Headlamp Performance Factors Affecting the Visibility of Older Drivers in Night Driving

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In 1985 in the United States 2,668 drivers over the age of 64 were killed in traffic accidents, representing 10.5 percent of all drivers fatally injured *(1)*. At that time 11.8 percent of the population in the United States was over 64, suggesting that they were not overrepresented.

However, drivers over 64 were only 7.7 percent of those involved in fatal accidents, yet were 10.5 percent of those who were killed, suggesting their lower tolerance to injuries. Only about 7 percent of drivers involved in fatal accidents who were over 64 had a blood alcohol content higher than 0.10, which is about one-third that of younger drivers.

Older drivers are involved in fatal accidents in darkness about half as often as younger drivers. Drivers over 64 appear to have 15 to 30 percent of fatal accidents in darkness (Table 1), whereas drivers as a whole have 50 to 60 percent of their fatal accidents in darkness. The lower percentage of nighttime accidents of older drivers may be due to a number of exposure factors as well as their driving less at night *(2)*.

Further analyses of these data taken together with the 1983 Nationwide Personal Transportation Study (which showed that drivers over 64 drove 14 percent of their mileage at night and younger drivers drove 26 percent at

TABLE 1 DRIVER INVOLVEMENT IN FATAL ACCIDENTS, 1985 *(1)*

	Percent of Involvement by Time of Day			
Age (years)	8:00 a.m. to 4:00 p.m.	4:00 to 8:00 p.m.	8:00 p.m. to 4:00 a.m.	4:00 to 8:00 a.m.
Over 64	60.3	23.9	10.9	4.9
All	30.2	22.9	37.4	9.5

night) indicate that the night-to-day minimum and maximum fatality rate ratios are 1.3 and 2.0, respectively, for older drivers. For drivers younger than 65 the ratios are 3.4 and 3.5.

The results indicate that the fatality rate at night is perhaps twice the daytime rate for drivers 65 or older, but for younger drivers the night fatality rate is about 3.5 times the daytime rate. Thus, the risk of driving at night increases relatively less for older drivers than younger drivers compared with the risk in the daytime.

Perhaps this could be due to a selection process among older drivers, so that only those who feel reasonably capable of driving at night do so. They may also be the same drivers who are not severely affected by glare and whose abilities to see at night are still relatively good. Such a hypothesis would need to be verified.

Accident analyses have rarely implicated glare as a factor. The Indiana University trilevel study of accidents *(3)* indicated that glare from headlights was a possible factor as an "environmental cause" in 0.5 percent of the accidents, but none were attributed to "vehicular factors" related to headlamps. Because about 22 percent of the accidents occurred in darkness, it is estimated that in 2.3 percent of those, headlamp glare was a causal factor. A study of 2,130 on-the-spot accident investigations by the Transport and Road Research Laboratory in Great Britain *(4)* indicated that glare was a factor in 30 of 231 accidents in which "adverse environment" was involved. More recently, a survey *(5)* in which drivers were asked about the causes of their run-off-the-road events found that glare was mentioned as the major contributing factor in 10 percent of the 30 cases that occurred at night.

Glare was also reported to be "bothersome" in night driving by 65 percent of drivers aged 19 to 39 *(6)* and in another study *(7)* 74 percent of drivers reported that they were occasionally dazzled and 33 percent said that glare was a frequent problem. Sixty-eight percent of drivers reported *(6)* that they became more rapidly fatigued driving at night than in the daytime. These reports show that drivers consider glare a problem in night driving.

CURRENT STATE OF THE ART

U.S. and European Designs

A brief history of the development of headlighting systems in Europe and the United States is provided in a number of recent publications *(8–10)*.

The basic design of the meeting (low) beam of motor vehicle headlamps in Europe and the United States differs primarily in the amount of glare that is permitted. The European philosophy has always been to try to minimize glare for oncoming drivers, and they have achieved this by use of a shield to block light from the filament reflected from the lower part of the reflector. In this way, sharp control of the vertical part of the beam is achieved, and it is aimed so as not to be above the horizontal on the side of the oncoming driver. The beam is characterized by a very sharp cutoff in the lane occupied by opposing traffic and by a rising vertical beam to illuminate the road lane ahead of the driver. Typically, the maximum permissible candle power above the horizontal in the glare zone is about 400 candelas in the European low beam. By comparison, the U.S. low beam provides about twice the intensity of the European beam in the glare zone. This means that drivers meeting each other with low beams will be exposed to more glare from the oncoming vehicle's headlamps.

However, the U.S. beam provides a more gradual transition between pavement illumination and illumination at the sides of the roadway as well as at signs mounted above the roadway. Historically, the U.S. beam has also provided greater illuminating intensities directed on the pavement.

Thus, there is a trade-off between illumination on the pavement, which needs to be maximized to provide visibility of the road and, if possible, objects of importance to a driver at the roadside and even above the roadway, and the need to minimize glare. This is because glare reduces visibility and increases discomfort and may lead to fatigue in long-distance driving.

Glare, however, occurs not only when vehicles are meeting each other in frontal situations but also as a consequence of illumination of the mirrors by a following vehicle. In fact, a number of studies have shown that the reflected glare from mirrors frequently exceeds that from oncoming vehicles *(11)* and adversely affects visibility, especially that of older drivers *(12)*.

Numerous tests of the visibility provided by the European and the U.S. low beams have been made *(13)*, with the general finding that the U.S. beam provides better visibility on the road lane ahead and to the right side of the road than the European beam, which provides slightly better visibility on the left side. These tests have generally been done under idealized circumstances in which lamps were correctly aimed, the roads were dry, and the atmospheric transmission was high. In those circumstances the differences in the visibility provided by these two beams are generally small *(14)*.

Aim and Alignment

In an evaluation of the performance of headlamps for night driving, many factors other than the beams need to be considered. Primary among these is the ability to aim headlamps correctly as well as to maintain their aim under a variety of circumstances in which vehicles are used *(15)*. Vehicle loading is a major determinant of the resulting alignment of headlamps, as are factors attributable to use and servicing *(16)*. The effect of changing bulbs or lamps on the resultant aim *(17)* has also been studied. The ability of service technicians to align headlamps properly has been evaluated; there are clear deficiencies in this area *(15)*.

Dirt

The performance of headlamps depends on a variety of factors, some of which are independent of the design of the beam or the type of light source used. For example, dirt on the face of headlamps can greatly reduce the light that they emit and hence the visibility available to the driver, in many cases increasing the effects of glare *(18, 19)*.

Rain and Fog

Although most headlighting tests have been conducted under ideal weather conditions, the weather is by no means always ideal. Night driving in clear conditions with low-beam headlamps provides marginal visibility. When bad weather is encountered at night, such as rain, the visibility provided by headlamps is substantially reduced because of the change in the reflective properties of the pavement; simultaneously, glare effects are increased because of reflections from water droplets on the windshield and the wet pavement. In such circumstances the visibility available to drivers is far less than that required for safety at normal highway speeds.

Nighttime fog is another condition in which visibility is substantially reduced, imposing heavy demands on headlamp technology.

Interaction with Streetlighting

Use of headlamps in areas where streetlighting is provided, and the interaction of the illumination and glare provided by headlamps with that of streetlighting can have complex effects on the ability of drivers to see pedestrians, bicyclists, and other objects. The result of this interaction can lead to an improvement in the ability of drivers to detect pedestrians along one part of a lighted road and a reduction in this ability in an adjacent section *(20, 21)*.

Future Trends

The situation in the United States and Europe concerning future developments in vehicle headlighting is becoming more complex. The recent changes that allow the use of headlamps with separate bulbs in place of sealed beam units, the use of halogen bulbs enclosed in small glass envelopes, the increase in the maximum intensity of the high beam, and a trend toward reducing the height of headlamps above the pavement all generally contribute to a less favorable night-driving environment.

Current trends in motor vehicle headlighting in the United States and elsewhere are to permit headlighting standards to be based entirely on performance criteria and thereby to permit headlamps to be designed in any size or shape. In some respects this may be considered to be a step forward because it could provide an incentive for designing headlamps with the primary aim of improving visibility. There is also the possibility, however, that even if a suitable performance criterion of headlamps could be devised and agreed on, the ultimate objective would be to improve the aerodynamics and styling of vehicles at the expense of improved visibility for drivers of all ages.

VISIBILITY FACTORS IN NIGHT DRIVING

Glare Disability

A definitive study on the effect of glare on the visibility of targets was carried out by Wolf *(22)*. For those in the driving age range, approximately 16 to 85 years old, the maximum differences in the thresholds attributable to age are approximately 1.0 to 1.5 log units.

Shortly after the work of Wolf, Christie and Fisher undertook a study concerned with the effects of glare from street lighting systems on visibility for drivers as a function of their ages *(23)*. The underlying intent of this study was to evaluate the predictive value of the Stiles-Holladay expression of the equivalent veiling luminance: $G = KE/O^N$ and to compare this with an equation proposed by Fry *(24)*: $G = KE/O$ (1.5 + 0).

The factor K in these formulas is a constant determined by the age of the observers; however, relatively little work has been done to establish the value. The conventional value of K is 10 pi.

Christie and Fisher reported three experiments *(23)* in which values for the age factor K were obtained. The results for the constant K in the three experiments were

1. $K = (0.2A + 0.4)$ pi,
2. $K = (0.19A + 5.8)$ pi,
3. $K = (0.2A + 6.8)$ pi.

These results showed that there was an effect of the background on the effect of the age variable. The general form of the equation is quite consistent in all experiments, however, and shows that age is an important variable in affecting the effective veiling luminance. The value of K = 10 pi is fairly representative of the findings of the study by Christie and Fisher. For drivers 60 to 70, K is approximately 16 pi, or a 60 percent increase. Therefore, the glare effect would also be increased by approximately 60 percent.

Computer simulations in which a constant value for the effect of age has been used could incorporate the equations of Christie and Fisher for the effects of age on disability glare.

These findings are consistent with studies made of visibility distances in situations simulating driving at night against the glare of headlamps of oncoming traffic. For example, in one study *(25)* with one group of subjects age 18 to 30 and another group 65 and over, the older subjects identified the test targets at distances 40 to 60 percent of those reported by the younger subjects for a number of different headlamp beams. In another study *(26)* subjects over the age of 61 were able to identify the orientation of a letter on a sign at distances 65 to 77 percent of those for persons under 25 years of age in a night-driving test.

Glare Discomfort

Glare not only causes a reduction in the visibility available to drivers, it can also create discomfort and perhaps hasten fatigue in night driving. The effects of disability glare in reducing visibility in night driving are noticeable first; glare levels must be greater to create discomfort *(27)*.

A study of headlamp beam use by Hare and Hemion *(28)* found that requests by oncoming drivers to dim their beams occurred at a mean distance of 1,700 ft. However, 25 percent of the drivers dimmed their high beams at 2,400 ft or more. At such a distance the angle between the headlamps of the oncoming vehicle and the opposing driver would be quite small and the glare illumination at the eyes of that driver would be about 0.01 footcandle (0.1076 lx). Thus, this level of illumination at the driver's eyes with small glare angles might represent a criterion for discomfort glare tolerance. This was confirmed by Farber and Bhise *(29)*, who evaluated the dimming requests against the discomfort glare scale developed by DeBoer *(30)* and found that requests occurred at "glare mark" values of 2 to 4, which indicates that the glare was disturbing.

In some experimental evaluations of various headlamp beams *(13)* drivers made ratings of the maximum discomfort they experienced when approached by each headlamp system. The results are shown in Figure 1. The data show that, even for the conventional U.S. low beam under good visibility and dry

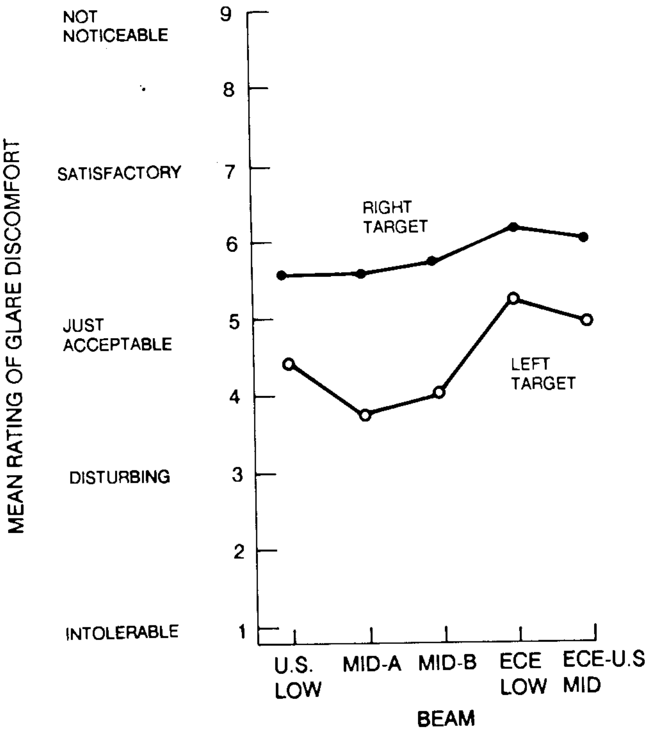

FIGURE 1 Mean ratings of maximum glare discomfort in meetings with five beams when driver is searching for targets on the right and left side of the lane *(13)*.

road conditions, the discomfort glare levels can vary on either side of the "just acceptable" value. It should be remembered that the observers in these experiments were looking for test targets, which directed their gaze either to the right or the left edge of the road. Under normal driving conditions recordings of drivers' eye fixations *(31)* have shown that they frequently look toward the oncoming vehicle and that the frequencies of those glances increase as the distance between the two vehicles decreases. This means that drivers will be exposed to higher glare levels than may be supposed based on experiments designed to evaluate the visibility of targets. It is understandable that drivers would look toward oncoming traffic, at least on two-lane highways, to make sure that the oncoming vehicle is in its proper lane.

Thus, the extent of discomfort glare experienced by drivers on two-lane roads from the use of the U.S. low-beam headlamp provides an indication of what levels of discomfort glare should not be exceeded. This is particularly striking because the data were obtained under ideal viewing conditions. When the roadway is wet or when it is raining, the visibility conditions are substantially worse and discomfort glare is greater. Furthermore, the current U.S. low-beam photometrics permit higher glare levels than in 1974, when the study was done. Combined with the growing use of halogen bulbs, this has resulted in a noticeable increase in glare.

None of the glare discomfort models reviewed has taken into account the age of the observers; this is a clear deficiency at this time. Some research shows that age does affect discomfort glare *(32)*; some suggests that it is not a significant factor in discomfort glare evaluations *(33)*. The latter study indicated that the differences between 16 "young" and 24 "old" subjects were negligible at low glare values, only diverging at higher glare levels, which caused more discomfort to the older drivers.

Glare from Rearview Mirrors

The interior mirror of automobiles has a reflectivity of about 0.85, and exterior mirrors have reflectivities of about 0.55. The interior mirror is often fitted with a feature to reduce the reflectivity to about 0.04 so that the glare of headlamps of following vehicles at night can be reduced. At this time, vehicles are not fitted to allow reduction in reflectivity of exterior mirrors other than to move the mirrors out of alignment so that they do not reflect the headlights of following vehicles. Clearly, this is undesirable because it means that much of the information provided by the exterior mirrors is lost.

Studies of the intensities directed at the rearview mirrors of automobiles by the headlamps of following vehicles have shown that they are frequently substantially greater than the intensities at the eyes of a driver from oncoming traffic *(11, 34)*. A small study in which discomfort glare of a rearview mirror was examined found that with headlamps positioned 50 ft behind the mirror drivers rated reflectivities of more than 55 percent as producing excessive discomfort *(35)*.

In addition, the following traffic tends to remain at relatively short distances, say 100 ft behind the vehicle, so that the illumination at the eyes of the driver by light reflected from the mirrors is high and present for relatively long periods compared with the time taken for an oncoming vehicle to pass the driver. Fortunately, the glare effect is mitigated by the relatively large angle between the driver's forward gaze and the mirror, except for those occasions when the driver looks directly at a mirror.

The exterior mirrors also frequently produce more glare for a driver, not only because they have no dimming feature but because when another vehicle is in the passing lane, its low-beam headlamps are directed with their high-intensity portions at the approximate position of the left-side exterior mirror, which results in high glare levels.

In a series of studies concerned with automobile rearview mirrors, Olson and Sivak *(12)* found that recovery time from glare for older drivers was substantially longer than for younger drivers and that the resulting thresholds were greater for the older drivers than the younger ones, as would be expected. In a driving study, the test subjects also rated the glare levels using the "glare mark" index *(W)* for 10-sec and 3-min exposures to the headlamps of a vehicle behind the vehicle they were driving. It was found that the longer the exposure of the glare, the more discomfort was experienced and, further, that the level of discomfort was related to the glare illumination at the eyes of the drivers produced from the following car's headlamps. The authors indicate that to avoid glare-mark values of less than 5, the illumination from the rearview mirror should not exceed 6 lx for short durations or 3 lx for longer durations.

A computer simulation of the effect of headlamps in the rearview mirror *(36)* provided data representative of the illumination due to the headlamps of a vehicle following at a distance of 100 ft, reflected from the rearview mirror into the driver's eyes (Table 2). The illumination criterion of 3 lx mentioned by Olson and Sivak *(12)* would be found in the case of low-beam headlamps at a mounting height of about 42 in. or for the midbeam headlamps mounted at about 24 in. when correctly aimed. In the case of a 1-degree upward misaim, the glare criterion ($W = 5$) would be exceeded for the low-beam headlamps at the lowest mounting height, indicating the debilitating effects of upward misaim.

Table 2 shows that there is a detrimental effect of glare from headlamps reflected in the rearview mirror of a preceding vehicle as headlamp mounting

TABLE 2 ILLUMINATION IN AUTOMOBILE DRIVER'S EYES FROM MIRROR-REFLECTED HEADLAMPS OF VEHICLE FOLLOWING IN SAME LANE AT 100 FT *(36)*

Aim (degrees)	Lamp Mounting Height (in.)	Illumination (footcandles) by Beam		
		Low	Mid	High
0;0	24	0.13	0.28	2.79
	30	0.16	0.42	
	36	0.20	0.66	
	42	0.29	0.99	
	48	0.45	1.48	
0;1,up	24	0.38	1.30	
	30	0.61	1.74	
	36	1.01	2.32	
	42	1.42	2.39	
	48	1.91	2.58	

NOTE: Interior mirror reflectivity, 0.85; exterior reflectivity, 0.55. (1 footcandle = 10.76 lx.)

height is increased between 24 and 48 in. (Federal Motor Vehicle Safety Standard 108 allows headlamps to be mounted as high as 54 in.) and due to upward misaim. It can also be noted that high-beam headlamps of a following vehicle at 100 ft clearly cause extremely high glare levels because of reflection in the rearview mirror of a preceding vehicle.

Table 3 shows the results of computer simulations *(36)* of the effects of a following vehicle on visibility for the driver of a preceding vehicle and the glare discomfort experienced by the driver because of reflections in interior and exterior rearview mirrors. The effects are shown for headlamp mounting heights on the following vehicle of 24 and 48 in. and for conventional low-beam headlamps and experimental midbeam headlamps on the following vehicle and when the driver of the preceding vehicle is viewing targets at the right edge and on the centerline of the road.

When the driver is viewing targets on the right of the road, the decrements in visibility attributable to the disability glare produced by the headlamps of the following vehicle are generally small except for the experimental midbeam headlamps when they are misaimed 1 degree upward. However, the

TABLE 3 EFFECT ON VISIBILITY DISTANCE OF MIRROR-REFLECTED HEADLAMPS OF FOLLOWING VEHICLE *(36)*

Beam on Following Vehicle	Minimum Visibility Distance (ft)	Percent	Maximum Visibility Distance (ft)	Percent	*W* at 500 ft Separation
Target on Right					
None	247	100.0	277	100.0	5.2
Low, 24 in., nominal aim	246	99.6	273	98.5	3.5
Low, 48 in., nominal aim	241	97.6	265	95.7	2.6
Mid, 24 in., nominal aim	244	98.8	269	97.1	3.0
Mid, 48 in., nominal aim	228	92.3	242	97.9	1.7
Low, 24 in., 1 degree up	242	97.9	266	96.0	2.7
Mid, 24 in., 1 degree up	230	93.1	245	88.4	1.8
Mid, 48 in., 1 degree up	218	88.2	229	82.6	1.3
Target on Left					
None	101	100.0	192	100.0	4.4
Low, 24 in., nominal aim	101	100.0	188	98.0	3.2
Low, 48 in., nominal aim	100	99.0	180	94.0	2.3
Mid, 24 in., nominal aim	101	100.0	184	96.0	2.7
Mid, 48 in., nominal aim	98	97.0	160	83.0	1.3
Low, 24 in., 1 degree up	101	100.0	182	95.0	2.4
Mid, 24 in., 1 degree up	98	97.0	163	85.0	1.4
Mid, 48 in., 1 degree up	95	94.0	147	77.0	0.9

NOTE: Following vehicle is at 100 ft (30.5 m). Interior mirror reflectivity, 0.85; exterior mirror reflectivity, 0.55. Results of computer simulations of meetings on a straight, level, two-lane road between automobiles using low beams.

glare-mark index calculated at a separation to an oncoming vehicle of 500 ft is substantially below the value of 5 ("acceptable") in all cases except the one in which no following vehicle is present. These increases in discomfort glare from the case in which the following vehicle does not exist (shown with a value of $W = 5.2$) are attributable to the effects of the headlamp conditions reflected in the rearview mirrors and are highly significant. The conditions are even worse when the driver is looking at the centerline of the highway, that is, slightly to the left of the vehicle, with all the other conditions the same (Table 3, lower half).

By comparison, the glare-mark index is calculated to have a value of 3.6 when two cars meet each other with high beams and are separated by 500 ft. It can be seen that the effects of a following vehicle are more severe than this in many of the conditions described in Table 3.

Although many vehicles have a day-night interior mirror, which permits the driver to reduce the extent of reflected light from a following vehicle substantially, there is no equivalent means of reducing the light reflected from the exterior mirrors. Following vehicles frequently provide glare for relatively long periods of time compared with oncoming traffic. Because of the effect on discomfort and visibility and the differential effect on the older driver, the problem posed by rearview mirror glare is significant. Clearly, then, it is important to provide a dimming device to reduce mirror glare in the exterior mirrors of motor vehicles as well as in the interior mirror.

Mounting Height of Headlamps

The current standard on the mounting height of headlamps indicates that the centers of headlamps may be mounted at a height of 22 to 54 in. (55.9 to 137.2 cm) above the roadway. Most automobile headlamps are now close to the lowest value in this range, whereas headlamps on pickup trucks and vans are substantially higher and those on large trucks are generally close to the upper value of the range. It is worth noting that European countries [Economic Commission for Europe (ECE) Regulation 48 and European Economic Community (EEC) Regulation 6-756] require mounting heights of 19.7 to 47.2 in. (50 to 120 cm) to the bottom edge of the lamp. However, in practice, vehicles have headlamp mounting heights that conform to a much narrower and lower range.

Within limits, the greater the mounting height the greater the visibility for the driver seated behind them. However, this is counteracted by increased glare for drivers of other vehicles, particularly the glare produced by rearview mirrors. Some of these latter aspects were discussed in the preceding section.

The visibility distances for the truck driver in truck versus car meetings (Figure 2) are greater than those for the car driver (car versus truck). Those

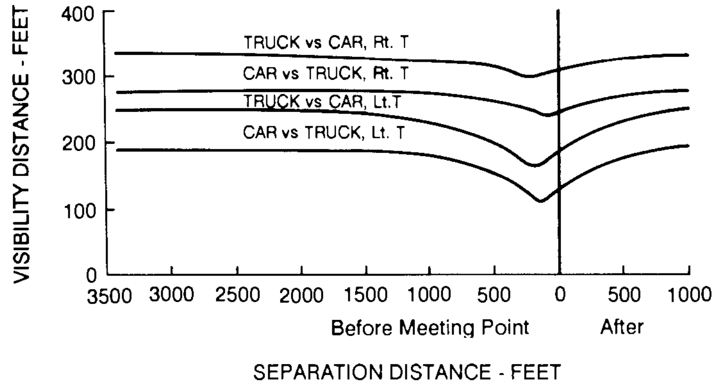

FIGURE 2 Computed visibility distances of 12 percent reflectance targets at right (*Rt. T*) and left (*Lt. T*) of lane for truck and car drivers meeting, both with low beams *(36)*. (Reprinted with permission, Society of Automotive Engineers, Inc.)

differences are due to the greater mounting height of headlamps on the truck (48 in.) than on the car (24 in.) *(36)*.

It appears, therefore, that the major problem of nonuniform mounting heights between cars and trucks is due to the indirect glare from rearview mirrors attributable to a truck, van, or pickup truck following a passenger car. It has already been shown (Table 3) that the higher mounting height of headlamps on trucks causes a reduction in forward visibility due to disability glare for car drivers and also large increases in discomfort glare levels.

For these reasons, the minimum and maximum mounting height regulations for headlamps of all types of vehicles should be reviewed. This is especially true for vans and pickup trucks, whose general performance and use are much like those of automobiles, and which accounted for about 30 percent of the U.S. vehicle market in 1986.

Headlamp Aim

Society of Automotive Engineers (SAE) Standard J599c indicates that headlamp aim should be maintained within tolerances of 0.8 degree from the horizontal and vertical axes of the lamp. Such a recommendation is quite liberal because changes in headlamp aim such as 0.5 degree up or down can cause substantial variations in illumination and glare. A variety of studies have examined the sources of headlamp misaim. One quite detailed examination of this problem *(15)* found that there were four major sources of headlamp misaim: differences between the beam and the mounting plane, photometric changes in use over time, errors in alignment of the long axis of the vehicle in aiming, and factors related to the operators of the aiming equipment. Results of the investigation suggested that 43 percent of lamps could be expected to be beyond the SAE tolerances in the vertical or the horizontal direction. For example, it would be expected that the 95th-percentile vertical error would be 1.27 degrees, which is a large error in headlamp vertical aim that would seriously affect visibility and glare. These errors could be reduced by improvement in the practices used by service personnel, by maintaining a constant relationship between the mounting plane of the headlamp and the aiming plane, and by ensuring greater rigidity of the position of the filament over time and correct initial aim.

Improvements in the technology (e.g., the luminoscope) used to aim headlamps at service stations, inspection stations, and at the factory *(37)* have been demonstrated to be beneficial.

Another serious contributing factor to headlamp misaim has to do with the pitch alignment of the vehicle, which can be significantly affected by vehicle loading. This factor can be controlled by automatic vehicle-leveling devices.

There have also been some suggestions that the horizontal aim position of headlamps can be properly stabilized by suitable design of the headlamp mounting plane so that adjustments of the headlamp in the horizontal would not be required. This would leave the vertical adjustment as the only one with which there need be concern. Automatic headlamp-leveling systems that operate through the vehicle suspension have been constructed and evaluated and appear to work well *(38)*. Such systems compensate not only for vehicle loading, but also for acceleration and deceleration, aerodynamic lift, and settling of the suspension over time. Jones and MacMillan *(39)* have shown that an automatic headlamp-leveling system that can maintain the standard deviation of aim to 0.25 degree would be satisfactory. They suggest a design goal of 0.3 degree maximum error, which was achieved by a mechanical system they evaluated. Costs of such systems are about $60 on a mass production basis.

A less expensive approach than the self-leveling system is for the driver to manually adjust the vertical aim of the headlamps, but the driver is only partially capable of solving the aim problem. Clearly, fully automatic headlamp-leveling systems are most desirable because they will account for both the effects of load and transient effects due to the pitching of the vehicle. Nevertheless, many of the advantages of automatic headlamp-leveling systems will not be obtained unless headlamps can be initially aimed with a greater degree of accuracy than they are now and are able to retain their aim over time.

Although automatic headlamp-leveling devices or some kind of driver-actuated headlamp-leveling device is not required in any country at this time, it was reported at a meeting of the SAE Lighting Committee in May 1987 that the Federal Republic of Germany has proposed regulations that would make headlamp-leveling devices mandatory.

Headlamp Washing and Wiping

Dirt on headlamps will act as a filter and also as a scattering medium, with the consequence that the illumination on the road will be reduced and the original photometric characteristics of the headlamp will be changed, with possible increases in glare levels.

One study *(18)* estimated that on dry, clean roads the reduction in light output from the headlamps was about 5 to 10 percent; at −15°C it was 15 to 20 percent; with a temperature just below 0°C and moist roads it was 30 to 45 percent; at temperatures of −5 to −10°C on snowy roads with salt it was 60 to 80 percent; and when the temperature was 0 to 5°C on slushy roads that had been salted the degradation was as high as 95 to 99 percent. It was also indicated that drivers are not likely to notice that their headlamps are dirty until the light output is reduced at least 60 percent, which was estimated to reduce the visibility of high beams by about 20 percent and of low beams by about 15 percent. Those data were reported for Sweden, where snow on roads and slush are not uncommon during the winter. Similar results could be expected in other regions having a similar climate.

A Finnish study *(7)* reported that the mean effect of dirt on a sample of 1,199 cars, 488 trucks, and 132 motorcycles was a 26 to 29 percent reduction in illumination. A lamp-washer system has been required in Finland since January 2, 1981. It was found that 21 percent of the cars and 44 percent of the trucks had such systems, but 5 percent of the cars and 27 percent of the trucks that were inspected lacked washing liquid.

High-pressure washers alone, without wipers, may be quite effective and are estimated to cost about $15. The estimated cost for a washing and wiping system by lighting experts in the United States was about $50.

It is obvious that under the worst night-driving conditions, such as in rain or snow or when there is slush and salt on the highway, there is the greatest opportunity for dirt accumulated on headlamps to reduce the illumination and increase the scattering of light from the headlamps. This occurs when the least reduction in visibility can be tolerated and suggests that efforts should be made to maintain cleanliness of the headlamp glass. Because the visibility in night-driving meeting situations is substantially less for older drivers than for others, the additional degradation caused by the loss of light output from headlamps under inclement weather conditions should be avoided. Clearly, this would be one area in which the older driver in particular could be aided.

Other Factors

Factors directly related to the design of motor vehicle headlamps, such as the beam patterns, the location of the lamps on the vehicle, washing and wiping systems, and headlamp aim, can clearly affect the visibility performance of the headlighting system. However, there is little question that the meeting beam of motor vehicles cannot be refined much further to provide improvements in visibility. Improvements under certain driving conditions, such as on straight roads, are attainable as demonstrated by so-called "midbeams," which provide more illumination along the lane being traveled without substantial increases in glare levels.

Overall, factors other than those related to the design of the vehicle are probably of more importance in affecting the visibility of all drivers and particularly older drivers at night.

Reflectorization of important hazards in the roadway is one general approach, as well as the use of paints containing reflective beads for roadway delineation. The types of materials that have been used on road signs have high reflective properties and indicate what can be done to achieve good visibility in night driving. Similar materials need to be used on salient roadside features such as bridge abutments and gore areas.

The roadway itself is frequently difficult to see, especially when wet. This most important of all objects for the nighttime driver must be as well defined as possible under all conditions of night driving; appropriate edgeline and centerline treatments should be used on all roads.

The visibility of the rear and sides of slower-moving vehicles such as trucks, farm equipment *(40)*, and vehicles that make frequent stops on the roadway at night such as garbage vehicles should be improved. Such vehicles need additional lighting to ensure their visibility and to advertise not only their presence on the roadway but also their size and position on the road. These objectives can be partly met by the use of reflective sheeting material that has been available for many years and by improved lighting.

Pedestrians are one class of road user that is particularly difficult to see under many night-driving conditions, especially if low reflective clothing is worn, which is normally the case. Pedestrians should be encouraged to wear very light-colored clothing and in particular to use reflective materials on their outer garments. Other road users such as cyclists and motorcyclists can also benefit substantially from the use of reflective materials on the sidewalls of tires, the vehicle itself, and the clothing of the operator.

Although it is difficult to increase the illuminating intensities of the low-beam headlamps of motor vehicles to attempt to gain an increase in visibility, it is relatively simple to increase the reflectivity of the objects that the driver needs to see and thereby obtain a substantial increase in visibility. It is only by this joint effort between persons responsible for the design and operation of motor vehicle headlamps and others responsible for the design of the highway environment that a reasonably safe night-driving environment can be attained. At this time, the night-driving environment in the United States and most other countries is far from safe at the speeds that are used on rural highways *(41)*.

CHANGES TO IMPROVE NIGHT-DRIVING VISIBILITY

In the previous sections the current state of the art of motor vehicle headlighting has been described, as well as some of the major problems.

The areas where improvements appear to be warranted and feasible relate to the aim and alignment of headlamps, the mounting height of headlamps, the reflectivity of rearview mirrors, the cleanliness of headlamps, and refinements to the meeting beam. In addition, it has been mentioned that other factors than those directly associated with vehicle systems and headlamps can greatly affect the visibility of objects in the driving environment. The characteristics of the environmental variables, that is, their reflectivity, interact with the headlighting variables to determine the effective visibility. Similarly, the variables that affect headlamp performance, such as aim and mounting height, interact with other factors such as the reflectivity of rearview mirrors in determining the disability and discomfort glare experienced by drivers.

These kinds of interactions indicate the complexity of the task of deciding how to best provide an improved night-driving environment under headlamp illumination. However, some general rules can be stated. For example, the photometric characteristics of headlamps, as defined by the beam they emit and their illumination of the roadway and glare characteristics, are obviously determined by the aim of the lamp, which includes not only the alignment of the headlamp at any instant but also its mounting location and its cleanliness. In simple terms, then, it is essential to maintain aim in the nominal design condition and to keep the lamp clean as well as to take into account the effect of the mounting height of the lamp on the effective beam distribution on the roadway and at oncoming traffic.

The complexity of the interaction among all these variables can probably be simplified by imposing certain restrictions, which are considered in the following sections.

Mounting Height of Headlamps

The mounting height of headlamps is recommended to be restricted to a narrower range than is now permitted (22 to 54 in.). The mounting height of the centers of headlamps on U.S. passenger cars has historically been at about

24 to 25 in., but recently the trend has been to lower it. This has been accompanied by lowering the eye height of drivers. The effect is to produce less visibility of the roadway. Placing the eyes vertically closer to the headlamps has negative effects in rain, snow, and fog because of the increased backscatter from the headlamps to the eyes of the driver. Low headlamp mounting heights also decrease the reach of the headlamps on the road and reduce the angle of incidence of the light reaching the pavement from the vehicle, which in turn will reduce the amount of light returned to the eyes of the driver. For these reasons there needs to be a limit on the lower mounting height of headlamps. The current minimum should not be reduced.

There is much justification for reducing the upper limit on the mounting height of headlamps. The overall benefits in the reduction of glare that would be obtained would be realized rapidly as the vehicle population changes. It is recommended that Federal Motor Vehicle Safety Standard 108 be revised to limit the mounting heights of headlamps to within the range of 22 to 30 in. on all passenger cars, pickups, vans, trucks, and motorcycles.

Rearview Mirrors

The reflection from rearview mirrors is a substantial cause of discomfort glare and in many instances also of disability glare. To counteract this it is necessary to change the reflectivity of the mirrors for nighttime use. The interior rearview mirror of many motor vehicles can be switched to a night position that has a reflectivity of approximately 4 percent. This value is lower than necessary; a higher value would be somewhat more beneficial. Nevertheless, the 4 percent value of the interior rearview mirror is not considered to be a significant impediment to safety.

However, the exterior mirrors, which generally have reflectivities of about 55 percent, should be reduced in reflectivity for nighttime use to reduce glare when there is following traffic. Reflectivities in the range of 10 to 20 percent would probably be reasonable in reducing glare as well as providing adequate visibility of vehicles to the rear. It is important that the reflectivity in the night setting for either the interior or the exterior mirrors be sufficiently different from the daytime setting so that it is clearly apparent to drivers which setting is in use. This is to ensure that in the daytime drivers will use the daytime position and not retain the nighttime one, which could make it difficult to see other vehicles, especially under overcast conditions when vehicles behind may not be using headlamps.

Headlamp Cleanliness

Headlamp-cleaning systems now appear to be of two types. One uses a high-pressure spray and another a spray and wiping action. If both methods are satisfactory, either one can be used. Such systems could be used in conjunction with the windshield wipers to operate only at night and on an intermittent, automatic basis and have a manual override for additional cleaning action at the option of the driver. In this way, headlamp cleaning would take place on an intermittent but relatively continuous basis even when the driver is not using the windshield-washing system. Headlamp cleaning can provide substantial increases in visibility under the very conditions when visibility is most degraded and when it would be of most advantage, especially to older drivers.

A reduction in visibility of 20 percent when the visibility is, say, 100 ft is much more serious than a 20 percent reduction in visibility when the visibility is 300 ft. Headlamp-washing systems can retain the integrity of the beam pattern in the most marginal visibility conditions. The need for such systems is also highlighted by the fact that drivers are not aware of the reduction in visibility created by dirt on their headlamps and may continue to drive with dirty headlamps even when the weather conditions that produced the dirt are no longer present. Unlike large levels of glare from rearview mirrors, the effect of dirt on headlamps is not readily perceived by drivers and therefore calls for some type of automatic cleaning system.

Headlamp Aim

Aside from the photometric distribution of light designed into the headlamp beam system, the factor that most affects the distribution of light emitted from the headlamps is the alignment of the lamp in practice on the vehicles. The theoretical effectiveness of any headlamp beam system cannot be achieved if aim variance is at all large. The meaning of the term "large" in this context is a very small amount of change from the nominal aim condition. That is, variations in aim of more than about 0.25 degree create relatively large changes in beam effectiveness. This implies a small tolerance in the aim of headlamps because of static and dynamic conditions.

Manual compensation for vehicle loading by providing driver control of the vertical alignment of the headlamps would be a beginning step—the Ford Motor Company believes that vertical adjustment only is necessary if proper mounting of the headlamp is provided so that horizontal adjustment is not required. Suitable design of the headlamp mounting plane, as mentioned earlier, would make reaiming unnecessary when sealed beam lamps are replaced or when bulbs are replaced in units that use separate bulbs. This would require sufficient structural rigidity as well as alignment of the aiming plane of the lamps to that of the vehicle. That would provide a first level of potential improvement that goes hand in hand with the ability to correctly aim the headlamps at the factory and in the field. The type of aiming equipment needed to accomplish this has been demonstrated in Europe *(37)*.

It would be more desirable to incorporate automatic headlamp alignment systems that compensate for both static loading changes as well as the dynamic changes that occur when the vehicle is in motion. Such systems would clearly minimize glare and retain the maximum effectiveness of the headlamp beam. However, glare would not be eliminated because of road geometry such as that on crests of hills or curves, but in other conditions the glare levels should be within design tolerances. If automatic alignment systems were to be incorporated, some small advances in the shaping of the meeting beam could be made and would be worthwhile, but it is questionable if such advances can be made at this time and achieve any significant improvements in overall visibility and comfort in night driving without automatic headlamp aligning and correct initial aiming systems.

Beam Shaping

Both the U.S. and the ECE meeting beam have evolved over many years of development and have become more similar over time and unquestionably are close to an optimal beam pattern. This is probably so within the constraints available on headlamp aim. Unless improvements in headlamp aim are made, it is questionable whether additional changes to the meeting beam can be achieved that would benefit the older driver.

It is quite clear that glare control must be a major consideration for older drivers. Thus, a headlamp beam that achieves this would probably be advantageous to them, even if it results in some overall loss in roadway illumination. In this respect, the ECE beam may well be advantageous for the older driver because of its overall lower glare levels. Therefore, if the vehicles of all drivers were equipped with ECE-type beams, glare levels should be lower under most conditions. However, ECE beams that are misaimed or misaligned can cause substantially greater glare levels than those of U.S. beams. This again emphasizes the importance of achieving better glare control by improved maintenance of aim. Yet it must be remembered that fewer states than in the past now have vehicle inspection requirements, providing little inducement for drivers to have their headlamps checked for aim. Although the quality of aiming by service stations is generally poor, as has already been indicated, that situation could be changed, and the necessary equipment to achieve good quality aim is available.

Recent proposals that would allow a multiplicity of headlamps on motor vehicles would have both positive and negative effects. They may aggravate the aim problem because of the increased number of lamps that may exist on vehicles and would increase the costs of headlamps themselves. However, the increased number of lamps would imply a degree of redundancy so that a lamp outage need not create a significant loss in illumination and improved beam shaping would become more feasible.

The use of more than two basic beam patterns on motor vehicles has been explored for a number of years with the midbeam. This intermediate between the low beam and the high beam is an approach to improve visibility under many circumstances on both divided highways as well as two-lane roads. It relies, however, on the driver to switch off the midbeam under conditions when it would provide excessive glare to oncoming traffic, primarily on curves. If the dimming function from the midbeam to the low beam, or any change in beam pattern commensurate with oncoming or preceding traffic, could be accomplished automatically and reliably, such beams would become more feasible. Up to now, headlighting engineers have believed that the driver cannot be relied on to adequately use a three-beam system. That is a debatable issue that has not been properly evaluated; with the probability of multibeam headlamp systems being permitted it is a matter that requires further consideration. Nevertheless, automatic beam selection appears to be a way in which improved illumination and visibility could be provided, and is therefore worth much more investigation.

Polarized Headlighting

The subject of polarized headlighting has been omitted from this review because it has been adequately dealt with elsewhere. The advantages and disadvantages of the concept have been evaluated, and it appears to be more and more feasible from a technical standpoint. The implementation problems are still quite large, but further consideration should be given to this concept.

Factors Unrelated to Vehicle Design

Factors other than those related to vehicle design considerations that determine the visibility of objects in the driving environment offer the greatest scope for improving night-driving visibility and permitting glare levels from headlamps to be reduced. The advantages of increasing the reflectivity of objects and the feasibility of doing so are far greater than providing increased illumination from headlamp beams. For example, an increase in reflectivity of an object by a factor of 2 may increase its visibility by 20 to 40 percent and would in many instances be entirely feasible. The same effect could be obtained by increasing the illumination from headlamps by a factor of 2, but this approach appears not to be feasible at this time. For this reason changes in the night-driving environment offer the most immediate hope for improving visibility and comfort.

RESEARCH NEEDS

Gaps in Knowledge

There is little question that sufficient information is not available on the types of accidents in which older drivers are involved as well as the risk of night driving among older drivers compared with others. The severity of accidents in which older drivers are involved should also be estimated.

In addition, more information is needed on the role of discomfort glare for older drivers and the extent to which it discourages them from driving at night. The percentage of older drivers for whom discomfort glare is a significant problem is not known, nor is it known if these are the same persons who reduce their night driving for that reason.

Improvements in the modeling of discomfort glare as a function of driver age would allow improved estimates to be made of the effects of changes to vehicle and environmental variables for older drivers by the use of existing computer simulation models.

The effects of age on disability glare and visibility in night driving should probably be further evaluated so that improved computer simulation models can be devised or changes to current models can be made if necessary. In addition, although both laboratory and analytical studies should be conducted to evaluate the effects of a host of variables upon night-driving visibility of older drivers, these should also be confirmed by studies conducted in the field. Dynamic field studies should be undertaken to assess the effect of visibility under a variety of weather conditions, not just under ideal conditions, as has been done in the past.

Cost-benefit analyses and effectiveness studies on factors such as automatic headlamp-aiming systems, headlamp-cleaning systems, and day-night exterior rearview mirrors should be made. It would be important to try to ascertain more clearly the role of vehicle lighting and associated factors that have an effect on the visibility available to drivers and their risk in night driving.

Research Programs

Perceptions of Older Drivers about Night Driving

The exposure of older drivers at night is low. Is it because of factors related to driving at night or to others unrelated to driving? Would mobility be increased among older drivers if night driving could be made safer and more comfortable for them? Do older persons who drive at night have better visual abilities than those who do not? What do older drivers perceive to be the major problems in night driving and do they think these problems could be reduced? Would they be willing to pay for improvements that would improve visibility and reduce glare? Questions of this type and others should be elicited in surveys of older drivers to learn more about their perceptions about night driving in general.

Effectiveness of Headlamp-Cleaning Systems

The effectiveness of headlamp-cleaning systems should be evaluated under actual or simulated rainy, wet road, slush, snow, and slush and salt conditions in terms of changes in the photometric distribution of the headlamps and for a number of beams (e.g., U.S. low, ECE low, U.S. high). Costs of installation at the factory and after sale of the vehicle, maintenance, frequency of operation for adequate performance in various environmental conditions, the manner of control by the driver, and whether the operation should be semiautomatic or fully automatic need to be determined.

Effect of Age on Discomfort Glare

The effect of age on discomfort glare from vehicle headlamps needs to be established so that age can be used as a factor in discomfort glare models. It will be important to ensure that the studies use background luminances within the range of those found in night driving, including those that are found in inclement weather and good weather conditions. Laboratory studies should be complemented by field tests, conducted dynamically in representative weather conditions.

Effect of Age on Disability Glare and Visibility in Night Driving

A study should be undertaken to confirm the relationship between the age of drivers and disability glare, preferably using a dynamic paradigm. The results of such a study would provide a confirmation of disability glare equations, including the age factor, or suggest revisions to them. The study should also attempt to model the "readaptation" and "recovery" process *(42)* from glare. Computer simulation models [e.g., that discussed by Bhise et al. *(27)* and by Mortimer and Becker *(14)*] should then be revised, if necessary, to better account for the age factor and the transition from glare to no-glare as the vehicles approach and pass each other in simulated meetings, and the effects of age on visibility should be determined for a variety of vehicle, headlamp, and road conditions.

The laboratory and analytical studies should be further confirmed by dynamic field tests of visibility in a variety of weather conditions.

Involvement of Older Drivers in Nighttime Crashes

There is now inadequate information on the involvement of older drivers in nighttime crashes. Analyses need to be conducted to take into account their exposure and their accidents to confirm the risk of older drivers compared with those of other ages in night driving. The character of the accidents in which older drivers, compared with younger drivers, are involved should also be investigated to discern whether visibility problems are greater or different among older drivers. Such analyses should also attempt to discover the potential role of variables that could be used to improve night-driving visibility for older drivers in particular.

Day-Night Exterior Mirrors

Exterior mirror glare is a severe problem in many night-driving conditions. Means to reduce the glare should be developed and an appropriate reflectivity of exterior mirrors for nighttime conditions should be ascertained, taking into account the age distribution of drivers.

Automatic Headlamp Beam Switching

In order to allow the use of multiple beams (e.g., three or more or infinitely variable beam systems) that enhance visibility on divided highways and on two-lane roads, automatic control of the beam is needed. Automatic beam selection must satisfy the need to reduce glare to oncoming traffic at crests of hills, on curves, and when following other vehicles.

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