OBSTACLE VISIBILITY IN RURAL NIGHT DRIVING AS RELATED TO ROAD SURFACE REFLECTIVE QUALITIES

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Night driving visibility distances were measured in a series of experiments. Road surface was the main independent variable. Two rough and 2 smooth road surfaces with large variations in their retroreflective qualities were used. Reflective qualities were further varied by measuring visibility distances on both dry and wet road surfaces. The size of the obstacles was 0.4 by 0.4 m (1.3 by 1.3 ft). The luminance factor was varied between 2 percent and 26 percent. Visibility distances were obtained in the following full-scale simulated driving situations: (a) low beams without opposing light, (b) low beams opposing low beams, and (c) high beams without opposing light. Safe visibility distances were normally obtained in high-beam situations. Low beams opposing low beams constituted the main safety problem. So, in meeting situations, a low degree of specular reflection (low glare) from the road surface is more important than high retroreflection (high brightness).

• A LARGE number of investigations and discussions on the effects of reflective road surfaces on obstacle visibility at night on illuminated roads have been carried out (3, 4, 5, 6, 13, 14, 15). One finding is that a road surface with a high degree of diffuse reflection has superior visual conditions compared with a road surface with a lower degree of diffuse reflection. In other words, when obstacles are seen as dark silhouettes against a brighter background, an increase of background uniformity and luminance level results in an increase of negative contrast between obstacle and background

Little research, however, has been carried out concerning the effects of reflective road surfaces on roads with no stationary overhead illumination. Rumar (16) reported on field experiments performed on 3 different road surfaces (dry, wet, snow) and compared the results with experiments carried out on different occasions. Frederiksen (6) made an extensive study of the visibility of obstacles in a model situation. Babkov (2) presented some results that indicate that visibility distance to a dark gray obstacle decreases as road surface retroreflection increases. And, Johansson and Rumar (12) reported that a wet road surface does not give silhouette effects to the same extent as does a dry one. Visual conditions in night driving situations on rural roads are quite different from those on roads with overhead illumination. With mobile lighting, the threshold contrast between obstacle and background is usually positive. Silhouette contrasts (negative contrasts) on nonilluminated roads occur only in special situations (12). There are also several variables that interact in a complex way with changing reflective qualities of the road surface. These include the retroreflective luminance of the road surface, the specular reflection of the road surface, the contrast between obstacle and background, and the level of reflected glare from opposing vehicles. Therefore, it is difficult to predict or simulate the effects of changing reflective qualities of the road surface on visibility distance.

PROBLEM

The purpose of this investigation was to measure rural night driving visibility distances to obstacles on the road as a function of the reflective qualities of the road

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surface. Reflective qualities were divided into retroreflection and specular reflection.

METHOD

The experiments were carried out on a 2-lane road that had 4 kinds of pavements. The experimental site, shown in Figure 1, was 1 km (3,280 ft) long. Each part of the road covered with 1 pavement was 4.5 m (≈ 15 ft) wide and 500 m (1,640 ft) long. At least 200 m (≈ 650 ft) of each section were completely straight and the rest very slightly curved. Road surfaces and their reflective qualities are given in Table 1.

Experiments 1 and 2

The experimental setup is shown in Figure 2. A stationary vehicle, A, was situated near the right edge of the road 200 to 300 m (≈ 800 ft) from its end. An obstacle, C, was placed on the left side 0.75 m (2.5 ft) from the front wheel of the stationary vehicle. The obstacle was 0.4 m (1.3 ft) wide and 0.4 m (1.3 ft) high and covered with woolen cloth. Experiment vehicle B approached vehicle A at a speed of 25 km/h (15.5 mph). The lateral position on the lane of vehicle B was identical to that of vehicle A. The vehicle positions and the size of the obstacle were chosen to ensure that the obstacle had an unbroken background of roadway surface.

Four subjects, the driver, and the experiment leader, were seated in vehicle B. The task of the subjects was to press a silent switch as soon as they could see the obstacle. The impulses from the switches were recorded with impulses from a fifth wheel that measured the distance traveled from a fixed starting position. The recorded visibility distances were translated into metres to an accuracy of ±1 m (≈ 3.3 ft). Similar full-scale simulations have been used in earlier studies (10, 11, 17).

The main independent variable was road surface type. To measure effects of interaction between obstacle and background, the luminance factor of the obstacle was varied in 3 steps: 2 percent (black), 7 percent (dark gray), and 26 percent (light gray). The visibility distance was measured both with and without meeting glare from vehicle A's low beams (European continental H_4).

A block design was used to adapt the subjects' eyes to the luminance distribution of each pavement. Six trials were made on the same road surface in each block in which the 3 luminance factors of the obstacle and the 2 meeting conditions were rotated. To keep the adaptation level of the subjects constant during each block, the driver reversed the vehicle after each trial and returned to the starting position. The blocks were rotated according to the ABBA principle. As an experimental control, the obstacle was taken away in a number of randomly chosen trials. The experiments were carried out at night in good weather. Two Hella halogen H_4 headlights were used on each vehicle. Each headlight was tested by the Swedish Institute for Materials Testing to conform to ECE R 20. The voltage was 13.2 V. The aiming of the dipped headlights was correct and controlled in every road surface condition. The age of the subjects was from 22 to 29 years. Their visual acuity was ≥1.0.

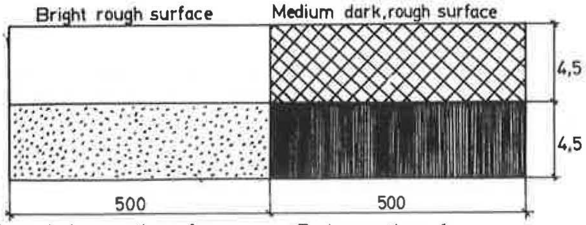
Experiment 1 was carried out under dry road surface conditions. Twenty-four experimental conditions were replicated 4 times. Experiment 2 was a replication of experiment 1 with 2 exceptions: (a) The road surface conditions were wet and (b) 3, rather than 4, replications of experimental conditions were made. Every road surface was flooded with water by a truck equipped with a water tank. The amount of water on the roadway material immediately before each block of 6 trials corresponded to 1 mm (0.04 in.) of heavy rain. The air temperature was 5 C (41 F). Evaporation was low.

Experiment 3

The purpose of the third experiment was to measure the visibility distances for high beams as a function of road surface and to measure the changes in visibility distance for low beams as a function of the distance to a meeting vehicle, B.

The method used was different from that of experiments 1 and 2. The luminance factor of the obstacle was constant (7 percent, dark gray). Three obstacles were used at the same time on each road surface. The positions of these obstacles, as shown in

Figure 1. Position and size of the 4 experimental road surfaces.

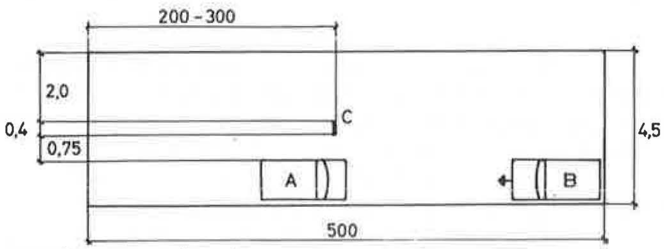


Note: Distances are in metres.

Table 1. Retroreflection and specular reflection of the 4 experimental road surfaces.

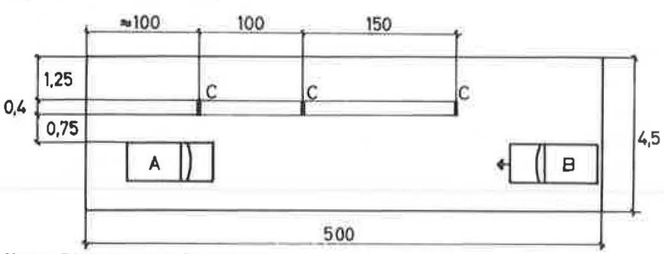
Road Surface	Dry: Retro-reflection (mcd/m²/lx)	Dry: Specular Reflection (mcd/m²/lx)	Wet: Retro-reflection (mcd/m²/lx)	Wet: Specular Reflection (mcd/m²/lx)
Dark, smooth surface (asphalt Ab 8 t)	≈3	≈400	≈0.6	>20 000
Medium dark, smooth surface (asphalt Ab 8 t + Viasole)	≈15	≈550	≈1.6	>20 000
Medium dark, rough surface (diabase Y3)	≈13	≈3	≈4	≈7
Bright, rough surface (Synopal Y3)	≈60	≈8	≈55	≈13

Figure 2. Setup for experiments 1 and 2.



Note: Distances are in metres.

Figure 3. Setup for experiment 3.



Note: Distances are in metres.

Figure 3, were 1.25 m (≈ 4 ft) from the left edge of the road at distances of 0, 100, and 250 m (0, ≈ 330, and ≈ 820 ft) in front of the stationary vehicle, A. The lateral distance between vehicle A and the obstacles was identical to the lateral distance in experiments 1 and 2—0.75 m (≈ 2.5 ft). Because the obstacles were positioned near the edges of the 4 roads the top of the obstacle was not always seen against a road surface background. Roadway materials were rotated according to the ABBA principle. The adaptation level of the subjects' eyes was not kept under the same degree of control as in experiments 1 and 2. Three headlight conditions were tested: high beams and low beams without opposing light and low beams opposing low beams. The speed of the experiment vehicle was 50 km/h (31 mph). [The visibility distances presented were corrected for a reaction time of 0.4 s (9)]. And, 4 replications were made for all conditions—2 replications with dry road surfaces and 2 replications with wet road surfaces.

Two independent series of measurements of the reflection qualities of the road surface materials have been carried out. The first was carried out by the National Swedish Road Research Institute. The geometry of each measurement situation, shown in Figure 4, was described by E. Persson in a private communication.

The instrument used was specially constructed for measurements of the retroreflection and specular reflection of road surface materials. In the second series, retroreflection was measured with a Pritchard telephotometer. This series was carried out in full scale using the normal high beams of the vehicle as a light source. The road surface was measured at 25 and 50 m (82 and 164 ft) in front of the vehicle under dry road conditions and at 32.5 m (107 ft) under wet road conditions. The illumination at each point was controlled to be constant. The height of the headlights was 0.75 m (≈ 2.5 ft) and the height of the telephotometer was 1.30 m (≈ 4.3 ft), or normal driver eye height.

A comparison between the results of the 2 measurement series showed consistency for rough road surface conditions. The special instrument, according to E. Persson, tended to give values of retroreflection on surfaces with a high specular reflection that were too high, so the measurement values of Synopal (in $mcd/m^2/lx$) were used as a base to translate the measurement values of the Pritchard telephotometer to $mcd/m^2/lx$. Thus, all specular reflection values given in Table 1 and the retroreflection values of Synopal were obtained with the special instrument. The retroreflection values (means of 4 measurements on dry roads and 2 on wet roads) of the other surfaces came from the Pritchard telephotometer measurements.

RESULTS OF EXPERIMENTS 1 AND 2

The results were based on group means because the individual results showed the same tendencies and the medians did not depart systematically from the means.

The group means of the 2 meeting and weather conditions were plotted against the retroreflection of the road surface as shown in Figures 5 through 8. The sensitivity of the eye is considered to be logarithmic, so retroreflection was presented along a log scale axis.

Analyses of variance were carried out on each of the 4 road surfaces. The following significant differences refer to those analyses.

Figures 5 and 6 show visibility distances for low beams without opposing light as related to the retroreflection of the road surface. Significant differences in visibility distance existed for both obstacle luminance and road surface retroreflection. In 3 out of 4 cases the interaction between these parameters is significant.

The visibility distances were longest to the light gray and the dark gray obstacles on the road surface with the lowest retroreflection. But, on a dry road, the black obstacle was detected at the farthest distance on the road surface with the highest retroreflection. On a wet road, visibility of the black object seemed to be as dependent on variation in the specular reflection as on variation in the retroreflection of the road surface. These results suggest that the visibility distance with low beams without opposing light depends to a high degree on the luminance contrast between the obstacle and the background (the road surface). Differences in visibility distances between dry and wet road surfaces could not be interpreted because the data were obtained in 2 different experiments and therefore were not directly comparable.

Figure 4. Geometrics of the special equipment for measuring reflection.

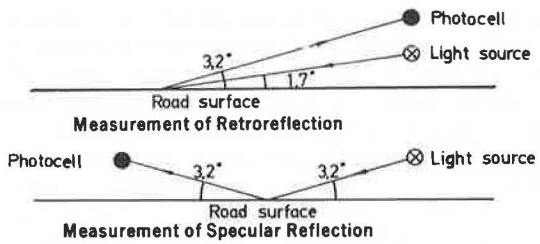


Figure 5. Mean visibility distances for low beams without opposing light on dry roads as a function of road surface retroreflection.

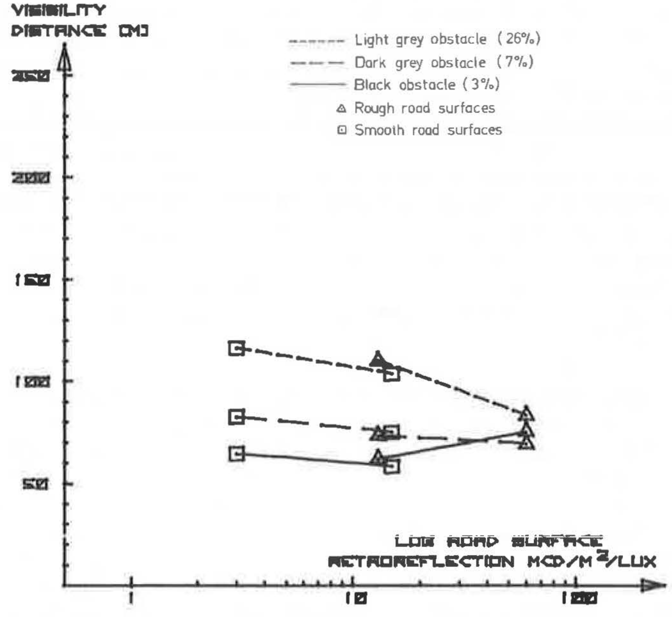


Figure 6. Mean visibility distances for low beams without opposing light on wet roads as a function of road surface retroreflection.

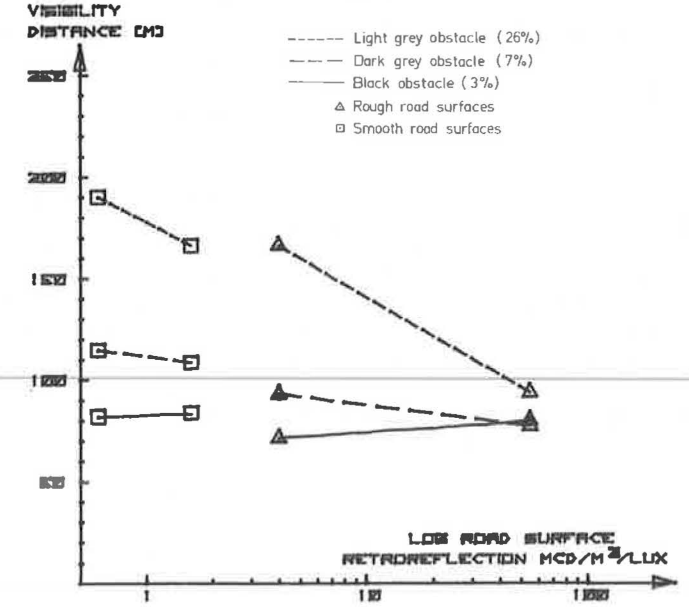


Figure 7. Mean visibility distances for low beams opposing low beams on dry roads as a function of road surface retroreflection.

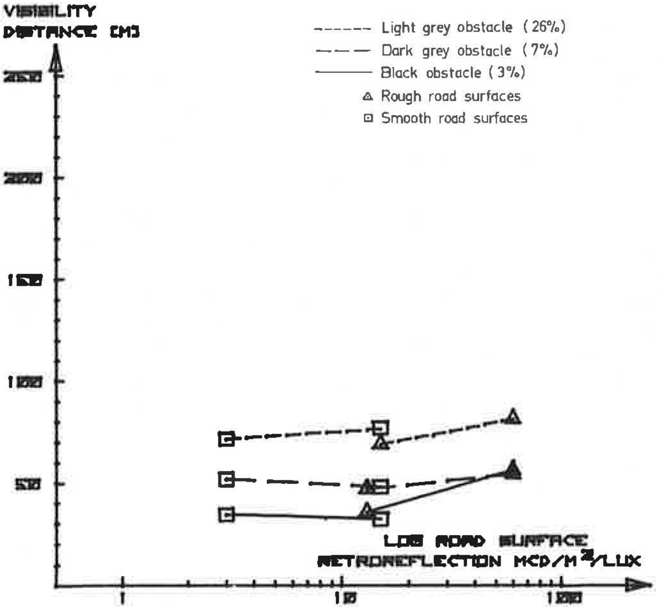
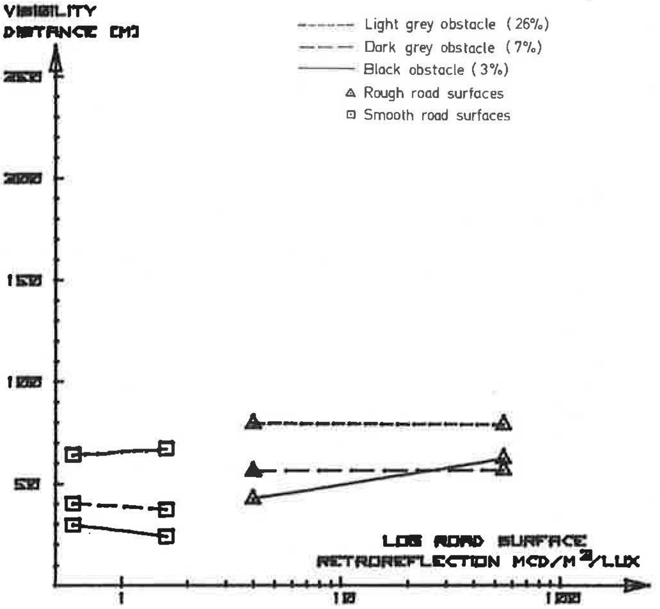


Figure 8. Mean visibility distances for low beams opposing low beams on wet roads as a function of road surface retroreflection.



Figures 7 and 8 show visibility distances for low beams opposing low beams as related to the retroreflection of the road surface. This situation is most important for traffic safety on rural roads at night. The dependence of visibility distance on road surface retroreflection was not so pronounced (although it was significant for the rough surfaces) in this situation as in the situation without opposing light. The visibility distance to the black obstacle showed a strong dependence on the retroreflection of the road surface. The dark and light gray obstacles, though, had visibility distances that were relatively constant despite variation in road surface retroreflection. On wet roads the visibility distance to the dark and the light gray obstacles seemed to depend more on specular reflection than on retroreflection of the road surface. These results suggest that, except for the black obstacle, the visibility distance for low beams opposing low beams depends mainly on the luminance factor of the obstacle and is relatively independent of the road surface retroreflection.

Figures 5 through 8 show visibility distances for low beams with and without opposing low beams as related to the specular reflection of the road surface. In comparing the visibility distances of the rough and smooth road surfaces that are most alike in the retroreflection variable, the effect of large differences in specular reflection can be studied. Especially on wet roads, the effect of specular reflection seemed to be pronounced as shown in Figures 6 and 8. Figure 6 shows that a high degree of specular reflection made the visibility distance longer when there was no opposing light. But, with opposing light as shown in Figure 8, a high degree of specular reflection decreased the visibility distance considerably. In this situation the decrease of visibility distance was about 15 percent for the light gray obstacle and 45 percent for the black obstacle when compared to the visibility distances obtained on the road surface with a low degree of specular reflection. On wet roads, significant differences were obtained for specular reflection.

RESULTS OF EXPERIMENT 3

Because the rankings between the road surface conditions were the same for the 2 experiment nights, the mean visibility distances were computed for all the data. The mean visibility distances to dark gray obstacles for low and high beams without opposing light are shown in Figures 9 and 10. The relationship between visibility distance and road surface reflection was much the same for both headlight conditions. Results were also consistent with the results from experiments 1 and 2. With only 1 exception in all 3 experiments, a smooth road surface resulted in longer visibility distances to a dark gray obstacle than did a rough road surface. Visibility distances decreased as road surface retroreflection increased.

Visibility distance, as related to the reflection qualities of the road surface, decreases as the distance between 2 vehicles in a meeting situation decreases. In Figures 11 and 12 the mean visibility distance to a dark gray obstacle for dry and wet roads is related to the distance between vehicles A and B.

Differences between smooth and rough road surfaces in dry and wet conditions were tested by analysis of variance. On dry roads the decrease in visibility distance as a function of decrease in distance between the vehicles was significant but independent of the texture of the road surfaces (specular reflection). On the other hand, on wet roads, the significant decrease in visibility distance depended on the specular reflection of the road surface and on an interaction between specular reflection of the road surface and the distance between the vehicles.

Visibility distance decreases to a much greater extent on a wet, smooth road than on a wet, rough one because of large differences in the amount of specular glaring light from wet, smooth roads compared with the amount from wet, rough roads.

DISCUSSION AND CONCLUSIONS

From a safety point of view, some traffic situations are more serious than others. In night driving on rural roads, the low beam opposing low beam situation is the most important because of severely limited visibility. When the driver is alone on the road, high beams should be used to create visibility conditions as favorable as possible. The low beam without opposing low beam situation also was studied to separate the

Figure 9. Mean visibility distances for low and high beams without opposing light on dry roads as a function of road surface retroreflection.

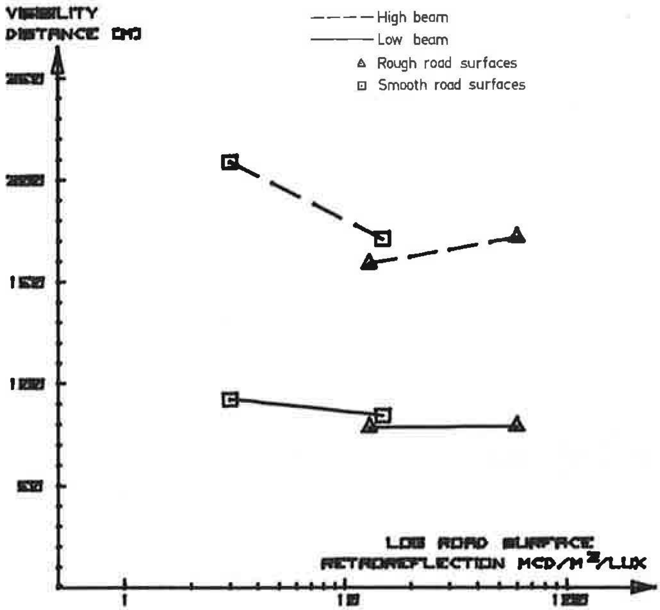


Figure 10. Mean visibility distances for low and high beams without opposing light on wet roads as a function of road surface retroreflection.

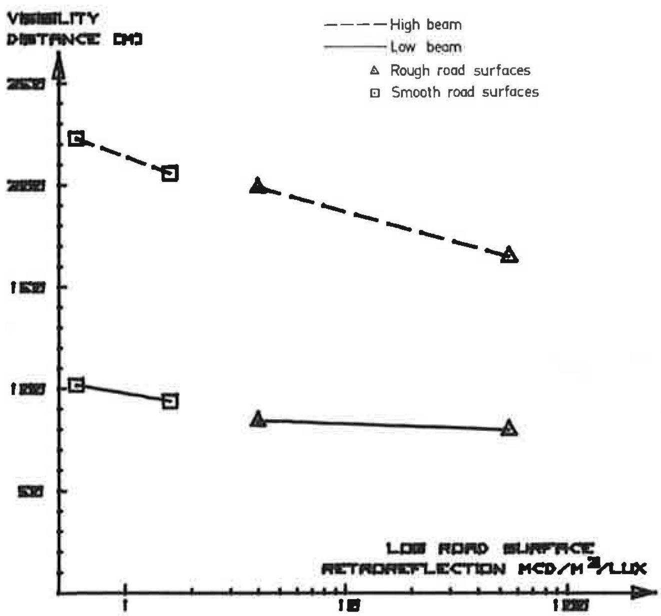


Figure 11. Mean visibility distances for low beams opposing low beams on dry roads as a function of distance between vehicles.

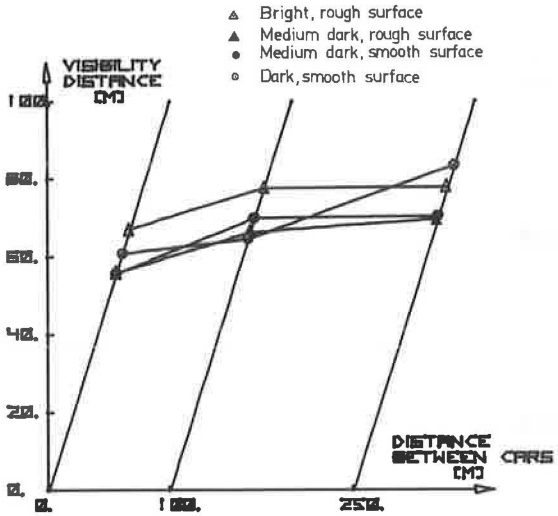
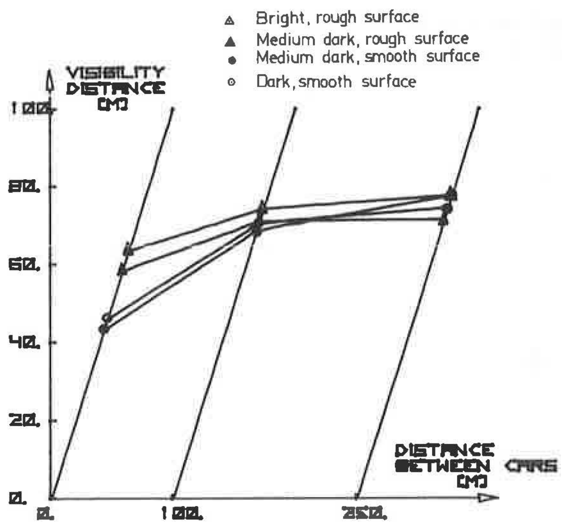


Figure 12. Mean visibility distances for low beams opposing low beams on wet roads as a function of distance between vehicles.



effect of glare in the meeting situation. But, conclusions about safety should be drawn from the data obtained in the 2 former situations.

The meeting situation used in these experiments resulted in shorter visibility distances to an obstacle than normal situations in which the stationary vehicle is placed in the adjacent (opposite) lane. Rumar et al. (17) have shown that the decrease of the visibility distance to an obstacle with a luminance factor of 10 percent is about 25 percent when the opposing vehicle is moved from the adjacent lane to the same lane as the car. Judging from the isolux diagrams presented by Rumar et al. (17), the main part of the difference in visibility distance seems to be caused by the decrease in visual angle between the obstacle and the glaring light source (the opposing headlights). A slight increase of light also falls into the subjects' eyes.

Obviously the experimental meeting situation used here is more glaring than the normal meeting situations on the road. In the experimental situation the lateral distances between the obstacle and the 2 opposing headlights were about 1.25 and 2.50 m (4.1 and 8.2 ft) respectively. The corresponding distances in normal car meeting situations are about 4 and 5.5 m ($\approx$ 13 and $\approx$ 18 ft). According to the Holladay formula for veiling luminance (L_{ekv}) as presented by Adrian et al. (1), the glare level in the experimental situation would be equivalent to an increase of about 10 times the headlight glare in normal car meeting situations. This corresponds largely to an upward headlight misaiming of about 0.017 rad (1 deg). The purpose of these glare calculations is to give a rough estimate, and the Holladay formula is only one of several ways to calculate veiling glare (8).

The road surfaces used are only representative for new pavement. The rough surfaces were very rough and therefore extreme in their specular reflection qualities. This was a great advantage experimentally, but it makes quantitative generalizations of the results to pavings of less extreme specular characteristics (for example, old rough pavings) difficult.

Because of the very limited width of each experimental road surface—4.5 m ($\approx$15) ft)—the car meeting situation was also extreme. Therefore, generalizations of the results to situations with less glare must be done with care.

The low obstacles that were used in this investigation were chosen to ensure that the road surface was the only background to maximize the visibility effects of the reflective qualities of the road surface. So, visibility distances to taller obstacles are probably less dependent on the reflective qualities of the road surface.

Because knowledge of this area is incomplete, this investigation was, by necessity, exploratory. Further experiments should be made in which road surface reflection parameters and the glare parameter could be varied.

The data obtained were surprisingly consistent. The severe effects of specular glare on the visibility distance in meeting situations on smooth, wet roads were clearly shown. The increase of the visibility distance for high and low beams without opposing glare on smooth, wet roads compared with rough roads was not important because high-beam visibility is generally good enough not to cause severe safety problems (10). These conclusions agree with recent British results that show that night driving accidents on wet roads are overrepresented in road accidents statistics (18).

The results of these experiments agree with those of Rumar (16) and Babkov (2) and also with some of the results published by Frederiksen (7). Rumar (16) showed that a black obstacle had better visibility than a dark gray obstacle on a snowy (very bright) road. Rumar also reported decreased visibility on bright roads and increased visibility on wet roads in conditions without opposing light. Babkov (2) presented results that showed that the visibility distance to a dark gray obstacle decreases as the luminance factor of the road surface increases. One of the results that agrees with the results of Frederiksen (7) is that the difference in visibility distance between bright and dark obstacles decreases with increasing road surface retroreflection. Frederiksen's main results—that the visibility distance to dark obstacles increases as road surface retroreflection increases—is reproduced here only for the black obstacle when road surface retroreflection is varied from medium to high values.

It should be noted also that very bright pavings might constitute a problem, for example, in bright sunshine.

The following conclusions on low-beam visibility distance to obstacles on the road can be drawn:

1. Visibility distance to black objects is longest on road surfaces, such as Synopal, that have very high retroreflection;
2. Except for black obstacles on very bright roads, obstacle visibility is directly dependent on the luminance factor of the obstacle;
3. Visibility distance to obstacles with a luminance factor larger than 5 percent is independent of road surface retroreflection for low beams opposing low beams;
4. Visibility distance on wet road surfaces with opposing vehicles depends more on the roughness of the road surface than on its retroreflection;
5. The decrease in visibility distance on wet road surfaces as a function of distance between 2 opposing vehicles is much less on rough than on smooth pavement; and
6. In low- and high-beam situations without opposing light the visibility distance to a dark gray obstacle increases as retroreflection of the road surface decreases.

Both obstacle visibility distance and road visibility distance (visual guidance) constitute the main safety factors of the road at night. In this investigation, only obstacle visibility distance has been studied systematically in relation to the road surface. The results indicate that in the critical situations rough road surfaces are superior to smooth ones. The same conclusions based on measurements of reflective qualities can be drawn on visual guidance of the road surface. Good visual guidance might also be obtained on dark road surfaces by good retroreflective delineations.

Retroreflection of the road surface is of minor importance for obstacle visibility. However, because of silhouette effects, a bright and rough road surface should be best in critical situations on rural roads at night (12). From a visual guidance point of view, the superiority of bright and rough pavings is evident.

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