This report reviews the night visibility needs of motorists and relates them to illumination levels provided by headlamps. It is recognized that low beam headlamps (whether U.S. or European) do not provide adequate illumination for safe operation at higher speeds. However, there is no complete solution to this problem available at the present.

A modification to the U.S. low beam (as described in FMVSS 108) is suggested, which will increase visibility distance in the right-forward field by 10-20%. This will also increase glare for some persons and under some conditions. The glare problem is felt to be manageable, however, and it is recommended that the concept be explored further.
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INTRODUCTION

Headlamps for automobiles have evolved over a long period of time. For U.S. lamps, the most important development took place in the latter 1930's, culminating in the introduction of the sealed beam in 1939. Work since then has largely been aimed at refining the concept.

Objective testing (generally in the form of seeing distance tests using low reflectance targets placed on the edge of the lane) has long been a part of headlamp development. But much of the work, perhaps most of it, has been based on subjective analysis. Given the complexity of the headlighting problem, e.g., multiple criteria, different situations, and measures which are difficult if not impossible to quantify, this is not a bad way to proceed. The main problem is that there are no agreed upon criteria by means of which one can develop a "optimum" headlighting system. This situation is not likely to change.

The purpose of the program which HSRI is currently carrying out for NHTSA is to review all materials relevant to vehicle headlighting and make recommendations for modifications to the present low beam which will result in improved performance.

Given the nature of most of the "research" on which present day headlamps are based, this project represents a formidable (perhaps presumptuous) undertaking. In this paper the authors will present a systematic overview of the approach which has been taken in reviewing the available information and working toward a recommendation.

APPROACH

A basic reference tool in headlamp design is the H-V diagram, where the horizontal and vertical axes correspond to planes passing through the center of the headlamp. The H plane is parallel to the road surface
and coincides with the horizon at infinite distance. The $V$ plane is perpendicular to the road surface and corresponds to the road center at infinite distance.

Figure 1 shows a H-V diagram superimposed over a picture of a flat, straight roadway segment. While it is recognized that not many of the world's roadways are perfectly flat or straight, this is a better approximation of a typical roadway environment than any other single configuration. As a basis for headlamp design it is a good starting point. However, it is necessary that the designer bear in mind that other roadway configurations exist in plentiful supply.

It will be noted that the $V$ axis is marked with distances (in feet) corresponding to points on the road surface ahead of the lamp (assuming a mounting height of about 30 inches [76 cm]). A dashed line appears in the upper left quadrant, which corresponds to the trajectory of the eyes of an approaching driver (assumed eye height about 42 inches [107 cm]). This is also marked with distances. Only one headlamp is shown in the diagram, this being located in the center of the right hand lane.

In considering beam distributions it is convenient to talk about different parts of the roadway environment as though they were completely separate entities. To some extent they are. However, there is considerable interaction, for two reasons:

First, due to changes in roadway alignment or a host of factors affecting lamp aim, illumination intended for one area will end up in another at least for brief periods of time.

Second, there are limits to what can be accomplished with hardware. Thus, changes in intensity intended for one area will inevitably alter illuminance directed to surrounding areas as well.
Figure 1. H-V diagram superimposed on road scene. Distances on V axis and eye trajectory are in feet.
In the discussion which follows, various areas of the forward field will largely be dealt with individually. Interactive effects will be discussed where appropriate.

There is no generally accepted way of dividing the forward field for purposes of discussing headlamp beams. Many persons refer to the foreground and the upper left and right quadrants as being significantly different areas. That practice shall be followed in this report, except that we shall also describe a "zone of critical seeing," which is an area extending from the left to the right portion of the figure, parallel to the H axis, and extending down about 1 1/2 degrees. This is the zone within which critical objects must be detected and identified if the driver of the vehicle is to deal with them effectively.

**FOREGROUND AREA**

For purposes of this report the foreground will be defined as that portion of Figure 1 which is shown outside the hatched area in Figure 2. It contains one test point from FMVSS 108 as follows:

4D - 4R 12,500 cd max

**Visual Needs**

There is some debate concerning the value of illumination in the foreground area. In the opinion of the authors of this report, foreground illumination is important for at least two reasons. First, there is evidence (e.g., Rockwell, et al., 1977) that peripheral vision is an aid to lateral station-keeping. That is, being able to detect the lane edges close to the car peripherally is a useful cue to basic vehicle control.
Figure 2. Foreground zone.
Foreground illumination is also helpful (under slow driving conditions) in avoiding obstacles such as chuck holes and road debris.

Reference is sometimes made to the need for "continuity" in illumination in the forward field. This is particularly difficult to evaluate, and may simply reflect a preference for that to which we have become accustomed.

Illumination Levels

The SAE low beam was designed to provide levels of foreground illumination minimally adequate for the needs described above. This was, apparently, based on an assumption that higher levels would reduce far visibility.

The testing on which the present minimum levels are based was entirely subjective. In the opinion of the authors, the foreground illumination provided by the SAE low beam does represent a barely adequate minimum. Significant reductions in foreground illumination below that represented by the present SAE low beam would not be wise.

The question then becomes, is there a desirable maximum level of foreground illumination? Obviously, the persons involved in the design of the SAE beam thought so. However, no documentation seems to be available.

The ECE beam pattern provides a much higher level of foreground illumination than the SAE. Among criticisms which have been directed toward it are that its high luminance foreground alters the dark adaptation level of the driver, making it more difficult for him/her to detect low contrast objects in the far field. Only one study seems to have been carried out investigating this problem specifically (Huculak, 1978). The results indicated that there was no significant difference
in terms of target detection distance with different levels of foreground illumination up to that provided by ECE units.

It has also been suggested that high levels of foreground illumination tend to draw the eye of the driver away from far field areas where attention should be directed. Research on this problem is scheduled to be undertaken as part of the current NHTSA funded project. Data are not available, however, as of this writing.

PERIPHERAL FOREGROUND

The peripheral foreground area constitutes those portions of Figure 1 which are outside the hatched area in Figure 3. This includes two test points as follows:

2D - 15 L and 15 R 700 cd min

Visual Needs

Illumination in these areas can be helpful in locating driveways, and making low-speed turns. It may also be beneficial in driving at higher speeds on winding roads.

Illumination levels

An effort was made to set illumination levels in the periphery based on performance on winding mountain roads (i.e., Helander, et al., 1979). Unfortunately, the results of this study provide no clear evidence to aid lamps design. In the absence of positive information, no recommendations can be made regarding illumination levels.

UPPER LEFT QUADRANT

The upper left quadrant is that portion of Figure 1 outside the hatched area in Figure 4. It includes three test points as follows:

7
Figure 3. Peripheral foreground zone.
<table>
<thead>
<tr>
<th>Illumination Level</th>
<th>Luminance (cd max)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 U to 90 U</td>
<td>125 cd max</td>
</tr>
<tr>
<td>1 U - 1 1/2 L to L</td>
<td>700 cd max</td>
</tr>
<tr>
<td>1/2 U - 1 1/2 L to L</td>
<td>1000 cd max</td>
</tr>
</tbody>
</table>

**Visual Needs**

There are at least two considerations which indicate a need for illumination in this quadrant. First, the roadway often curves into this area and an ability to see where the road is going and what is on it can be essential from the point-of-view of driver comfort and safety. Second, some traffic signs appear in this quadrant, particularly close to the V axis. These overhead guide signs provide important information about routing.

The manual of Uniform Traffic Control Devices requires that all freeway guide signs be either illuminated or fully reflectorized. Signing practices in the United States vary from state to state. However, with the growing cost of energy, many traffic engineering agencies are looking into the possibility of dispensing with illumination and relying on reflectorization. Since reflectorized signs derive their luminance from the headlamps of an approaching vehicle, some illumination must be directed toward them. Reducing illumination in this area reduces the target value of the sign and its legibility as well.

Some gains may be had through the use of more efficient retroreflective materials and/or more frequent replacement of material. However, traffic engineering agencies have the same problems as virtually all other government units, in that they have more problems than funds to solve them. Hence, it can be anticipated that many signs will have lower levels of reflectivity than is desirable.
Figure 4. Upper left quadrant.
Illumination Levels

The trade-off between glare effects (both discomfort and disability) and visibility is nowhere more critical than in this quadrant. The design philosophy behind the ECE low beam has been to emphasize glare protection. Given that some illumination is desirable, the key question is whether levels could be increased above that provided by the ECE standards.

In terms of discomfort glare, the experience of countries which use the SAE system seems to indicate clearly that higher glare levels than provided by ECE units can be tolerated.

In terms of disability glare, it is helpful to look at test results such as those shown in Figure 5. These are based on field seeing-distance tests (Mortimer and Olson, 1974). For purposes of this discussion, consider only the U.S. (SAE) and ECE low labels (X and \( \Phi \) respectively). For targets on the left side of the lane, no-glare performance was virtually identical, and the ECE unit was better under maximum glare conditions. For targets on the right side of the lane, the SAE beam was slightly better under no and low glare and about the same under maximum glare. In all cases, differences, where they occur at all, are small. It would appear from these data that there is no obvious penalty in terms of disability glare for the improved visibility into the upper left quadrant provided by the SAE beam pattern. (Note: there have been many other studies comparing SAE and ECE beams. These have been recently reviewed by Olson [1977]. The results differ, from one to another, to a considerable extent. However, the most usual finding is of small differences, such as reported above.)
Figure 5. Mean visibility distances obtained with five lighting systems and two target positions.
Whether glare could be significantly increased above the present SAE levels, and, if so to what extent, is a question which is more difficult to answer. In the absence of more definitive information, the authors feel that it would be desirable that illumination projected into the upper left quadrant not exceed that which is presently provided by the SAE low beam.

**UPPER RIGHT QUADRANT**

The upper right hand quadrant is that portion of Figure 1 which is outside the hatched area in Figure 6.

Two test points are in this area. These are as follows:

- $1\ 1/2\ U - 1R\ to\ R$  
  1400 cd max
- $1/2\ U - 1R\ to\ 3R$  
  2900 cd max

**Visual Needs**

In this quadrant appear not only portions of overhead guide signs but also all ground mount guide signs and almost all of the very important regulatory and warning signs. Post mounted delineators also appear in this quadrant.

**Illumination Levels**

The adequate detection and identification of traffic control devices is an important aspect of vehicle control at night. Illumination directed into this quadrant ought to be adequate to fulfill this important function. Sign reflectivity levels and delineators have been designed, at least to some extent, with present levels of illumination in mind. Therefore, the illumination directed into this quadrant by the present SAE low beam should be regarded as a minimum.
Figure 6. Upper right quadrant.
Increasing illumination in this quadrant would assist in the detection, identification and legibility of the devices described earlier, especially by older drivers. This would create glare problems for some persons under some conditions. The problems are very similar to those described in the following section, and will be discussed there.

**ZONE OF CRITICAL SEEING**

The zone of critical seeing is that portion of Figure 1 outside the hatched area in Figure 7. It includes five test points as follows:

<table>
<thead>
<tr>
<th>Test Point</th>
<th>Illumination Levels</th>
</tr>
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<tbody>
<tr>
<td>1/2 D - 1 1/2 L to L</td>
<td>2,500 cd max</td>
</tr>
<tr>
<td>1/2 D - 1 1/2 R</td>
<td>20,000 cd max</td>
</tr>
<tr>
<td>1 D - 6 L</td>
<td>8,000 cd min</td>
</tr>
<tr>
<td>1 1/2 D - 2 R</td>
<td>750 cd min</td>
</tr>
<tr>
<td>1 1/2 D - 9 L and 9 R</td>
<td>15,000 cd min</td>
</tr>
</tbody>
</table>

**Visual Needs**

As noted earlier in this report, this is the zone within which critical targets must be detected and identified if the driver is to deal with them effectively under various driving conditions. The "targets" include pedestrians and animals as well as inanimate objects such as holes and road debris. It should be noted that many of these objects have a low probability of occurrence, which makes their detection more difficult.

Important lane delineation also occurs in this zone.

**Illumination Levels**

Since the zone extends completely across the field shown in Figure 7, it is first necessary to ask whether all portions of it are of equal importance.
Figure 7. Zone of critical seeing.
When considering mobile targets moving across the vehicle's path, whether they are coming from the right or left side of the picture is probably of no consequence. However, mobile targets moving parallel to the vehicle's path, and fixed targets are only of concern if they are in or near the vehicle's lane. Therefore, a reasonable weighting scheme would most favor illumination at and just to the right of the V axis in this zone.

It seems clear that the present-day low beam, whether SAE or ECE, does not provide adequate illumination for driving at or near the national speed limit. That is, low contrast targets cannot be reliably detected and identified within a safe maneuvering or stopping distance by drivers who are reasonably alert and prudent. This problem can be aided by increased illumination in that portion of the zone of critical seeing directly ahead of the driver.

If there is a visibility need and increased illumination is a potential solution, the question now becomes one of who will be adversely affected by increased illumination, and under what circumstances?

In turns out that the zone contains a number of people. The very pedestrians, bicyclists, etc. we are interested in seeing are there, as well as the drivers of crossing or merging vehicles. However, there is no reason why these persons should feel compelled to look at the headlamps of an approaching vehicle, if they find that experience unpleasant.

The eyes of oncoming drivers will, on occasion, appear in this zone. However, if the intensified zone is narrow enough, the experience will be relatively brief. Perhaps of greater concern are the effects of
system misaim and the inevitable increases in illumination projected to surrounding areas when increasing illumination in one area. The aim issue has been considered and will be discussed later. The matter of scatter illumination in areas where it is not necessarily wanted is currently under analysis.

One group who will suffer from the effects of increased intensity for fairly long periods of time, with limited opportunity to escape, is drivers of lead vehicles.

Although the problem of discomfort and disability glare from rearview mirrors has often been mentioned, virtually no research has been reported. Therefore, as part of this program, four studies were carried out to look at various aspects of the problem. These will be described in a report to be published later. The data indicate that rearview mirror glare is a problem under some conditions even at today's illumination levels. Obviously, increases in illumination can only make the problem worse.

In the case of rearview mirror glare, it seems to the authors of this report that there are solutions. The solutions lie in the direction of better mirror systems, and we recommend further work in this area, concentrating on the question of reflectivity levels.

POTENTIAL BEAM MODIFICATIONS

The material presented in this report indicates that: (1) improvements in low beam performance are desirable, and (2) a promising means to improvement lies in substantial increases in beam intensity near the H axis and just to the right of the V axis.

The beam modifications just described are precisely those utilized in so-called mid-beam systems. Tests have shown that, by using a sharp
cutoff beam of fairly high intensity (e.g., 60,000 cd), aimed along the right edge of the road, it is possible to match the seeing distance performance of high beams for right side objects, yet produce no more glare for oncoming drivers than the standard low beam (e.g., Schmidt-Clausen, 1976). This is not to suggest that a mid-beam could be used in place of a low beam under all conditions. However, the general concept, with reduced intensity, approximates the beam modifications thought appropriate.

The beam development work carried on by HSRI has used a rather conventional mid-beam (see iso-candela diagram in Figure 8), combined with a standard SAE low beam. Using our computer seeing-distance model (Mortimer and Becker, 1973), it is possible to adjust the mid-beam intensity to any level desired. In a long series of tests, beam intensity, aim, target location, lamp mounting height and driver eye height were systematically varied. The results indicate that the supplementary beam at 25% of design level (i.e., 15,000 cd max rather than 60,000) yielded a 15-20% increase in the visibility distance of right side targets, yet seemed acceptable in terms of glare. The system is relatively tolerant of vertical misaim, which is an important benefit since vertical aim is most affected by transient conditions such as fuel, passenger load, and acceleration. It is this concept the authors will recommend for field evaluation in Phase II of the program.
Figure 8. Iso-candela diagram of mid-beam system used in test.
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Rockwell, T.H., Balasubramanian, K.N., Kretovics, T. and Wilfong, E.J. The utility of peripheral vision to motor vehicle drivers. Department of Industrial and Systems Engineering, Ohio State University, Report No. 784244, August 1, 1977.