Lighting the way: IIHS headlight ratings predict nighttime crash rates

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Contents

ABSTRACT

Introduction: Vehicle headlights are the primary means of providing visibility illumination for drivers at night, when crash rates are several times higher than during the day. Based on research indicating a wide range of headlight performance in the passenger vehicle fleet and the absence of a comprehensive and objective consumer evaluation program, the Insurance Institute for Highway Safety (IIHS) began testing and rating headlight systems in 2015. The purpose of this study was to examine the relationship between headlight visibility, as quantified by IIHS, and real-world crash occurrence.

Material and methods: Poisson regression was used to estimate the effects of the headlight rating and the underlying demerits on the rate of nighttime single-vehicle crashes per vehicle mile traveled, while controlling for differences in daytime crash rates and other factors.

Results: Vehicles with better headlight visibility have lower nighttime crash rates. Achieving 10 fewer visibility demerits, the equivalent of one overall rating band, was estimated to reduce the nighttime crash rate by 4.6% (95% confidence interval [CI]: 2.1%–7.0%). While statistical significance was limited by small sample sizes, good-rated headlights were estimated to reduce crash rates by 12 to 29% relative to those with poor ratings for the different types of single-vehicle crashes studied. Among different components of the IIHS rating, the assessments of low- and high-beam curve visibility were associated with the greatest crash rate reductions.

Conclusion: This study demonstrates that the IIHS evaluation program encourages headlight designs that reduce the risk of nighttime single-vehicle crashes.

Keywords: headlights, headlight ratings, nighttime driving, single-vehicle crashes

INTRODUCTION

In the United States, it is estimated that vehicle travel between 7:00 p.m. and 6:00 a.m. accounts for around 22% of miles traveled (Environmental Protection Agency, 2020) but 46% of the fatalities caused by traffic crashes (Insurance Institute for Highway Safety [IIHS], 2020c). This implies the crash fatality rate per mile traveled at night is around 3 times the rate during the day. Differences in alcohol use, speeding, and restraint use are just three driver factors that likely contribute to this disparity (National Highway Traffic Safety Administration [NHTSA], 2007). Another source of increased risk is the reduced ambient illumination available at night. Even the relatively small difference in illumination between a full and new moon can affect the rate of certain types of crashes (Sivak et al., 2007).

Vehicle headlights are the primary method of increasing the illumination available to drivers at night. In the U.S, Federal Motor Vehicle Safety Standard (FMVSS) 108 regulates headlight design by prescribing minimum headlight intensity values for specific angular locations of the beam pattern corresponding to visibility and maximum values for locations that may cause glare to other road users. However, several aspects of the regulation prevent it from guaranteeing either comparable or adequate headlight performance. Among these are the lack of any aiming requirements after a certified headlight is installed on a vehicle; allowance for the headlight orientation to be adjusted during certification if a test point fails; and the use of the same angular test points for all vehicle types, regardless of headlight mounting height or spread.

While the headlight requirements in FMVSS 108 have remained largely unchanged since going into effect in 1968, vehicle and headlight manufacturers continually have made voluntary changes. Halogen, xenon high-intensity discharge (HID), and light-emitting diode (LED) light sources each have brought additional improvements over prior technology (e.g., Van Derlofske et al., 2001). Swiveling curve-adaptive headlights have improved drivers' target detection performance (Reagan et al., 2015). Analyses of insurance data have shown reduced claim frequencies for vehicles with more advanced headlamp technology, including curve-adaptive HID vs. static halogen (HLDI 2016, 2018b) and static

HID vs. static halogen (HLDI, 2018a). Many of the advanced technologies have been introduced as optional equipment, which add to the overall cost of a vehicle. Since 2004, Consumer Reports has included a headlight rating as part of its vehicle testing program (Consumer Reports, 2016). However, these are based on subjective assessments, are conducted after adjusting the headlight aim, and typically only include one headlight option per vehicle model. Before 2015, there was no comprehensive or objective source of information for consumers to compare the performance of different options with one another or with base equipment headlights.

IIHS begins headlight evaluation program in 2015

Based on the gaps in the federal standard and the apparent range of performance in the fleet, the Insurance Institute for Highway Safety (IIHS) introduced a headlight evaluation program in 2015. Headlight systems are tested on the vehicle in the condition they would be received by a consumer. Ratings are assigned based on measurements of low- and high-beam visibility illuminance as well as low-beam glare illuminance while the test vehicles are driven on a straightaway and four different curves (IIHS, 2018). When measurements from testing do not meet specific targets or thresholds, a system of demerits is applied.

Visibility illuminance is measured 25 cm above the ground on the left and right edges of the road (straightaway) or travel lane (curves), while glare illuminance is measured at a typical eye location for the driver of an oncoming vehicle. As a single example of the range of results for low beams without any glare downgrades, headlights have provided 5 lux illumination on the right edge of the straightaway at maximum distances ranging from 38–141 m. At a speed of 80 km/h, these distances are covered in 1.7 s and 6.3 s, respectively. If the 5 lux visibility distance in any of the test conditions is below the specified target level (e.g., 100 m in the previous example), a demerit score is calculated. Glare above a certain level also is converted to a demerit score, with the overall headlight rating based on the sum of all visibility and glare demerits. Headlights with 10 or fewer demerits are assigned a good rating, with demerit levels of 20 and 30 defining the acceptable/marginal and marginal/poor rating boundaries, respectively.

Since the introduction of the program, the proportion of headlight systems receiving good ratings has increased from 4% of those tested in 2015–2016 to 34% in 2020 (Figure 1). However, improved test performance is meaningful only to the extent that it translates into fewer nighttime crashes. Previous human factors research has demonstrated that greater headlight illumination improves detection performance in controlled environments (Bullough et al., 2016; Reagan et al., 2015; Van Derlofske et al., 2001). However, since actual crash events are relatively rare, studying them requires greater on-road exposure than can be achieved in typical volunteer studies. Insurance analyses have shown claim frequency reductions for different headlight features, but any underlying illumination differences were unknown. As the IIHS rating program is the first source of objective on-vehicle headlight performance data for a large portion of the passenger vehicle fleet, it provides the first opportunity to directly evaluate the effect of headlight illumination measures on crash incidence for a wide range of vehicles. The current study explored the relationship between headlight visibility as measured in the IIHS test and the occurrence of police-reported, single-vehicle crashes at night.

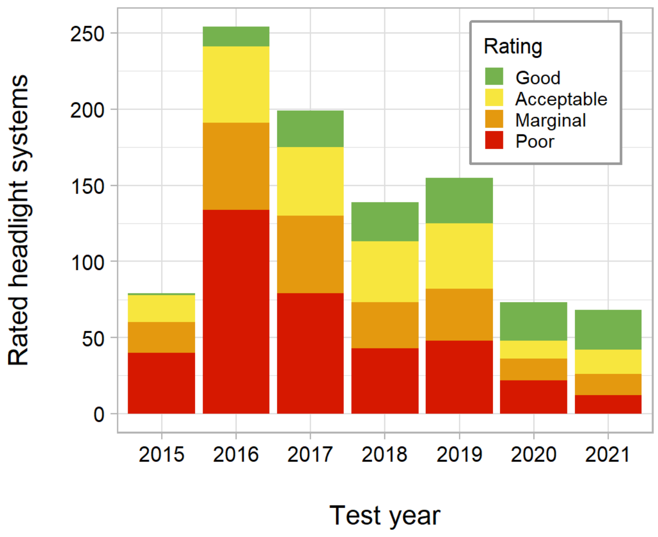

Figure 1. IIHS headlight ratings by test year.

MATERIAL AND METHODS

The effect of headlight visibility illumination on the nighttime single-vehicle crash (SVC) rate per vehicle mile traveled (VMT) was estimated using Poisson regression while controlling for crash, vehicle, and driver risk factors. In 2019, SVCs accounted for 64% of nighttime fatalities and 56% of daytime fatalities (IIHS, 2020c). As the presence of multiple vehicles introduces additional potential sources of visibility illumination, glare illumination, and crash risk, only SVCs were included. The effect of headlight performance on nighttime crash risk was estimated for all SVCs as well as different SVC types.

Headlight performance data

Vehicle manufacturers offer many of their models with multiple headlight options. IIHS tests and rates each system individually, but only vehicle models with a single headlight system or with optional systems that could be discerned from the Vehicle Identification Number (VIN) were included in the current study. This criterion was met by 365 distinct headlight systems on 187 vehicle models ranging from model years 2015 to 2020.

IIHS assigns headlight ratings of good, acceptable, marginal, or poor based on the total number of demerits resulting from all test conditions. Demerits resulting from excessive low-beam glare are not relevant to driver visibility in SVCs, so adjusted ratings were calculated using only the visibility demerits. The demerit calculations otherwise were identical, including adjustments for vehicles with high beam assist. This system automatically switches between low- and high-beam settings based on its detection of other vehicles using a forward-facing camera.

Crash data

Databases of police-reported crashes from 11 different states provided the real-world data for the study. In order to qualify for inclusion, state records included the full VIN, driver age, driver gender, and the crash date, time, and geographic coordinates. In addition, because the evaluation program began in late 2015, we excluded states that only had crash data for 2015 or 2016.

All qualifying states include a code for the daylight status at the time of crash, but these are based on subjective assessments and include missing or unknown values. Sun position was determined independently using the date, time, and geographic coordinates of each crash with the "maptools" package (Bivand & Lewin-Koh, 2019) in the R programming language (R Core Team, 2018). Nighttime crashes were defined as those occurring when the sun was more than 6° below the horizon, the position that corresponds to civil dawn or dusk. All other crashes were treated as daytime crashes. When the distribution of crash times suggested that codes of 12:00 a.m. and/or 12:00 p.m. were disproportionate, crashes with these coded times were excluded.

VMT and insured driver data

VMT data were obtained from data supplied to the Highway Loss Data Institute (HLDI) by CARFAX, a IHS Markit unit that maintains a vehicle history database. These data were obtained at the VIN level and categorized by HLDI according to the state in which each vehicle was insured as well as the gender and age of the rated driver on each policy. Rated driver age is categorized into three groups: < 25, 25–65, and > 65 years old. The VIN-level mileage data were transformed to average VMT per day for each unique combination of headlight system, state, rated driver age group, and rated driver gender. Details of the transformation process are described by Teoh (2020). Finally, the average VMT was multiplied by the total number of insured vehicle days for each group and summed across calendar years to produce the total estimated VMT.

Approximately 7% of the total miles traveled were recorded in vehicles with unknown rated driver age or gender. These miles were redistributed among the six possible groups (three for age and two for gender) according to their proportion of known VMT for each headlight system and state.

Poisson regression

The total number of police-reported daytime and nighttime SVCs for each combination of state, headlight system, and the six driver demographic groups were linked to the matching estimated VMT. The effect of IIHS headlight test performance on the rate of SVCs per VMT was evaluated using Poisson regression with the log of VMT included as an offset term. Separate models estimated the effect of test performance as a continuous visibility demerit variable and as a categorical rating variable with values of good, acceptable, marginal, or poor. Each regression model included covariates for crash state, vehicle type, standard advanced driver assistance systems (ADAS), driver age, and driver gender. Scale parameters were estimated within the Poisson models to control for overdispersion.

The visibility illumination provided by a headlight can be affected by the technology of the light source. The base trim level of many vehicles, especially on less expensive models, comes with halogen headlights. As of June 2021, no vehicle with halogen low beams has received a good IIHS rating in the headlight test, while 11% and 23% of those with HID and LED low beams, respectively, have received good ratings. Vehicle models with more expensive standard headlights, or trim levels that may package headlight upgrades with other optional features (IIHS, 2020a), may be associated with differences in driver demographics or vehicle use patterns that affect crash rates in ways that are not fully controlled by the other covariates. To minimize the influence of these differences, a two-way interaction term between crash time (daytime = 0, nighttime = 1) and headlight performance was included in each of the regression models. The value of $exp(x)$, where x is the parameter estimate for this interaction term, is taken as the nighttime crash rate ratio for headlight performance adjusted for any apparent effect on daytime crash rate (RR_{adj}). A crash time interaction term also was included for each of the other covariates since their effects may differ between nighttime and daytime. Each of the covariates is described below.

State differences in crash rates may be due in part to different urbanization, road system mix, travel speeds, terrain, weather, length of daylight, and the location within a time zone. A categorical variable was used to control for state differences. A vehicle type variable with four levels (car, minivan, SUV, or pickup) accounted for possible differences due to usage patterns by time of day, rurality, or other factors. Driver age and gender can influence both crash risk and exposure. Older drivers often limit their driving at night (Braitman & McCartt, 2008), at least partly due to physiological aging effects that may translate to higher crash risks when they do drive (Brooks et al., 2004; Owens & Tyrrell, 1999). Conversely, younger drivers drive more often at night than older drivers (Federal Highway Administration [FHWA], 2017) and engage in more high-risk behaviors (Jonah, 1986). Relative to females, males drive more at night (FHWA, 2017) but have lower reported crash rates per mile (Massie et al., 1997).

Various ADAS technologies have been demonstrated to reduce SVC rates (Cicchino, 2018; HLDI, 2015) and may have different effects at night. ADAS features may be packaged with headlight options, partly because high beam assist systems may utilize the same forward-facing camera. We assessed vehicles in the current study for the presence of automatic emergency braking (AEB), forward collision warning (FCW), lane departure prevention (LDP), and lane departure warning (LDW) as standard features. The majority of SVCs involved vehicles without any of these features as standard equipment (82%) followed by those equipped with both AEB and LDP (14%). A two-level variable was established to account for standard ADAS, differentiating between vehicles with any of the four features as standard and those where these features were optional or not available. Most (88%) SVCs involving a vehicle in the standard ADAS group had either AEB or FCW in addition to LDP or LDW.

Additional regression models were used to study the effect of overall headlight performance in different SVC types as well as the individual effects of the components of the IIHS headlight rating. The overall headlight effect was estimated for five subsets of SVCs: driver injury crashes, tow-away crashes, crashes involving an animal, crashes involving a pedestrian, and crashes involving a pedestrian or cyclist. For all SVCs, six separate models were fit to estimate the effect of low- and high-beam visibility illumination as captured by three IIHS test metrics: the left road edge on the straightaway, the right road edge on the straightaway, and the average of the minimum lane edge measured on each of the four curves. Measures from the four curves were not included individually, as they were strongly correlated with each other. Table 1 shows correlation coefficients for the six measures that were included. To facilitate the comparison of effects, the 5 lux distances were standardized by subtracting the mean and dividing by the standard deviation.

Table 1. Pearson correlation coefficients for individual rating components

		High beam			Low beam		
		Curves	Straight L	Straight R	Curves	Straight L	Straight R
High beam	Curves	1	0.51	0.35	0.78	0.33	0.28
	Straight L		1	0.54	0.25	0.10	0.12
	Straight R			1	0.09	−0.13	0.14
Low beam	Curves				1	0.66	0.58
	Straight L					1	0.60
	Straight R						1

Note: L = left. R = right.

Multiple imputation was used to account for SVC cases that were missing required data. The elements with missing data were driver age group (10% of cases), driver gender (11%), driver injury (9%), and vehicle tow status (34%). The "mice" package in R was used to impute the missing data 20 times and to estimate the resulting uncertainty in the model results. Additional variables used as predictors were crash state, time (daytime or nighttime), vehicle type, the number of visibility demerits, standard ADAS status, and the involvement of a pedestrian, cyclist, or animal.

RESULTS

In the 11 states meeting our inclusion criteria, there were 101,823 SVCs involving a vehicle with one of 312 different headlight systems with a known IIHS rating (Figure 2). Based on the crash date, time, and geographic coordinates, it was determined that 43,659 (43%) of the crashes occurred at night. The Poisson regression models of crash rate were based on 15,427 unique combinations of state, headlight system, standard ADAS status, driver age group, and driver gender, representing a total of 9.7 million insured vehicle years and 144 billion VMT. The distribution of crashes by headlight visibility demerits and vehicle type is shown in Figure 3. Fifty-six percent of the crashes occurred in vehicles with headlight systems that would have been rated poor even without the addition of any glare demerits, while 1.6% would have been rated good.

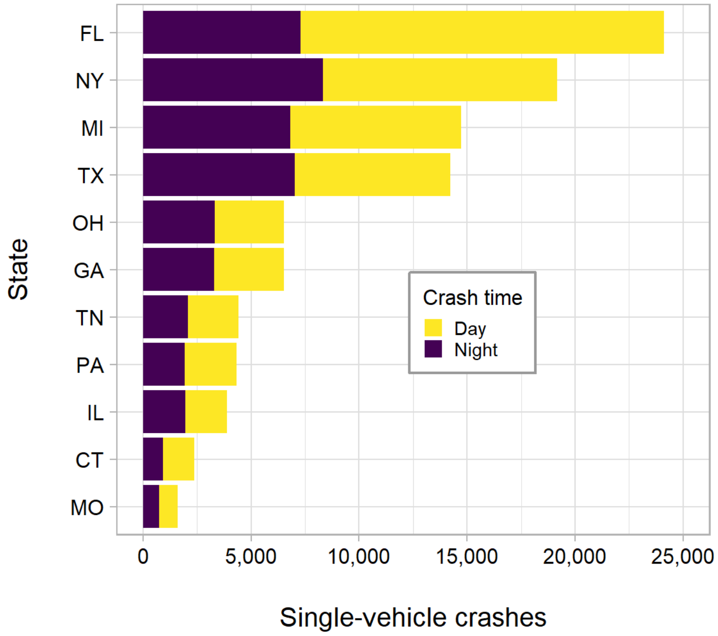

Figure 2. Distribution of single-vehicle crashes by state and crash time.

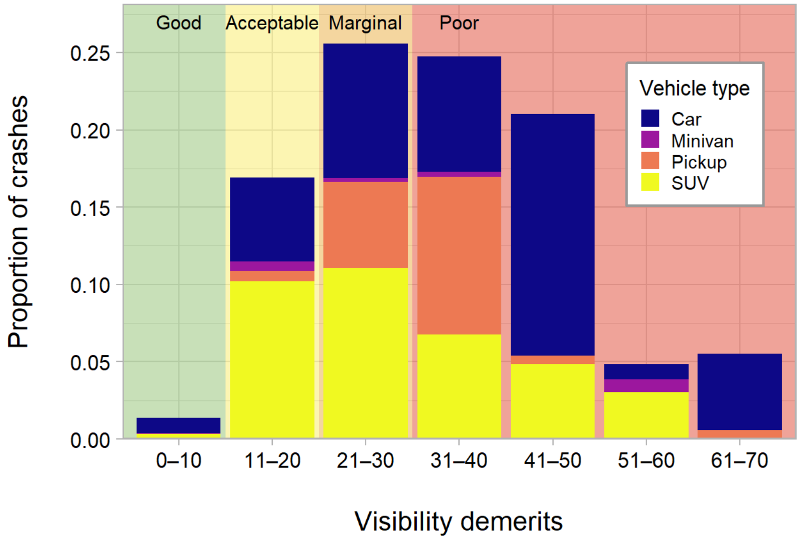

Figure 3. Proportion of single-vehicle crashes by IIHS headlight demerits and vehicle type.

Regression model results for the effect of headlight visibility performance are presented in Table 2 (see page 14). Relative to the estimated effect on daytime crashes, achieving 10 fewer visibility demerits in the IIHS headlight evaluation was associated with a 4.6% reduction in the nighttime SVC rate per VMT ($RR_{adj} = 0.954$; 95% confidence interval [CI]: 0.930–0.979; $p < 0.001$). Modeling headlight visibility as a categorical rating variable also identified nighttime SVC rate reductions for better headlight performance. Compared with headlights with poor ratings, those with good ratings demonstrated the largest rate reduction (0.813; 0.624–1.06; $p = 0.12$), followed by those with acceptable (0.853; 0.776–0.938; $p < 0.001$) and marginal (0.904; 0.837–0.976; $p = 0.01$) ratings.

A good IIHS headlight rating was associated with reductions in the rate of each of the evaluated SVC types at nighttime relative to daytime (Table 2 and Figure 4). Compared with vehicles with poor-rated headlights, rate reductions were greatest for driver injury (RR_{adj}: 0.71; $p = 0.11$), tow-away (0.76; $p = 0.01$), and pedestrian (0.77; $p = 0.42$) crashes. Acceptable and marginal headlight ratings also were associated with rate reductions for every group of crashes, as was the effect for fewer demerits. With the exception of one crash group (the combination of pedestrian and cyclist crashes), the order of the estimated effect magnitudes for the rating variable aligned with the order of the IIHS rating categories.

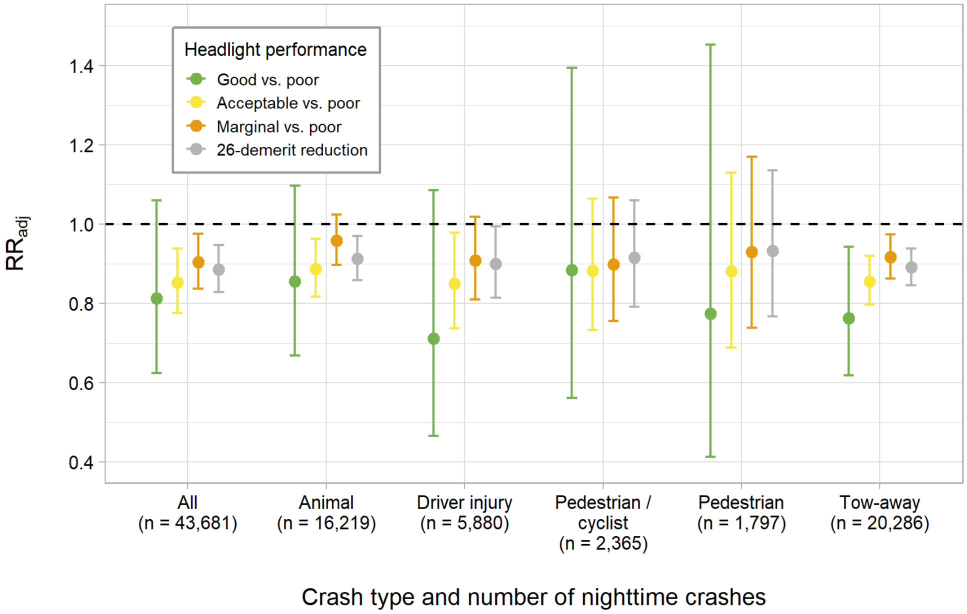

Figure 4. Effect of headlight performance on nighttime crash rate relative to the effect on daytime crash rate. The demerit effect was scaled to 26, the difference between the median values in the poor and acceptable IIHS rating categories.

Table 2. Poisson regression model results for headlight performance metrics

Headlight performance metric		All 43,659	Animal 16,213	Driver injury 5,856	Pedestrian 1,796	Pedestrian or cyclist 2,364	Tow-away 20,243
		Single-vehicle crash type with number of nighttime crashes					
10 fewer demerits	RR_{adj}	0.954	0.965	0.960	0.974	0.967	0.956
	95% CI	0.930, 0.979	0.943, 0.988	0.924, 0.998	0.903, 1.05	0.914, 1.02	0.938, 0.976
	p value	< 0.001	0.003	0.04	0.49	0.24	< 0.001
Good rating (ref: Poor)	RR_{adj}	0.813	0.855	0.710	0.774	0.884	0.763
	95% CI	0.624, 1.06	0.668, 1.10	0.465, 1.09	0.412, 1.45	0.561, 1.39	0.618, 0.942
	p value	0.12	0.22	0.11	0.42	0.6	0.01
Acceptable rating (ref: Poor)	RR_{adj}	0.853	0.887	0.849	0.881	0.882	0.856
	95% CI	0.776, 0.938	0.816, 0.963	0.737, 0.978	0.688, 1.13	0.732, 1.06	0.796, 0.919
	p value	< 0.001	0.004	0.02	0.32	0.19	< 0.001
Marginal rating (ref: Poor)	RR_{adj}	0.904	0.958	0.908	0.929	0.898	0.917
	95% CI	0.837, 0.976	0.897, 1.02	0.810, 1.02	0.738, 1.17	0.755, 1.07	0.863, 0.974
	p value	0.01	0.21	0.1	0.53	0.22	0.005

Note: CI = confidence interval.

RR_{adj} is the estimated rate ratio of nighttime single-vehicle crashes (SVCs) per vehicle mile travelled (VMT) associated with each headlight metric divided by the estimated rate ratio of daytime SVCs per VMT. For each type of SVC, one regression model was used to estimate the effect of headlight performance as a continuous demerit variable and a second model was used to estimate its effect as a categorical rating variable. Nighttime crash counts for driver injury and tow-away crashes are average counts across imputed data sets.

Models estimating the effect of individual components of the IIHS headlight rating showed that changes in the high- and low-beam curve illumination distances had the greatest effects on the overall nighttime SVC rate (Table 3). When converted to visibility demerits, these results indicate that the existing rating scheme underweights the curve conditions relative to their apparent effect on crash rates, especially for the high beams, while overweighting the low-beam straightaway conditions (Figure 5).

Table 3. Poisson regression model results for individual rating components

	5 lux distance (m)		Regression model results for 1 SD increase		
Rating component	Mean	SD	RR$_{\text{adj}}$	95% CI	*p* value
High beam: curves	65.6	9.6	0.896	0.851, 0.944	< 0.001
High beam: straight L	125.4	24.9	0.954	0.930, 0.980	< 0.001
High beam: straight R	147.8	18.7	0.976	0.943, 1.01	0.170
Low beam: curves	53.0	9.3	0.906	0.849, 0.966	0.003
Low beam: straight L	48.4	12.0	0.959	0.926, 0.994	0.020
Low beam: straight R	86.9	19.6	0.951	0.905, 0.999	0.040

Note: CI = confidence interval. L = left. R = right. SD = standard deviation.

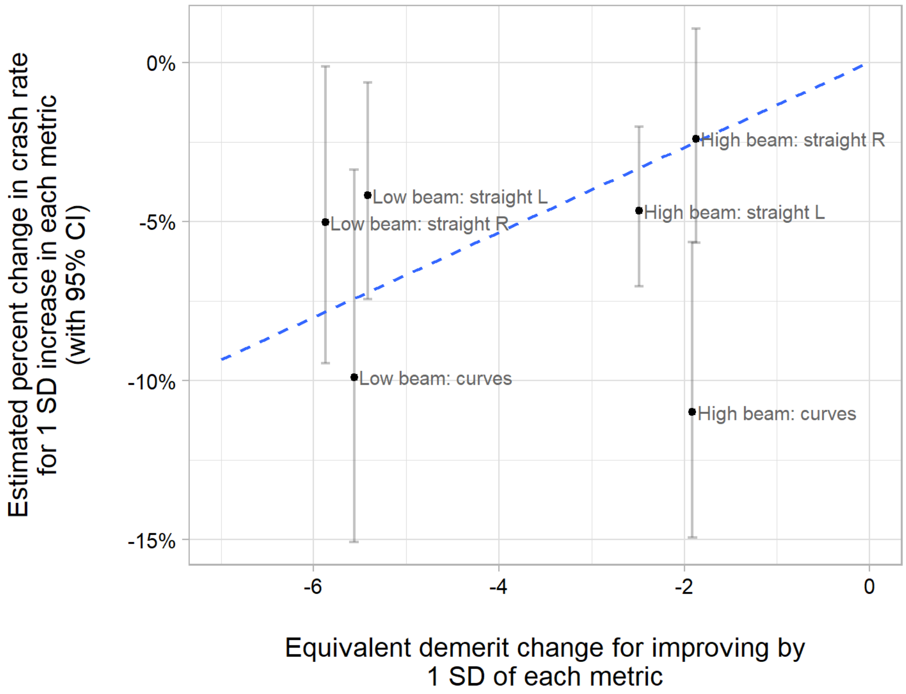

Figure 5. Rating components. The dashed line represents a linear fit with the intercept fixed at 0. CI = confidence interval. SD = standard deviation.

Estimated effects for all covariates other than crash state are shown in the Appendix for the model of overall SVC rate. The nighttime rate reduction associated with fewer IIHS visibility demerits was relative to a significantly lower daytime crash rate per mile traveled ($p < 0.001$). Most of the other covariates were estimated to have significant effects, both on the daytime crash rate and on the difference between daytime and nighttime crash rates. Standard ADAS was estimated to reduce the rate of daytime SVCs by 10% (RR: 0.90; $p < 0.001$) and provide an additional nonsignificant 6% reduction in the rate of nighttime SVCs (RR_{adj}: 0.94; $p = 0.16$).

DISCUSSION

The IIHS headlight evaluation program is the only assessment of on-road lighting that is based on objective illuminance measures and that covers the majority of the fleet. The results of this study demonstrate that headlight visibility performance, as defined by this program, has a strong effect on the rate of police-reported nighttime SVCs. This was true whether measuring the effect of discrete headlight rating categories or the underlying demerits. In addition, the benefit of improved headlight visibility illumination was apparent in all the different types of SVCs that were considered.

Rating components

As described in the Introduction, IIHS assigns categorical headlight ratings based on the total number of visibility and glare demerits from all test conditions. Model estimates based on the visibility portion of the rating indicate the existing boundaries produce categories that are well-aligned with crash outcomes (Figure 4). However, there is some indication that the weighting of the different test conditions could be adjusted to better reflect their relative benefits in real-world driving scenarios (Figure 5). While an improvement in any of the test metrics is estimated to reduce the nighttime crash rates, the greatest benefits are associated with improvements in the low- and high-beam curve visibility measurements, which are strongly correlated (Table 1). An improvement of one standard deviation, or around 10 m, in the average 5 lux distance for the high-beam curve conditions is estimated to reduce the nighttime SVC rate by around 10%, but this only improves the headlight rating by 2 demerits, or one fifth of a rating band. This apparent shortcoming may be at least partially offset by two considerations. First, the strong correlation with low-beam curve visibility means that an improvement for high beams would also likely result in fewer demerits for the low-beam test conditions. Second, vehicles with high beam assist qualify for additional credit based on their high-beam performance.

The IIHS rating program was developed based on a distribution of 5 lux visibility distances measured during research testing (IIHS, 2015). The demerit equations were established to target weighting ratios of 3:1 for low vs. high beams and 3:2 for the straightaway vs. curves, with straightaway demerits split equally between measurements on the left and right side of the road. The low- vs. high-beam ratio was chosen based on research indicating a high-beam use rate of 25% for isolated vehicles on unlit rural roads (Mefford et al., 2006). A subsequent study found a similar rate of 18% (Reagan et al., 2017). As of June 2021, the median demerit values for all vehicles without any glare downgrades reflected a ratio of 3.2:1 for low vs. high beams (Table 4), indicating that the relative performance of the overall fleet has been similar to the original IIHS research tests.

Table 4. Median visibility demerit values by condition for all vehicles tested by IIHS as of June 2021

	All vehicles			Vehicles without glare demerits		
	Straightaway	Curves	Total	Straightaway	Curves	Total
Low beam	6.3	7.2	13.4	10.9	8.9	19.8
High beam	2.6	2.9	5.5	2.8	3.3	6.1
Total	8.9	10.0	18.9	13.7	12.1	25.8

Note: Any credits for high beam assist are not reflected.

By contrast, the fleet's headlight visibility on curves relative to the straightaway has been worse than expected, producing median demerit values that are very similar (straightaway-to-curves ratio of 2.3:2). This means that an adjustment of the demerit equations to increase the curve weighting would result in a ratio even more divergent from the original target ratio of 3:2. This target was intentionally chosen to weight curves somewhat more heavily than their observed 32% frequency in fatal nighttime crashes (Brumbelow, 2015), based on the assumption that the wider beam patterns necessary for improved curve illumination would provide additional benefits on straight sections of road. At least three potential explanations, or some combination thereof, may account for the finding that curve visibility is underweighted compared with its real-world effects. First, relative to headlights with median illumination levels, an increase in the width of the beam pattern may be more effective at reducing straightaway SVC rates than an increase in reach. Second, the benefit of wider beam patterns on curves may be greater than the benefit of longer beam patterns on straightaways. Third, the proportion of nighttime SVCs that occur on curves may be greater when considering all police-reported crashes in general than fatal crashes alone. Exploring these possibilities likely requires crash data sources with more consistent horizontal curvature information than the state databases used for this study. Road horizontal curvature codes did not exist in five of the 11 states, and when they were present they appeared underutilized. Fewer than 10% of crashes were coded as occurring on curves in the six states with available data.

Glare

This study demonstrates that vehicles that provide more visibility illumination have lower nighttime SVC rates. To perform well in the IIHS evaluation, a headlight design must provide this illumination without producing excessive low-beam glare illuminance. The median visibility demerits in Table 4 illustrate this balance. Vehicles without any glare downgrades have around one-third more demerits than all vehicles. While research has shown that drivers tend to overestimate the disabling effects of glare (Sewall et al., 2016), glare can reduce driver visibility and performance (Theeuwes et al., 2002; Van Derlofske et al., 2005) and it may be a contributing factor in some of the 36% of nighttime crashes that involve more than one vehicle. Assessing this possibility is complex and remains an area for further research. In two-vehicle crashes, it may require knowledge of the visibility and glare illumination of both involved vehicles as well as data elements, such as vehicle crash configuration, that were not available in some of the states used in this study. Furthermore, if the primary effect of disabling glare is to increase the risk of crashing into vehicles or objects other than the glare-producing vehicle, its effects would not be discernable in retrospective crash data.

Limitations

This study has a few limitations. The controls for driver age and gender assume the rated insured driver associated with each vehicle is responsible for the miles traveled and crash involvements. Any systematic differences between the rated driver and the primary or crash-involved driver that are associated with headlight performance could bias the results. Some confounding with ADAS status also may remain, since effects may differ by system type and manufacturer, and since ADAS status was unknown when it was offered as an optional feature. In fact, even standard features can be disabled by the driver and often are (Reagan et al., 2018).

Another limitation concerns the VMT exposure variable used in this study, which is not specific to daytime or nighttime. If the nighttime proportion of VMT is lower for vehicles with better visibility, then it is possible that the visibility benefits are overestimated. However, this would mean that the daytime proportion of VMT is greater, and the expected daytime SVC rate would be higher when controlling for other factors. Results indicated the opposite, with lower rates of daytime SVCs for vehicles with better headlight scores. One possible explanation is that drivers of vehicles with better headlights actually drive a lower proportion of their miles during the day and a greater proportion at night, for example because they proactively shop for vehicles with better ratings or reactively adjust to better visibility by reducing their tendency to self-limit nighttime travel. If this is the case, the true headlight visibility benefit may be underestimated.

Another limitation of this study is its inability to evaluate real-world effects of the glare portion of the IIHS rating. Finally, the low sample size for headlights with the best visibility performance leads to wide confidence intervals for good-rated vehicles relative to the other ratings. More precise estimates should be possible in the future, as ratings improve overall and as more high-quality headlight systems become available as standard equipment (IIHS, 2020b), enabling the inclusion of more vehicle models in the analysis.

CONCLUSIONS

Vehicles with greater levels of headlight visibility in the IIHS evaluation have lower rates of nighttime SVCs per mile traveled. Achieving 10 fewer demerits, equivalent to an improvement of one rating category for most vehicles, is estimated to reduce the crash rate by 4.6% after adjusting for differences in daytime crash rates and other factors. Nighttime SVC rate reductions also were estimated for driver injury crashes, tow-away crashes, and crashes involving an animal, a pedestrian, and a pedestrian or cyclist. There is some indication that the real-world benefits of wide beam patterns are underweighted by the IIHS test. Nevertheless, the existing rating categories are well-aligned with nighttime crash rates. While limited by low exposure and correspondingly wide confidence intervals relative to other rating categories, good-rated headlights were estimated to reduce overall nighttime SVC rates by around 20% relative to those with poor ratings, with slightly greater reductions in the rates of driver injury, tow-away, and pedestrian crashes.

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REFERENCES

Bivand, R., & Lewin-Koh, N. (2019). *maptools: Tools for handling spatial objects* (R package version 0.9-8). https://CRAN.R-project.org/package=maptools

Braitman, K. A., & McCartt, A. T. (2008). Characteristics of older drivers who self-limit their driving. *Annals of Advances in Automotive Medicine: 52nd Annual Scientific Conference of the Association for the Advancement of Automotive Medicine, 52,* 245–253.

Brooks, J. O., Tyrrell, R. A., Frank, T. A., & Isenhower, R. W. (2004). Effects of visual challenges on steering ability: Testing the selective degradation hypothesis. *Proceedings of the Human Factors and Ergonomics Society 48th Annual Meeting, 48*(19), 2364–2368. https://doi.org/10.1177/154193120404801934

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

Bullough, J. D., Van Derlofske, J. V., & Akashi, Y. (2006). Strategies for optimizing headlamp illumination and visibility along curves (SAE Technical Paper Series 2006-01-0489). SAE International. https://doi.org/10.4271/2006-01-0489

Cicchino, J. B. (2018). Effects of lane departure warning on police-reported crash rates. *Journal of Safety Research, 66,* 61–70. https://doi.org/10.1016/j.jsr.2018.05.006

Consumer Reports. (2016). *Car headlight performance found to be not so bright*. https://www.consumerreports.org/car-safety/car-headlight-performance-found-to-be-not-so-bright/

Environmental Protection Agency. (2020). *Population and activity of onroad vehicles in MOVES3* (EPA-420-R-20-023). https://cfpub.epa.gov/si/si_public_record_report.cfm?Lab=OTAQ&dirEntryId=328870

Federal Highway Administration. (2017). 2017 National household travel survey. U.S. Department of Transportation. http://nhts.ornl.gov

Highway Loss Data Institute. (2015). Volvo City Safety loss experience—A long-term update. *HLDI Bulletin, 32*(1). 1–24.

Highway Loss Data Institute. (2016). 2010 Mazda 3 adaptive front lighting system. *HLDI Bulletin, 33*(26). 1–13.

Highway Loss Data Institute. (2018a). Mercedes-Benz collision avoidance features—A 2018 update. *HLDI Bulletin, 35*(33). 1–22.

Highway Loss Data Institute. (2018b). Volvo collision avoidance features: 2007–10 model years. *HLDI Bulletin, 35*(7). 1–13.

Insurance Institute for Highway Safety. (2015). *Rationale and supporting work for headlight test and rating protocol*. Ruckersville, VA. https://www.iihs.org/ratings/about-our-tests/test-protocols-and-technical-information

Insurance Institute for Highway Safety. (2018). *Headlight test and rating protocol (Version III)*. Ruckersville, VA. https://www.iihs.org/ratings/about-our-tests/test-protocols-and-technical-information

Insurance Institute for Highway Safety. (2020a). *Headlights are still an afterthought on many vehicles*. https://www.iihs.org/news/detail/headlights-are-still-an-afterthought-on-many-vehicles

Insurance Institute for Highway Safety. (2020b). *IIHS award criteria push manufacturers to scrap inferior headlights*. https://www.iihs.org/news/detail/iihs-award-criteria-push-manufacturers-to-scrap-inferior-headlights

Insurance Institute for Highway Safety. (2020c). *Unpublished analysis of Fatality Analysis Reporting System data*.

Jonah, B. A., (1986). Accident risk and risk-taking behaviour among young drivers. *Accident Analysis & Prevention, 18*(4), 255–271. https://doi.org/10.1016/0001-4575(86)90041-2

Massie, D. L., Green, P. E., &Campbell, K. L. (1997). Crash involvement rates by driver gender and the role of average annual mileage. *Accident Analysis & Prevention, 29*(5), 675–685. https://doi.org/10.1016/s0001-4575(97)00037-7

Mefford, M. L., Flannagan, M. J., & Bogard, S. E. (2006). *Real-world use of high-beam headlamps* (UMTRI Report No. 2006-11). Ann Arbor, MI: University of Michigan Transportation Research Institute.

National Highway Traffic Safety Administration. (2007). *Passenger vehicle occupant fatalities by day and night—A contrast* (Traffic Safety Facts Research Note, DOT HS 810 637). U.S. Department of Transportation.–

Owens, T., & Tyrrell, R. A. (1999). Effects of luminance, blur, and age on nighttime visual guidance: A test of the selective degradation hypothesis. *Journal of Experimental Psychology: Applied, 5*(2), 115–128. https://doi.org/10.1037/1076-898X.5.2.115

R Core Team. (2018). R: A language and environment for statistical computing. R Foundation for Statistical Computing. https://www.R-project.org/

Reagan, I. J., Brumbelow M. L., Flannagan M. J., & Sullivan J. M. (2017). High beam headlamp use rates: Effects of rurality, proximity of other traffic, and roadway curvature. *Traffic Injury Prevention, 18*(7), 716–723. https://doi.org/10.1080/15389588.2016.1228921

Reagan, I. J., Brumbelow M. L., Frischmann, T. (2015). On-road experiment to assess drivers' detection of roadside targets as a function of headlight system, target placement, and target reflectance. *Accident Analysis & Prevention,76,* 74–82. https://doi.org/10.1016/j.aap.2014.12.021

Reagan, I. J., Cicchino, J. B., Kerfoot, L. B., & Weast, R. A. (2018). Crash avoidance and driver assistance technologies—Are they used? *Transportation Research Part F: Traffic Psychology and Behaviour, 52,* 176–190. https://doi.org/10.1016/j.trf.2017.11.015

Sewall, A. A. S., Borzendowski, S. A. W., Tyrrell, R. A., Stephens, B. R., & Rosopa, P. J. (2016). Observers' judgments of the effects of glare on their visual acuity for high and low contrast stimuli. *Perception, 45*(7), 755–767. https://doi.org/10.1177/0301006616633591

Sivak, M., Schoettle, B., & Tsimhoni, O. (2007). *Moon phases and nighttime road crashes involving pedestrians* (UMTRI Report No. 2007-41). University of Michigan Transportation Research Institute.

Teoh, E. R. (2021). Crash rates of convertible cars. *Traffic Injury Prevention, 22*(3), 256–260. https://doi.org/10.1080/15389588.2021.1888084

Theeuwes, J., Alferdinck, J. W, & Perel, M. (2002, Spring). Relation between glare and driving performance. *Human Factors, 44*(1), 95–107. https://doi.org/10.1518/0018720024494775

Van Derlofske, J., Bullough, J. D., & Hunter, C. M. (2001). *Evaluation of high-intensity discharge automotive forward lighting* (SAE Technical Paper 2001-01-0298). SAE International. https://doi.org/10.4271/2001-01-0298

Van Derlofske, J., Chen, J., Bullough, J. D., Akashi, Y. (2005). *Headlight glare exposure and recovery* (SAE Technical Paper 2005-01-1573). SAE International. https://doi.org/10.4271/2005-01-1573

APPENDIX

Table A1. Poisson regression model results for all single-vehicle crashes

	Daytime effect			Nighttime effect relative to daytime effect		
Parameter	RR	95% CI	*p* value	RR_{adj}	95% CI	*p* value
Visibility demerits (−10)	0.926	0.911, 0.942	< 0.001	0.954	0.93, 0.979	< 0.001
Minivan (ref: car)	1.08	0.941, 1.25	0.26	0.789	0.628, 0.992	0.04
Pickup (ref: car)	0.937	0.882, 0.995	0.03	0.825	0.753, 0.903	< 0.001
SUV (ref: car)	0.757	0.722, 0.793	< 0.001	0.840	0.781, 0.903	< 0.001
Age > 65 (ref: age 25–65)	0.413	0.39, 0.437	< 0.001	0.792	0.729, 0.86	< 0.001
Age < 25 (ref: age 25–65)	0.558	0.518, 0.602	< 0.001	0.404	0.356, 0.458	< 0.001
Male (ref: female)	1.06	1.02, 1.11	0.005	1.42	1.33, 1.51	< 0.001
Standard ADAS (ref: not standard)	0.899	0.847, 0.954	< 0.001	0.937	0.852, 1.03	0.18

Note: CI = confidence interval. RR = rate ratio.

State effects are not shown.