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**RELATIVE MERITS OF THE U.S.
AND ECE HIGH-BEAM MAXIMUM
INTENSITIES AND OF TWO- AND
FOUR-HEADLAMP SYSTEMS**

Kåre Rumar

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16. Abstract The current maximum high-beam intensity per lamp is 75,000 cd in the United States and 140,000 cd in the ECE and Japan. The primary goal of this study was to evaluate the relative merits of these two intensity levels for visibility and safety. The analysis reviewed evidence related to the following nine factors: visibility without opposing headlights, glare from opposing and following vehicles, dimming distance, sensitivity to degradation, priority between the high and low beams and within the high beam, driver eye-fixations, difference between the intensity of the low beam and the high beam, range of high beam intensities in actual traffic, and high-beam usage. Although some relevant data do not yet exist, the available information generally favors raising the U.S. maximum from 75,000 cd to the current ECE/Japanese level of 140,000 cd. It is also recommended that the minimum high-beam intensity be raised in both the U.S. and the ECE/Japanese regulations in order to improve visibility and safety. The second topic of this study, the relative merits of two- and four-headlamp systems, is briefly discussed in the Appendix.			
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CONTENTS

ACKNOWLEDGMENTS.....	ii
1. MAIN ISSUE.....	1
2. PRESENT U.S., ECE, AND JAPANESE HIGH-BEAM MAXIMUM INTENSITIES.....	2
3. PURPOSE AND USE OF HIGH BEAMS.....	4
4. MAIN EFFECTS OF HIGH-BEAM MAXIMUM INTENSITY.....	6
4.1. Visibility without opposing vehicles.....	6
4.2. Glare.....	9
4.3. Dimming distance.....	10
4.4. Sensitivity to degradation.....	16
4.5. Priority between the high and low beams and within the high beam.....	16
4.6. Driver eye-fixation patterns.....	17
4.7. Intensity difference between low beams and high beams.....	18
4.8. Range of high-beam intensities.....	18
4.9. High-beam usage.....	19
5. STUDIES OF HIGH BEAM INTENSITY.....	20
6. PUBLIC REACTIONS TO HIGH-BEAM INTENSITY.....	23
7. EFFORTS TO HARMONIZE HIGH-BEAM REQUIREMENTS.....	24
8. SUMMARY.....	27
8.1. Present differences.....	27
8.2. Direct effects.....	27
8.3. Indirect effects.....	28
9. NEEDS FOR FUTURE RESEARCH.....	32
10. CONCLUSIONS.....	34
11. APPENDIX: RELATIVE MERITS OF TWO- VERSUS FOUR-HEADLAMP SYSTEMS..	37
12. REFERENCES.....	41

1. MAIN ISSUE

The maximum intensity of the high beam is important for driver visibility and comfort, with consequent implications for road safety. The two primary, internationally accepted regulations are those of the ECE and the United States. (The Japanese regulations are mainly adapted from the ECE regulations.) The ECE and Japan allow almost double the maximum intensity allowed in the United States.

The primary goal of this study was to analyze and evaluate the arguments for and against the different high-beam maxima required by the present U.S., ECE, and Japanese regulations. In the Appendix, a brief discussion is presented on the relative merits of two- and four-lamp systems.

2. PRESENT U.S., ECE, AND JAPANESE HIGH-BEAM MAXIMUM INTENSITIES

Of primary interest here is the maximum intensity allowed on the headlamp axis (H-V), and not necessarily the overall maximum of the beam. The reason is that the overall maximum might be situated anywhere in the light distribution and could be of limited interest relative to visibility and glare. Except for the maximum intensity and the width of the high beam, the differences between the U.S. and the ECE high-beam requirements are minor and therefore constitute no serious obstacle to harmonization. The maximum intensity at the H-V point, on the other hand, differs considerably between the existing regulations, and furthermore, it is the most critical factor relative to visibility of distant objects and glare to the opposing driver.

In the present ECE Regulation 48 (ECE, 1981) and the Japanese Safety Regulation Article 32 (JASIC, 1999), the maximum allowed intensity at the H-V point is 112,500 cd. The intensity at H-V must be at least 80% of the overall maximum of the beam. (The corresponding percentage in Japan is 75%). The overall maximum of the beam must be greater than 30,000 cd. Consequently, the ECE minimum at H-V is 24,000 cd, while the Japanese minimum is 22,500 cd. All of the preceding values are at a flux value corresponding to about 12 V (see Table 1). In Japan, there is currently a transition period, during which both the U.S. and the ECE requirements are being accepted. After 2005, only the ECE beam-pattern regulations will be valid.

Table 1
Required intensity values in candelas at 12.8V.

	United States	ECE*	Japan*
H-V minimum	20,000/40,000	30,000 (29,760)	30,000 (27,900)
H-V maximum	75,000	140,000 (139,500)	140,000 (139,500)

*Values in parenthesis are the actual values obtained by transforming the values in the regulations from 12 V to 12.8 V.

The present U.S. regulations (FMVSS, 1999) allow a maximum intensity at H-V of 75,000 cd. The U.S. regulations do not specify the size and position of the overall maximum. The minimum at H-V varies with the light source from 20,000 cd (e.g., for light sources 9004 and 9007) to 40,000 cd (e.g., for light sources 9005, H4, HID), all at 12.8 V (see Table 1).

The operating voltage is an important factor in relation to headlight intensity. According to the IES Lighting Handbook (IES, 1984), light output for filament lamps changes with voltage

according to the formula $(V_2/V_1)^{3.4}$. Consequently, to transform the candela values at 12 V to candela values at 12.8 V, the formula would be $(12.8/12.0)^{3.4} = 1.24$. Sivak et al. (1999) showed that this general transformation factor is valid for all points in the beam pattern. Consequently it is valid also for the maximum intensity. After such a transformation, the ECE high-beam maximum and minimum values at 12.8 V are approximately 140,000 cd and 30,000 cd, respectively. Consequently, the difference between the U.S. and the ECE/Japanese high-beam maximum is even larger than it appears at first. ECE and Japan allow the central intensity of high beams to be almost twice as high as in the United States. Thus, in an international comparison, the U.S. high-beam maximum intensity is rather low.

3. PURPOSE AND USE OF HIGH BEAMS

The primary purpose of the high beam is to illuminate the road and traffic scene in front of the driver when there are no opposing vehicles or lead vehicles. In this simple situation, more light provides better visibility, and is positive from a safety and comfort standpoint.

High beams could also be used, however, in some of the situations where there is opposing or preceding traffic. In these special situations, although the high beam is visible to the other drivers, it does not cause disturbing glare. Such situations occur, for instance, when the longitudinal distance between the vehicles is very large, and/or when the angle between the approaching vehicles is large (e.g., at intersection, on curves, etc.).

If high beams are used in meeting situations, the glare steadily increases until a point when one of the drivers decides that the glare is too strong and dims his or her high beams, thereby also signaling to the opposing driver to do the same. The distance between the vehicles at which the dimming takes place varies with a number of factors, such as intensity of the high beams, angle between the vehicles, lateral distance between the vehicles, low beam intensity, etc. The glare from the opposing high beam is the main restrictive factor concerning how intense high beams should be allowed to be.

High beams are also used when approaching a vehicle from behind, with no opposing traffic. Here it is up to the approaching driver to switch to low beams when he is close enough to cause disturbing glare to the preceding driver through rearview mirrors. In this situation, there is no signaling system between the drivers.

Drivers sometimes use high-beam flashes to improve driver visibility in situations where they think there is an obstacle ahead, but cannot see it clearly. Here, transient glare and image aftereffects could be restrictive factors for increased high-beam intensity.

Finally, high beams are used as a signal with various meanings. The most common message is to remind the opposing driver to dim his or her high beams. However, high beams are also used to send messages that have nothing to do with the lighting situation. In some countries a flash of high beams means “Here I come—give way!” In other countries it means “Please go ahead, I will wait.”

Here we will discuss the effect of high-beam maximum in all of the above-mentioned situations, except those where visible high beams do not cause any disturbing glare (very large distances and large angles). Also, high-beam signaling flashes will not be dealt with.

With increasing traffic, the number of occasions when high beams can be used gradually decreases. In most regions, high beams are probably used less than 10% of the total driving time. Furthermore, in regions with dense traffic, like in Germany, high beams are used only a small percent of the total driving time (Hoermann, 1995). There are no recent studies of high-beam

usage in the United States. The most recent study on this topic was performed by Hare and Hemion (1968). They report that even in situations without opposing vehicles and with no leading vehicle within 180 m, only 25 % of the drivers used high beams. Interestingly, 67% of the drivers of heavy vehicles (professional drivers) used high beams in the same situations. Possibly, the professional drivers are more aware of the advantages of high beams.

Hare and Hemion noted considerable differences between various regions in the United States. On roads with very low traffic volume (0 to 11 vehicles per hour) high beams were used as much as 80% of the time. At a volume of about 100 vehicles per hour, the high-beam usage was about 25%. When the volume exceeded 500 vehicles per hour, the time interval between oncoming vehicles was less than 10 seconds, and high beams were never used. Note that at the time of that study (in the late 1960s), the high-beam maximum intensity in the United States was only half of its current value.

4. MAIN EFFECTS OF HIGH-BEAM MAXIMUM INTENSITY

4.1 Visibility without opposing vehicles

As stated above, the H-V intensity is the main factor influencing driver visibility distance to targets in the central part of the visual scene. In a pioneering study, Roper and Howard (1938) pointed out two factors that are often overlooked. First, in most of the studies concerning visibility distances, the alertness level of the subject drivers is rather high. According to Roper and Howard, the effect of alertness is considerable, with alerted visibility distances averaging 100% longer than unalerted visibility distances. Second, seeing takes time. Consequently, detection distance is gradually reduced with increased speed. Roper and Howard argue that the loss in visibility distance is roughly 4 m per each 10 km/h increase in speed.

Roper and Howard also studied visibility distance as a function of high-beam intensity and the reflectance of the target. If we reverse the alertness and speed corrections that Roper and Howard applied to their data, their visibility distances are similar to the Swedish data reported below (Figure 1). In each case, the function is negatively accelerated, but the Roper and Howard's function does not have any marked elbow. After these corrections are applied, the visibility distances reported by Roper and Howard are only about 50% of the Swedish figures. Roper and Howard also demonstrated that the effect of target reflectance is considerable. Increasing the reflectance from 2% to 7% increased visibility by almost 70%, and increasing the reflectance from 7% to 14% increased visibility by about 20%. Roper and Howard's general conclusion was that in order to be able to stop in front of a dark target at 80 km/h, you need a minimum of 75,000 cd (a combined value from both lamps) under good conditions, and substantially more in actual traffic (considering all the degrading factors present). Roper and Howard also commented on the large future potential of multibeam systems. Thus, already in 1938 they predicted the eventual development of adaptive headlighting!

As shown by Roper and Howard, visibility does not increase linearly with increased intensity. The relation between high-beam intensity and visibility to various objects, without oncoming traffic, has been studied in a number of experiments (Johansson et al, 1969; Rumar, 1974; Helmers and Rumar, 1975). These results are summarized in Figure 1 (adapted from Rumar, 1975).

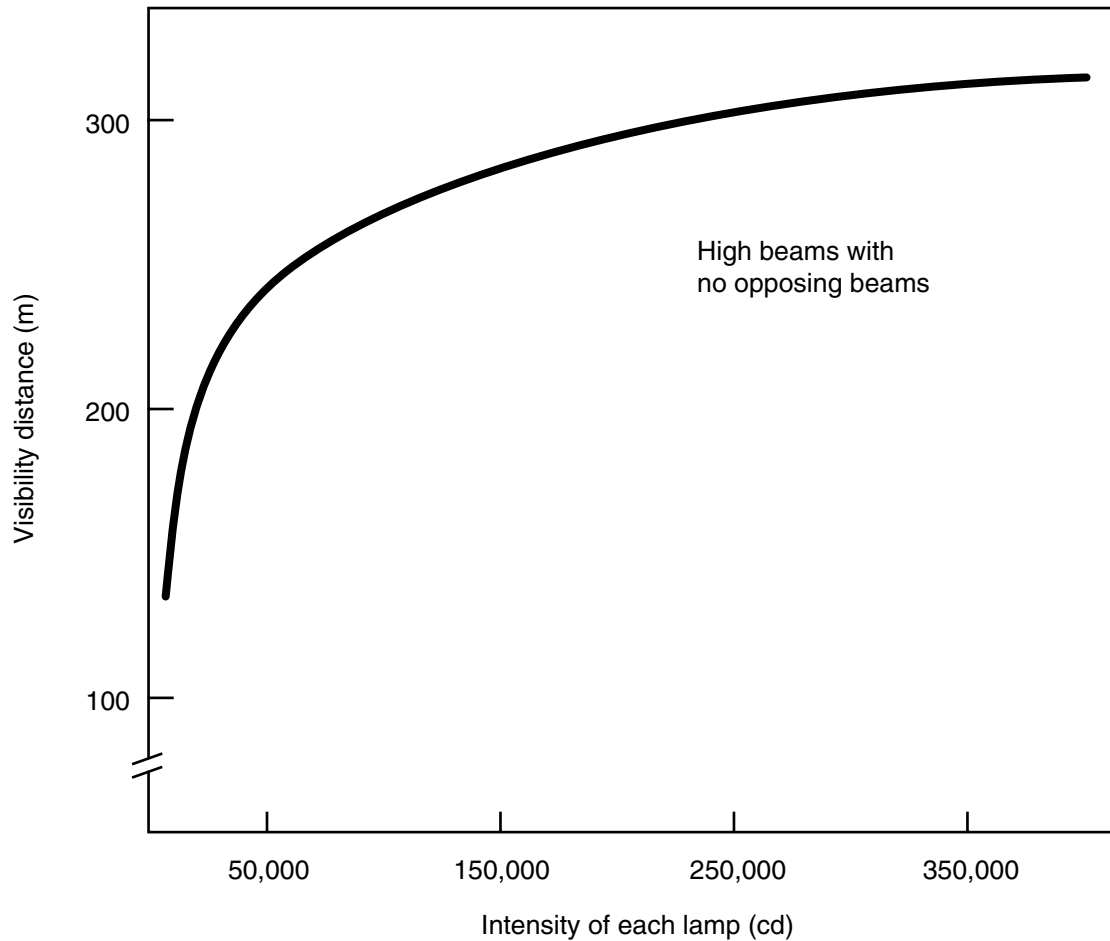


Figure 1. Visibility distance to dark obstacles (reflectance 4.5%) as a function of high-beam intensity without opposing headlights, based on several Swedish studies (Johansson et al., 1969; Rumar, 1975; Helmers and Rumar, 1975).

As can be seen from Figure 1, the visibility distance to dark obstacles is a negatively accelerated function of high-beam intensity. This tendency to an asymptotic function is due to the gradually smaller angle subtended by the object, the inverse square law of the illumination, and the so-called Ricco's law. At low levels of illumination, the smaller angles involved at greater distances make visual acuity critical. The inverse square law of illumination states that the amount of light from headlights reaching an object is reduced with the square of the distance. Consequently, to obtain the same amount of light on an object at 300 m as at 150 m requires four times the intensity. Ricco's law states that for targets with small projected areas, the eye is sensitive to the product of luminance and area. With the very long distances relevant here, this means that the effect of the previously mentioned factors are further enhanced.

The curve in Figure 1 shows that visibility is improved rapidly when high-beam intensity is increased from very low values to about 50,000 cd per lamp. At 50,000 cd the visibility distance

to dark obstacles (with a reflectance of 4.5%) is about 240 m. Tripling the intensity from 50,000 cd to 150,000 cd yields only about a 15% increase in visibility distance. Increasing the intensity from 150,000 cd up to 400,000 cd (the highest intensity tested), increases visibility only marginally (by about 10%).

Hemion (1968) reports detection distances from two experiments that employed high beams without opposing headlights and a gray (reflectance of 17%) pedestrian. In one study the median detection distance was 200 m, with a range between 180 m and 230 m. In the other study, the median was 235 m, and the range 145 to 335 m. The intensities of the high beams were not specified.

JARI (1988) explored the effect of harmonization of the Japanese standards with those in Europe. They considered three issues:

- (1) Visibility at far distance without opposing vehicles.
- (2) Glare towards oncoming drivers prior to dimming.
- (3) Visibility after switching from high to low beams.

The first issue, visibility without opposing traffic, was studied in five different road conditions (expressway, two-lane rural road, straight road, small-radius curve, and a very wide road). The high-beam intensity used ranged from 67,000 cd to 261,000 cd (total per vehicle). The obstacles were small (0.2 x 0.2 m) or large (0.4 x 1.5 m), and had a reflectance of 5%.

JARI concluded that visibility and comfort increased with increasing intensity. However, 150,000 cd (total per vehicle) was considered satisfactory in most situations, and the rate of improvement above that intensity was lower. One of the reasons was that the very small objects (0.2 x 0.2 m) could not be seen at long distances because of the small subtended visual angles involved. The visibility distances varied from about 100 m for the small objects to about 200 m for the large objects. These Japanese data largely support the above-mentioned Swedish results. However, it should be noted that all these results were obtained in ideal situations, with new and clean headlights without any degradation, and with young and attentive observers. In reality, with lower attention, degradations in headlights, windscreens, and driver vision, and in inclement weather, the relationship will likely look different. A reasonable hypothesis is that the effects of most of these degrading factors will be equivalent to a reduction in beam intensity. If several degrading factors are present at the same time, the reduction may very well reach 50%. Another effect of several degrading factors, working as noise on the ideal curve, may be that the apparent elbow at about 50,000 cd will not be as pronounced as it is in the ideal situation. Thus, the relation between high-beam intensity and visibility distance could in normal traffic be more linear.

4.2. Glare

If intensity is increased, it not only increases visibility for the driver, but it also increases the glare for other drivers. Glare is normally divided into two aspects, disability glare and discomfort glare.

4.2.1. Opposing vehicles

Disability glare, an objective aspect, is defined in terms of visibility with opposing headlights (see Figures 2 and 3). Discomfort glare, a subjective aspect, refers to the perception of the opposing headlights. Discomfort glare from opposing high beams is probably what causes a driver to dim the lights. Discomfort glare also determines (as the term implies) to what extent a driver is bothered and disturbed by the opposing headlights. A high level of discomfort can lead to public complaints, an important issue for governmental regulators.

The generally accepted scale for discomfort glare was originally developed by de Boer (1967). As shown by Schmidt-Clausen and Bindels (1974), Sivak et al. (1988, 1997b) and Flanagan et al. (1989, 1991, 1993, 1999), discomfort glare is influenced by a number of factors other than intensity, such as angle, distance, adaptation, range of glare normally experienced, general context, stimulus duration, as well as size and spectral distribution of the glare source.

Hemion (1968) measured the veiling luminance caused by opposing high beams with various longitudinal and lateral distances between the cars. His results show that on two-lane roads, the maximum glare (veiling luminance) occurred at a separation of about 60 m between the cars. On three- and four-lane roads, the maximum glare is attained at 130 m and 215 m, respectively.

In the high-beam study by JARI (1988), mentioned in Section 4.1, two of three situations dealt with glare. These two situations were glare towards an oncoming driver before dimming, and visibility after dimming. The results from the first situation show that drivers were able to see equally well immediately after dimming as they could when both vehicles had been on low beams for an extended period. Furthermore, there were no differences between the various high-beam intensities.

Results from the second situation (visibility after switching from high to low beams) show that visibility distance was not impaired immediately after the dimming. However, many of the subjects indicated that the level of subjective visibility was slightly lower. Because no difference could be found between high-beam intensities, the authors suggest that the slight difference in the perceived visibility could be an effect of filament rise time in the low beam. If that is correct, it

suggests an advantage of headlamp-systems that keep the low beam on together with the high beam.

Alferdinck and Theeuwes (1997) found that drivers were quite good at adapting to the amount of glare they were exposed to. They reduced their speed when they experienced disability glare (reduced visibility). However, contrary to expectation, the relation between discomfort glare, on the one hand, and visibility and behavioral changes, on the other hand, was weak. This points to one of the problems with subjective estimations in general, and discomfort glare in particular. Perceived discomfort is not the same as reduced performance.

4.2.2. Following vehicles

Hare and Hemion (1968) found that when the distance between cars was about 90 m or less, 93% of the following drivers were using low beams.

Olson and Sivak (1984) studied the discomfort created by glare via the rearview mirrors from a car approaching from behind. They found that glare intensity and glare duration were the two main factors. They also pointed out that older drivers are considerably more sensitive to rearview mirror glare than are younger drivers.

There are many factors that influence the intensity of the glare reaching the eyes of a driver via the rearview mirrors. To begin with, the mirror of the leading driver is situated near the center of the high beams. This makes the effective intensity very high. On the other hand, the rearview mirrors are situated at fairly large angles relative to the normal line of sight of a driver. The angle in passenger vehicles to the interior rear view mirror and the left exterior rear view mirror is 35 to 45 degrees, and to the right exterior mirror it is about 60 degrees. At such large angles, the harmful effect of the glaring intensity is reduced approximately in an inverse relation to the square of the angle. A further reduction is possible by having automatic dimming mirrors.

4.3. Dimming distance

4.3.1. Opposing vehicles

Another effect of high-beam intensity has to do with driver behavior when an opposing vehicle enters the scene. At some stage of the vehicle-meeting process, one of the two opposing drivers experiences glare and wants the oncoming driver to dim his or her high beams. Some drivers obviously dim their high beams without being really disturbed (Hare and Hemion, 1968). The reasons for early dimming are unclear. It might be courtesy, habit, or simply misunderstanding of the dimming process. When a driver is dimming his or her own high beams,

the other driver is supposed to do the same immediately. From this point on, both drivers drive on low beams until close to the meeting point, where they both switch to high beams again (if there are no other oncoming drivers). On a straight, flat road, the relation between the intensities of the two opposing high beams determines the optimal dimming distance (the optimal distance between the vehicles when first one and then the other driver switches to low beams). In vertical and/or horizontal curves, the dimming distance also depends on angles between the corresponding vehicles.

Hare and Hemion (1968) found that the dimming distance averaged 525 m, with a large standard deviation of 385 m. This means that about 25% of the dimming distances were longer than about 700 m. There are, however, a large number of factors, from high-beam intensities to driver characteristics, that contribute to this variation in dimming distance. Note that these large dimming distances were obtained with the considerably weaker high beams of that time.

These results illustrate a general observation concerning dimming distances. As indicated above, drivers very often dim too early from the visibility point of view. Research clearly shows that visibility for both opposing drivers would improve if they dimmed their high beams at shorter distances. These findings underscore the fact that the fear of late dimming, as illustrated in the dimming legislations in all U.S. states, is exaggerated.

Dimming distance in real traffic as a function of headlight intensity was systematically studied by Bhise et al. (1975) in their efforts to create a dimming-request prediction model. Using the de Boer discomfort scale (de Boer, 1967), they found that the glare intensity and the duration of discomfort predicted the probability of a dimming request quite well. In other words, if duration is constant, the dimming distance is well predicted by the intensity. If duration is shorter (as on roads with narrow vertical and horizontal curves), the dimming-request frequency is lower.

In their study of oncoming drivers' dimming requests, Bhise et al. (1975) used four beam intensities: 3,000, 25,000, 60,000, and 105,000 cd. They found very large differences in dimming requests between 3,000 cd and the other intensities. That makes sense, because 3,000 cd corresponds to oncoming low beams. A high-beam intensity of 25,000 cd caused 33% fewer dimming requests than 60,000 cd. The increase of dimming distance between 60,000 cd and 105,000 cd was about 15% for the 7-inch two-headlamp system, about 50% for the 5.75-inch two-headlamp system, and about 150% for the 5.75-inch four-headlamp system. Consequently, not only intensity, but also size of the headlamp and number of headlamps seems to have a considerable influence on dimming distance. This observation is supported by Hull et al. (1971), Mortimer and Olson (1974), and Hemion (1975), who reported markedly increased dimming frequencies with four-lamp systems, as compared with two-lamp systems with the same intensity. It seems that the drivers, to some extent, count the headlights rather than experience a certain level of discomfort.

According to Bhise et al. (1975), dimming distance is closely related to experienced glare level (discomfort glare), which in turn is related to, but not identical to, reduced visibility distance (disability glare). Discomfort glare may appear at glare levels that are too low to be measurable in terms of disability glare. A driver whose visibility is seriously reduced by glare from an oncoming vehicle is obviously exposed to disability glare, but is also most probably experiencing discomfort glare.

As can be seen from Figure 2, the visibility distance is virtually unaffected by high-beam intensity as long as the two opposing vehicles are equipped with equally strong high beams. Figure 3 illustrates the findings for situations with the opposing high beam always of a higher intensity (Helmers and Rumar, 1975). Figures 2 and 3 also contain the visibility provided by ECE H4 low beams (with identical oncoming low beams).

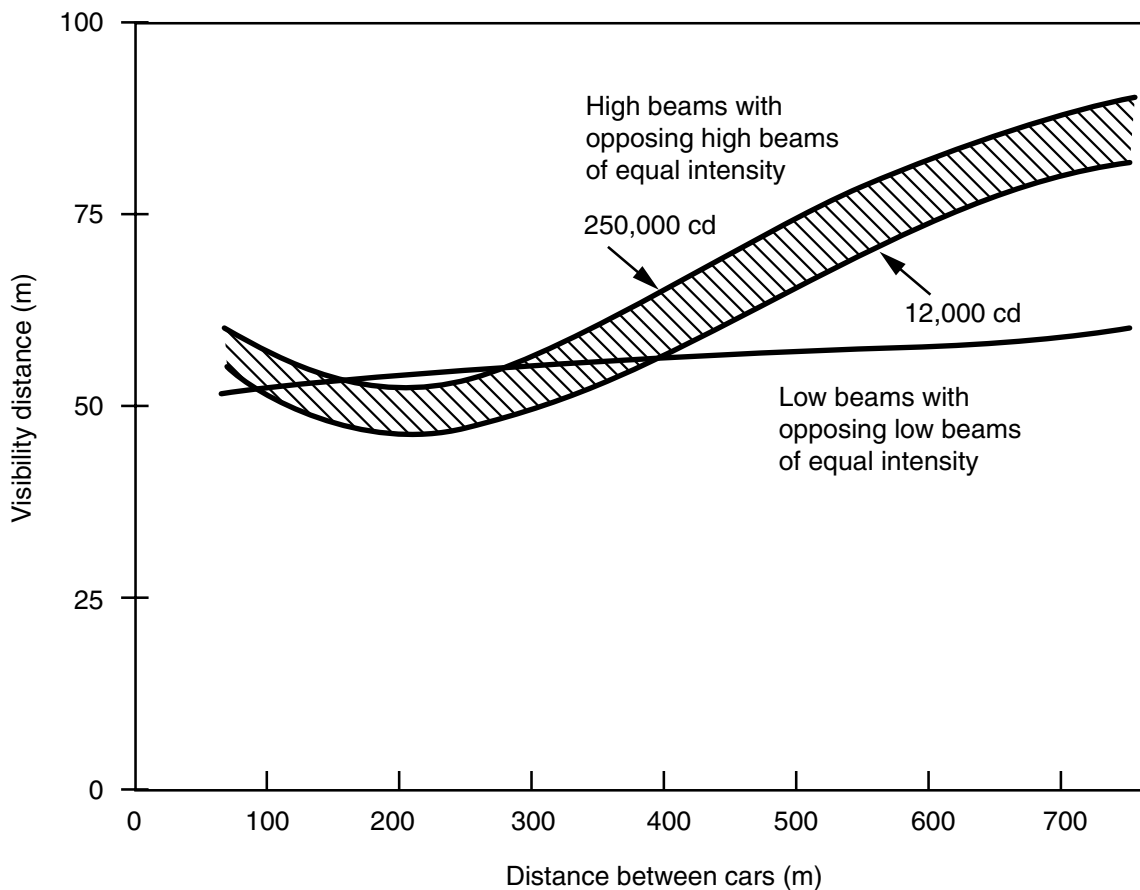


Figure 2. Visibility distances to dark obstacles (reflectance 4.5%) as a function of distance between two oncoming vehicles, both having the same high-beam intensity in a range from about 12,000 cd to 250,000 cd per lamp. Visibility with an ECE low beam opposing an ECE low beam is also indicated. (Based on Helmers and Rumar, 1975.)

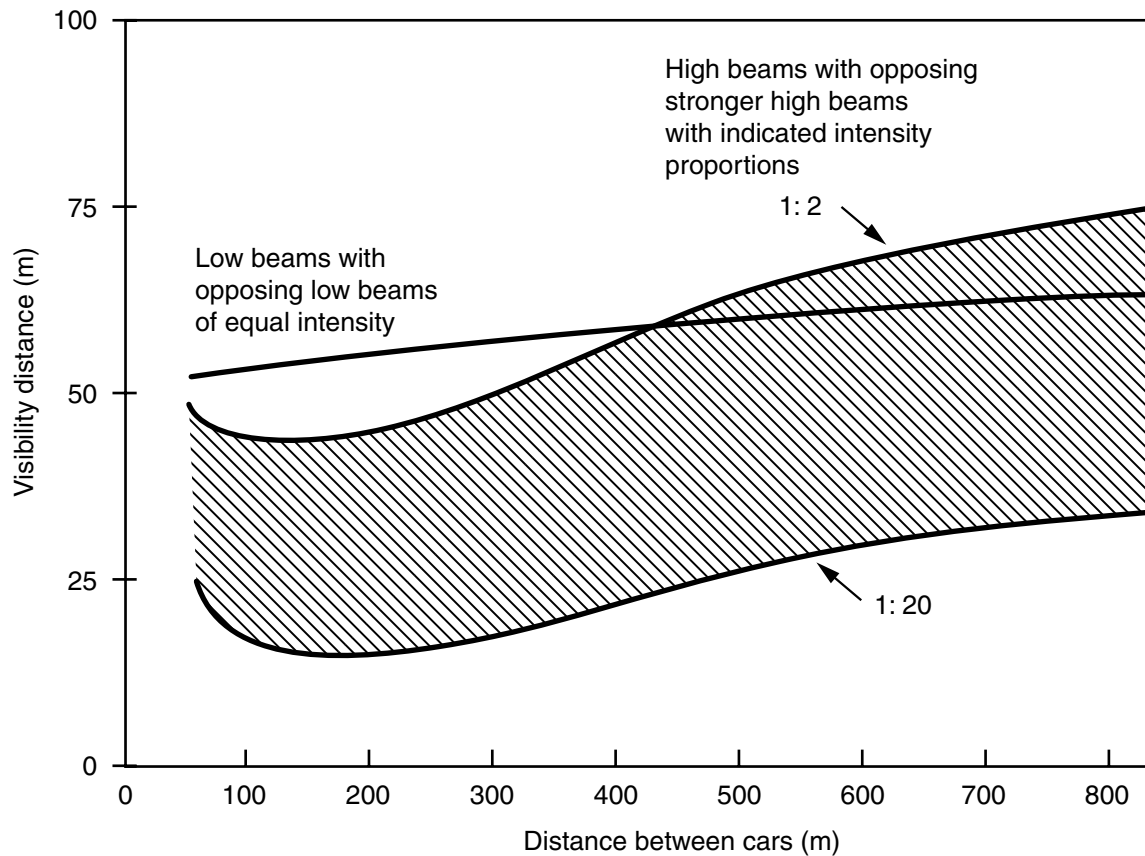


Figure 3. Visibility distances to dark obstacles (reflectance 4.5%) as a function of distance between two oncoming vehicles, with different high-beam intensities. The opposing high beam (33,500 cd to 265,000 cd per lamp) is always stronger than the subject beam (13,000 cd to 115,000 cd per lamp). The ratio between the two opposing high-beam intensities ranges from 1:2 to 1:20. Visibility with an ECE low beam opposing an ECE low beam is also indicated. (Based on Helmers and Rumar, 1975.)

The point where the high-beam and the low-beam visibility curves cross each other indicates the optimal dimming distance, because at shorter distances the low-beam visibility becomes longer than the high-beam visibility. On a straight, flat road, this occurs when the separation between the vehicles is between 250 and 400 m. However, an implication of Figure 2 is that when both opposing high beams are equally strong, optimal dimming distance depends at least as much on the visibility level offered by the low-beam system as the visibility level by the high-beam intensity. Figure 2 shows only one low beam system meeting an identical system. The range of low beam visibility is probably greater than the high-beam range (with the opposing system of the same intensity as the subject system).

Older studies, such as Johansson et al. (1963) and Roper and Meese (1952), present visibility curves for high beams and low beams with each beam being opposed by the identical

beam. In their curves, the low-beam and the high-beam curves never cross each other, because the high-beam visibility curve is generally longer than the low-beam visibility curve. In other words, there is no optimal dimming distance. A later study by Flannagan et al. (1996), in which both illumination and glare were varied together on two opposing low beams, yielded similar findings. Specifically, increased intensity increases both visibility and glare, but visibility increases more. However, they used relatively low glaring intensities varying from 1,100 cd to 3,645 cd.

Flannagan et al. furthermore showed that this effect is valid for young as well as for old drivers. Visibility increases when headlight intensity increases. Increased illumination has a higher weight than the correspondingly increased glare. From a pure visibility point of view, opposing drivers should never dim their lights, but should drive on high beam through the whole meeting process. There are, however, certainly other reasons for dimming the lights, such as discomfort glare and fatigue over a longer period with repeated high-beam meetings.

The study of Helmers and Rumar (1975) indicates that the improvements in the low beam since the fifties and sixties have been considerable. That is probably the main reason why the high-beam visibility curve and the low-beam visibility curve in later studies do cross each other—at least when the intensity differences between the two opposing high beams are not too large (about triple or less).

When the two opposing high beams differ substantially in intensity, the visibility differences between the two opposing drivers are quite pronounced (see Figure 3). In such situations, it is most probable that the driver with the weaker high beams will be the one who wants to initiate the dimming, because the driver with the weaker high beam experiences substantial disability and discomfort glare. On a straight, flat road, such a driver will want to dim the high beams at a very large distance between the vehicles.

An early dimming means that both drivers will have to drive on low beams for an extensive part of the meeting process. However, as stated above and illustrated in Figures 2 and 3, at larger separations low beams normally offer shorter visibility distances than high beams. This means that an early dimming leads to short visibility distances for a greater distance traveled, for both opposing drivers.

The two main conclusions drawn by Helmers and Rumar (1975) were as follows: (1) The intensity of the high beams need not be very strong, because the gain in visibility above about 50,000 cd is limited. (2) The range of high-beam intensities on the road should not be too large. If the range is too large, the dimming distance becomes much larger than the optimal dimming. This means that both drivers lose visibility relative to the situation in which they have equally strong high beams and can continue on high beams until around the optimal dimming distance.

However, as was pointed out earlier (at the end of Section 4.1), the situation studied by Helmers and Rumar, and the conditions present in their experiments, produce results that represent

the ideal condition, both concerning the absolute visibility distances and the optimal dimming distances. Their results point toward the true relations between various factors in idealized situations. However, they do not represent the performance and the behavior of real drivers in real traffic. Therefore, we must not base decisions on high-beam intensities exclusively on these well-controlled field data. We must consider the effects of a number of real-life factors. Unfortunately, we have very limited data on how these would affect the idealized findings.

4.3.2. Following vehicles

Olson and Sivak (1984) measured disability effects of glare from rearview mirrors situated 35, 45, and 55 degrees from the line of sight. One of their conditions corresponded to glare from high beams. They found no effect of the glare angle in the range tested. However, the age of the observer and the intensity of the glare source were critical. A glare intensity of 1 lux, which for a pair of high-beam lamps each with an intensity of 75,000 cd corresponds to a distance of about 390 m, and for high beams with intensities of 112,500 cd corresponds to a distance of 475 m, did not reduce visibility for younger drivers. But for older drivers the visibility was reduced substantially.

Miller et al. (1974) calculated the values of illumination that reached the eyes via rearview mirrors from cars approaching from behind. They argued that glare levels corresponding to opposing high beams at 180 m (1.7 lux) could be a suitable limit for glare in rearview mirrors. However, such values might be too low, considering the large angles at which glare in rearview mirrors appear.

Olson and Sivak (1984) measured the discomfort from rearview mirrors using the de Boer discomfort scale. The “just acceptable level” was reached at about 5 lux. With high beams of 75,000 cd and a windscreen transmittance of 80%, this illumination level is reached at about 155 m between the vehicles. With a high beam of 112,500 cd, the same value is reached at about 190 m. These figures can be taken as an indication of suitable dimming distances for following vehicles. These results also coincide with older, unpublished Swedish data, which indicate that the optimal dimming distance when approaching a vehicle from behind is about half of the opposing dimming distance, that is, 100 to 200 m. Optimal dimming distance from behind is reached when the visibility of the lead driver is more than marginally reduced by the glare from the following vehicle.

Another glare effect of relevance here is the time it takes to overcome the afterimages created in the eye after having looked at intense headlights of opposing vehicles or following vehicles in the rearview mirrors. Our knowledge of the effects of such afterimages is limited.

4.4. Sensitivity to degradation

Rumar (1974) found that for high beams in dry weather the typical light reduction due to dirt was about 15%. In wet weather it was 55%, and in slushy weather it was 75%. The corresponding visibility losses on high beams are approximately 3%, 15%, and 30%. (This degradation depends primarily on light scattering. This is important because light scattering, as opposed to other types of degradation, causes changes in the beam pattern.)

Other causes of degradation are light absorption, corrosion, voltage loss, lens cracks, etc. These have marginal influence on the beam pattern. They primarily reduce the intensity. The degradation may not have its origin only in the headlight system. It may also be in other optical media in the vehicle (e.g., the windscreen). Or it could be caused by the driver's spectacles or visual status, which is influenced by age (Flannagan et al., 1996; Rumar, 1998). Flannagan et al. found that younger subjects (average age 22 years) had 23% longer visibility distances than did older subjects (average age 72 years). Another factor is the clarity of the air. For a driver on high beam without oncoming vehicles, slight haze reduces driver visibility by about 15% compared to clear atmosphere (Johansson et al., 1969). Therefore, it is logical that when visibility is reduced due to slightly adverse weather, the usage of high beams increases. According to Hare and Hemion (1968), light fog, wet roads, rain, and blowing snow increase the usage of high beams by about 5%. On the other hand, if really poor weather such as dense fog is present, the usage of high beams is reduced. The reason is probably backscattering of light.

A high beam with central intensity close to the minimum acceptable level for visibility and safety is, of course, more sensitive to these various sources of degradation than a stronger high beam. The central part of a high beam always has a higher intensity than the rest of the beam. Therefore, it is more sensitive to scattering than the rest of the beam pattern. The reason is that the scattering degradation normally diffuses the light. Consequently, illumination at wider angles is not as much reduced as is the central maximum part of the beam; sometimes it is even increased. The ECE high beam, with its sharper central part and less intense side illumination, changes the beam pattern more due to scattering than does the more uniform U.S. high beam.

4.5. Priority between the high and low beams and within the high beam

Lighting engineers have always had a limited amount of light at their disposal. Gradually, new light sources, giving more light per wattage, have been developed. Another line of development has been to increase the number of headlights. But at the same time the headlights have become smaller and smaller. Therefore, lighting engineers always had to make compromises.

Typically, they give first priority to the low beam pattern—partly because that is the beam that is most frequently used, partly because it is the most difficult beam to design. High beams come second for the opposite reasons—they are easier to design, and they are not used for very long periods. Therefore, the light available for high-beam design is still limited, in spite of all technical developments. Furthermore, even within the high-beam pattern, there is a choice. Should more weight be given to long-distance visibility (spot light) or to wide visibility? The U.S. philosophy seems to have been to weight wide visibility more. The ECE philosophy has been the opposite, with emphasis on long-distance visibility.

Peculiarly, the positions on low beams are almost the opposite. The reason for the ECE position could be that low beams are designed as meeting lights and therefore glare must be limited. Also, the low beam is designed for lower speeds in areas where unprotected road users appear frequently, and, therefore, wide visibility is more important.

4.6 Driver eye-fixation patterns

Another factor that influences visibility distance, in addition to illumination, is the eye-fixation pattern of the driver. In daytime driving, drivers fixate the road scene several hundred meters ahead of the vehicle, in order to be well prepared for what is going to happen. This is not possible in night driving, but it should be something to strive for. One way to improve the situation would be to offer more light in the distant area.

Olson and Sivak (1983) studied driver eye movements at night with low beams as a function of foreground brightness. They found that when foreground brightness was very bright, drivers tended to look further down the road. However, detection distances did not increase. Their interpretation was that with a very bright foreground a driver could use peripheral vision for the foreground and foveal vision for areas near the convergence point. However, here we are dealing with high beams, and it is not eye fixations on the foreground or further away that is the issue. It is how far away drivers are able to focus their attention.

Three studies support the hypothesis that with more intense high beams, drivers tend to fixate further away. Mortimer and Jorgeson (1975) studied driver eye fixations for ECE low beams and for a more intense mid beam. They found that the mid beam resulted in eye fixations being further away, and they more resembled the daytime eye fixation pattern. Graf and Krebs (1976) compared eye-fixation patterns for the standard U.S. high beam and a proposed more intense U.S. high beam. They found that drivers fixated further away with the more intense beam, and the fixation pattern was also closer to the daytime pattern. Damasky and Hosemann (1998) studied eye movements of drivers as a function of the headlamp beam pattern. They found that the more light that is directed further away from the vehicle, the higher is the probability that the driver

will fixate in that area. According to Cohen (1987), the chance of detecting obstacles increases with a reduced angle between the target and the line of vision. Consequently, the fact that drivers are looking further away should improve their visibility distances.

4.7. Intensity difference between low beams and high beams

In discussions of a harmonized low-beam light distribution, the main dispute between the U.S. and the European positions concerns the glare level of the low beam. Europeans object to the high glare levels of the U.S. low beam. The U.S. representatives argue that we have to accept some glare to achieve good visibility (Moore, 1998).

It is peculiar that in the case of high-beam glare, the positions are reversed. That seems irrational. The high-beam glaring intensity should be related to the glare level of the low beam. One argument for maintaining the current U.S. situation seems to be that a larger difference between high and low beams could lead to a reduction in the use of high beams because of the higher glare. It could be argued, on the other hand, that if the difference between high- and low-beam intensity is not large enough, then the difference in illumination is limited, and thus there is not much reason to use the high beams. The limited data we have seem to indicate that this is indeed the case.

Another argument for a less intense U.S. high beam could be that in the ideal situation (straight, flat road), the U.S. low beam with its softer vertical gradient, is more sensitive to glare than the ECE low beam with its very sharp cut-off. However, this argument has as far as we know never been studied systematically.

4.8. Range of high-beam intensities

One of the conclusions of Helmers and Rumar (1975) was that the range of high-beam intensities in real traffic should not be too large, because that would seriously prolong the dimming distances. Considering that in Sweden in the early seventies there were a large number of cars with very low high-beam peak intensity (about 10,000 cd), Helmers and Rumar suggested not to raise the high-beam intensity from 112,500 cd to 150,000 cd. The current range of intensities of high beams in the United States is not known. But most likely, the minimum has increased considerably during the last decade because of, among other things, the increased use of halogen light sources.

4.9. High-beam usage

The intensity of high beams probably affects the likelihood of their use. If the high beams offer marginally better visibility than low beams, then the motivation to use them in situations where they could be used, but perhaps only for a limited time, are weak. However, if high beams offer clearly improved visibility relative to low beams, then the motivation to switch between the two systems would be much stronger. The fact that professional drivers in the United States use high beams more frequently than private drivers (Hare and Hemion, 1968; Hemion, 1975) points in that direction.

The available data on high-beam usage in the ECE and the United States are, unfortunately, not comparable. No data have been found on the usage of high beams in Europe when conditions conducive to high-beam usage are present. However, the sparse existing data and our experience indicate that European usage of high beams is much higher than it is in the United States. According to Hoermann (1995), high beams on small curved roads are used 9% of the total driving time (day and night) in Germany. Could one of the reasons for the comparatively low usage of high beams in the United States be the considerably lower intensity of the U.S. high beams?

5. STUDIES OF HIGH-BEAM INTENSITY

Roper and Meese (1952) and Johansson et al. (1963) studied high- and low-beam visibility to dark obstacles with identical opposing headlights. Both of these older studies found that the high beams generally offered superior visibility as compared with the low beams. The intensity of the high beams used is not known, but it was certainly below 50,000 cd. (Note that the low beams used by Johansson et al. were symmetrical.)

In opposed situations, Schwab (1965) found that for some targets (e.g., road markings) the low-beam visibility was superior to the high-beam visibility, while for other targets (e.g., retroreflectors), the high-beam visibility was superior to the low-beam visibility. Again, the intensity of the high beams used was not specified.

Hemion (1968) studied visibility and discomfort from high and low beams. The results indicate that for a dark pedestrian the high-beam visibility distance was about 240 m without opposing headlights and about 75 m with opposing high beams. The analogous visibility distances for low beams were 115 m and about 75 m, respectively. Hemion (1968) also evaluated the discomfort from high and low beams. His conclusion was that the discomfort experienced when meeting a low beam is more than half of the discomfort when meeting a high beam. Note that the maximum high-beam intensity at that time was only half of what it is now.

Schwab and Hemion (1972) found, as expected, that the usage of high beams in the United States was strongly related to traffic volume. With traffic volumes above 300 vehicles per hour, only a few percent of the nighttime driving is carried out with high beams. At 200 vehicles per hour, about 10% of the driving is done with high beams. At 100 vehicles per hour, about 30% is carried out with high beams. Interestingly, approximately 39% of all unopposed driving at night in rural areas is done with high beams. From a visibility and safety point of view, this figure should, of course, be 100%. One reason for this surprisingly sparse use of high beams could be that the beam switch at that time was positioned on the floor, and it was operated by the foot, as compared to now when it is positioned at the steering wheel and much more easily operated by the hand.

Devaux (1973) studied both theoretically and practically the relation between high-beam intensity and visibility distance. His conclusion was that 300,000 cd is an appropriate maximum total value for both high beams (or 150,000 cd per headlamp). One argument was that in order to get acceptable visibility on long distances, it is necessary to reach 3 lux near 300 m. Such an illumination level requires a total intensity of near 300,000 cd. Another argument was that by increasing the total high-beam intensity from 150,000 cd to 300,000 cd, 16% is gained in visibility (at separations of 1200 to 150 m between the vehicles). Devaux studied the glare situation between two opposing cars using high beams. His conclusion was that, presuming that drivers

dim their lights at the maximum intensity they accept from low beams (1.4 lux), the optimal dimming distance would increase from 330 m at 75,000 cd to 460 m at 150,000 cd.

Hemion (1975) reports that the U.S. Department of Transportation at that time presented a proposal to increase the maximum intensity of high beams to 175,000 cd, and at the same time, to introduce a midbeam for multilane roads and to increase the low-beam intensity to 80,000 cd. According to his measurements this would increase the visibility distance on high beams without oncoming traffic by approximately 20%. Hemion reported that even when they were alone on the roads, as many as 70% of the drivers did not use high beams.

Schmidt-Clausen (1979) made a comparison between observed dimming distances and estimated discomfort glare. He found that dimming seems to take place between the discomfort values 5 and 4 on the de Boer scale. Level 5 corresponds to “just acceptable”, with 4 being slightly more glaring. The dimming distance as a function of high-beam intensity, based on discomfort level, is very long. For instance, a high-beam intensity of 200,000 cd (total per vehicle) yields dimming distances well over 1,000 m. This calculation, however, does not take into account that perceived glare depends also on one’s own high-beam intensity (and low-beam performance). Still, it underlines what was pointed out several times in this report, that drivers show a clear tendency to dim their lights too early in a meeting process—too early for visibility and safety.

NHTSA (1978) suggested increasing the maximum high-beam intensity from 75,000 cd to 150,000 cd. In their response, the Ford Motor Company (1978) presented results from simulations using the Ford Headlamp Evaluation Model. According to these simulations, the proposed increased intensity would lead to a 35% increase in visibility distance of pedestrians and 15% of road markings when driving alone. The larger visibility improvement calculated with the Ford model (as compared with the Swedish data obtained in field trials) could be explained by the fact that the Ford model includes several real-life factors, such as driver age, beam pattern changes, pavement reflection, etc. When both opposing cars have high beams, the more intense high beams would increase visibility distances by about 10% to pedestrians. However, Ford estimated the negative effects to be even greater. For the driver with the weaker high beam, the stronger opposing high beam would result in a 10 to 30% decrease in visibility distances to most targets.

Furthermore, discomfort would increase and force the opposing drivers to dim earlier (see Section 2 above). For drivers using low beams, the stronger oncoming high beam would result in a 10% decrease of visibility distance, as compared with the present opposing high-beam intensity—that is, before the opposing driver has dimmed his high beams. In conclusion, Ford stated that the advantage of increased visibility in the unopposed situation is more than offset by the increased glare in the opposed situation. Visibility conditions on roads with low traffic volume

might be improved at the price of decreased visibility on roads with traffic high volume. (However, data indicates that on high-volume roads, high beams are not used.)

Hoermann (1995) measured the proportion of time drivers were using various vehicle lights. According to this study, which covers several hundred thousand kilometers on different roads, overall high beams were used 2% of the total time and low beams 38% of the total driving time (day and night). As expected, for city driving, the proportion of high-beam driving was lower (about 0.3%), and for smaller country roads it was greater (about 9%). On motorways, high beams were used about 6% of the total time. Judging from these data, high beams seem to be more frequently used in Europe than in the United States.

Schmidt-Clausen and Bindels (1974), using the de Boer discomfort-glare index, reported that the relation between log illumination at the eyes and experienced discomfort is linear.

6. PUBLIC REACTIONS TO HIGH-BEAM INTENSITY

Flannagan (2000) reported that drivers are only moderately interested in headlight performance compared with, for example, crash performance and vehicle handling performance. The earlier mentioned results that show that a large proportion of drivers use low beams in situations where they should use high beams underline the finding that drivers rate headlight performance low among vehicle characteristics. Within the headlight variables, however, they rate high-beam visibility as secondary only to low-beam visibility and slightly before low-beam glare. Consequently, drivers are interested (relatively speaking) in high-beam performance, in spite of the fact that they do not use high beams as frequently as they should.

7. EFFORTS TO HARMONIZE HIGH-BEAM REQUIREMENTS

Moore (1998) comprehensively reviewed headlamp developments for the past 100 years. The initial acetylene high beams around 1910 could give about 5,000 cd as a maximum in a narrow beam. Electric bulbs introduced at that time had the capacity to raise the maximum to about 30,000 cd. In 1940, the U.S. maximum high-beam intensity was raised from 25,000 cd to 37,500 cd. In 1978, NHTSA raised the maximum high-beam intensity to 75,000 cd, most likely to accommodate halogen bulbs. Another reason could be the above-mentioned studies during the early seventies. The higher maximum made it possible for the headlight designers to make real use of the stronger halogen light source.

There was no internationally agreed upon maximum specified for high beams in Europe before 1971. There were certainly many national requirements, though. According to ECE Regulation 20 (1971), the maximum high-beam intensity was 150,000 cd. But when ECE Regulation 48 was introduced (1982), the maximum intensity was reduced to 112,500 cd. The reason for that reduction is not known. Since 1982, 112,500 cd has been the maximum allowed by the ECE.

CIE (The International Commission on Illumination) stated already in 1921 that lighting regulations should be framed in international agreements, so that light from automobile headlamps may be uniform for all countries (Moore, 1998). That is a very early and clear position in favor of international harmonization of automobile lighting. Unfortunately, very little has happened since then. No major effort has been made to harmonize U.S. and ECE high-beam patterns or maximum intensities before the current GTB (Groupe de Travail-Bruxelles 1952) effort that started in 1995. GTB initially gave priority to the low beam, and recently presented a draft proposal for a harmonized low-beam light distribution. A few years ago, work started on high-beam harmonization. The same working group that made the low beam proposal (Moore, 2000) is now preparing a proposal for a harmonized high beam. In the latest version (which is not yet agreed upon), the maximum intensity at 12.8 V is 140,000 cd, and the minimum intensity is 40,000 cd.

In the United States, NHTSA was petitioned by Automotive Lighting to raise the high-beam maximum value (Spingler, 1996). The petition was denied. But a new petition was again made late in 1999 (Spingler, 1999). So far no action has been taken.

NHTSA has listed several arguments against such a change in its answer to the petition (NHTSA, 1996). One argument is that the present U.S. and ECE regulations overlap, which makes it possible to make a high beam meeting both regulations. Another argument is that visibility of distant targets is not the only criterion on which to base maximum high-beam intensity. A third argument is that many of the states have legislation stating that drivers should dim their

high beams at a typical distance of 500 feet (about 150 m) between approaching vehicles (direct glare). When driving on high beams and approaching another vehicle from behind (glare via rearview mirror), the typical average dimming distance, according to state legislations, is 200 feet (about 60 m). These state regulations were initially made for the maximum high-beam intensity of 37,500 cd. According to NHTSA, these state laws would have to be changed if the intensity were to be raised to 140,000 cd, because of the increased glare and the resultant increased dimming distances, but NHTSA has no jurisdiction over state legislations. However, dimming distance depends not only on the glare from the oncoming vehicle, but also the intensity of a vehicle's own high beams. In other words, the situation is very much the same as it was in 1978 (before the high-beam intensity was raised the last time), and that worked without any changes in state laws. Furthermore, dimming distance probably should not be legislated. It is highly dependent on the specific situation. To be safe, high beams should be used as often as possible, and in some situations dimming is not even necessary (e.g., sharp depression or outside left curve).

Another argument against raising the current U.S. maximum is that the number of glare complaints that NHTSA receives from drivers is already very high. However, most of the complaints most likely concern misaimed low beams. High beams are so rarely used that they cannot raise too many complaints. Furthermore, a high beam with higher intensity might even reduce the complaints regarding low beams, because then the anchoring point for discomfort is raised.

Another counter-argument concerns the aging population. NHTSA argues quite correctly that glare sensitivity increases with increased age. However, light and contrast sensitivity also increase with increased age. One of the few studies found on this problem (Flannagan et al., 1996), showed that both young and old drivers benefit when two oncoming vehicles both have increased headlight intensity. Illumination of the road and traffic scene seems to be more important (for visibility) than reduced glare, for both young and old drivers.

In their revision of state legislations, Adler and Lunenfeld (1973) noted that the states tend to specify minimum visibility distances. They found the range to be 500 to 200 feet (about 150 to 60 m), for high beams and 100 to 200 feet (about 30 to 60 m), for the low beams. That is a surprisingly short legislative visibility distance for high beams. According to Hemion's measurements (1968), glare from opposing high beams when two vehicles approach each other increases until a separation of about 60 m. At smaller separations, glare is reduced due to the large angles involved. Notice also that the high-beam visibility minimum and the low beam visibility maximum are equivalent. The states obviously do not expect much from the high beams. But it should be pointed out that at the time of Adler and Lunenfeld's review, the U.S. maximum high-beam intensity was only 37,500 cd.

Another issue related to international harmonization has to do with whether or not low beams are on together with high beams. Therefore a new proposal is being discussed within GTB in which two different photometric tables are presented, one for high beams with low beams on, and the other for high beams without low beams. The difference between the requirements in these two conditions is in the width of the beam pattern, with the required beam being narrower when the low beam is on together with the high beam.

Also under discussion is whether the minimum requirement of the harmonized high beam (40,000 cd) is too high for headlights with two filament bulbs, and if so whether it should be reduced to 30,000 cd. Also to be determined is whether the requirement should be specified for the H-V point, and whether the 80% of the maximum should be specified at the H-V point. However, the discussion about the suggested maximum intensity (140,000 cd) in the GTB working group deals exclusively with the technical question of whether it is possible to reach that intensity with a two-filament bulb in one headlight and at the same time to have a wide high beam.

The U.S. requirements mandate a wider high beam than do the ECE requirements (See Section 4.5.). The U.S. regulation indicates minimum candela values as far out as 12 degrees right and left, both in the horizontal plane and at 2.5 degrees down. The ECE high beam, on the other hand, has no requirements outside 5 degrees, and the requirements are only in the horizontal plane. With limited total flux available, it is of course more difficult to achieve both a high central intensity and illumination at large angles than if there are no angular requirements. But with modern, efficient light sources and a normal size headlight, this should not pose any technical problem at the angles and intensities that are relevant here. A wide high-beam illumination pattern seems good for targets to the side of the road and for road markings (visual guidance), at least as long as the low beams are not left on together with the high beams. Without a wide illumination pattern there is a risk that the high beam becomes a spot beam.

Another, related, technical reason for having problems with a higher central intensity is that the priority task considered by most designers is to design a good low beam (as discussed earlier). Therefore, a large part of the reflector is used for this purpose. What remains is used for the design of the high-beam pattern. And if the headlight is small, this remaining part may not be enough to reach high intensity values, at least not at the same time as a wide beam pattern. The four-lamp system offers a solution to this problem (see the Appendix).

8. SUMMARY

This section summarizes the main studies and arguments that have been presented in the previous sections. The summary and analysis consists of three parts:

- (1) The present difference between the U.S. and ECE/Japanese high-beam maximum intensity.
- (2) Direct effects of the difference in maximum intensity.
- (3) Indirect effects of the difference in maximum intensity.

8.1. Present differences

As described in Section 2, the U.S. requirements on the one hand and the ECE and Japanese requirements on the other hand differ concerning the maximum allowed intensity in the central part of the high beam. The U.S. requirements allow a maximum intensity at H-V of 75,000 cd at 12.8 V. The corresponding ECE value, measured at the same voltage, is 140,000 cd.

Another main difference is that the U.S. high beam is wider, with requirements out to 12 degrees left and right versus 5 degrees left and right for the ECE high beam. It goes without saying that it is easier to reach a high central intensity when there are limited requirements to the sides.

Frequently, it is a matter of choice for a designer of headlamp beam patterns whether to have high central intensity or a wide high beam. For four-headlamp systems, there is an obvious solution to the dilemma. By leaving the low beam on together with the high beam, the low beam takes care of the side illumination, and the high beam may be focused on its main task—long distance visibility.

The harmonization efforts presently in progress within GTB consider proposing 140,000 cd as the maximum intensity at 12.8 V, which corresponds to the current ECE requirement.

8.2. Direct effects

“Direct effects” are effects that are immediate, possible to measure directly as a result of the high-beam intensity levels.

One direct effect is visibility without opposing headlights (without glare). Here, the results from the various studies discussed in Sections 3 and 4 are unanimous, in that they all predict visibility gains as an effect of more intense high beams. However, there is no consensus concerning the size of this positive effect. The Swedish studies (Figure 1) indicate that the

visibility gain, as a consequence of the more intense ECE high beam, should be around 5%, or 10 to 15 m improvement for dark obstacles. According to some other studies, such as Roper and Howard (1938), Devaux (1973), and Ford Motor Company (1978), including a number of more realistic conditions yields a considerably larger visibility gain—up to about 35%. Visibility to brighter, or even retroreflective obstacles, would increase by the same proportion but would be longer in absolute distance. These visibility improvements would favor a more intense high beam such as the current ECE high beam.

Another direct effect of a change in high-beam intensity is a change in discomfort (from opposing vehicles and via the rearview mirrors from vehicles approaching from behind), experienced primarily by drivers still having the older, less-intense high beam. Such discomfort reactions would probably result in a larger number of high-beam complaints, as compared with the present situation. Even now, there is a considerable number of glare complaints reaching NHTSA. Although it is unclear whether these complaints concern low beams or high beams, it is likely that a majority of the complaints concerns opposing, misaimed low beams. (A stronger high beam might even reduce the low-beam complaints because it would change the anchoring point for the subjective discomfort experience.) If there is such a negative consequence, it is likely to be gradually reduced because of two reasons. First, successively new, more intense high beams would reduce the perceived discomfort for drivers that have them. Second, discomfort is a subjective variable strongly influenced by habits, experience, and the normal situation (anchoring point). However, at least initially, this effect would favor retaining the less intense high beam in the United States.

8.3. Indirect effects

“Indirect effects” are effects that are not directly observable from the intensity difference, but which will follow from it.

One important indirect effect is the longer dimming distances due to increased discomfort and disability glare. Longer driving on low beams would normally mean shorter visibility distances. This effect would initially (before most headlights are increased to the new, higher level) be larger than it would be after a number of years when most high beams would be more intense. The important aspect here for opposing vehicles is the difference between the high beam intensities of the two oncoming vehicles, and not the absolute value.

It is difficult to estimate the difference in dimming distance. Let us assume that with the current U.S. high-beam maximum (75,000 cd) the dimming distance is 150 m (based on state legislations), and apply the inverse square law to calculate the new dimming distance for a maximum of 140,000 cd. The new estimated dimming distance would be about 210 m. If the

concept of optimal dimming distance, as used by Helmers and Rumar (1975), is used, the difference would be an increase of dimming distance from between 250 and 400 m to between 500 and 600 m. Note that, on the one hand, all these dimming distances are greater than those dimming distances legislated by the states, and, on the other hand, they are shorter than most of the dimming distances observed in real traffic.

These differences in dimming distances due to an increase in high-beam intensity would appear during a transition period, while differences between high-beam intensities in traffic are still large. The optimal dimming distance for drivers approaching from behind would also be increased during such a transition period. In the future it is probable that an effective automatic dimming system will be developed. This would also solve the educational problem concerning how to make drivers make better use of high beams in vehicle-meeting situations.

Considering the fairly long transition period, this would favor not changing the maximum high-beam intensity from its present value either in the United States or in ECE/Japan.

Another indirect effect is a change in sensitivity to degradation. Headlight degradation may be looked upon as a reduction in intensity, especially in the central part of the light distribution. If the initial high-beam intensity is low, the sensitivity to degradation is, of course, greater than if the initial intensity is higher. Such a reduction of intensity is not critical if the effect on visibility distance is marginal, but critical if there is a strong monotonic relation between intensity and visibility distance. For new, clean, and correctly aimed headlights, baseline intensities will be high enough that the effect of changes in intensity will be rather small (see Figure 1). But with degradations, the effect is likely to be stronger.

Considering that there are a large number of potentially simultaneous causes of degradation, each with a considerable effect on luminous output or on the need for luminous output, degradation seems to be a very important factor. For instance, age may reduce the visibility distance by up to 25%. Weather may reduce visibility even more. A slight haze, for instance, reduces visibility by about 20%. Headlight degradation (dirt, corrosion, cracks, voltage, misaiming, etc.) would reduce visibility by at least 30%, and probably much more.

Figure 1 shows that the degradation effects on visibility may correspond partly to a reduction of luminous output (moving to the left on the curve), but also partly to a change in the curve form (reducing the sharpness of the elbow). The reality of degradation favors a more intense high beam, such as the ECE.

Another indirect effect is more technical. If the available headlight flux for various reasons (primarily body design) is severely limited, the headlight designers have to make priorities concerning where to put the available light. Their first priority, quite rightly, is the low beam, and only then the high beam. Consequently, for the high-beam performance the available flux is then even more limited.

The next choice is between central intensity and a wider beam. For two-headlamp systems, this is not an easy choice. However, for a lighting system intended for high speeds, it seems to be more important to have long distance visibility. For four-headlamp systems, on the other hand, the solution seems simple. If the low beams are left on with the high beams, the high-beam light distribution may be focused on central intensity and leave side visibility primarily to the low-beam. This factor favors a high beam with more intensity in the central part, such as the ECE.

An important indirect effect is the eye-fixation pattern of drivers. At night, drivers tend to look towards areas that are well illuminated. Consequently, the more intense the central part of the high beam, the higher the probability that drivers will direct their visual attention farther ahead. A reasonable hypothesis is that this will extend their visibility distance. This factor would favor a more intense high beam, such as the ECE, which directs more light farther away.

On the other hand, it may be argued that a better illumination of the sides (as in the U.S. high beam) would improve visual orientation and guidance. However, Sullivan et al. (1999) have shown that the main safety handicap (in terms of crash risk) in darkness concerns visibility of obstacles (such as pedestrians) and not the visibility of the road itself.

Another important consideration is the difference in intensity between high beams and low beams. Why is the U.S. position on high-beam maximum intensity so different from the U.S. position on low-beam glare? In the beginning of a vehicle meeting situation both vehicles are (and should be) on high beams. There is no reason why Europeans, who are normally much more sensitive to glare, should be able to stand high-beam glare better than Americans, who are normally much more tolerant of glare.

From a psychological and a physiological point of view, the glare difference between low beams and high beams should not be too small and not too large. The U.S. low beam is more glaring than the ECE low beam, and the minimum intensity requirement of the U.S. high beam at H-V is generally higher. Consequently, it is illogical that the U.S. high beam has a lower maximum than the ECE high beam. It should, if anything, be allowed to be higher. A reasonably fixed and constant glare difference between high beams and low beams could also favorably affect dimming distances. According to the ECE regulations, the glare ratio between the maximum high beam and the maximum low beam (at H-V) is approximately 180:1 (140,000:775 at 12.8 V). In the United States, the corresponding ratio is more difficult to estimate because the U.S. regulations do not control the luminous intensity of low beams at H-V. However, if we use the closest glare point (0.5U, 1.5L), we will underestimate the low-beam value at H-V, and thus overestimate the ratio. Using this approach, the ratio is still only 75:1 (75,000:1,000). This consideration favors a more intense U.S. high beam.

Another indirect effect is the intensity range between the most and least intense high beams. This range should not be too large because it would increase the dimming distance unduly. Therefore, the general advice is not to raise maximum high-beam intensity too much at any given time, in order not to create too large a range. The maximum should be raised in reasonable steps and then be stable for some years. A reasonable step could be no more than twice the existing intensity. A reasonable time interval between changes could be about 20 years (roughly the upper limit of a vehicle life).

The U.S. maximum high-beam intensity was raised from 37,500 cd to 75,000 cd in 1978. It could therefore be possible to double U.S. high-beam maximum intensity today, more than 20 years later, because almost all vehicles with the lower high-beam intensity have now disappeared from the roads. It should be remembered that the more intense halogen bulb was introduced during this period. This in itself has improved low beams and increased high-beam intensities on the roads.

The ratio between the minimum high-beam intensity and the maximum high-beam intensity in the regulations is of relevance here, as was discussed in Section 8.3.1. That ratio in the United States is approximately 1:2 (40,000:75,000) for the higher minimum, and approximately 1:4 (20,000:75,000) for the lower minimum. In ECE, the corresponding ratio is about 1:5 (30,000:140,000). Considering dimming distances, this supports the U.S. situation. In fact, this argues for raising *minimum* high-beam intensity, primarily in the ECE but also in the United States.

The final indirect effect to be discussed involves the use of high beams. One problem with U.S. high beams seems to be that, to a large extent, they are not adequately used, even when drivers are alone on the road. A reasonable assumption is that the better the high beams are, the stronger will be the motivation to use them, and vice versa. It is possible, however, to assume just the opposite. If the high beam is too intense, it might be so glaring that it would be used less often. The limited available data on the usage of high beams in the United States indicates that the high beam is already used much too seldom. Consequently, this factor seems to favor a more intense high beam, such as the ECE. Another consideration is that the authorities should produce and publicize information concerning the appropriate conditions for the use of high beams.

9. NEEDS FOR FUTURE RESEARCH

In this analysis it has become obvious that some important information concerning the optimal intensity of high beams is not available. In this section, an effort is made to point out the major gaps that should be filled.

- (1) There are no data on the current use of high beams by U.S. drivers. There are some good data from the late sixties, but it is hazardous to generalize from these. Data are needed to find out average use of headlights, use of headlights as a function of road type, traffic, general illumination levels, weather conditions, and when alone on the road.
- (2) Data concerning headlight intensities in traffic are also missing. Sivak et al. (1997c and 2000) report low-beam intensities in various relevant directions for the best-selling vehicles in the United States and Europe. However, we are lacking data on high beams and on vehicles in traffic. Five recent U.S. high beams used by Sivak et al. (1997a) for another study had an average maximum intensity of about 55,000 cd.
- (3) In order to know more about how drivers use their high beams, we also need to have data on dimming distances on various types of roads. That knowledge is important, not only for designing headlights, but also for informing and educating drivers to improve their usage of high beams.
- (4) There are two schools of thought concerning the way available light is used in high beams. ECE gives priority to long-distance visibility. In the United States, priority is given to wide visibility. While far visibility is likely to be more important for safety, we do not have any data.
- (5) We are lacking data on the usage of two- and four-headlamp systems in the United States as well as in other areas (see Appendix). We do not know the proportions of vehicles in traffic with the two types of headlight system, and we do not know how the systems are functioning relative to high and low beams.
- (6) A mid-beam was discussed and tested in the seventies both in the United States and in Europe. Now, when the high beams are more intense and the traffic volumes have increased substantially, it seems reasonable to raise the feasibility of a mid-beam again. It is possible that a mid-beam would constitute a visibility and safety improvement, and be a suitable first step towards a multi-beam system.
- (7) Data on driver eye-fixation patterns in night driving are somewhat conflicting concerning low-beam driving. Available data on the fixation patterns in high-beam driving are old and sometimes difficult to interpret. Such information is important not only for headlight designers, but also for educational purposes. Aftereffects of glare on detection time, when

subjects have been looking into the headlights of oncoming vehicles or into the image of beams in their rear-view-mirrors, should be studied more systematically.

- (8) Automatic headlamp dimming has been proposed and used earlier with questionable results (Rumar, 1997). With new sensors and microcomputer systems, it might be worth exploring this concept again, especially because drivers do not seem to use their high beams enough to optimally enhance their safety. (Neither this topic, nor the next one, is directly relevant to high-beam intensity.)
- (9) A Japanese study (JARI, 1988) suggests that filament rise time of the low beam creates some (small) visibility problems in connection with dimming of the high beams and switching on the low beams. To our knowledge, this problem has neither been suggested nor studied before.

10. CONCLUSIONS

The summary in Section 8 presents nine factors relevant to the choice of maximum high-beam intensity. The picture that emerges from the analysis is not completely clear. The evaluation of each of the relative merits of the U.S. and the ECE high-beam maxima is sometimes difficult due to a lack of data. The weighting of the various merits against each other is even more complicated. Consequently, additional relevant data are needed (see Section 9).

One critical issue is the extent to which the relation between visibility distance and high-beam intensity, as illustrated in Figure 1, is valid for real traffic conditions. As has been argued above, we have reasons to believe that in actual traffic the curve is both moved to the right (less visibility for any intensity level) and is changed in form to be more linear (with a less pronounced elbow). The main reasons for such expected changes are the various factors of degradation, always more or less present in real traffic, and the results from other studies presenting larger gains and a more linear relation.

Another question is the obvious discrepancy between optimal dimming distances and dimming distances in real traffic. In reality, dimming takes place at distances between oncoming vehicles that are far too great for safety. It seems as though drivers often dim their high beams as soon as they see each other, and not when they get seriously glared. The glare levels and dimming distances discussed here are primarily based on carefully controlled visibility experiments. We do not know to what extent such data would be valid also for the behavior of drivers in traffic. Probably the predicted absolute visibility distances are too long (see the previous paragraph). However, the direction of the changes, and the relative differences presented here would most likely apply in real traffic as well.

Table 2 summarizes the evaluation of the comparisons between U.S. and ECE high-beam intensities. Note that each system is evaluated relative to its current status, not in direct comparison with the other system. For instance, concerning glare, the action suggested for both the United States and ECE/Japan is to keep the present level, in spite of the intensity difference. This is because each system has to be evaluated in its present situation, with the range of high-beam intensities occurring in the respective traffic.

Table 2
A summary of the analysis concerning the maximum intensity of high beams in the U.S. and ECE/Japanese regulations.

Factor	Weight	United States		ECE/Japan	
		Keep the current level	Increase to the current ECE level	Decrease to the current U.S. level	Keep the current level
Unopposed visibility	Very important		√		√
Susceptibility to degradation	Very important		√		√
Glare	Important	√			√
Dimming distances	Important	√			√
Beam pattern quality	Important		√		√
Intensity range between high and low beams	Important		√		√
Intensity range within high beams	Relevant	√			√
Driver eye fixations	Relevant		√		√
Usage	Relevant		√		√
Overall			√		√

The three factors that support keeping the present U.S. high-beam intensity (glare, dimming distance, and high-beam range), will most probably be present primarily during a transition period until the old, less intense high beams have disappeared.

The primary goal of this study was to evaluate the relative benefits of the current U.S. and ECE/Japanese high-beam *maxima*. But in the analysis of this problem it has become evident that the *minimum* allowed high-beam intensity is at least as important for visibility and safety. Figure 1 illustrates the strong relation between high-beam intensity and visibility at intensity levels close to the current minima (between 20,000 and 40,000 cd). The current minima are in a range in which increases, say to 50,000 cd, would have substantial effects on driver visibility.

Another argument for raising the minimum high-beam intensity is that it would reduce the range of high-beam intensities in traffic. It has been argued repeatedly that limiting this range would be desirable with respect to dimming distance. Therefore, it is not good to have two different minima depending on the bulb used (20,000 and 40,000 cd) as in the U.S. regulations. A third argument is that a higher minimum will widen the gap between low-beam intensities and high-beam intensities, thereby possibly stimulating more frequent use of high beams. Raising the minimum allowed high-beam intensity in the United States would constitute another argument for raising the maximum because, although the window between minimum and maximum intensity should be limited, it should not be too narrow either.

Most of the factors based on empirical studies, and analytical arguments, favor a more intense high-beam maximum intensity, such as the present ECE/Japanese level (as illustrated in Table 1). It is therefore recommended that the maximum high-beam intensity in United States be increased from 75,000 cd to 140,000 cd (at 12.8 V).

11. APPENDIX: RELATIVE MERITS OF TWO- AND FOUR-HEADLAMP SYSTEMS

11.1. Introduction

From the early years of 1900 until the late 1950s, almost all cars had two separate headlamps (one on each side). Then the four-lamp system was introduced (two on each side). Typically, a four-lamp system has four separate headlamps, two for the low beam and two for the high beam.

In the past few years, the definition of two- and four-lamp systems has become less straightforward. In many modern headlamp systems with two headlamp assemblies, each assembly contains two (or more) reflectors and two (or more) bulbs. According to the NHTSA classification, these are still two-lamp systems. However, their characteristics and performance corresponds closely to the traditional four-lamp systems, and they are treated as such in the discussion to follow. (The main functional difference is that in most of such systems, aiming of the separate reflectors cannot be made independently.)

The main argument for a four-lamp system is that separate headlamps can be designed and optimized for each of the two beams. A number of compromises between the two beams which would otherwise be necessary are thereby eliminated from the optical design task. In this brief discussion, we will consider only the illumination performance of the two systems; nonillumination issues (such as design freedom) will not be considered.

11.2. Factors differing between the two systems

When the four-lamp system was first introduced, the headlamps were smaller and were often placed lower than in the traditional two-lamp system. These changes could result in disadvantages, especially for low-beam performance. For each headlamp type, a larger reflector (if fully used) offers a higher luminous output and a better-controlled beam pattern. Furthermore, a lower mounting height reduces the reach of the low beam, because the low beam is angled slightly down. However, these two advantages for the two-lamp system have by now almost disappeared, because headlamps in the two-lamp systems are now as small and placed as low as the headlamps in the four-lamp systems. In the ECE four-lamp system, however, the whole reflector could be used for the low beam, unlike with the two-filament, shielded bulb (e.g., H4) which uses only slightly more than half of it. That meant that in the ECE headlamp size could be reduced and low beam performance could be increased.

The characteristics of a beam pattern depend on many factors (e.g., type of optical system, type of bulb, position of filament, form of reflector, form of prisms, aiming of headlamp, etc.). In a four-lamp system all these factors can be addressed individually to improve each beam pattern. In a two-lamp system, a number of compromises have to be made in order not to destroy the beam pattern of the other beam. Normally, the low-beam illumination pattern is given priority in this compromise. In other words, it is normally the high beam that suffers from the compromises in a two-lamp system. Consequently, the high beam is the primary beneficiary in the four-lamp system. As indicated in Section 4.2.1, JARI (1988) pointed out that the rise time of the low-beam filaments could be a negative visibility factor. If so, four-lamp systems that leave the low beam on with the high beam also improve the low beam by eliminating that issue.

A specific use of the four-lamp system is mentioned in Section 8.3.3. The low beam may solve the dilemma of whether to use the light available for the high beam to reach far or to offer a wide beam. The four-lamp system makes it possible to have the low beam on together with the high beam. That way, the low beam can cover the foreground for the high beam, and the high beam can be designed specifically to offer good distant illumination. The only problem with this solution is that caution must be taken not to make the foreground illumination too strong.

Table 3 summarizes the evaluations carried out on the aspects mentioned above.

Table 3
Summary of the relative advantages of the two- and four-lamp systems. √ indicates the system that offers the better solution for that aspect.

Aspect	Two lamps	Four lamps
Reflector		√
Bulb type		√
Filament position		√
Headlamp size	√	
Design of prisms		√
Aiming of headlamp		√*
Rise time of low beam filaments		√
Costs	√	
Low-beam performance		√
High-beam performance		√
Overall		√

*Does not apply to systems with multiple bulbs and reflectors within the same cavity (see p. 37).

11.3. Usage of the two systems

The only empirical data found on usage of four-lamp systems were presented by Hare and Hemion (1968). They observed about 50,000 vehicles on U.S. roads. According to their results, 67% of the vehicles at that time had four headlamps. Of the trucks, 15% had four headlamps and of the passenger vehicles, 79%. Presently in the United States, about half of the passenger vehicles are believed to have four-lamp systems. The proportion seems to be decreasing. In Europe, the current proportion of four-lamp systems is probably higher than in the United States and it appears to be increasing. The Japanese situation is probably somewhere in between the U.S. and the ECE. Because of the higher cost of four-lamp systems, more expensive vehicles are more likely to have four-lamp systems.

Automobile manufacturers have used the four-lamp system in one of three main categories:

- (A) Two lamps exclusively for the low beams and two different lamps exclusively for the high beams.
- (B) Two lamps for the low beams and all four lamps for the high beams; the “low-beam” lamps use the same filament in both cases. (The low-beam lamps are supporting the high beams with additional foreground illumination and spread.)
- (C) Two lamps for the low beams and all four lamps for the high beams; the “low-beam” lamps use different filaments depending on whether they are used for the low beams or high beams.

In the United States, Category C was initially the only four-lamp system, and it still exists on older vehicles. Next to be developed was Category A, which still exists on many vehicles. But now the trend is towards Category B, which is the most common four-lamp system, and this trend is increasing. In Europe, Category B dominates and is increasing, while both Category A and Category C are not frequent. Category C, however, is increasing. The situation in Japan is not known.

The rules for positioning the headlamps in a four-lamp system differ between the United States and Europe. In the ECE there is no limitation vertically and horizontally concerning where the low beam headlamp may be positioned in relation to the high-beam headlamp. In the United States, on the other hand, the low beam headlamp must be the most outboard and highest-mounted lamp.

11.4. Discussion

Both the two- and the four-lamp systems have their advantages and disadvantages. However, the advantages of the four-lamp system appear to be considerably greater than its disadvantages. The only disadvantages related to performance are smaller headlamp size and initially lower mounting height. However, current trends in two-lamp systems are also for smaller and lower-mounted lamps. Consequently, differences in both of these aspects are gradually disappearing.

In all other aspects (except cost) the four-lamp system is superior. It provides much more freedom to the headlamp designer to come up with an optically good product. The four-lamp system especially improves the high-beam performance, without decreasing the low-beam performance. But in the ECE low beam performance is also improved in a four-lamp system (by use of the whole reflector).

The four-lamp system was discussed here as if it was a final system. However, the four-lamp system is probably only a step on the way from the two-lamp system to a multi-lamp system. Several adaptive lighting systems currently being considered include a number of sublamps with different beam patterns. Each combination of sublamps delivers a different total beam pattern. Each beam pattern is designed for a specific purpose, such as for curves, rain, city, expressway, etc.

Such a development seems logical and probable. The four-lamp system, therefore, is not the end of a development but the start of one. It could be the same type of development that Churchill described when he addressed the people of Britain after the planned German invasion was fought off (the Battle of Britain). Churchill said, "This is not the end, this is not even the beginning of the end, this is only the end of the beginning."

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