Safety Hazard of Tinted Automobile Windshields At Night*

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The effects of tinted optical media, particularly of heat-absorbing automobile windshields, upon visibility distances on the highway at night are analyzed theoretically. The loss percentages in visibility distances caused by replacing clear windshields with tinted ones are calculated as functions of the variables involved, viz., transmittance of the tinted optical medium, isocandle profile of the headlamp, angular size and reflectance of the target. It is found that the loss percentages in visibility distances are further dependent upon the distance of the target itself, with the losses increasing with decreasing distances. Losses in visibility distances caused by commercial brands of tinted windshields amount to between 9 and 15 percent at visibility distances ranging between 1000 and 200 feet. These results agree fairly well with the data of Blackwell and with data obtained experimentally in the field by other authors. The analysis shows further that the losses in visibility distances are greatest for targets so nearly matched to the background that they may be seen even with clear windshields only at short distances. Under these conditions the losses may be as high as 30 to 45 percent. A reconsideration of the 70 percent minimum transmittance requirement for windshields in the American Standard Safety Code Z26.1-1950 is recommended.

● IN recent years the automobile user has been offered various devices using tinted optical media which are designed to alleviate the discomfort of glare and to reduce transmission of radiant heat. Tinted optical media are presently finding widespread application in automobiles which are being equipped with tinted windshields by the manufacturer upon option of the consumer. In addition to tinted windshields, various other manufacturers advertise so-called "night-driving glasses" which are offered as a solution to the glare problem on the highway. The interposition of a light-absorbing medium between the eye of the driver and the highway, of course, poses the question to what extent this has an adverse effect upon seeing, particularly during night. Various authors have discussed this question (1, 2, 3) and experimental studies in the field have been carried out by Roper (4) and, from this Institute, by Heath and Finch (5). In the following an attempt is made to evaluate further the work done here as well as elsewhere[1] by attacking the problem theoretically.

Two types of tinted windshields are presently in use: (1) laminations having a uniform density and (2) laminations having a graduated density with a horizontal band of greatly reduced transmittance (0.18) at the top of the windshield, designed to eliminate glare from the sky. Tinted windshields are greenish with the maximum of transmittance at 515 mμ; a typical spectral transmittance is shown in Fig. 1(A). "Night-driving glasses" (e.g., brand A) have a sigmoidal spectral transmittance favoring the long wavelengths as shown in Fig. 1(B); their tint is amber. Tinted windshields having transmittances between 0.15 and 0.40 in the 0.8 to 6-μ region, are fairly effective infrared absorbers. Their optical properties vary somewhat from sample to sample; representative transmittance values of various tinted optical media used in the automo-

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[1] While this paper was in the process of being published, the results of a further series of field experiments were reported at the January, 1955, meeting of the Highway Research Board by H. Doane and G. M. Rassweiler (Cooperative Road Tests of Night Visibility Through Heat-Absorbing Glass). The experimental setup used by these authors and their results are essentially the same as those of Roper (4) so that the conclusions drawn in this paper are not affected by this new series of field experiments.

TABLE 1

TRANSMITTANCES OF VARIOUS TINTED OPTICAL MEDIA[a]

	Luminous transmittance (equal energy spectrum) T_V	Luminous transmittance (CIE source A[b]) T_A	Infrared transmittance (0.8 - 6μ)
1. Safety plate (clear windshield)	0.883	0.881	0.436
2. Tinted windshield (brand I)	0.730	0.692	0.153
3. Tinted windshield (brand II)	0.667	0.614	-
4. Night driving glass (brand A)	0.534	0.704	0.636
5. Rayban sunglass	0.395	0.410	-

[a] Instrumentation: Range 400-700 mμ: GE recording spectrophotometer; range 0.8-6μ: Beckmann spectrophotometer.

[b] CIE source A was used to represent the spectral distribution of sealed-beam headlamps, although their color temperature averages about 150 degrees K higher. However voltage differences can be expected to produce variations greater than this difference.

bile field are given in Table 1, according to measurements made in this Institute.

Although tinted windshields offer fair protection against radiant heat and thus afford a more comfortable climate inside a car during the summer, their transmittances in the visible region of the spectrum are inadequate for glare protection. According to Farnsworth (6), sunglasses with transmittances as low as 0.25 furnish negligible glare protection; to be effective, transmittances of not more than 0.12 are recommended. On the other hand, tinted windshields must have a transmittance of not less than 0.70 in order to meet the recommendation of the ASA Safety Code (7). These two specifications, of course, are incompatible, and the conclusion must be drawn that there can be no tinted windshield that affords glare protection and simultaneously meets safety standards.

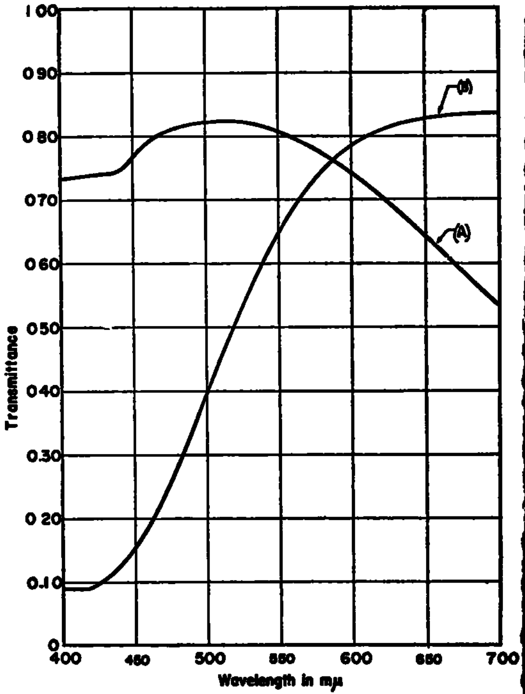

Figure 1. Transmittances of tinted optical media used in the automobile. (A) Typical tinted windshield. (B) Sample of "night-driving glass."

Perhaps the most critical among the potential hazards of tinted windshields is that they may cause a reduction of visibility distances on the highway at night. The object of the aforementioned field studies was to measure this potential hazard. In their study, Heath and Finch (5) placed various objects of different sizes, shapes, and spectral reflectances on the road and measured the distances at which each of the objects was first seen from the approaching car when viewed through a clear safety plate windshield and tinted windshield, respectively. The targets consisted of various objects, such as road signs, boxes of various colors, stakes, dirt piles, and the like. Roper (4) applied essentially the same method, but the targets used were identical 16-in. square paper panels having a reflectance of 0.075. Roper's measurements were mostly concerned with determinations of target visibility distances against the glare of an oncoming automobile.

The results and conclusions of these authors are conflicting. Heath and Finch found a reduction of visibility distances of up to 22 percent when the clear windshield was replaced by the tinted one. Roper, however, found an over-all reduction of less than 6 percent for observations with no approaching vehicle, and an average reduction of 2 percent with the glare of an oncoming automobile. Heath and Finch conclude that "it does not appear feasible to assign an over-all percentage value to represent the difference between the two types of glass," even though they point out that a significant reduction in visibility distance exists. Roper concludes that "the daytime benefits to be derived from the heat-absorbing glass windshields offset the small reduction in seeing distance at night."

Both authors point out that their results exhibit great variations in the effect of tinted windshields on visibility distances. These variations are due to the great number of variables having an influence upon the results, such as light sources other than the headlamps (e.g., the moon), variations of target illumination owing to the moving vehicle, the size, reflectance, color, shape, and location of the target objects, and physiological and psychophysical factors involved in the performance of the observer. In addition, it can be shown that the loss percentage in visibility distance caused by tinted optical media in night-driving is a function of distance, but the authors did not attempt to separate their data to account for this effect.

In the following treatise an attempt is made to attack the problem by theoretical analysis with the expectation of arriving at a better understanding of its nature. The analysis is based on the fact that the brightness contrast threshold rises steadily with decreasing levels of the brightness of target and background. This relationship holds over a wide range of luminances, in dark surrounds (8), light surrounds (9), and if the surround is equal in luminance to that of the background (10), at least so far as luminance levels below 1 footlambert (that is, luminance levels encountered on the highway at night) are concerned. The luminance contrast between target and background is defined by the ratio

$$C = (B_t - B_b)/B_b,$$

in which B_t is the luminance of the target, and B_b the luminance of the background. Obviously, C is independent of the illumination. For a target of a given angular subtense, then, to become visible it is required that the illumination be great enough, so that luminances B_b and B_t are reached for which C becomes equal to or greater than the contrast threshold. Let us now assume that a target on the nocturnal road is illuminated by the headlights of the driver's car with an illumination sufficient to produce luminances corresponding to the contrast threshold that is valid for the given angular subtense of the target; this threshold condition may be reached at a distance D_o. If, then, a filter having a transmittance of T is interposed between the target and the eye of the observer, the apparent luminances of both the target and the background are reduced by the factor of T. This reduction causes the target to dip below the threshold, and it is no longer visible. Since the illumination of the target and background as well as the angular subtense of the target are increased if the car approaches the target, there must exist a distance $D_t (D_t < D_o)$, at which the apparent size and luminances of target and background are rendered sufficiently great to lift the target above the visibility threshold. It follows that D_t depends only upon the following quantities and relationships: (1) the original visibility distance D_o; (2) the transmittance T of the filter interposed; (3) the relationship (for a certain position of the target) between distance and illumination (and depending on target reflectance, luminance) afforded by the headlights of the car; and (4) the relationship between distance and angular subtense of the target. A determination of D_t, of course, requires information concerning visual thresholds in terms of luminance, contrast, and angular size. All other variables can be neglected because their combined effects must be assumed to be equal in both cases.

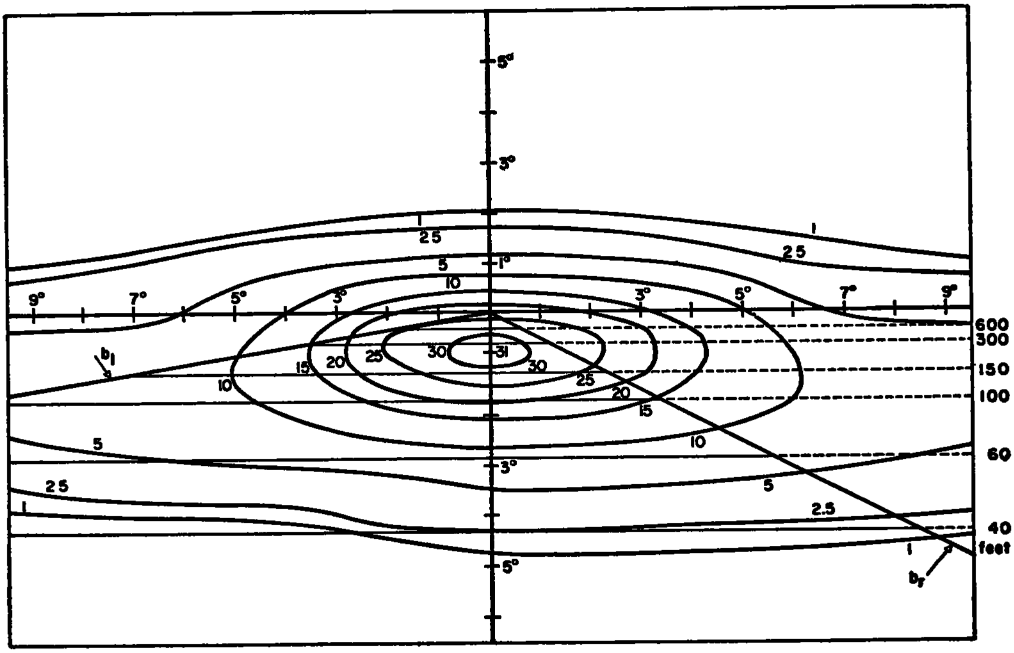

Figure 2. Isocandlepower diagram of an American-made sealed-beam headlamp, upper beam. Values are in thousands. For details see text. (After Finch (11) and de Boer and Vermeulen (12).)

Only if all variables are assumed to be equal, does a comparison between viewing with and without the filter become meaningful. This is the reason why a theoretical analysis of this kind can be expected to yield meaningful results, particularly since the many variables involved cannot be controlled satisfactorily in experimental studies.

The relationship between target luminance and distance can be obtained from measurements made by Finch (11) on American-made sealed-beam headlamps. Figure 2 shows the isocandlepower diagram of the upper beam of one of the headlamps measured. The solid lines b_r and b_l are the perspective images of the right-hand and left-hand roadbank, respectively, while the horizontal lines are the projections of transverse lines on the road at the indicated distances. This kind of graph was first used by de Boer and Vermeulen (12) in studies of automobile headlamps. Diagrams of this type from two different brands of headlamps were used to determine graphically the desired relationship between the luminance of targets located at the right-hand roadbank and the distance from the driver. Assuming a certain reflectance R of a target, its luminance can be represented as a function of its distance from the car. The results are shown in Figure 3 giving the desired relationship for two different brands of headlamps based on a reflectance of R = 0.15 for the target. Different target reflectances would be represented by identical curves shifted parallel to the horizontal (luminance) axis by a corresponding amount.

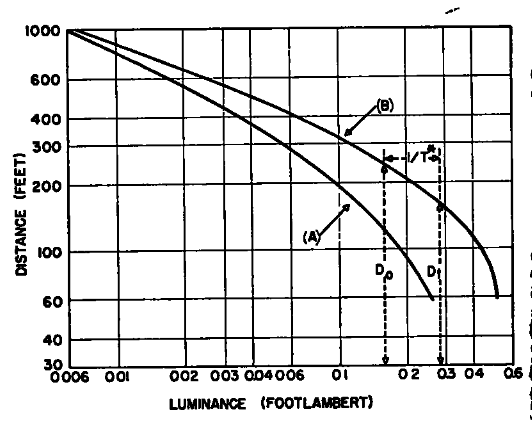

Figure 3. Relationship between distance and luminance of a target (of reflectance R= 0.15) located at the right-hand roadbank , (A) headlamp brand I; (B) headlamp brand II

The relationship between the thresholds of the three visual parameters — luminance, contrast, and angular subtense —

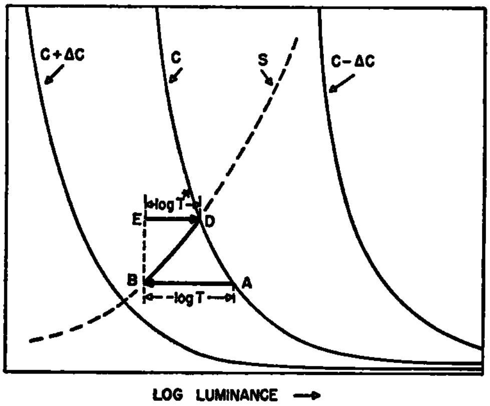

Figure 4. Graphical determination of log T*, for details see text.

has been determined by various authors (3, 10, 13, 14); of these data those by Blackwell (3) are the most suitable ones and were used in this study. The relationship between the three parameters can be represented in several ways; the representation best suited for the purposes of this study gives curves pertaining to different contrast values (C) in a coordinate system with luminance and angular subtense as axes. A graph of this kind is shown in Blackwell's paper.[2]

The relationship between angular subtense of the target and distance is easily computed for any target of given physical size. For the purpose of this study, however, this relationship must be expressed in terms of luminance of the target rather than of distance. This latter relationship is easily derived by means of Figure 3.

The previously described conditions of a target at the threshold of visibility are now represented by a point A in the diagram of Figure 4. This figure indicates how the plot of angular subtense against log luminance may be used to determine the effects of apparent target size on visibility distance. The solid lines define the combinations of angular subtense and luminance at which a target of some fixed contrast C, C + ΔC, or C - ΔC, with its background, is at the threshold. The dotted curve indicates the angular subtense of a target of some fixed size as a function of luminance, the latter in turn being a function of distance as represented by Figure 3. If a target of some given size and contrast represented by point A is viewed through a filter having a transmittance of T, the apparent luminances of the target and the background are reduced by the same factor leaving contrast, C, unchanged. Since the luminance is plotted logarithmically in Figure 4, the condition achieved by interposing the filter is represented by a horizontal shift from point A by the distance of -log T to the point B. The point B, however, represents the conditions of a target which is below the threshold of visibility. The target can be made visible again by increasing its luminance, which in our case means by approaching the target with the car. However, while the car advances the angular subtense of the target increases simultaneously according to their mutual relationship, as is represented by the curve S in Figure 4. The curves S and C intersect at the point D which represents the threshold conditions for which the target becomes visible again when viewed through the filter. Obviously the increase in brightness ED = +log T* is required to render the target visible again after it had been dipped below the threshold by the interposition of the filter.

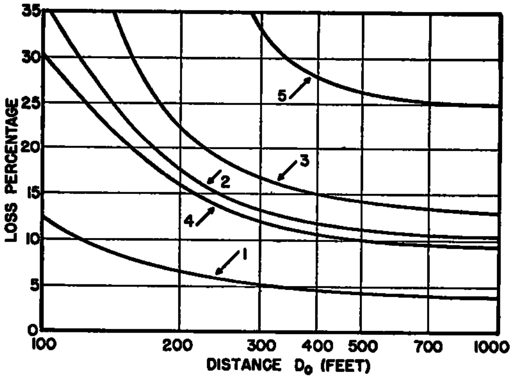

Figure 5. Loss percentage of visibility distance as function of distance for various absorbing media. (1) Clear safety plate. (2) Tinted windshield brand I. (3) Tinted windshield brand II. (4) " Night-driving glass." (5) Rayban sunglasses.

The value T* which can be determined graphically in this fashion can then be used to determine the distance D_t at which the target becomes visible when being viewed through the filter. This is done by means of Figure 3. Since the luminance values in this graph are plotted logarithmically, the distance D_t can easily be read from the graph for any value of D_o in the manner indicated in Figure 3. The relationship between luminance and distance is not linear when plotted on log-

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[2] See Reference 3, Figure 13, p. 58.

log paper and consequently, the loss percentage LP in visibility distance, i. e.,

$$LP = 100\left[1 - (D_t/D_o)\right],$$

becomes a function of the initial visibility distance D_o.

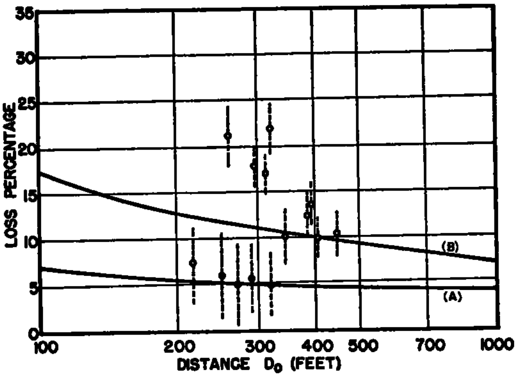

Figure 6. Loss percentages in visibility distances as functions of distance, resulting from replacing clear safety plate by tinted windshield, brand I. Curve (A) and solid dots refer to data by Roper (4), curve (B) and open circles refer to data by Heath and Finch (5).

Figure 5 shows some representative values of loss percentages in visibility distances for various tinted optical media as a function of the initial visibility distance D_o assumed to exist without any interposed medium (the air, of course, is assumed to be perfectly clear). The results are valid for a target having the mean linear dimensions of three feet, and a reflectance R = 0. 15 — that is, the target may represent a dark-clad human figure. The graphs show that even a clear safety plate windshield causes an appreciable reduction in visibility distance, whereas tinted windshields, night-driving glasses, and normal sunglasses cause significant reductions. In all cases the reduction in visibility distance rises more or less steeply as the initial visibility distance D_o becomes smaller. This effect is perhaps the most significant finding of this analysis, because the loss in visibility distance due to a tinted windshield is most critical under conditions of small initial distances. Take, for instance, a dark-clad person projected against a dark pavement: in such a case the luminance values of target and background may be such that the initial visibility distance D_o is only 150 feet. A driver of a car equipped with tinted windshields of brand II would then detect the person at a distance of only 100 feet (see Figure 5).

The values presented in Figure 5 are related to no windshield at all as a base line. In order to make the theoretical results comparable to experimental findings, curves must be derived which compare a clear windshield with a tinted one. If, for instance, a clear safety plate is replaced by a tinted windshield of brand I, the base line must be represented by visibility distance D_o obtained initially while viewing through a clear windshield. The experiments previously mentioned (4, 5), were carried out by comparison between these two types of windshields. Figure 6 shows the experimental data obtained from the applicable test series in both experiments (e. g., test series without external illumination and glare). The targets used by Roper (solid dots) and by Heath and Finch (open circles), respectively, were grouped together according to their D_o values furnishing a total of 4 and 10 points, respectively. The range of the probable errors is indicated in all cases. In the case of the experiments of Roper, who used targets uniform as to size and reflectance, a theoretical curve ((A) in Figure 6) can be derived which represents the experimental results. In the case of the experiments of Heath and Finch, who used a variety of targets of widely differing sizes and reflectances, no single theoretical curve can be derived which would be completely representative of all the targets used. However, by use of a mean value of target size (major dimension: 3 feet) and available data on headlamp profiles, a theoretical curve ((B in Figure 6) was derived that corresponds to this set of experiments. It appears from Figure 6 that the experimental data of both Roper and of Heath and Finch agree fairly well with the theoretical results, considering the difficulties of controlling the many variables involved in the experimental determination of the D_o and D_t values, as shown by the relatively large probable errors in both sets of experiments.

The experiments cover only a few isolated, special cases of the seeing task of the driver during night. These cases are characterized mainly by four variables: the specific brand of (1) tinted windshield and (2) headlamps, and the (3) size and (4) reflectance of the targets used in the experimental studies. The highly selective conditions of the experiments are also characterized by the fact that the majority of the targets are confined between the limits $D_0 = 250$ feet and $D_0 = 400$ feet. In particular, no experimental data exist for D_0 values smaller than 200 feet, which could verify the most critical reductions in visibility distance caused by tinted optical media.

It appears desirable, therefore, to analyze theoretically the relative importance of the aforementioned four variables. This was done in this study by choosing four pairs of variables, namely, (1) two windshields, brand I and brand II (W_1 and W_2); (2) two headlamps, brand I and brand II (L_1 and L_2); (3) two targets assumed to be disks 2 feet and 12 feet in diameter, respectively (S_1 and S_2); and (4) two values of reflectance, 0.15 and 0.075, respectively (R_1 and R_2). It is further assumed that all targets are located at the right-hand roadbank and that the background reflectance does not vary with the distance between D_0 and D_t. The precentage reduction of visibility distances was then calculated for five combinations of the 8 variables listed in the foregoing; the calculations are based upon original visibility distances D_0 as they would result from viewing through a clear windshield. In other words, the results are representative of the losses in visibility distances as they would result when a clear windshield is replaced by a tinted one. The following combinations of the 8 variables listed previously were taken:

(1) W_2 - L_1 - S_1 - R_2,
(2) W_1 - L_1 - S_1 - R_2,
(3) W_2 - L_2 - S_1 - R_2,
(4) W_2 - L_1 - S_2 - R_2,
(5) W_2 - L_1 - S_1 - R_1.

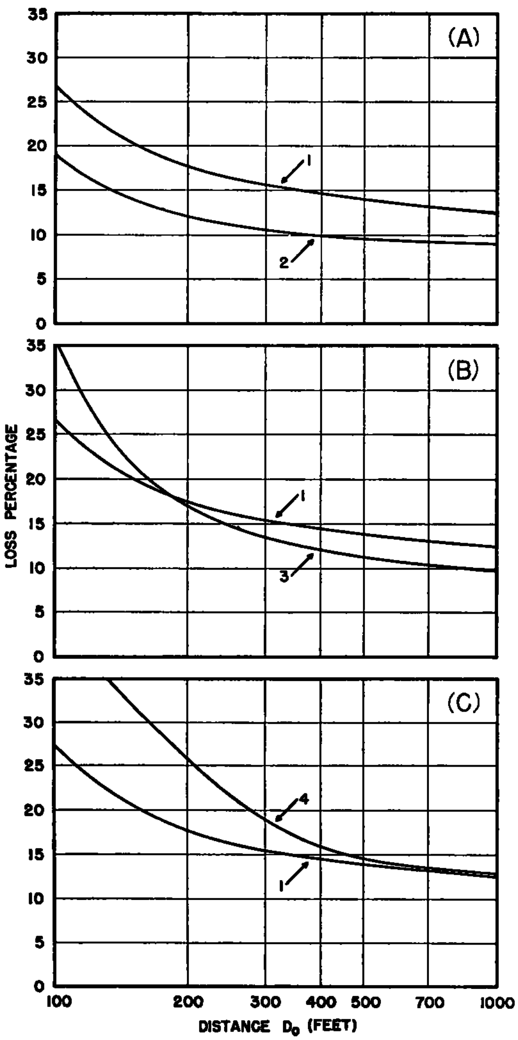

Figure 7. The effects upon visibility distances caused by varying: (A) transmittance of the filter, (B) brand of headlamp, and, (C) size of target. For details see text.

If case (1) is taken as a reference case, it is seen that in cases (2) through (5) only one variable has been changed. As a result of the comparisons between these cases, it was found that varying the target reflectance between 0.075 and 0.15 did practically not change the results, so that a total of three comparisons, namely (1)-(2), (1)-(3), and (1)-(4) were obtained.

The results of these comparisons are shown in Figure 7. Graph (A) of Figure 7 shows the effect of changing the transmittance of the filter; as expected, the losses in visibility distances decrease with increasing transmittance of the filter applied. Graph (B) of Figure 7 shows the effect of changing the brand of headlamp; here the results indicate that the losses in visibility distances are particularly sensitive to changing the isocandlepower distribution of the headlamp. A lamp, for instance, having a steep angular gradient in its isocandlepower distribution (Figure 2), will cause a steep increase of the losses in visibility distances for decreasing D_0-values. This fact, namely the pronounced influence of the type of headlamp upon the losses in visibility distances, may also explain the differences in the experimental results obtained by different observers. Graph (C) of Figure 7 shows the effect of changing the size of the target with the result that the losses in visibility distances increase with increasing target size.

The results of this study indicate that tinted optical media, particularly the darker brands of tinted windshields contribute significantly to the hazard in night-driving, particularly under conditions of low luminances and, consequently, small visibility distances caused by poorly reflecting targets and backgrounds. Similarly dangerous reductions in visibility distances were obtained by Blackwell (3) for twilight conditions, that is, when the driver has not yet turned on his headlamps — a condition which is not considered in this study. Furthermore, because of their relatively high transmittance, the effectiveness of tinted windshields as a protection against glare during the day is negligible. Thus, their only advantage seems to be their ability to absorb radiant heat. As can be seen from Table 1, however, the clear safety plate also absorbs up to 50 percent of infrared radiation between 0.8 and 6 μ, indicating that the advantage of the tinted windshield over a clear one, in this respect, does not seem to warrant increasing the hazards in night driving. The best compromise appears to be the use of dark sunglasses for glare protection during the day, and clear windshields of the highest attainable transmittance. In closing, the author wishes to endorse strongly the recommendation made by Heath and Finch (5), namely that the 70 percent minimum transmittance requirement for windshields in the American Standard Safety Code Z26.1-1950 be reconsidered.

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