Lighting Res. Technol. **29**(4) 206–210 (1997) Printed in Great Britain L414

Summary This analytical study examined the effects of mounting height on discomfort glare from reduced-power high-beam headlamps used as automotive daytime running lamps. Of interest were the effects for mounting heights between 0.864 m (34 in) and 1.372 m (54 in) — the range in which full-power low beams are currently allowed, but reduced-power high beams are not. Three analyses were performed. The first analysis involved estimating the illuminance reaching a preceding driver via rear-view mirrors. The second analysis compared glare illuminance from reduced-power high beams with that from full-power low beams. The third analysis evaluated the expected changes in discomfort-glare ratings from reduced-power high beams as a function of increased mounting height. The analyses were based on photometric information from five high beams and 43 low beams from lamps manufactured for the United States market. They were performed for five following distances and three lateral offsets of the vehicles. The results indicate that allowing reduced-power high beams with mounting heights between 0.864 m and 1.372 m would not appreciably increase discomfort glare for preceding drivers as compared with (*a*) glare from reduced-power high beams at a mounting height of 0.864 m, or with (*b*) glare from currently allowed full-power low beams.

Glare and mounting height of high-beam headlamps used as daytime running lamps

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Received 2 January 1997, in final form 14 August 1997

1 Introduction

Current United States regulations allow a variety of lamps to be used as daytime running lamps (DRLS). Included among these lamps are high beams, but with the restrictions that the luminous intensity at H-V (the intercept of the horizontal and vertical axes) is no more than 7 000 cd, and that the mounting height is not greater than 0.864 m above the road surface(1). These restrictions are based on concerns with rearview-mirror glare for preceding vehicles under low-light conditions (e.g., dusk, dawn or heavy overcast)(2,3). On the other hand, when low beams are used at full voltage as DRLS, there is no DRL-specific mounting-height restriction. Consequently, the maximum mounting height for low-beam DRLS is 1.372 m — the same as for any conventionally used headlamps (high beam or low beam)(1).

Of interest in this study was the above-mentioned mounting-height restriction for reduced-power high beams when used as DRLS. Because the maximum mounting height of headlamps is 1.372 m, this restriction requires dedicated DRL headlamps if (*a*) high-beams were to be used as DRLS, and (*b*) the mounting height of the standard headlamps on the particular vehicle was between 0.864 m and 1.372 m.

The limiting aspect of glare in automotive headlighting is generally discomfort as opposed to disability glare. Schmidt-Clausen and Bindels(4) have developed a model for predicting the amount of discomfort experienced as a function of illuminance at the eye, glare angle, and adaptation luminance. However, this model cannot be used for setting the upper limit of glare illuminance because later studies have shown that discomfort glare is a function of additional factors, including the range of other stimuli present(3), the angular size of the glare source(5), and the difficulty of the driver's concurrent task(6). On the other hand, the model of Schmidt-Clausen and Bindels can be used to estimate the relative effects of changes in parameters of interest (i.e., changes in illuminance, glare angle, or adaptation luminance) on ratings of discomfort(4).

The present analytical study was designed to evaluate the effects of increasing the mounting height of high-beam DRLS from 0.864 m to 1.372 m. Three analyses were performed. The first analysis examined glare illuminance at the eyes of the preceding driver via rear-view mirrors. The rationale was that if the difference in illuminance at a mounting height of interest and at the current maximum allowed height of 0.864 m is 25% or less, then the difference is not noticeable(7).

The second analysis compared the illuminance from reduced-power high beams with that from full-power low beams. The logic here was that glare illuminances from full-power low beams (at the mounting heights in question) are currently considered to be acceptable. Consequently, the illuminance from reduced-power high-beams would have to exceed the illuminance from full-power low beams by more than 25% to be of potential consequence.

The third analysis estimated the relative changes in discomfort glare for reduced-power high beams as functions of mounting height. The changes in discomfort glare were estimated by using the model developed by Schmidt-Clausen and Bindels(4).

The analyses were based on photometric information from five US high beams photometered for this study, and 43 US low beams.

2 Method

2.1 *Overview*

The basic calculations involved computing the illuminance reaching the driver's eye point from reduced-power high beams and full-power low beams via all three rear-view mirrors. Of interest were illuminances for mounting heights between 0.864 m (34 in) (the current maximum for reduced-power high-beam DRLS) and 1.372 m (54 in) (the current maximum for any headlamp). The illuminance values were then used to estimate changes in discomfort glare using an equation developed by Schmidt-Clausen and Bindels(4). The calculations were performed for a range of following distances and lateral offsets of the vehicles. Table 1 lists the three specific analyses that were performed.

Table 1 also lists the criterion values that were used to evaluate the results of the analyses. The particular criteria selected are important because they determine the interpretation of the analyses. The same criteria were chosen for the first two analyses. Specifically, if the difference in illuminance were 25% or less, then the difference was considered not to be of practical consequence. This criterion was based on findings by Huey, Decker, and Lyons(7) on just-noticeable differences.

The third analysis, evaluating discomfort glare, used as the criterion 0.5 units on the de Boer scale(8). The de Boer scale is a nine-point rating scale, with qualifiers only for the odd points as follows: 1 (unbearable), 2, 3 (disturbing), 4, 5 (just acceptable), 6, 7 (satisfactory), 8, 9 (just noticeable). Schmidt-Clausen and Bindels(4) developed a model that predicts de Boer discomfort-glare rating as a function of glare illuminance, glare angle and adaptation luminance. However, as indicated above, other factors (such as the range of other stimuli present, the angular size of the glare source, and the difficulty of a concurrent task) affect discomfort-glare ratings. Consequently, the Schmidt-Clausen and Bindels model cannot be used to estimate a universally applicable upper limit of tolerable glare illuminance. On the other hand, the model of Schmidt-Clausen and Bindels can be used to estimate the relative effect on discomfort glare of changes in a given parameter. It was used here to estimate the changes in glare ratings as a function of changes in illuminance. The selected criterion of 0.5 units can be interpreted as one quarter of the difference between 'just acceptable' and 'disturbing,' or one quarter of the difference between 'satisfactory' and 'just acceptable.' In comparison, de Boer ratings have been shown to change by more than 1 unit in response to the range of other stimuli present(3), 0.8 units in response to the difficulty of a concurrent task(6), 0.7 units in response to prior experience(9), and 0.2 units in response to the angular size of the glare source(5).

The first analysis was performed for all conditions of interest. The second analysis was performed only for conditions which exceeded the criterion on the first analysis. Analogously, the third analysis was performed only for conditions which exceeded the criterion on the second analysis. A flow chart diagramming the interrelations of the three analyses is shown in Figure 1.

2.2 *Rear-view mirrors*

We calculated the combined illuminance from all three rear-view mirrors. It was assumed that the left outside and centre inside mirrors were plane, and that the right outside mirror was convex (applicable for right-hand traffic). The reflectance levels chosen for the two plane mirrors were 50% (left outside) and 80% (centre inside). The illuminance produced by the reflected light from a convex mirror is a more complex matter. It corresponds to the square of the relative magnification, which in turn depends on the radius of the mirror, eye-to-mirror distance, and distance of the source of illumination from the mirror(10). The reflected illuminance from a convex mirror is always less than that from a corresponding plane mirror. Platzer(10) presents calculations showing that the effective reflectance of a typical convex mirror for objects at intermediate distances is about one fifth of that of a corresponding plane mirror. Thus, if we assume the reflectance of an outside plane mirror to be 50% (as used in our simulation for the left outside mirror), then a reasonable value for a typical right outside convex mirror is 10%. That is the value used in the present calculations.

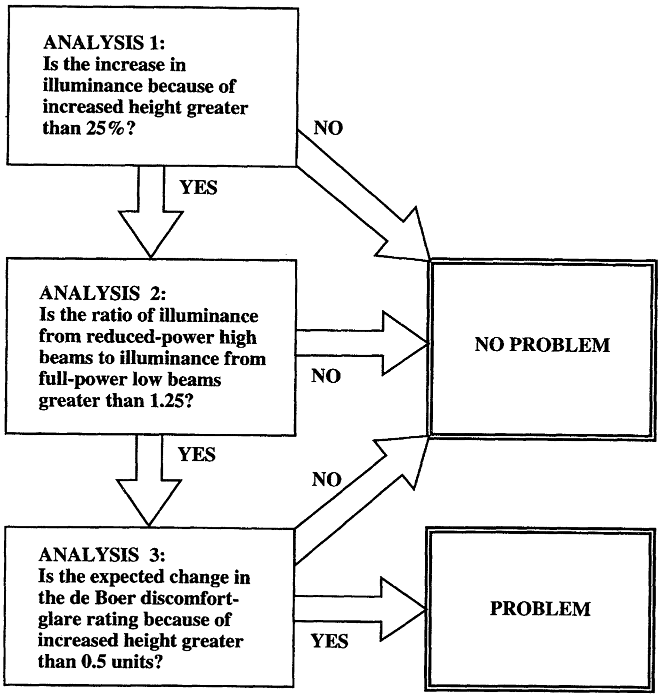

Figure 1 Flow-chart of the three analyses performed

There is evidence that discomfort glare is affected by glare angle(4) (the angle formed by the stimulus the observer is looking at, the observer's eye point, and the glare source). In our simulation, the differences in the glare angles for the left outside and centre inside mirrors were relatively small (36° and 42°, respectively). The glare angle for the right outside mirror was substantially larger (63°), but its contribution to the total illuminance was small because its reflectance was set at only 10%. Consequently, the present calculations disregarded the differences in glare angles for the three mirrors.

The locations of the mirrors (as well as the field-of-view angles listed below) were selected to approximate those on a 1994 Ford Taurus — the best-selling passenger car in the US for that model year(11). The locations are described in Table 2.

The field of view for the centre inside mirror was set at ±20°, with the limiting factor being the width of the rear window. The fields of view for the left outside and right outside mirrors were set at –15° and +2.5°, and –2.5° and +28°, respectively.

Table 1 Analyses performed as functions of mounting height

Analysis	Description	Criterion
1	Illuminance from reduced-power high beams	Increase of more than 25% as compared with that at 0.864 m
2	Ratio of illuminance from reduced-power high beams to illuminance from full-power low beams	Ratio of more than 1.25
3	Changes in discomfort glare using the de Boer scale	Increase in discomfort of more than 0.5 de Boer units

2.3 *Headlamp location*

The following headlamp mounting heights were examined: 0.864, 0.966, 1.067, 1.168, 1.270, and 1.372 m (measured from the ground to the centre of the lamp). (These values correspond to 4-inch steps from 34 inches to 54 inches.)

The headlamp separation was set at 1.22 m. This separation was used for both high beams and low beams.

2.4 *Headlamp photometry*

Five high-beam headlamps, manufactured for the US market, were photometered for this study. The lamps included one of each of the following types: H4666, H5001, H5051, H6024, and H6054. The photometric information for each lamp consisted of a luminous-intensity matrix in 0.5° steps from 20° left to 20° right, and from 5° down to 10° up. All lamps were measured at 12.8 V. The photometry was performed in 1995, and thus the high beams represent a sample of lamps from the mid 1990s. The data were normalised so as to have the highest luminous output at H-V. This was achieved by adjusting the horizontal and vertical co-ordinates, if needed. The luminous intensities were then scaled down so that the peak intensity (at H-V) was 7 000 cd — the maximum allowed for high beams used as DRLs.

The low beams in this study included 43 US-market lamps documented in detail by Sivak, Flannagan and Sato(12). The photometric information for each lamp consisted of a candela matrix in 0.5° steps from 20° left to 20° right, and from 5° down to 5° up. All lamps were measured at 12.8 V. The photometry was performed between 1990 and 1993, and thus the low beams provide a sample of lamps from the late 1980s and early 1990s.

The calculations for high beams and low beams used the corresponding median values at each test point.

2.5 *Additional geometry considerations*

Lane widths of 3.7 m were simulated. The glare car was always in the centre of its lane. Three lateral offsets of the preceding car in relation to the glare car were simulated: –3.7, 0 and 3.7 m. These offsets represent the preceding car being in the centres of the left adjacent lane, the same lane, and the right adjacent lane respectively. Other, intermediate offsets are also possible, but they represent conditions that are likely to be more transient than the offsets corresponding to the centres of lanes.

2.6 *Driver position*

Driver eye height was set at 1.14 m from the ground, while the lateral displacement from the centre of the vehicle was set at 0.41 m.

2.7 *Windows*

The attenuation through the rear window was taken into account in calculating the illuminance falling on the centre inside mirror. Similarly, the attenuation through the side windows was included in deriving the illuminance reaching the driver from the side mirrors. The transmittance of the rear and side window glass was set at 75%.

2.8 *Following distances*

Five following distances were examined: 8.5, 15, 25, 50, and 100 m (measured from headlamp to the eye point of the preceding driver).

3 Results and discussion

3.1 *Analysis 1: Illuminance from reduced-power high beams at the driver's eye point*

Tables 3 to 5 show the total illuminance reaching the preceding driver from all three mirrors as functions of mounting height, lateral displacement, and following distance. There are five noteworthy trends in relation to mounting height as follows.

(*a*) The total illuminance was generally an inverted-*U*-shaped function of mounting height, with the maximum not at the highest mounting height but near the mounting heights of the mirrors (0.97 m and 1.23 m).

(*b*) Increasing the mounting height from 0.864 m to 1.372 m did not always increase the total illuminance.

(*c*) The maximum percentage increase in illuminance from that at 0.864 m tended to decrease with increasing following distance.

(*d*) For following distances of 25, 50, and 100 m, all increases in illuminance were less than 25% for all lateral offsets, and thus of insignificant practical consequence.

(*e*) For following distances of 8.5 m and 15 m, and lateral offsets of –3.7 m and 0 m, increases in mounting height from 0.864 m tended to result in an increase of more than 25% in the total illuminance. Consequently, for these two following distances and two lateral offsets it was examined whether reduced-power high beams produce substantially more illuminance than do full-power low beams. That analysis is presented in the next section.

3.2 *Analysis 2: Ratio of the illuminance from reduced-power high beams to the illuminance from full-power low beams*

Tables 6 and 7 present the ratios of the illuminance from reduced-power high beams to that from full-power low beams for mounting heights between 0.966 m and 1.372 m. These calculations were performed only for following distances of 8.5 m and 15 m, and for lateral offsets of –3.7 m and 0 m, because the preceding analysis showed that only in these conditions were the changes in high-beam illuminance, as a function of mounting height, of potential consequence. (See Tables 3 to 5.)

The main findings of this analysis are as follows.

(*a*) For both lateral offsets, the ratio of the illuminance from high beams to that of low beams was generally a decreas-

Table 2 Location of rearview mirrors

Mirror	Mounting height (m)	Longitudinal distance from driver's eye point (m)	Lateral separation from driver's eye point (m)
Left outside	0.970	0.670	0.465
Centre inside	1.230	0.470	0.410
Right outside	0.970	0.670	1.285

Table 3 Total illuminance (lx) at driver's eye point for lateral offset of –3.7 m (preceding car is one lane to the left in relation to the glare car)

Following distance (m)	Mounting height (m)						Largest increase from 0.864 m (%)
	0.864	0.966	1.067	1.168	1.270	1.372	
8.5	0.49	0.62	0.61	0.46	0.38	0.30	27
15	1.11	1.31	1.62	1.77	1.76	1.61	59
25	1.18	1.24	1.30	1.36	1.38	1.38	17
50	1.12	1.14	1.16	1.18	1.18	1.17	5
100	0.92	0.93	0.94	0.94	0.94	0.92	2

Table 4 Total illuminance (lx) at driver's eye point for lateral offset of 0 m (preceding car is in the same lane as the glare car)

Following distance (m)	Mounting height (m)						Largest increase from 0.864 m (%)
	0.864	0.966	1.067	1.168	1.270	1.372	
8.5	28.06	39.07	39.98	38.01	32.58	23.19	42
15	21.14	25.68	28.07	28.73	27.47	24.14	36
25	12.40	13.71	14.15	14.21	13.68	12.47	15
50	5.05	5.14	5.10	5.06	4.97	4.80	2
100	1.37	1.38	1.37	1.37	1.36	1.34	1

Table 5 Total illuminance (lx) at driver's eye point for lateral offset of 3.7 m (preceding car is one lane to the right in relation to the glare car)

Following distance (m)	Mounting height (m)						Largest increase from 0.864 m (%)
	0.864	0.966	1.067	1.168	1.270	1.372	
8.5	0.94	1.00	1.06	1.15	1.03	0.69	22
15	2.26	2.43	2.62	2.69	2.71	2.76	20
25	1.95	2.08	2.12	2.11	2.09	2.05	9
50	1.42	1.44	1.45	1.47	1.47	1.47	4
100	0.80	0.81	0.81	0.81	0.82	0.82	2

ing function of mounting height. As a consequence, this ratio was always smaller at the highest mounting height than at the lowest mounting height. In all instances this ratio was less than 1 (i.e. high beams produced less glare illuminance than did low beams) for the two greatest mounting heights.

(*b*) For a lateral offset of –3.7 m (the preceding car in an adjacent lane to the left), in all but two tested situations the illuminance ratios were either less than 1 or were between 1 and 1.25 (and thus, from a practical point of view, in these situations high beams did not produce appreciably more glare illuminance than did low beams). The two exceptions were ratios of 1.3 and 1.28.

(*c*) For lateral offset of 0 m (the preceding car in the same lane), the illuminance ratios were greater than 1.25 for all but one combination of following distance and mounting height between 0.966 m and 1.168 m.

For those conditions in which the ratio of the illuminance from high beams to the illuminance from low beams exceeded 1.25, a third and final analysis was performed. That analysis estimated the likely changes in discomfort glare from reduced-power high beams as a function of mounting height. That analysis is documented in the next section.

3.3 Analysis 3: Estimated changes in discomfort glare from reduced-power high beams as functions of mounting height

The data in Tables 6 and 7 indicate that the ratio of the illuminance from reduced-power high beams to the illuminance from full-power low beams exceeded 1.25 for seven combinations of lateral offset, following distance, and mounting height greater than 0.864 m. For these seven conditions we calculated the expected change in the de Boer discomfort-glare rating compared with that for the same condition, but at a mounting height of 0.864 m. The results of these calculations are shown in Table 8. (According to the model of Schmidt-Clausen and Bindels(4), the magnitude of the change in the de Boer rating as a function of a change in illuminance is the same regardless of the particular values selected for the glare angle and adaptation luminance.)

The main finding in Table 8 is that for all conditions examined, the increases in the mounting height resulted in changes in the de Boer discomfort-glare rating of less than our criterion of 0.5 units (as compared with the ratings at a mounting height of 0.864 m — the current upper limit).

Table 6 Ratio of the illuminance from reduced-power high beams to the illuminance from full-power low beams for a lateral offset of –3.7 m

Following distance (m)	Mounting height (m)				
	0.966	1.067	1.168	1.270	1.372
8.5	1.21	1.02	0.60	0.34	0.16
15	1.30	1.28	1.07	0.78	0.51

Table 7 Ratio of the illuminance from reduced-power high beams to the illuminance from full-power low beams for lateral offset of 0 m

Following distance (m)	Mounting height (m)				
	0.966	1.067	1.168	1.270	1.372
8.5	3.67	2.26	1.12	0.46	0.18
15	3.71	2.52	1.53	0.85	0.46

4 Conclusions

This analytical study examined the effects of mounting height on discomfort glare from reduced-power high-beam daytime running lamps. The effects of interest were for mounting heights between 0.864 m and 1.372 m — the range in which full-power low beams are currently allowed, but reduced-power high beams are not. Three analyses were performed. The first analysis involved estimating the illuminance reaching a preceding driver via rear-view mirrors. The second analysis compared glare illuminance from reduced-power high beams with that from full-power low beams. The third analysis evaluated the expected changes in discomfort-glare ratings from reduced-power high beams as a function of increased mounting height. The analyses were based on photometric information from five high beams and 43 low beams, and they were performed for five following distances and three lateral offsets of the vehicles.

The results showed that allowing mounting heights from 0.864 m to 1.372 m would increase glare illuminance at following distances of 25, 50 and 100 m by less than 25% — an amount generally considered to be inconsequential. At following distances of 8.5 m and 15 m the resultant illuminance increase was generally more than 25%. However, for some of the conditions at these following distances, the illuminance from reduced-power high beams was less than that from full-power low beams. Finally, for those conditions at 8.5 m and 15 m in which high beams produced more illuminance than low beams, the expected change in discomfort glare produced by high beams compared with that at the current maximum mounting height was found to be only modest.

The present findings indicate that allowing reduced-power high beams with mounting heights between 0.864 m and 1.372 m would not appreciably increase discomfort glare for preceding drivers as compared with (*a*) glare from reduced-power high beams at a mounting height of 0.864 m, or (*b*) glare from currently allowed full-power low beams.

Acknowledgements

Appreciation is extended to the members of the University of Michigan Industry Affiliation Program for Human Factors in Transportation Safety for support of this research. The current members of the Program are: Adac Plastics, Bosch, Chrysler, Corning, Delphi Interior and Lighting Systems, Denso, Ford (Automotive Components Division), GE, GM NAO Safety Center, Hella, Hewlett-Packard, Ichikoh Industries, Koito Manufacturing, LESCOA, Libbey-Owens-Ford, Magneti Marelli, North American Lighting, Osram Sylvania, Philips Lighting, PPG Industries, Reflexite, Stanley Electric, TEXTRON Automotive, United Technologies Automotive Systems, Valeo, Wagner Lighting, 3M Personal Safety Products, and 3M Traffic Control Devices. We thank Mr Walter Kosmatka from GE Lighting for providing the photometric data for the high beams that were used in this study.

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Table 8 Estimated change in the de Boer discomfort-glare rating for conditions in which the ratio of the illuminance from reduced-power high beams to the illuminance from full-power low beams exceeded 1.25. The calculations were made using the equation of Schmidt-Clausen and Bindels(4).

Lateral offset (m)	Following distance (m)	Mounting height (m)	Difference in the de Boer discomfort-glare rating compared with that for mounting height of 0.864 m
–3.7	15	0.966	0.14
–3.7	15	1.067	0.33
0	8.5	0.966	0.29
0	8.5	1.067	0.31
0	15	0.966	0.17
0	15	1.067	0.25
0	15	1.168	0.27