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Visual Performance and Safety Benefits of Adaptive Curve Headlighting Systems

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Abstract

Very few data have been published that demonstrate the possible benefits to safety from advanced headlighting technologies on nighttime driving safety. By comparing insurance claim information for different vehicle models equipped with such systems, the Highway Loss Data Institute (HLDI) compared vehicles with and without adaptive curve lighting (ACL) systems. Overall, the HLDI data are consistent with a safety benefit when these systems are used, as defined by reductions in property damage and injury claim frequencies. Injury claim frequency reductions were larger than those in property damage claims. To help interpret the HLDI findings, visual performance analyses were conducted based on prior studies of ACL for curves varying in radius. Reaction times using conventional headlights and ACL systems and light levels at oncoming drivers' eyes from vehicles with and without ACL systems were used to estimate the potential benefits of these systems on visibility as well as to estimate disability glare impacts to other drivers. The average improvements in RVP for these combined scenarios associated with ACL systems were compared to a previously published transfer function relating visual performance and nighttime crash reductions associated with lighting. The correspondence between overall visibility improvements and nighttime crash reductions can provide a rational foundation for predicting the potential safety benefits of adaptive vehicle headlighting systems.

Keywords: .... headlamps, safety, adaptive lighting, glare, visual performance, visibility

TABLE OF CONTENTS

ABSTRACT

Very few data have been published that demonstrate the possible benefits to safety from advanced headlighting technologies on nighttime driving safety. By comparing insurance claim information for different vehicle models equipped with such systems, the Highway Loss Data Institute (HLDI) compared vehicles with and without adaptive curve lighting (ACL) systems. Overall, the HLDI data are consistent with a safety benefit when these systems are used, as defined by reductions in property damage and injury claim frequencies. Injury claim frequency reductions were larger than those in property damage claims. To help interpret the HLDI findings, visual performance analyses were conducted based on prior studies of ACL for curves varying in radius. Reaction times using conventional headlights and ACL systems and light levels at oncoming drivers' eyes from vehicles with and without ACL systems were used to estimate the potential benefits of these systems on visibility as well as to estimate disability glare impacts to other drivers. The average improvements in RVP for these combined scenarios associated with ACL systems were compared to a previously published transfer function relating visual performance and nighttime crash reductions associated with lighting. The correspondence between overall visibility improvements and nighttime crash reductions can provide a rational foundation for predicting the potential safety benefits of adaptive vehicle headlighting systems.

INTRODUCTION

It is obvious that vehicle headlighting systems are critical for safety when driving at night. Most roadways in the U.S. are unlighted (NHTSA, 2007), requiring drivers to depend wholly on their headlights to provide forward visibility when driving at night. Conventional low and high headlight beam patterns are specified by the Federal Motor Vehicle Safety Standard (FMVSS) No. 108. It is permitted that headlights in the U.S. can swivel horizontally (to the left or right) as long as they produce an overall beam pattern that is in conformance with the intensity distribution requirements in FMVSS 108. Swiveling can be performed in response to turning the steering wheel toward the right or left when drivers are turning into curves in the road.

A number of vehicle models are equipped with this type of *adaptive* lighting system under various trade names, including "Active Front Lighting System," "Adaptive Front Lighting System," "Active Curve Illumination," and "Active Bending Lights." In the present report, all of these systems are denoted as adaptive curve lighting (ACL) systems. Several analytical and field studies have been conducted in North America in order to understand the potential safety benefits of ACL systems in terms of visibility, glare, and/or both (Sivak et al., 2001; Bullough et al., 2007; Bullough, 2009).

Using photometric data from market-weighted low beam patterns in the U.S., Sivak et al. (2001) calculated light levels on targets located along small- (80 m) and large-radius (240 m) curves, and light levels from oncoming vehicles when driving through the same curves. They found that oncoming headlight illuminances tended to be lower from ACL systems along right-hand curves, but higher along left-hand curves, compared to conventional static headlamps. Bullough et al. (2007) measured reaction times to small (8-in. square) flip-dot targets located along the perimeter of a small-radius (30 m) curve. Similarly, Bullough (2009) measured reaction times to targets along a large-radius (335 m) curve. Both swiveling and non-swiveling headlamps were evaluated; overall, shorter reaction times were elicited under the swiveling headlighting systems.

While only about a quarter of overall vehicle traffic occurs during the night (Box, 1970), fatalities in vehicle crashes that occur along curves make up half of the total curve-related fatalities in the U.S. (Torbic et al., 2004). This nonuniformity in the temporal distribution of crash frequencies indicates that better visibility along curves might possibly contribute to improved safety, although it in impossible to discount the impact of factors such as the increased likelihood of alcohol or drug use at night, or the increased potential for fatigue and drowsiness at night, which likely also contribute to higher nighttime fatal crash rates.

The Highway Loss Data Institute (HLDI) recently compared insurance claim information for four vehicle models that offer ACL systems in the U.S. (HLDI, 2011a, 2011b, 2012a, 2012b), in addition to corresponding models without ACL systems. HLDI investigated the frequency and number of claims. Critically, these analyses attempted to control for a number of potential safety-related factors as age, gender, marriage status, the drivers' risk level, U.S. state, the size of the deductible on the owner's vehicle insurance policy, and the overall vehicle density near the vehicle owner's residence. Table 1 summarizes the HLDI results from these comparisons when they were statistically significant ($p<0.05$); when they were not, effects of 0% were assumed.

Vehicle Make	Collision	Property Damage	Bodily Injury	Medical Payments	Personal Injury Protection
Mazda (HLDI, 2011a)	-6%	-10%	0%	-29%	-29%
Acura (HLDI, 2011b)	0%	0%	0%	0%	0%
Volvo (HLDI, 2012a)	0%	-9%	-17%	0%	0%
Mercedes-Benz (HLDI, 2012b)	0%	-5%	-10%	-14%	0%
Overall	-4%		-8%		

Table 1: *Estimated changes in property-related and injury-related insurance claim frequency for four vehicle makes with ACL systems (HLDI, 2011a, 2011b, 2012a, 2012b).*

HLDI has acknowledged that the crash statistics summarized in Table 1 probably exhibit confounds that are not completely addressed by the controls they used in conducting the analyses. For example, for one of the vehicle makes in Table 1, the property damage claim frequency was reduced by 10% with ACL systems compared to conventional headlights. However, HLDI noted that only 7% of crashes leading to property damage claims involving damage to another vehicle occurred during the nighttime (HLDI, 2011a). This would lead to a non-intuitive conclusion that ACL systems contribute to avoiding at least some crashes during the day! One factor that was noted by HLDI as a possible confound was that ACL systems tend to use high-intensity discharge (HID) headlight sources whereas vehicles with conventional forward lighting tend to use halogen light sources in headlights (HLDI, 2011a). HLDI (2012b) found that HID headlights appeared to be associated with a 3% average reduction in property-related crashes and a 5% average reduction in injury-related crashes for one of the vehicle makes, using the same methodology as illustrated in Table 1. Since these values are lower than the average reductions in Table 1, there is a possibility that the use of HID headlamps in ACL systems might be partially responsible for any safety improvements ACL systems might yield. Nonetheless, this would not explain a reduction in daytime crashes where vehicle illumination would be superfluous to visibility (Rea et al., 2010).

Still, the data in Table 1 are notable because all of the statistically significant ($p<0.05$) effects found by HLDI were *reductions*, not increases, in insurance claim frequencies. Additionally, the finding that claim frequency reductions associated with injury-related crashes were greater than the reductions for property-related crashes are consistent with the idea that ACL systems might provide drivers with increased visibility, which in turn could give drivers more time to respond to potential roadway hazards.

In a recent study of fixed roadway intersection illumination, Bullough et al. (2013) used the relative visual performance (RVP) model (Rea and Ouellette, 1991) to evaluate improvements in visibility that were associated with roadway lighting (while keeping the presence of vehicle lighting constant in all scenarios). Bullough et al. (2013) found that visual performance improvements for drivers between the ages of 30 and 60 years (inclusive), and for different types of roadway intersections (signalized or unsignalized, and rural or urban/suburban) were strongly correlated with statistical associations between lighting and nighttime crashes (see

Figure 1). According to the best-fitting linear function relating visual performance improvements to nighttime crash reductions, a 0.1-unit RVP change in visual performance is associated with a 7.2% change in nighttime crash frequency.

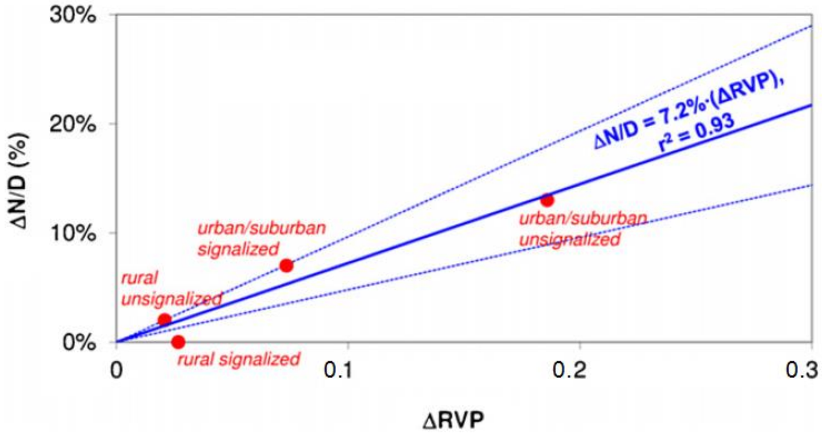

Figure 1: *Relationship and 95%-confidence interval between visual performance improvements (denoted by ΔRVP) associated with roadway intersection lighting and reductions in nighttime crash frequency (denoted by ΔN/D) from Bullough et al. (2013).*

The RVP model (Rea and Ouellette, 1991) has been validated under a considerable range of outdoor and roadway lighting conditions including evaluations of pedestrian identification times at midblock crosswalks (Bullough et al., 2012) and along roundabouts (Bullough and Skinner, 2012), and dynamic driving field tests using different types of headlight illumination sources including halogen and HID headlamps (Bullough and Skinner, 2009). Using to this model, the speed and accuracy of human visual processing is predicted by the light level (luminance), luminance contrast and angular size of a target of interest as well as on the age of the observer. RVP values range from zero at the threshold for identification, to values greater than one for suprathreshold visibility conditions, such as reading large printed text on white paper under office illumination levels. Using this model of RVP, different scenarios associated with driving along small-radius and large-radius curves were developed in order to estimate the reduction, if any, in nighttime crash frequency that might be associated with ACL systems. In each of the analyses, the driver age was assumed to be 40 years.

VISUAL PERFORMANCE MODELING: SMALL-RADIUS CURVES

As mentioned previously, Bullough et al. (2007) measured reaction times to small, square targets located along left- and right-hand curves with a small radius under forward headlighting systems that swiveled 10° into the corresponding direction of the curve, or under static conventional headlamps pointing straight ahead. The average reaction times to the targets located between 45 and 55 m ahead were 552 ms for the static headlamp condition, and 506 ms for the swiveling (or ACL) headlamp condition. These reaction times correspond to RVP values of 0.71 and 0.77, respectively, using the following relationship between reaction times (RT) and RVP values (Rea and Ouellette, 1991):

$$\mathrm{RVP} = 1.42 - 0.00129\ \mathrm{RT} \qquad (1)$$

In their analysis of conventional and swiveling headlighting systems, Sivak et al. (2001) estimated that the vertical illuminance at an oncoming driver's eyes in small-radius left-hand curves averaged 0.28 lx with static headlamps and 0.65 lx with swiveling ACL systems. For right-hand curves, the oncoming illuminances averaged 0.67 lx with static and 0.53 lx with ACL headlights. The overall averages were 0.48 lx for conventional static headlights and 0.59 lx for ACL systems. Applying these overall averages to the RVP values for vehicles without ACL systems (RVP=0.71), and assuming that the oncoming illuminances produce a veiling luminance (Fry, 1954) at oncoming drivers' eyes that corresponds to an angular location 12° off-axis from the line of sight, the adjusted RVP value in the presence of conventional (static) headlights would be 0.69, while the adjusted RVP value in the presence of an oncoming ACL system would be 0.68. Averaging the RVP values for drivers of vehicles equipped with ACL systems and for drivers who might be facing them in an oncoming vehicle situation, there is a net RVP benefit associated with ACL systems of 0.05 RVP units; this works out to a 3.6% reduction in nighttime crash frequency along small-radius curves. (As already mentioned above, headlamp configurations not be expected to have any visibility-related effects on safety during the daytime.)

VISUAL PERFORMANCE MODELING: LARGE-RADIUS CURVES

An analysis similar to that detailed in the previous section of this report was performed for larger-radius curves. Bullough (2009) measured reaction times to small, square targets located along left-hand and right-hand curves with a large radius, under headlighting systems that swiveled 10° into the corresponding direction of the curve, or under static headlamps pointing forward. The average reaction times to the targets located between 25 m and 150 m ahead were 653 ms for the static headlighting condition, and 623 ms for the swiveling (ACL) headlighting condition. These reaction times correspond to RVP values of 0.58 and 0.62, respectively.

Sivak et al. (2001) estimated that the vertical illuminances at oncoming drivers' eyes in large-radius left-hand curves averaged 0.14 lx with static headlamps and 0.33 lx with swiveling (ACL) headlighting systems. For right-hand curves, the oncoming illuminances averaged 0.32 lx with static and 0.26 lx with ACL headlighting systems. The overall averages were 0.23 lx for conventional static headlamps and 0.30 lx for ACL systems. Applying these overall averages to the RVP values for vehicles without the ACL system (RVP=0.58), and incorporating the veiling luminance (Fry, 1954) at drivers' eyes that corresponds to an angular location 8° off-axis from the line of sight, the adjusted RVP value in the presence of conventional static headlights would be 0.51, while the adjusted RVP value in the presence of oncoming ACL headlights would be estimated to be 0.49. Averaging the RVP values for drivers of vehicles equipped with ACL systems and for drivers who would be facing them in an oncoming vehicle situation, there is a net RVP benefit associated with ACL systems of 0.02 RVP units, which corresponds to a 1.4% reduction in nighttime crash frequency along large-radius curves.

DISCUSSION

Several important caveats associated with the visual performance modeling analyses described in the previous sections of this report should be noted. The distributions and types of crashes that occur at curves during both daytime and nighttime (as well as the types of curves), which involved different numbers of vehicles, were not precisely characterized in the present study. Greater precision regarding the radius and direction of curve-related nighttime crashes could lead to more refined estimates of nighttime crash reductions that might be associated with ACL systems. The transfer function in Figure 1 linking visibility improvements to nighttime crash safety was based on data for roadway intersections and might exhibit a different functional relationship between visual performance and safety for different roadway situations such as curves. Also, as has been mentioned previously, the use of ACL headlighting systems is often simultaneous with the use of HID headlamps, which probably have their own contribution to nighttime crash reduction.

Nonetheless, the approach to safety analysis described in this report provides one way to develop preliminary quantitative assessments of nighttime crash reductions that could be attributable to improved vehicle lighting. The estimated nighttime crash reduction values of 3.6% and 1.4% for small-radius and large-radius curves, respectively, yields an overall average reduction of about 2.5% when combining these two classes of roadway curves. Since such reductions should only be applicable to nighttime crashes, and since the findings from HLDI (2011a, 2011b, 2012a, 2012b) represent total reductions in insurance claim frequencies, it seems even more likely that the analyses from HLDI include non-visibility related effects related to factors other than lighting. If and when further data like those published by HLDI (2011a, 2011b, 2012a, 2012b) become available and include additional crash avoidance systems, analyses such as the ones presented in this report could be useful in isolating the potential safety benefits of ACL systems. They might also assist in developing estimates of the safety benefits of other adaptive vehicle lighting systems such as cornering lights, expressway beams, and adaptive driving beam systems (Skinner and Bullough, 2009).

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