two times brighter than presently recommended by the Institute of Transportation Engineers to enable the elderly driver to perform as well as a 20-29 year old driver, the associated difference in performance between the young and elderly drivers is not great enough to warrant increased signal luminance.

The laboratory study of the intensity needs of color-vision-deficient drivers, including protanopes (red deficient), deuteranopes (green deficient), and anomalous protanopes and anomalous deuteranopes (red-green confusers), utilized a signal simulator to present test subjects with all combinations of four signal intensity levels, three chromaticity variations of each signal plus one white stimuli, three levels of nighttime background complexity, and four positions of the stimulus within the field of view. The dependent variables were 1) the time required to indicate the color (either red, yellow, green or white) of the stimulus, and 2) the accuracy of the color identification. It was found that the protan class color-vision-deficient drivers required 40-70 percent more time than normal drivers to make a color choice while the deutan class and elderly drivers required 30-40 percent more time. The absolute magnitude of this difference was approximately one half second. Red color-vision-deficient drivers correctly identified the red stimulus color an average of 20-35 percent less often and the green stimulus color 15-75 percent less often than normal drivers. Green color-vision-deficient drivers failed to correctly identify the red signal color in fewer than 10 percent of trials and were incorrect in 15-25 percent of green stimulus trials. Elderly drivers correctly named the stimulus color about as often as normal drivers. Significantly, it was found that the performance of the protan class drivers improved as signal intensity was reduced.

A controlled field study that utilized full-scale 8 in. (200 mm) and 12 in. (300 mm) traffic signals was conducted to further evaluate the effects of reduced signal luminance. Response time and accuracy of color identification were again the dependent variables, while intensity (3 levels: 100%, 30% and 10%), signal size (2 levels) and background complexity (3 levels) were independently varied. Each subject was required to perform an auxiliary task (track a moving target with the steering wheel) while the signal trials were taking place. The findings indicated that reduced signal luminance had no significant effect on the accuracy of response for normal drivers of all ages and for deutan class drivers. For protan class drivers, response accuracy improved at the two lowest levels of signal intensity. Reaction time was found to increase as signal luminance decreased, but in general, there was not a significant difference in response time between the highest and medium intensity levels. It was suggested that signals could be dimmed at night to about 30 percent of the luminance recommended for daytime operation without negative impacts.

An additional controlled field study using observers who were experts in traffic signal systems or visibility research found that within urban settings, dimming of 12 in. (300 mm) signals can commence when the sky darkens to 50-80 ftL (170-270 cd/m^2), and may be dimmed to 30% of full luminance when the sky darkens to 20-30 ftL (70-100 cd/m^2). Urban 8 in. (200 mm) signals can begin to dim at 30-90 ftL (100-300 cd/m^2) until dimmed to 30% at 3-25 ftL (10-85 cd/m^2). Rural 12 in. signals may commence dimming at 170-370 ftL (580-1260 cd/m^2) until dimmed to 30% at 30-70 ftL (100-240 cd/m^2). Rural green and yellow 8 in. signals may commence dimming at 150-450 ftL (510-1530 cd/m^2) and be dimmed to 30% at 50-120 ftL (170-410 cd/m^2). The red rural 8 in. signal was deemed not sufficiently bright when dimmed to 30%.

In the observational field study, traffic operations were measured at six intersections that represented a range of site types at which signal dimming would be just marginally recommended. Three luminance levels (100%, 65% and 30% of the daytime recommendation) were tested. Measures of effectiveness were start-up delay and the frequencies of undesirable maneuvers including red interval violations, yellow interval entries, stop line encroachments, sudden rapid acceleration/deceleration, accident avoidance maneuvers and others. Preliminary analysis of approximately 6,000 observed vehicles indicated that drivers are no more likely to execute undesirable maneuvers at dimmed signals than at undimmed signals, and that in some cases, there may be a slight (0.4 seconds) increase in initial vehicle start-up delay at the dimmest signal setting, although the finding was not highly significant statistically.

Economic analysis has indicated that the use of proper dimming equipment at night combined with good maintenance of signal equipment can reduce energy consumption from 20 to 30 percent while also extending lamp life, thus reducing the cost of relamping.

VISIBILITY THRESHOLDS IN NIGHT DRIVING CONDITIONS

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In night driving conditions, more than during daytime, road users have to detect and perceive a certain number of signaling devices which are supposed to help them in their choice of path and routing.

Physical properties of these signals in terms of luminance and contrast are evidently of prime importance. But these physical values make sense only when evaluated in relation with the various possible functions of the signal, taking into account the variability of real world conditions in which it is encountered by road users.

Basic data (Blackwell's curves, for example) can and must be used as a starting point but may have to be validated in specific experimental conditions when practical questions have to be answered.

Several experiments have been performed with groups of human observers, in which various practical requirements have been incorporated.

Experiment I

A study of Reflectorized Raised Pavement Markers (RRPM) has been made on a closed road circuit. Observers (48) moved in a vehicle starting from 500 meters from the RRPM. These were positioned at the end of a track and their number was varied. Observers had to report, as soon as possible, when they saw them.

The markers were illuminated by the car's headlamps under various conditions: high or low beams, wet or dry pavement, with or without an opposing car with low beams (when observer's car was in low beams). Visibility distances are determined as a function of the coefficient of luminous intensity (R) which is measured with the usual procedure.

Results indicate that under the worst conditions (low beams, opposing vehicle and wet pavement) a value of 50 mcd/lx for R is necessary for detecting the markers at an average distance of 150 meters. If the value for R is double (100 mcd/lx) this visibility distance increases by 20 meters only.

So it was recommended to adopt the R value permitting detection at 150 meters, this distance being considered sufficient. However, it must be noted that brand new markers were tested and that, in fact, as their qualities degrade with time, these visibility distances may not be attained in real conditions.

Experiment II

Visibility distances of delineators were studied on a track. To ensure a good precision, delineators were simulated with controlled equivalent light sources. Luminance values (L) ranged from 0.125 to 2 cd/m^2 according to a logarithmic scale. Delineators were positioned along the track, 40 meters apart and for each value of L the observers had to report the number of delineators seen. This number gave the maximum distance of visibility for each L. Observers were in a car with low beams and in half the situations there was an opposing car with low beams also.

It was found that for a delineator to be detected at 150 meters with 100% probability in the worst condition, its luminance must be about 1 cd/m^2. This means that if it is illuminated by a car with low beams giving an average illuminance of 0.044 lx, its coefficient of luminous intensity has to have a value of 230 mcd/lx. Comparing this value with that of 1,500 mcd/lx now required for acceptance, it appears that this material presents an important margin of safety which permits an 85% decrease in quality due to age and dirt without losing its usefulness. These results permit defining the frequency at which the delineators have to be cleaned.

Experiment III

The aim was to evaluate visibility distances of road signs according to the use of various retroreflective materials. For experimental convenience the experiment was conducted indoors, the road sign dimensions being reduced by a factor of 10. Observers had to perceive either Landolt rings or town names and letters.

Background of the road signs was either white, green or blue and symbols were white or black in various arrangements, according to French regulations. Symbols had an apparent angle of about 8, 6 or 4 minutes of angle for the observers. Ambient lighting simulated rural or urban conditions. Observers (46) had to record on a sheet of paper what they could read. Background luminance varied for road signs with a white background between 0.1 and 5 cd/m^2.

For each kind of message a curve has been obtained relating rate of perception (expressed as a percentage) and background luminance. For example, for six-letter words (black letters on white background) having 8' angle apparent dimension, in a rural ambience, results are:

0.24 cd/m^2 give a detection of 50%
0.88 cd/m^2 give a detection of 80%
3.24 cd/m^2 give a detection of 95%

Results with Landolt rings are similar to what could be obtained by calculation from Blackwell's curves. These results will enable defining conditions for use of retroreflective materials (class I or II) in various conditions: urban, rural, overhead signs, etc.

Conclusions

These results may suggest some questions which do not concern so much the threshold values themselves but their meaning relative to real night-driving situations.

First, independently of the fact that a threshold can be defined with different procedures and calculations, one can ask on what criteria should a decision be based for use. When is it safe or sufficient to consider classically 50% as a threshold and when should one try to attain 100% performance? It should not be overlooked that performance for the road users population cannot be predicted if, for example, it is not known exactly how visual acuity is distributed among this population.

Second, one may ask if three different problems should not be investigated at the same time:

- thresholds
- rules for implementation
- physical properties of the materials

Last, perhaps we could suggest that at least two other aspects of road sign visibility deserve more effort:

1) an acquisition of data on real world values concerning road user visual capacities and characteristics of illuminating sources (headlamps mainly) and of atmospheric states (fog, rain, windshield properties, etc.). Is it not possible that with these data (value distribution) many experiments would not be necessary anymore, correct predictions being possible with calculations?

2) investigation of functional aspects of signaling systems, for example:

   - consistency with road users' needs
   - intelligibility of symbols and messages
   - conditions of credibility.

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VERTICAL ILLUMINANCE AS A CRITERION FOR TUNNEL LIGHTING DESIGN

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From experiments conducted at the Ministry of Transportation and Communications' (Ontario) laboratory, and measurements taken at the Thorold and East Main Tunnels (Ontario), it was concluded that lighting geometrics which favor vertical illuminance will result in enhancement of visibility conditions with respect to the eye adaptation process at the threshold zone and object detection in the tunnel interior.

From the findings of these investigations it was concluded that with respect to drivers' visibility needs, a tunnel should not be isolated from the rest of the traffic system. A motorist, in performing his driving task, should consider a tunnel as an integral part of a complex scene.

It is understood that data required for steering and vehicle guidance are drawn from the immediate surroundings; however, in planning the overall trip strategy a driver requires visual contact with 3-dimensional space. In that case, the road surface forms only part of the complex scene and data on contrast are only part of the visual information.

At a distance of approximately 80-100 m from the tunnel portal all drivers are concentrating on the tunnel portal, at which time the eye adaptation process begins to take place.

The most difficult visibility obstacle for a driver is to overcome the sudden drop in luminance level at the tunnel threshold zone. The main factors of this phase contributing to eye adaptation are vertical planes ahead of him -- tunel portal and tunnel walls. Therefore it is very important in designing a tunnel lighting system to ensure that the luminances of these vertical planes are properly coordinated and related to eye adaptation requirements.

From our observations conducted at many tunnels we have noticed an important phenomenon which is very easy to check in the field: as soon as a driver crosses the threshold into the tunnel eye adaptation takes place very quickly. The problem of visual difficulty disappears, even under mediocre lighting conditions. (We have experienced this phenomenon under luminance levels as low as 30 cd/m^2). This phenomenon indicates that the contrasts between objects and their backgrounds are factors of lesser importance than that of luminance of walls.

From experiments conducted in laboratories and in the field, using asymmetrical directional light distribution, the following conclusions were drawn:

a. When the main light beam is directed at an angle of 30-50 degrees to the driver's line of vision, it assures adequate vertical object illuminance for visibility by positive contrast (better in object identification than those of silhouette viewing).

b. It provides a high value of vertical illuminance on the walls, making eye adaptation less difficult to the approaching driver at the most critical time.

Using similar lighting sources, and with the main beam directed against the driver's line of vision, the contrast between test objects and pavement were found to be of lower values and considerable glare from the light sources interfered with the driver's visibility.

The counterbeam system advocates assume that the only visibility problem in a tunnel interior is to detect relatively small objects; therefore, they concentrate their efforts on creating a high brightness on the tunnel pavement. From our investigations we have concluded that counterbeam lighting, although by using directional light creates better contrasts on the pavement, at the same time ignores the more important aspect in the visual process by neglecting to emphasize the wall luminance.

From data obtained in these investigations it was concluded that asymmetrical directional light distribution offers better visibility (compared with lateral or counterbeam methods) by increased vertical wall and object illuminance, and offers the possibility of reduction in energy requirements in tunnel lighting design.

A SYSTEMS APPROACH TO THE OPTIMIZATION OF VISUAL CONDITIONS IN LOW BEAM ILLUMINATION

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The beam pattern of the low beam is designed to illuminate the road in front of the vehicle as well as possible and at the same time to cause as little glare as possible for oncoming drivers. The net effect of the beam pattern should be an optimized visibility of the road and of objects on the road in opposing situations.

In order to optimize visibility, all beam patterns of the low beam have a strong light intensity directed towards the road surface and the near edge of the road and a weak light intensity directed towards the lane of opposing traffic. Between these areas of strong and weak light intensities there is a more or less steep gradient of light.

On straight level roads the optimum beam pattern should not be much of a problem. But this is not the normal appearance of a road. On the contrary, there are horizontal as well as vertical curves of different radius. Besides this variation there is a large variation in low beam aiming. The important vertical aiming varies to a high degree as a consequence of vehicle attitude deviations due to load.