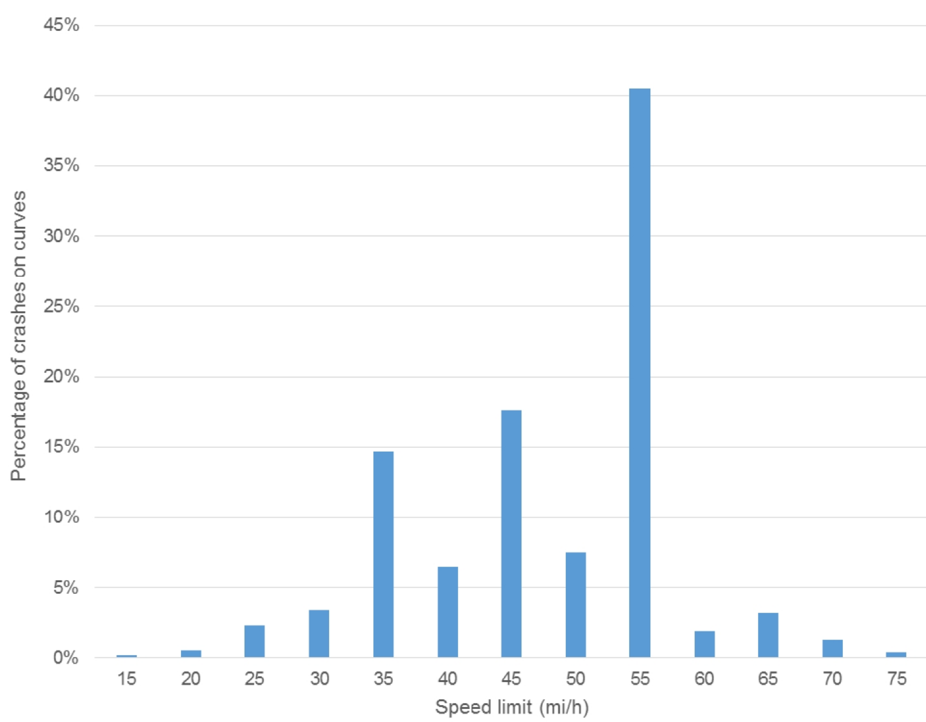


Figure 3
Speed Limits for Fatal Nighttime Crashes on Curves



VISIBILITY AND GLARE METRICS

Visibility Metric

Visibility performance is assessed using the distance at which the vehicle headlights project 5 lux to the measurement location 25 cm above the road. In real-world driving, the amount of illumination necessary to detect an object depends on many factors such as the object's angular size, reflectance, contrast with the background, angular position within the driver's field of view, as well as the driver's contrast sensitivity and visual acuity. Headlamp beam patterns often are represented with isolux plots that include lux values such as 1, 3, 5, 10, 20, etc. overlaid on a typical roadway (e.g., Commission Internationale de l'Eclairage, 2010; Schoettle et al., 2004). The most common single illuminance value used to assess visibility distance of low contrast objects likely is 3 lux (Commission Internationale de l'Eclairage, 2010; Sivak et al., 2005; Sullivan and Flannagan, 2009). For dynamic testing, the lower the threshold value that is selected, the more difficult it is to measure because vehicle pitch changes and instrumentation inaccuracies have greater proportional effects. The 5 lux value chosen for the visibility metric can be measured more accurately than 3 lux, will be correlated to the 3 lux distance (i.e., the 3 and 5 isolux plots are similarly shaped), and should ensure sufficient light levels for detecting obstacles with very low contrast.

The visibility measurement locations are the left and right edges of the travel lane for the curved approaches, and the left and right edges of a two-lane road for the straightaway. While there are many other locations where visibility likely is important, good illumination at the lane/road edges is considered to be a minimum requirement. Considering both left and right edges should provide a counterbalance against beam patterns that are too narrow, as will the general benefit that wider beam patterns provide in curves. Another concern is adaptive swiveling strategies that are optimized to one specific location and actually reduce visibility at other locations on the road (Sivak et al., 2005). Using whichever lane edge (left or right) that produces the shortest 5 lux distance measurement in the curved approaches should discourage such systems.

Glare Metric

The IIHS headlight evaluation primarily is an assessment of visibility. However, acceptance of the evaluation program requires that it does not encourage headlight systems that substantially increase glare for oncoming drivers. FMVSS 108 glare limits do not ensure an absolute maximum in practice because they do not control for variables such as headlamp aim, mounting height, or even vehicle heading through horizontal curves. For these reasons, the IIHS evaluation includes assessments of glare. Glare is not rated on a scale with a range of different levels of acceptability, but vehicles that produce glare illumination above specified thresholds do not receive full credit for their visibility measures.

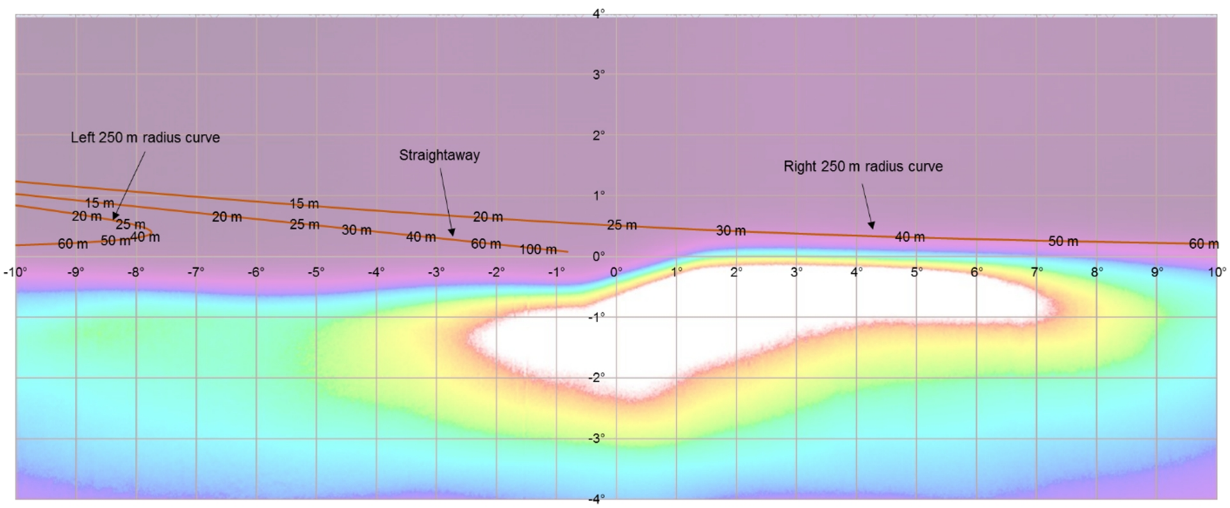
Taking the FMVSS 108 glare intensity maxima as a baseline requirement, a multi-step process was used to establish the glare illuminance threshold values for distances greater than 10 m:

1. The low beam headlamp patterns for seven different vehicle models were measured with an imaging photometer.
2. Using software, the output for each headlamp was adjusted to simulate all 14 different lamps (left and right on seven vehicles) set to the maximum positive vertical aim that still allowed compliance with the FMVSS 108 maxima at the two test points closest to the horizontal (1 degree right to 3 degrees right, 0.5 degree up) and (1.5 degrees left to max left, 0.5 degree up).
3. Using software, the output for each headlamp was adjusted to simulate a mounting height of 90 cm.

4. Using software, the output for each headlamp at the glare measurement point was calculated for both right curve approaches and the straightaway approach used in the evaluation (e.g., Figure 4). The left and right headlamp outputs were summed for each of the seven vehicles.
5. The glare illuminance versus clearance distance data were transformed to illuminance versus exposure distance (i.e., the total length that a given illuminance value was maintained).
6. Glare threshold values were chosen that minimally exceeded the glare illuminance versus exposure distances for the measured vehicles.

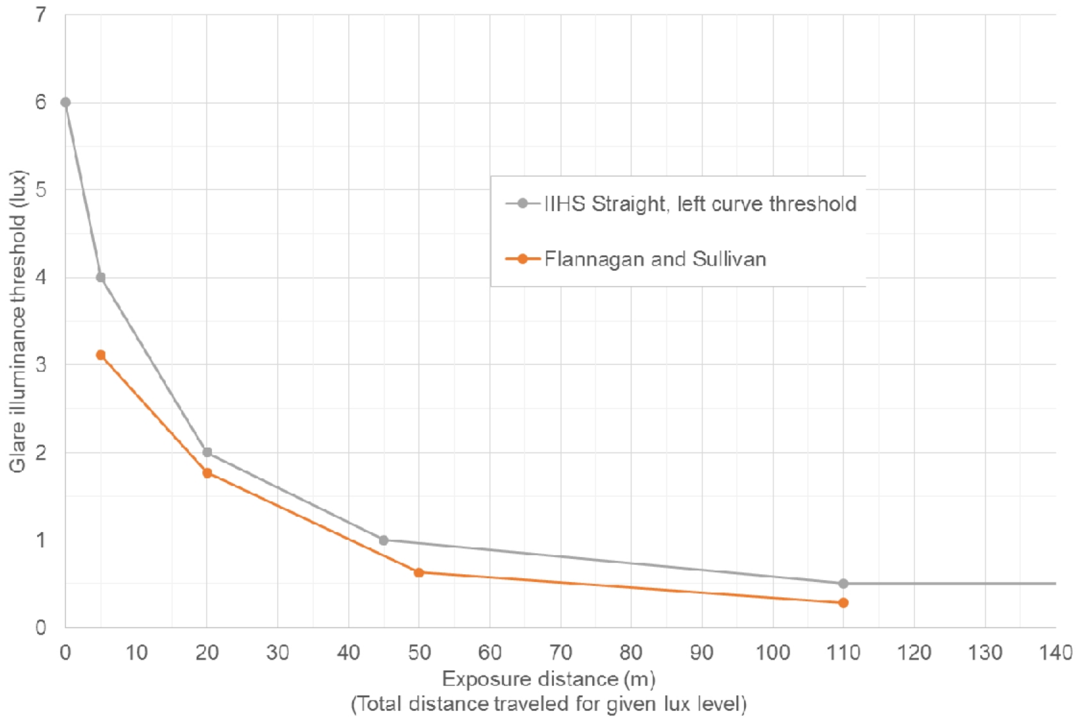
The glare illuminance versus exposure distance curves resulting from this process are based on the low beam gradients of actual production vehicles certified to comply with FMVSS 108. The mounting height of 90 cm was chosen as this is the maximum height recommend by SAE J599 at which headlamps should be aimed with a horizontal low beam cutoff (SAE 1997). Vehicles with headlamps mounted higher than 90 cm may need to be aimed downward in order to produce glare illuminance less than the threshold values. Assuming glare illuminance continually increases as a vehicle travels the straightaway approach, the IIHS glare threshold can be compared with values reported by Flannagan and Sullivan (2011) (Figure 5), who made some simplifying assumptions to estimate the glare illuminance that would be produced by a pair of headlamps with the maximum glare intensity allowed by FMVSS 108. The distances shown in Figure 5 are adjusted to account for the fact that the IIHS glare threshold values are applied when the vehicle is more than 10 m from the measurement point. Flannagan and Sullivan used a headlamp mounting height of 62 cm in their calculations.

Figure 4
Example of Glare Measurement Locations in
Headlamp Coordinate System for Different Approaches



The glare thresholds for right curves are greater than for straight and left curve approaches. As a vehicle negotiates a right curve, its trajectory crosses the perspective of drivers in the oncoming lane of traffic. This results in oncoming drivers being exposed to the right side of the beam pattern (Figure 4), which has higher allowed intensity values in FMVSS 108. On left curves, glare illuminance generally will be lower than on straightaways for standard beam patterns. However, curve-adaptive systems that swivel the headlamp in the direction of the curve will increase glare illuminance relative to static headlamps. (Conversely, on right curves swiveling systems will reduce glare illuminance relative to static systems because oncoming drivers are exposed to the higher intensity portion of the beam pattern while the light source is farther away.) The glare illuminance thresholds calculated using the straightaway geometry also will be used to assess left curves.

Figure 5
IIHS Glare Threshold for Straightaways and Left Curves Compared with Theoretical Application of FMVSS 108 Values (Flannagan and Sullivan, 2011)



By assessing glare illuminance in terms of overall exposure distance instead of the clearance distance between the vehicle and measurement point, both the peak illuminance and overall "dosage" of glare exposure are considered. Previous glare research has considered both of these factors (Porter et al., 2005; Van Derlofske et al., 2005) From their results, Bullough et al. (2008) inferred that "dosage is the primary factor impacting recovery times following exposure to oncoming headlamp illumination, but that subjective impressions of that illumination is dependent more upon the peak illuminance experienced during that exposure than by the dosage." In addition, using exposure distance thresholds simplifies comparisons on the curve approaches, where the changing vehicle heading means that glare illuminance does not increase monotonically during the approach.

At distances between 5 and 10 m, up to 10 lux of glare illuminance is allowed for all approaches. At these smaller distances, drivers are less likely to be focused on the oncoming vehicle headlamps, and greater angular distances from the light source are associated with less discomfort glare (Schmidt-Clausen and Bindels 1974). In addition, at smaller distances it is possible that additional light sources may contribute to the measured glare illuminance. Glare illuminance is ignored at distances below 5 m, where the high incidence angles result in greater sensor inaccuracies.

IIHS has conducted volunteer experiments (Reagan and Brumbelow, in press; Reagan et al., in press) that allow comparisons between subjective ratings of perceived discomfort glare and the proposed glare exposure boundaries in the IIHS headlight evaluation. After observing each subject vehicle approach, the volunteers would give a rating of perceived discomfort glare using the DeBoer rating scale. This scale consists of ratings from 1 to 9, with higher numbers indicating more acceptable levels of glare, and with the odd numbers anchored to verbal descriptors. The average ratings for selected conditions are shown in Figure 6. The glare illuminance experienced by the volunteer observers was photometrically measured for these conditions. The glare exposure distances for left curves and straightaways are shown in Figure 7, along with the proposed glare boundary in the IIHS evaluation. It should be noted that the two curve radii are not the same as those used in the IIHS headlight evaluation (80 and 180 m for the experiments vs. 150 and 250 m for the evaluation). The curve lengths also were shorter for the volunteer experiments.

The labels in Figure 7 identify all the approaches for which the average DeBoer rating was below 6. The lowest average rating (highest perceived glare) for the exposure curves below the proposed boundary was 5.6 for the Mazda 3 HID high beams on the sharp left curve. Of the approaches exceeding the proposed boundary, the Mazda 3 HID high beams on the gradual left curve produced the lowest glare exposure and highest average rating of 4.2 (least perceived glare).

On the right curves, all of the four high beam approaches were well above the proposed right curve glare exposure boundary, and all had average DeBoer ratings close to 2.0 (Figure 8). All of the six low beam approaches were well below the proposed glare exposure boundary and had average DeBoer ratings around 6.0 or higher. While none of the low beam right curve approaches were close to the proposed boundary in the volunteer experiments, higher values have been seen during research testing of other vehicles on the larger curve radii to be used in the evaluation program. Coincidentally, the glare exposure for the gradual left curve for the Mazda 3 HID high beams mentioned above would fall just below the proposed right curve boundary.

Figure 6
Average Volunteer Subjective DeBoer Glare Ratings for Different Headlight Systems and Curve Approaches

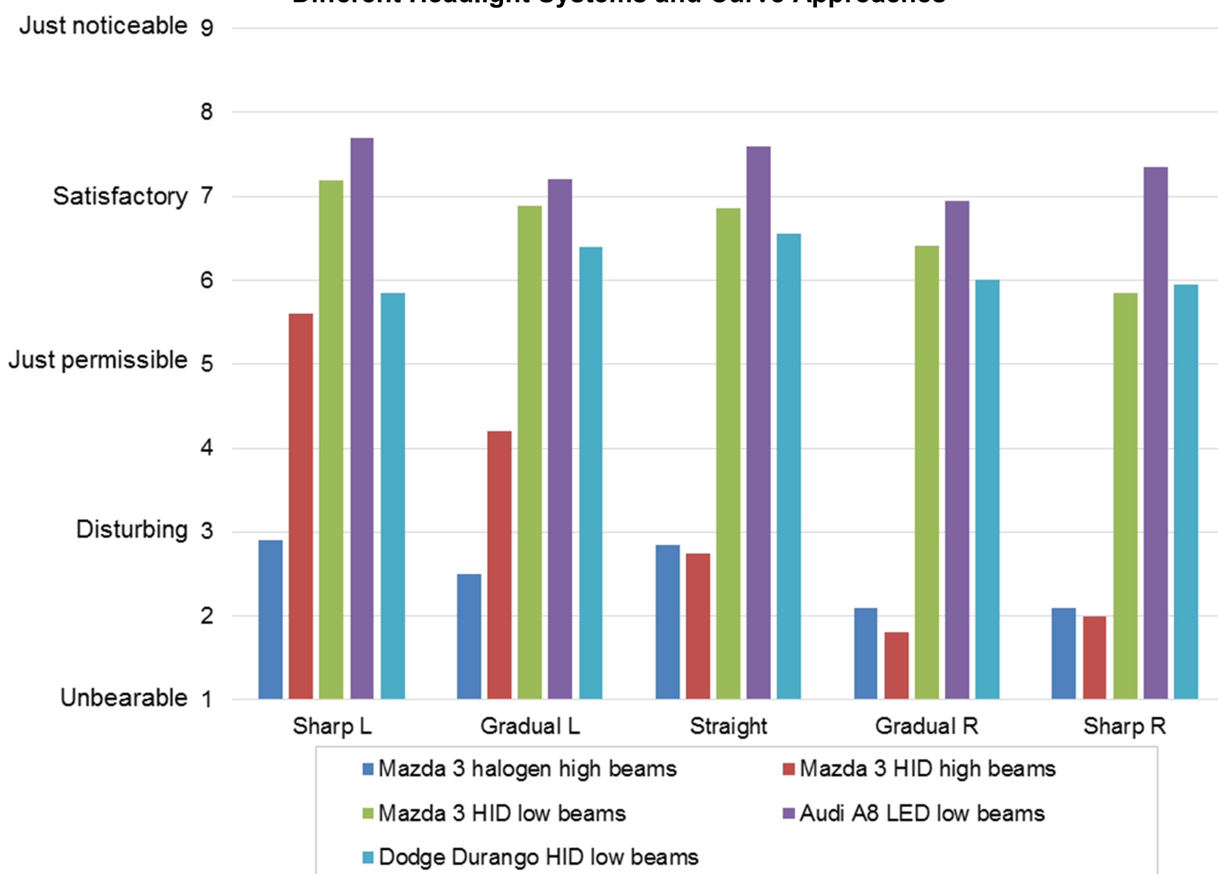


Figure 7
Glare Exposure Distances for Left Curves and Straightaways with Average DeBoer Ratings

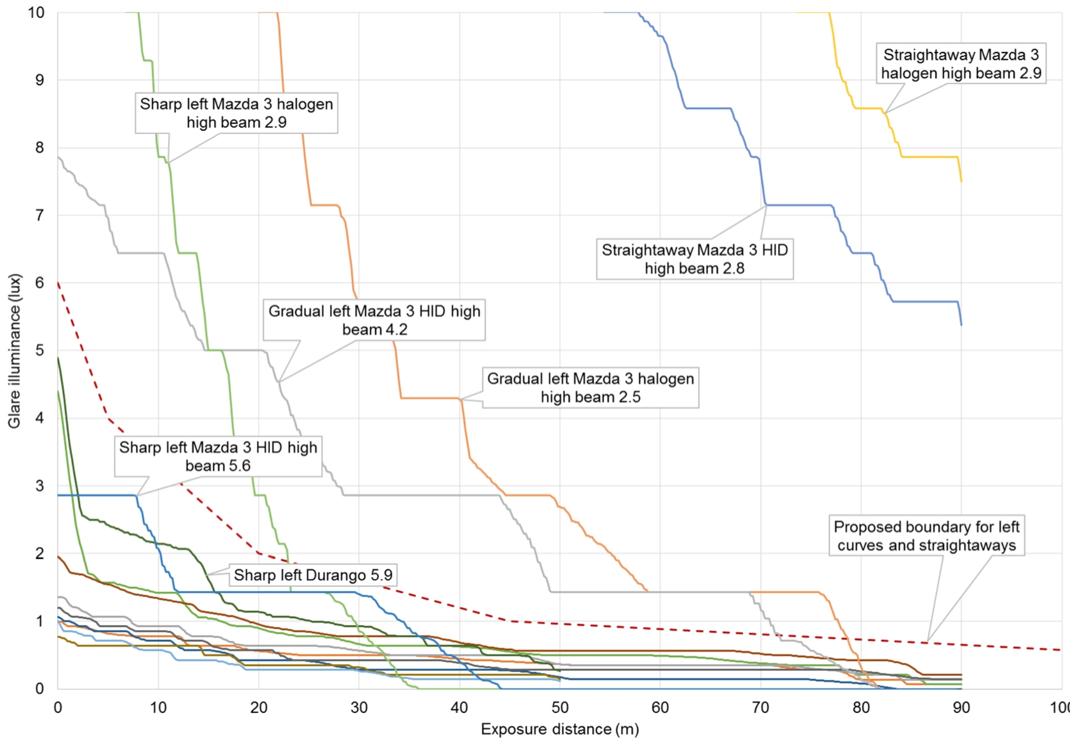
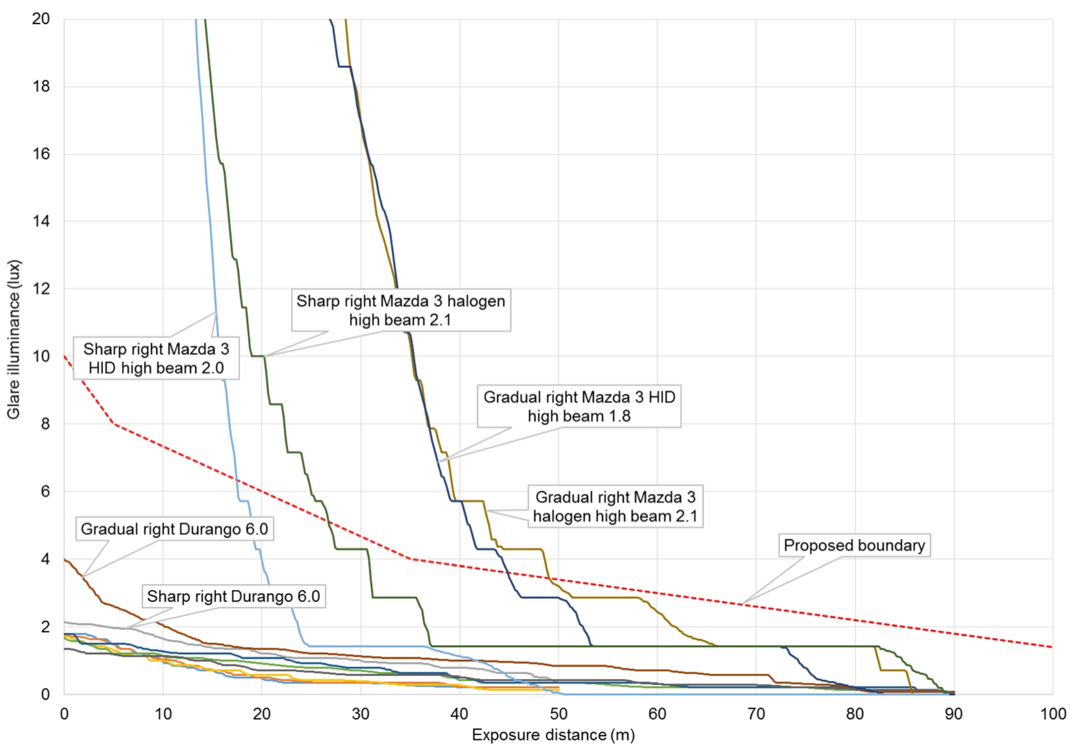


Figure 8
Glare Exposure Distances for Right Curves with Average DeBoer Ratings



OVERALL ASSESSMENT

The visibility and glare metrics are combined using a system of demerits to produce an overall assessment of a vehicle's headlight system. The demerit calculations were selected to weight the straightaway approach more heavily than the curved approaches. An analysis of 2012 FARS data found that around twice as many nighttime crashes occurred on straight sections of road as on curves (Brumbelow, in press). In addition, low beam test results are weighted more heavily than high beam tests based on research that has shown drivers only use their high beams around 50 percent of the time on unlit rural roads without other vehicles present (Iragavarapu and Fitzpatrick, 2012; Sullivan et al., 2004). Mefford et al. (2006) reported an even lower rate of 25 percent under ideal conditions, and only 3 percent of the total distance driven at night.

The following procedure was used to establish the demerit calculations for the different test conditions:

1. Research tests of around 20 different vehicle models were conducted, with headlamps adjusted to level aim.
2. The range of performance of the vehicles for each of the measurement locations was established.
3. Using multiples of 10 m, the 5 lux distance needed for no demerits was selected based on the best performing vehicles in each test condition (i.e., only a few vehicles had longer 5 lux distances).
4. Using multiples of 10 m, a "critical value" distance was selected that described inferior performance in each test condition (i.e., only a few vehicles had shorter 5 lux distances than the critical value).
5. The demerits associated with the critical value distance were determined by:
    a. Assigning 1 demerit for the lowest weighted test conditions (high beam curves).
    b. Multiplying the high beam demerits by 3 to produce the low beam demerits. This preserves a 25/75 ratio between high and low beams.
    c. Multiplying the total number of demerits for the curved conditions by 1.5 to produce the total number of demerits for the straightaway condition (high beams: 4 curves x 1 demerit each x 1.5 = 6 straightaway demerits; low beams: 4 curves x 3 demerits each x 1.5 = 18 straightaway demerits). This weighting emphasizes straightaways less than the 2/1 ratio observed in the 2012 FARS analysis, but will help encourage wider beam patterns as well as the types of curve-adaptive systems that have been demonstrated to improve visibility distance (Bullough and Skinner, 2009; McLaughlin et al., 2004; Reagan et al., 2015a; Sivak et al., 1994) as well as reduce insurance claims rates (Highway Loss Data Institute, 2011, 2012a, 2012b, 2013).
    d. Evenly splitting the total straightaway demerits between the right and left road edge measurements. While the right road edge measurement likely is more relevant for lane keeping and detection of obstacles in the travel lane, Sullivan and Flannagan (2007) found that more nighttime pedestrian crashes occur with pedestrians crossing from the left than from the right.
6. The linear equation describing the line that fits the "no demerit" and "critical value" points was determined. This equation is used to assign demerits for each test condition.

The demerit equations are continuous and extend through the critical values, therefore a vehicle with a shorter 5 lux distance than the critical value distance will be assigned more demerits for that condition. This means that the proportional contribution of the specific test conditions to the overall rating of different vehicles will not always be the same. However, continuous demerit functions ensure that meaningful differences will still be captured. For example, a 10 m difference in visibility distance should be helpful even if the higher distance remains below the critical value distance. In addition, the fact that the proportional contribution of different test conditions to the overall rating is allowed to vary is likely a better reflection of the real-world differences between vehicle headlight systems.

In any low beam condition where a glare boundary is exceeded, the demerits associated with the critical value for that condition are assigned, unless the measured 5 lux distance produced an even higher demerit value. Thus, visibility gains associated with systems that increase glare beyond FMVSS 108 compliant headlamps aimed according to SAE guidelines will not receive full credit.

The evaluation procedure includes a means of reducing the calculated demerits for the fitment of automatic high beam switching systems. This reflects the low rate of high beam usage described above, and the potential for automatic switching systems to increase the average overall real-world visibility provided by a vehicle lighting system. Qualifying criteria are placed on the demerit reduction to ensure that an automatic switching system cannot mask the demerits of a low beam that produces excessive glare, that there is actually an increase in visibility between the low and high beam conditions, and that the high beams provide at least nominal visibility relative to other high beams (i.e., the 5 lux distance must exceed the critical value for high beams in the given test condition).

The overall evaluation is assigned based on the total number of demerits in all test conditions, minus any reductions for automatic high-beam switching systems.

REFERENCES

American Association of State Highway and Transportation Officials. 2001. A policy on geometric design of highways and streets. Washington, DC.

Brumbelow ML. 2015. A survey of horizontal road curvature for fatal nighttime crashes. *Proceedings of the 11th International Symposium on Automotive Lighting*, in press. Berlin, Germany: IAV Automotive Engineering.

Bullough JD, Skinner NP. 2009. Predicting stopping distances under different types of headlamp illumination. *Proceedings of the 8th International Symposium on Automotive Lighting* 312-317. Munich, Germany: Herbert Utz Verlag.

Bullough JD, Skinner NP, Pysar LC, Radetsky LC, Smith AM, Rea MS. 2008. Nighttime glare and driving performance: research findings. Report no. DOT HS-811-043. Washington, DC: National Highway Traffic Safety Administration.

Commission Internationale de l'Eclairage (CIE). 2010. Performance assessment method for vehicle headlighting systems. Report no. CIE 188. Vienna, Austria.

Flannagan MJ, Sullivan JM. 2011. Feasibility of new approaches for the regulation of motor vehicle lighting performance. Docket no. NHTSA-2011-0145. Washington, DC: National Highway Traffic Safety Administration.

Highway Loss Data Institute. 2011. Mazda collision avoidance features: initial results. *Loss Bulletin* 28(13). Arlington, VA: Highway Loss Data Institute.

Highway Loss Data Institute. 2012a. Mercedes-Benz collision avoidance features: initial results. *Loss Bulletin* 29(7). Arlington, VA: Highway Loss Data Institute.

Highway Loss Data Institute. 2012b. Volvo collision avoidance features: initial results. *Loss Bulletin* 29(5). Arlington, VA: Highway Loss Data Institute.

Highway Loss Data Institute. 2013. Acura collision avoidance features: an update. *Loss Bulletin* 30(15). Arlington, VA: Highway Loss Data Institute.

Iragavarapu V, Fitzpatrick K. 2012. High beam usage on low-volume rural roads in Texas. *Transportation Research Record* 2298:88-95. Washington, DC: Transportation Research Board.

McLaughlin S, Hankey J, Green CA, Larsen M. 2004. Target detection distances and driver performance with swiveling HID headlamps. SAE Technical Paper 2004-01-2258. Warrendale, PA: Society of Automotive Engineers.

Mefford ML, Flannagan MJ, Bogard SE. 2006. Real-world use of high beam headlamps. Report no. UMTRI-2006-11. Ann Arbor, MI: University of Michigan Transportation Research Institute.

Porter RJ, Hankey JM, Binder SC, Dingus TA. 2005. Enhanced visibility series; Volume VII: Phase II, Study 5: Evaluation of discomfort glare during nighttime driving in clear weather. Report no. FHWA-HRT-04-138. Washington, DC: Federal Highway Administration.

Reagan IJ, Brumbelow ML. 2015. Perceived discomfort glare from an adaptive driving beam headlight system compared with three low beam lighting configurations. *Proceedings of the 6th International Conference on Applied Human Factors and Ergonomics*, in press. Louisville, KY: AHFE International.

Reagan IJ, Brumbelow ML, Frischmann T. 2015a. On-road experiment to assess drivers' detection of roadside targets as a function of headlight system, target placement, and target reflectance. *Accident Analysis and Prevention* 76(2015): 74-82.

Reagan IJ, Frischmann T, Brumbelow ML. 2015b. Test track evaluation of headlight glare associated with adaptive curve HID, fixed HID, and fixed halogen low beam headlights. *Ergonomics*, in press.

Schmidt-Clausen HJ, Bindels JH. 1974. Assessment of discomfort glare in motor vehicle lighting. *Lighting Research and Technology* 6:79-88.

Schoettle B, Sivak M, Flannagan MJ, Kosmatka WJ. 2004. A market-weighted description of low beam headlighting patterns in the US. Report no. UMTRI-2004-23. Ann Arbor, MI: University of Michigan Transportation Research Institute.

Sivak M, Flannagan MJ, Traube EC, Aoki M, Sayer JR. 1994. Evaluation of an active headlight system. Report no. UMTRI-1994-17. Ann Arbor, MI: University of Michigan Transportation Research Institute.

Sivak M, Schoettle B, Minoda T, Flannagan MJ. 2005. Potential visibility gains on straight and curved roads from proportional increases in current low beam intensities. Report no. UMTRI-2005-34. Ann Arbor, MI: University of Michigan Transportation Research Institute.

Society of Automotive Engineers. 1997. Surface Vehicle Standard J599: Lighting inspection code, Revised. Warrendale, PA.

Sullivan JM, Adachi G, Mefford ML, Flannagan MJ. 2004. High beam headlamp usage on unlighted rural roadways. *Lighting Research Technology* 36:59-67.

Sullivan JM, Flannagan MJ. 2007. Characteristics of nighttime pedestrian crashes: Implications for headlighting. Report no. UMTRI-2007-3. Ann Arbor, MI: University of Michigan Transportation Research Institute.

Sullivan JM, Flannagan MJ. 2009. Photometric indicators of headlamp performance. Report no. UMTRI-2009-18. Ann Arbor, MI: University of Michigan Transportation Research Institute.

Van Derlofske J, Chen J, Bullough JD, Akashi Y. 2005. Headlight glare exposure and recovery. SAE Technical Paper 2005-01-1573. Warrendale, PA: Society of Automotive Engineers.

