UMTRI-94-20

FACTORS INFLUENCING VISIBILITY THROUGH MOTOR VEHICLE WINDSHIELDS AND WINDOWS: REVIEW OF THE LITERATURE

James R. Sayer
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Report No. UMTRI-94-20
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Technical Report Documentation Page

1. Report No. UMTRI-94-20	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Factors influencing visibility through motor vehicle windshields and windows: Review of the literature		5. Report Date July 1994 6. Performing Organization Code
7. Author(s) James R. Sayer and Eric C. Traube		8. Performing Organization Report No. UMTRI-94-20
9. Performing Organization Name and Address The University of Michigan Transportation Research Institute 2901 Baxter Rd, Ann Arbor, Michigan 48109-2150		10. Work Unit no. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address The University of Michigan Industry Affiliation Program for Human Factors in Transportation Safety		13. Type of Report and Period Covered 14. Sponsoring Agency Code

15. Supplementary Notes

The current members of the Affiliation Program are: Adac Plastics, Bosch, Carello Lighting, Chrysler, Donnelly, Ford (Plastic and Trim Products Division), General Motors (Inland Fisher Guide Division), Ichikoh Industries, Koito Manufacturing, Libbey-Owens-Ford, LESCOA, Muth Advanced Technologies, Osram Sylvania, Philips Lighting, PPG Industries, Stanley Electric, United Technologies Automotive Systems, Valeo, Wagner Lighting, and 3M.

16. Abstract

A review of the literature concerning factors that influence visibility and privacy through automotive glass was performed. Thirty-three articles were summarized and critiqued. Critiques were based upon the contribution to the current state of knowledge. While research in this area has been conducted for more than 40 years, substantial controversy remains. This is particularly true of research that addresses the effects of transmittance on driver visual performance.

With few exceptions, the existing research suggests that factors such as transmittance, wear, rake, and dirt all contribute significantly to limiting driver visual performance. The results of studies vary due to the variety of tasks examined, the number of variables involved, and the performance criteria selected. Almost no literature exists that addresses the issue of privacy as it relates to automotive glass.

On the basis of a re-examination of previously reported data, it appears that transmittance has generally a linear effect on driver visual performance with a reduction in transmittance levels from 100% to 50% resulting in a reduction in visual performance of 10-20%.

17. Key Words automobile, critique, dirt, driver visual performance, driving, glare, glazing, heat-absorption, literature review, motor vehicle, privacy, reflectance, spectral properties, tint, transmittance, visibility, vision, wear, window, windscreen, windshield	18. Distribution Statement Unlimited		
19. Security Classification (of this report) none	20. Security Classification (of this page) none	21. No. of Pages 91	22. Price

ACKNOWLEDGMENTS

Appreciation is extended to the members of The University of Michigan Industry Affiliation Program for Human Factors in Transportation Safety for support of this research. Current members of the Affiliation Program are:

Adac Plastics

Bosch

Carello Lighting

Chrysler

Donnelly

Ford (Plastic and Trim Products Division)

General Motors (Inland Fisher Guide Division)

Ichikoh Industries

Koito Manufacturing

Libbey-Owens-Ford

LESCOA

Muth Advanced Technologies

Osram Sylvania

Philips Lighting

PPG Industries

Stanley Electric

United Technologies Automotive Systems

Valeo

Wagner Lighting

3M

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INTRODUCTION

The purpose of this report is to review, critique, and summarize the open literature describing the effects of motor vehicle window transmittance, reflectance, veiling glare, wear, dirt, and spectral properties on driver visual performance and privacy. Thirty-three articles, primarily from the published literature, were examined and summaries provided. Articles that did not include new analytical or quantitative information regarding the effects of tinted motor vehicle windows were only briefly discussed. Articles that reported analytical or quantitative information, including models, were critiqued individually. For each of the experimental research-oriented articles, summaries include, when available, a description of the independent variables, dependent variables, subject population, and results. Abstracts, when available, are provided for each of the articles. In addition, a summary of the literature, as well as conclusions, that are based upon the review are offered.

Allen, M. J. (1974). Windscreen dirt and surface damage effects. *Australian Road Research*, 5(6), 7-19.

Abstract

It is reasonable to assume that the condition of the windscreen has something to do with the ability of the driver to see through it. One study implies that seeing ability is impaired by scratched windscreens, a second evaluates cleaning methods for improving the wetability of the glass surface to improve the ability to see through it, a third evaluates water repellent materials for use on aircraft windscreens and a fourth concludes from three windscreens that surface damage reduces the perceptibility of objects on the roadway. (See text). This study was designed:

(a) to obtain a population sample of automobile windscreen surface damage and dirt accumulation,

(b) to evaluate the ability to see through the dirt and surface damage in a static and dynamic driving situation, and

(c) to evaluate the practicability of resurfacing automobile windscreens.

This research sought to quantify and examine several factors that may influence visibility through motor vehicle windshields including dirt, surface damage, and the practicality of resurfacing damaged windshields. Only that portion of the study that discusses the ability to see through dirt and surface damage in static and dynamic situations is addressed in this review.

Static Experiment

Independent Variables

Windshield condition. Four types of windshields were used, a fifth condition was no windshield. One windshield was new and blemish free with a veiling luminance index of 0.0078. Another windshield was new with dirt applied and a veiling luminance index of 1.25. A third windshield was clean and used, with a veiling luminance index of 0.47. Finally, the fourth windshield was dirty with a veiling luminance index of 1.90. A mixture of dirt and alcohol was sprayed on windshields to simulate dirt that would naturally occur.

Glare. Three levels of glare were produced from a vehicle that was positioned to represent an oncoming car. Glare levels were varied by changing the distance separation between the subject and the oncoming vehicle. No additional information related to the levels of glare was provided.

Dependent Variables

Detection distance. The subject's task was to distinguish the farthest visible target, in a series of targets, while looking through windshields of varying condition. All targets were 30.5 x 30.5 cm black squares with a reflectance of 8%. Targets were spaced 5 m apart.

Subjects

Seven persons participated in this experiment. No additional information regarding subjects is provided.

Results

The author states that dirt and scratches on windshields reduced detection distances at night under conditions of glare. The closer the oncoming vehicle, and therefore the greater the amount of glare, the greater the reduction in detection distance by subjects. The condition in which no windshield was used produced the largest mean detection distance.

Dynamic Experiment

Independent Variables

Windshield condition. In the dynamic test, a clean windshield was used in conjunction with a clean pane of glass and a scratched pane of glass. The windshield in the car was not removable for this study so the extra pane of glass was introduced between the subject and the windshield to simulate a scratched windshield. The clear pane of glass was used for the "un-scratched" condition. The glass panes were 5 cm wide by 30.5 cm in length. Subjects were passengers in the test vehicle.

Dependent Variables

Threshold detection. The first task for subjects in the dynamic test was to press a button linked to a tape recorder as soon as they detected a target located on the edge of the roadway. Targets were 30.5 x 30.5 cm gray squares of cloth with a reflectance of 20%. Tapes were later analyzed to determine detection distances.

Certainty of recognition. Once subjects detected a target they were asked to press a second button when certain there was an object in the roadway, and asked to identify the object.

Subjects

No information about the subject population is provided.

Results

Mean detection distances, at threshold, obtained in the dynamic test ranged from 40 m for the dirty and scratched windshield to 70 m for the clear windshield. Mean detection distances, for certainty of recognition, ranged from 40 m for the scratched windshield to 58 m for the clear windshield.

Critique

In general, not enough information is provided about the state of the windshields to generalize on the influence of windshield dirt or scratches on driver visual performance.

Boyce, P. R., and Gu, Y. (1992). *Calculations of visibility levels and reaction times as a function of light transmittance for four driving scenarios* (Report submitted to the International Window Film Association). Troy, NY: Lighting Research Center, Rensselaer Polytechnic Institute.

Abstract

Calculations of the effect of light transmittance of automobile glazing on Visibility Level and reaction time have been made for a range of parameters, in four simplified driving scenarios. The calculations of Visibility Level used the empirical model of Adrian (1989). The calculations of reaction time used the empirical Relative Visual Performance model of Rea and Ouellette (1988). The four driving scenarios examined were

- the detection of a motorcycle approaching an intersection on a major road, by a driver stopped at an intersection
- the detection of a pedestrian starting to use a crosswalk, by a driver stopped at the crosswalk
- the detection of a child standing behind an automobile, by a driver, using backing-up lights
- the detection of the onset of an external, high mounted stop light, by a driver two cars behind, who is looking through the intermediate vehicle

For each scenario, the Visibility Level of and the reaction time to the target is calculated for a range of ambient luminances, varying from daylight to twilight, and for three driver ages, 25, 40 and 65 years. The results of these calculations are displayed in a series of figures. The results show that decreasing the transmittance of the automobile glazing always reduces the Visibility Level and increases the reaction time. However, the rate of the deterioration depends markedly on the scenario and the conditions examined. The calculations allow quantitative estimates to be made of the effects of glazing and window film transmittance on visibility and reaction time. As such they can be used to guide judgment of appropriate automobile glazing light transmittance standards.

Independent Variables in Modeling

Transmittance. Visibility Level (VL) calculations were performed for transmittance levels ranging from 1% to 100%.

Age. Calculations of visibility and reaction time were made for each of three ages: 25, 40, and 65 years.

Luminance. Calculations of visibility and reaction time were made for each of four levels of ambient luminance: 0.1, 1.0, 10.0, and 100 cd/m^2.

Driving scenario. Four driving scenarios were examined: detection of a motorcycle approaching an intersection on a major road, detection of a pedestrian starting to use a crosswalk, detection of a child standing behind an automobile using backing-up lights, and detection of the onset of an external, high-mounted brake light, by a driver two cars behind looking through the intermediate vehicle.

The following table provides values of target size, contrast, and target exposure time used in the model calculations for each of the four scenarios.

Scenario	Angular target size	Target contrast	Target exposure time
Motorcycle	54.8 min arc* $2x10^{-4}$ steradians§	1.5†	0.2 sec
Pedestrian	452.5 min arc 0.0136 steradians	1.25	0.2 sec
Backing-up/ Child	190.0 min arc 0.0024 steradians	1.25	0.2 sec
CHMSL	2.09 min arc $29x10^{-8}$ steradians	variable	0.2 sec

* Angular size used in Visibility Level calculations.
§ Angular size used in reaction time calculations.
† Contrast is equal to $(L_{max} - L_{min})/L_{min}$.

Dependent Variables in Modeling

Visibility Level. Measures of visibility were based upon the empirical modeling of Adrian (1989), where Visibility Level (VL) is defined as the ratio of a target's actual luminance contrast to its threshold luminance contrast at the same adaptation luminance level.

Reaction Time. Measures of reaction time were based upon the empirical modeling of Rea and Ouellette (1988), where Relative Visual Performance (RVP) is defined as the reaction time for detecting stationary square targets of various sizes and contrasts at differing levels of adaptation luminance.

Results

The results were presented in a series of figures that plot the modeled visibility and reaction time as functions of windshield transmittance for each of the four scenarios described. Assuming the conditions outlined in the various scenarios, and knowing the transmittance of a windshield film/glazing combination, the authors state that values of Visibility Level and driver reaction time can be determined for the three levels of age and four levels of ambient luminance.

On the basis of the work of Adrian (1987) the authors state that a minimum Visibility Level value of 10 is required, but that values ranging between 10 and 20 may result in a slight visibility problem. As for reaction time, the authors state that there is no minimum value that is independent of the scenario. However, for all scenarios, reaction time is shown to increase as a function of decreasing windshield transmittance. The authors leave it up to the reader to determine what level of transmittance, for a given scenario, would result in "acceptable" levels of visibility and reaction time for drivers.

Critique

The authors rely heavily on previous research by Adrian (1987) to determine the necessary values of Visibility Level when assessing the effect of windshield transmittance. The authors state that a Visibility Level between 10 and 20 is necessary "to secure traffic safety," yet further state that this range of visibility is an "intermediate" level that "may cause a visibility problem." Visibility Levels below 10 are said to result in visibility problems. If values between 10 and 20 are simply "intermediate," and one were to take a conservative approach to determining the permissible levels of tinting, then it is possible that a minimum Visibility Level of 20, or greater, should be expected. Results of the modeling for the pedestrian detection task, for the oldest age group (65 years) at the lowest level of ambient luminance (0.1 cd/m^2) never reach a Visibility Level of 20. In addition, the visual performance of drivers older than 65 needs to be taken into consideration.

For every scenario and age group examined by the authors, calculated Visibility Levels exceeded 20 for ambient luminance greater than 1.0 cd/m^2. However, the region that appears to be most critical for determining problematic levels of windshield tinting/glazing, based upon a VL of 20, is between 0.1 and 1.0 cd/m^2. This report would have benefited from additional calculations that considered ambient luminance levels within the 0.1 to 1.0 cd/m^2 range.

Clark, B. A. J. (1993). Day-time hazards of windshield tinting. *Road & Transport Research, 2(4)*, 76-86.

Abstract

From 1970 to 1991, Australian regulations limited motor vehicle windshields to be clear in the Primary Vision Area (PVA), with some tinting allowed in windshield areas outside the PVA and in other vehicle windows. In many other countries, tinting of the whole windshield is permitted.

Worldwide, there are two opposing views on the matter. The anti-tinters, mostly vision specialists, claim that less light in dim lighting conditions inevitably results in making things harder to see, and believe that tinting increases the road traffic accident rate at night. The pro-tinters, often from the motor vehicle industry, dispute the accident hazards and claim improved buyer appeal, harmonization of standards, and modest improvements in air conditioning.

In April 1991, the Australian Transport Advisory Council acted against technical advice on the road safety hazard by directing that tinting be allowed. The driver visual handicap thereby introduced may eventually increase the night accident rate by 2% or more.

It is shown that tinting can also cause hazardous losses in driver vision under day-time conditions, especially when sunglasses are in use, and that the approval of windshield tint has unwittingly interfered with the basis under the Trade Practices Act for prohibiting the sale of sunglasses which are unsafe for drivers.

Further restriction of the current sunglasses safety limits for luminous transmittance and coloration to suit the presence of windshield tinting is impracticable and has been rejected by the standards committee responsible, so that the removal of the road safety hazard requires a return to clear windshields.

The author reviews the history of Australian legislation concerning the use of windshield tinting and its effects. The article addresses the arguments offered by persons both for and against the use of windshield tinting, and points out the hazards associated with tinting. However, the author does not provide any new research either for or against the use of windshield tinting.

Cunningham, G. (1993). After-market-film on passenger car windows and light transmission. In A. G. Gale, I. D. Brown, C. M. Haslegrave, I. Moorehead, and S. Taylor (Eds.), *Vision in Vehicles IV* (pp. 79-88). Amsterdam: North-Holland.

Abstract

In August 1988, producers of an after-market-film, which through application on passenger car windows causes further reduction of light transmission, submitted a petition to the National Highway Traffic Safety Administration (NHTSA) in Washington, D.C. for a change of the current regulation as regards light transmission. Application of after-market-film on all side and rear windows of passenger cars, as propagated by the petitioners, would result in a light transmission of 35% and less, a contradiction to the current regulation in the United States which stipulates a light transmission of 70% on all passenger car windows. NHTSA accepted the petition for discussion without changing the regulation. At the same time, the Safety Administration called on various private and state agencies, organizations, businesses as well as persons active in traffic safety research and related areas to offer their answers and opinions to a series of 85 questions and proposals deriving from the petition. In a study of 78 responses (submitted to NHTSA before September 1989) conducted at the Research Institute A.S.S.e.V. in Cologne, Germany, it was found that two-thirds of these responses are strictly against a change of the current transmission regulation. This report gives an analysis of the major pro and con reasons submitted in the responses to the NHTSA inquiry.

The author categorizes, and provides brief summaries of, the responses that NHTSA received related to the petition for changes in Federal Motor Vehicle Safety Standard 205, which regulates glazing materials. While this paper offers some brief critique of previous studies, it does not provide any new analytical or quantitative results.

Dain, S. J., Pye, D. C., Bogaert, N., Cooper, S. J., Klaunzer, P. M., and Nicolson, A. (1993). The combined colour effects of tinted hydrogel contact lenses, sunglasses and tinted automotive windscreens. *Road & Transport Research, 2(3)*, 74-82.

Abstract

The consequence of a recent move to lower the permissible minimum luminous transmittance of automotive windscreens, without the specification of coloration limits, leads to the possibility for the supply and fitting of windscreens that can significantly affect the detection and recognition of the objects in the road environment and, in particular, traffic signal lanterns.

These effects can be compounded with the coloration effects of contact lenses and sunglasses.

In this study, the potential for compounding the effects of windscreens with sunglasses and contact lenses is demonstrated in theory.

Sunglasses are already restricted in coloration and the need for similar regulation of the coloration of windsrceens is demonstrated.

Decreased luminous transmittance associated with the use of tinted windshields, eyeglasses, sunglasses, and contact lenses. The authors discuss the potential hazards associated with the combinations of light absorbing media, and provide worst-case scenarios involving the combined use of contact lenses, sunglasses, and tinted windshields. No quantitative data related to driver visual performance or sight distance is presented.

The authors conclude that a reduction in luminous transmittance has been associated with the combined use of tinted contact lenses, sunglasses and tinted windshields present a risk to drivers, although the level of risk is difficult to demonstrate. None-the-less, the authors propose that requirements be set which specify limits for transmittance that consider the potential cumulative effect of these items, rather than addressing transmittance requirements in isolation.

Derkum, H. (1991). Stray light in windshields - measurement and effect. In A. G. Gale, I. D. Brown, C. M. Haslegrave, I. Moorehead, and S. Taylor (Eds.), *Vision in Vehicles III* (pp. 107-116). Amsterdam: North-Holland.

Summary

Perception experiments in the laboratory using windshields in varying states of preservation showed that typical stray light characteristics (craters, scratches, traces from the windshield wipers) differ in their effects on perception. Thus, in order to evaluate relevance to the process of perception, it is necessary to consider the specific characteristics of the damage in addition to the stray light mean value.

This means that the question as regards a possible cut-off point for stray light in windshields remains open. First, a physical parameter must be found which will include both aspects in one measured value.

Measurements of the windshields used in laboratory perception experiments when compared with those made with other stray light measuring methods show in an analysis that perception components may only be grasped with physical methods when the concerned windshield is measured in its mounted position. Stray light measurements were thus carried out on mounted windshields in the field. Data were gathered in various regions: in the area of Cologne, in Bavaria, and Norway. Distribution of these data varies. Climate and environmental conditions are the assumed reasons.

Via regression analysis, we found that the average of two measurements represents the condition of a windshield's main visual fields. We plan to investigate the effects of various transmission levels by means of a dynamic perception test. An attempt will be made to find a physical parameter that correlates higher with perception impairment than the mean value under 55 degrees. In order to approach the question of a cut off point from an empirical point of view, crashes during darkness will be studied.

This paper has three objectives. The first objective is the testing of visual perception through a series of windshield samples in various states of wear. The second objective is the physical measurement and characterization of defects that are present in weathered windshields. The final objective is to examine the correlation between the results of visual perception testing and physical measurements of the windshields (i.e., is it possible to establish a relationship between the perceptual and physical parameters of stray light?).

Independent Variables

Windshield wear. Twenty-eight samples of windshield in various states of wear were examined. Damage to the samples that would produce stray light included pitting, damage caused by wiper blades, and scratches. No specific detail regarding the states of wear is provided. Measurements of stray light produced by the various states of wear were made only through that region of the sample which subjects viewed.

Windshield slope. Two levels of windshield slope were examined: 0° and 55°.

Target contrast. Four levels of target contrast were examined: 1:23, 1:2, 1:1.47, and 1:1.25.

Dependent Variables

Visual acuity. Subjects performed a Landolt-ring visual-acuity task, viewing the targets through the windshield samples. The distance of the windshield sample from the subject's eyes was 40 cm. Landolt rings were presented randomly to subjects in six different orientations and at four levels of contrast. The order of presentation for windshield samples was systematically varied. The number of correctly identified targets for each windshield sample served as the performance measure.

Preference ratings. Subjects performed paired comparisons with all 28 windshield samples. The number of times a sample was preferred served as the preference measure.

Subjects

Twenty-eight persons served as subjects in this experiment. All subjects had static visual acuity of at least 20/16. Subjects were also screened for stigmatisms. No additional information regarding the subject population was provided.

Results

The author reported a moderate-to-high level of correlation (r = -0.74 for a 55° slope and -0.54 for 0°) to exist between mean measures of stray light and visual performance on the visual acuity task. Measures of peak stray light, associated with large windshield defects, resulted in considerably lower correlation coefficient values (r = -0.36 for a 55° slope and -0.43 for 0°). Correlations between subject preference and measures of stray light were higher for mean stray light measures (r = -0.81 for a 55° slope and -0.58 for 0°) than for peak measures (r = -0.50 for a 55° slope and -0.60 for 0°). The authors reported that, in general, subject performance on the visual acuity task worsened with increasing amounts of stray light, but that no simple connection between measures of mean stray light and visual acuity could be made. The lack of a simple connection was stated to be due in large part to the variety of windshield defects that existed in the tested samples.

Critique

Despite not quantifying the levels of wear, the author presents some important findings related to the effects of windshield wear on static visual acuity. However, the question remains as to the applicability of these results to a dynamic environment where drivers are subject to a sufficient amount of additional workload. Mean values of stray light that have been derived from only two locations may not correlate well with a person's ability to detect moving objects thought the entire forward field of view (FFOV). The process of obtaining measures of windshield wear (i.e., stray light production) would be greatly complicated if the entire FFOV were to be considered, and further complicated by the additional factor of optical distortion associated with windshield curvature. Despite having included target contrast as an independent variable in the experiment, the author never reported the result of varying the target contrast.

Derkum, H. (1993). Effects of various transmission levels in windshields on perception. In A. G. Gale, I. D. Brown, C. M. Haslegrave, I. Moorehead, and S. Taylor (Eds.), *Vision in Vehicles IV* (pp. 63-68). Amsterdam: North-Holland.

Conclusions

As for the question about a cut-off point for transmission in mounted windshields, the results are not homogeneous. Looking for the lowest value with no significant difference from clear windshields, we found 68% without glare, but 63% with glare. Analyzing the best fitting mathematical model, we could suggest 62% as well. So what we can say from our experiment's point of view is that the exact transmission value, from which drivers' vision becomes significantly worse, lies between 60% and 70%, a result, which corresponds with results from a static perception experiment in the same tunnel carried out by Staatliches Materialprüfungsamt (Federal Materials Testing Agency) in 1990.

We will repeat our experiment during this year, using subjects with an acuity which is on the borderline of exclusion from driving.

Field experiments will follow which will also give an answer to the question as regards a cut-off point for stray light in windshields.

Independent Variables

Windshield transmittance. Thirteen levels of transmittance were examined. Transmittance values range from 35% to 89%, in steps of approximately 5%, as well as one level with no filter (100%). The authors state that not enough windshields were available in the levels of transmittance required, and therefore one windshield served for five levels of transmittance by varying its slope.

Target format. Two target formats were examined. The first was a Landolt ring, and the second was a stripe-pattern of the same diameter of the Landolt ring. Both targets had a contrast of 0.6, where contrast equals object luminance minus background luminance divided by background luminance, $(L_O - L_B)/L_B$.

Glare. Two levels of glare (glare and no glare), intended to simulate on coming headlamps, were examined. The glare source was 0.02 lx at 4° of eccentricity, and was located at a fixed distance of 11.6 m from the subject.

Dependent Variables

Target recognition distance (orientation). Subjects were asked to define the orientation of the target as it approached them at a rate of 0.25 m/s from a starting point 18 m away. Targets were never closer than 5.8 m to subjects. Target recognition for the Landolt ring consisted of correctly identifying the location of the ring's opening. Target recognition for the striped pattern consisted of identifying the angle of the target's stripes. The distance at which subjects could recognize the orientation of targets at each level of transmittance served as the performance measure.

Subjects

Twenty-two subjects, minimum age of 40 years, participated in the experiment. All subjects had a minimum of 20/20 static visual acuity (corrected or uncorrected), and were also examined for stereo vision, visual field, and stigmatic abnormalities.

Results

The author reported that as windshield transmittance values decreased, target recognition distances decreased. In other words, the heavier the tint, the closer the target had to be for the subject to correctly recognize its orientation. Average recognition distances ranged from approximately 15 m for 100% transmittance (no glare and striped target) to 8 m for 35% transmittance (glare and Landolt ring). The data provided showed that subjects could recognize the orientation of the striped target pattern at farther distances than they could recognize the Landolt-ring pattern under all conditions tested. Furthermore, recognition distances decrease linearly with decreasing transmittance levels. However, no statistical analyses were performed concerning these variables.

Analyses of variance and multiple range tests were performed to evaluate the influence of transmittance on target recognition for the striped target only. The results showed a significant difference between the transmittance levels tested in both the glare conditions. Results of the multiple range tests found windshield transmittance levels greater than 68% for the nonglare condition and 63% with glare were not significantly different from the results at 90% transmittance. Conversely, levels of windshield transmittance below 63%, with or without glare, resulted in a significant increase in target recognition distance for the striped pattern.

The influence of glare on subjects' recognition performance was mixed. While glare seemed to influence the recognition of the striped target, the influence is not as evident for the Landolt target. No statistical analyses are provided.

Critique

Subjects appear to have performed the recognition task in the absence of any additional workload. Subjects in the experiment were free to concentrate on target recognition, whereas drivers face a considerably heavier workload. The results of this experiment would be more informative were it to be performed in a simulated driving environment. However, added subject workload would have reduced performance (i.e., recognition distances would have decreased). While some statistical analyses were performed, the results for some independent variables were not analyzed. Furthermore, when analyses were performed, the results are only reported in general terms.

Dietzel, K. (1991). Influence of light energy distribution on night vision through tinted windshields. In A. G. Gale, I. D. Brown, C. M. Haslegrave, I. Moorehead, and S. Taylor (Eds.), *Vision in Vehicles III* (pp. 97-105). Amsterdam: North-Holland.

Abstract

Generally speaking, vision can be regarded as the transfer of optical information, wherein the parameters, Luminosity (or brightness), luminosity differences and object dimensions are transferred to the brain which acts as "information compiler" and "hard disk". Only a few results of our work are presented here.

The problem of "vision in automobiles" is considered here divided into four sections:

* Information transfer in vision
* Influence of tinted glass on vision (especially by night)
* Influence of tinted glass on stray light
* Aesthetic aspects of tinted glass

In this article the author describes a number of elements that influence visual perception through windshields, including tinting, and discusses the use of modulation transfer theory to assess the level of influence. However, no experimental results or analytical models are provided.

Doane, H. C., and Rassweiler, G. M. (1953). Cooperative road tests of night visibility through heat-absorbing glass. *Highway Research Board Bulletin, 127*, 23-44.

Abstract

Seventeen thousand individual observations of "seeing distance" have been made in road tests carried out cooperatively by the Automobile Manufacturers Association, General Electric, and General Motors. The purpose of the tests was to determine, under actual night driving conditions, the effect of heat-absorbing glass on nighttime visibility. Observations were made of the distance at which obstacles could first be seen from cars traveling 40 mph against approaching headlights. The tests were similar to those previously described by Roper except that the seeing task of the observer was made much more difficult in some of these more recent tests by using blacker obstacles, by using a black-top road instead of concrete, and by reducing illumination from the headlights. The average difference in nighttime seeing distance through heat-absorbing glass compared to ordinary windshield glass in these experiments was around 3%. This agrees with the earlier observations described by Roper taken under less difficult seeing conditions.

Independent Variables

Windshield transmittance. A total of six windshields of two different transmittance levels were used. The untinted windshields had transmittance values of 87.5%, 87.0% and 87.0%. The tinted windshields had transmittance values of 73.3%, 72.0%, and 74.3%. The authors do not make clear whether the three windshields in each of the two groups were used interchangeably. All transmittance measurements were made normal to the windshield surface, and any reduction in transmittance associated with installation angle was not addressed.

Target reflectance. Two levels of target reflectance were examined. Twelve targets were cut out of plywood into the size and shape of pedestrians. These targets were then painted dark gray on one side (7% reflectance) and flat black on the other (3% - 3.5% reflectance).

Headlamps. Two sets of headlamps, one used and the other new, were used in the experiment. Both sets of headlamps were sealed beam lamps, although one set had been used for approximately half of its normal life expectancy.

Headlamp aim. In two of the conditions examined, the used headlamps were misaimed 2° below horizontal and the voltage reduced just slightly. The new lamps were misaimed 2° above horizontal and the voltage increased just slightly.

Dependent Variables

Seeing distance. The performance measure was the distance at which subjects could locate and identify targets placed at both the left and right-hand sides of a roadway. The roadway was an asphalt test track, 1.9 kilometers in length. Testing was conducted only on moonless nights when no other illumination, other than that provided from the test vehicle headlamps, was present. The experiment was conducted on four different nights, between sunset and 4 a.m. The authors note that fatigue could have, and likely did, play a role in the results.

The procedure was similar to that employed by Roper (1953) in that two test vehicles started from opposite ends of the test track and drove towards each other at a rate of 64 kph. The vehicles had high-beam headlamps on until they were 458 m apart, at which time they switched to low-beams. Three subjects were in the front of each of the two test vehicles, one drove and the remaining two were observers. Subjects used one of three switches to record, via a paper-tape recorder, when they detected a target.

Subjects

A total of six persons participated in this experiment. Four subjects had 20/20 or better static visual acuity, corrected or uncorrected. The remaining two subjects' acuity was 20/50 and 20/60, respectively. No additional information regarding the subject population was provided.

Results

The independent measures listed above were not systematically controlled by the experimenters in this study. Therefore the experiment resulted in four separate conditions. The major findings for all four conditions are presented in the table below.

Condition	Seeing distance (m) Un-tinted	Seeing distance (m) Tinted	Difference Meters	Difference %
1	105.5	103.7	1.8	2
2	59.5	58.3	1.2	2
3	73.8	71.7	2.1	3
4	92.4	88.4	4.0	4

Condition 1. In the first condition the only variable examined was windshield transmittance. Subjects viewed the targets at 7% reflectance; new headlamps were used in the test vehicle (not misaimed). The result of a decrease in windshield transmittance on the order of 14% resulted in only a 2% decrease in seeing distance.

Condition 2. In the second condition the test vehicle had used headlamps as installed (not misaimed), and the target reflectance was reduced to 3%. The use of lower reflectance targets and reduced headlamp illumination resulted in shorter seeing distances than were observed in condition 1. However, the difference attributable to windshield tinting was only 1.2 m (2% of the seeing distance).

Condition 3. The third condition examined the effect of reducing the illumination from the test vehicle headlamps and increasing the glare from an opposing vehicle's headlamps, while target contrast was held at 3%. The test vehicle was equipped with used headlamps, and the opposing vehicle was equipped with new headlamps. The test vehicle's headlamps were misaimed 2° low, and the opposing vehicle's headlamps were misaimed 3° high. The resulting seeing distances were less than those observed in condition 1, but greater than those found in condition 2. The difference attributable to windshield tinting was 2.1 m (3% of the seeing distance).

Condition 4. The fourth condition, again, examined the effect of reducing the illumination from the test vehicle headlamps and increasing the glare from an opposing vehicle's headlamps, while target contrast was held at 3%. In this condition the test vehicle was equipped with new headlamps, and the opposing vehicle was equipped with used headlamps. The test vehicle's headlamps were misaimed 3° high, and the opposing vehicle's headlamps were misaimed 2° low. The resulting seeing distances were greater than those observed in condition 3, but less than those found in condition 1. The difference attributable to windshield tinting was 4 m (4% seeing distance).

Overall results. The authors reported that seeing distances for individual subjects varied considerably, independent of a subject's static visual acuity. The reduction of target-to-background contrast, decreased headlamp output, and increased glare from oncoming vehicles all resulted in significantly decreased seeing distances. However, the difference in seeing distances observed between tinted and untinted windshields was not of practical significance. The authors state that while a 3% decrease in seeing distance can be attributed to a reduction in windshield transmittance of 14%, they believe that drivers adjust their speeds at night to account for driving conditions (including visibility).

Critique

While large numbers of observations were included, in part to overcome some of the problems encountered by Roper (1953), relatively few subjects participated. In addition, the authors reported that subjects were fatigued. More importantly, only two levels of windshield transmittance were examined. The levels of transmittance examined, roughly 87% and 73%, were not sufficient to address the question of how windshield tinting influences seeing distances, and the authors never address the effect that oncoming headlamps had on target contrast. Additional levels of lower windshield transmittance needed to be examined. For the most part, the authors did not perform any statistical analyses on the data obtained from this experiment. The results were frequently reported on the basis of "examining" the data. In addition, the absence of a systematic control of the independent variables reduces the data's value.

Dunipace, D. W., Strong, J., and Huizinga, M. (1974). Prediction of nighttime driving visibility from laboratory data. *Applied Optics, 13(11)*, 2723-2734.

Abstract

The application of laboratory threshold visibility data to the subject of driving visibility with heat absorbing glass has been reviewed in an attempt to resolve excessive differences between calculated predictions and road test observations. New calculations are described that yield predicted losses of visibility distance due to the use of heat absorbing glass rather than regular glass in automobile windshields. The predicted losses agree satisfactorily with the observed losses for road tests, which average approximately 3%. The new calculations have made use of a revised visual exposure interval of 1/5 sec corresponding with five visual fixational pauses per second and a new simulation model that assumes that the target to background contrast increases with reduced headlamp to target distance.

This article presents the results of an attempt to model the effects of heat-absorbing motor vehicle glass. This model relies heavily on the laboratory data obtained by Blackwell (1954), and compares model calculations to a limited amount of field data. Model parameters include target contrast, luminance level, target size, and observation time. The authors report general agreement between predicted and observed results.

Dunn, A. R. (1973). *The effect of light absorbing media on driver visual performance* (Final report No. DOT/HS 800 815). Huntsville, AL: Brown Engineering Company, Inc.

Abstract

Analytical and experimental determinations were made of the effects of windshields and filters on probability of detecting objects and on seeing distances after dark. The analytical study showed that visual degradation increases more rapidly for filter transmittances less than 79 percent. The experimental study showed that seeing distances through clear windshields are greater than those through tinted windshields; the difference is less than 15 feet. The seeing distances attained by individual observers ranged from 200 to 600 feet.

The possibilities of eye damage from looking at the sun through automobile glasses were studied. Damage can be sustained through all types of glass studied. In particular, the shaded bands at the tops of windshields may increase the probability that a driver will sustain a retinal burn. Recommendations for automobile glass transmittances were made from the results of the analyses.

This report presents both empirical and analytical results on the effects of windshields and filters on probability of detecting objects and on seeing distances. The analytical portion of this report will only briefly be discussed; the primary focus will be on the results of the experiment conducted.

Analytical Discussions

The author discusses a number of issues to be considered when attempting to model or study vision. The report also addresses the issue of eye damage produced by excessive solar radiation. Under the heading of "Factors Affecting Visual Ability," the author discusses how factors such as background luminance, visual acuity, age, and color deficiencies influence a person's ability to drive. This portion of the report is fairly comprehensive, and well written, but some of the material is dated. It would serve as a good overview for persons with little background in visual capabilities as they relate to the task of driving.

Experimental Investigation

Independent Variables

Age. Two groups of subjects, ages 20 - 35 and 50 - 65, participated in the experiment.

Transmittance. Two levels of windshield transmittance were examined in the experiment. The first windshield, "clear," had transmittance values of 0.86% and 0.82% for windshield installation angles of 26° and 56°, respectively. The second windshield, "tinted," had transmittance values of 0.74% and 0.68% for installation angles of 26° and 56°. All transmittance values are based upon measurements made parallel to the line of sight, as opposed to perpendicular to the windshield surface. The order in which levels of transmittance were presented to subjects was partially blocked.

Target. Almost all trials were conducted using a small neutral-colored square as the target. A number of different sized targets were used in the experiment in order that target size could be maintained at 4° of visual angle, regardless of individual differences in seeing distance. For some of the subjects an additional short sequence of trials used a human figure dressed in gray as a target. The reflectance of the square target was 9.3%, and the reflectance of the "pedestrian" figure was 3%.

All targets were viewed under lighting conditions simulating automotive headlamps, with subjects seated behind the windshields of interest. The experiment was conducted on a straight, quarter-mile long, roadway with very little artificial illumination (0.68 cd/m^2) other than that provided by the simulated automobile headlamps. Luminance contours of the headlamp illumination patterns are provided.

Dependent Variables

Detection. The procedure employed in detecting the presence of targets was a "yes-no" task to determine threshold seeing distances. Targets were presented for a fixed period of time (0.7 s) over numerous viewing distances. Subjects were instructed to state whether or not they detected the target. A small percentage of the trials were catch trials, where no target was shown.

Subjects

A total of 35 subjects was involved in the experiment. All subjects had a minimum of 20/40 visual acuity, corrected or uncorrected, although most subjects had acuity of 20/30 or better. The use of tinted contact lenses or eye glasses was not allowed. Only naive subjects participated.

Results

The authors reported that threshold seeing distances varied widely across subjects. Differences in seeing distance that were associated with viewing the target through a tinted vs. clear windshield were small, thought in the direction that would be anticipated. However, the standard deviation of thresholds obtained across subjects was so large that the difference between the mean seeing distances between windshields was small in comparison. Due in part to the experimental procedures employed, the author reported that the data were too noisy to determine exact seeing distances. The author does, however, suggest that the difference in detecting the target between the two windshields translates into less than 4.58 m of seeing distance. The range of seeing distance across subjects was 61 m to 183 m.

The author reported no reliable correlation between subject age and seeing distance, though there was a slight tendency for subjects with better visual acuity to have longer mean viewing distances. It is suggested by the author that these results were, in part, the result of limited data (number of subjects). As for the pedestrian target that was presented for a limited number of trials, the results indicate that this form was detected at greater seeing distances than was the square target. However, this is likely due to a dramatic difference in target size.

Critique

While the analytical work of the author addressed a wide range of transmittance values, only a narrow range of transmittance was examined in the experimental portion of the study (0.68% to 0.86%). This limitation likely contributed to no significant differences being found between seeing distance across transmittance levels. On a positive note, this investigation was one of only a few that attempted to control for the size of the stimuli as a function of seeing distance.

Filkins, L. D. (1979). *Tinted windshield involvement among CPIR accidents* (Final Report No. UM-HSRI-79-16). Ann Arbor, MI: The University of Michigan Highway Safety Research Institute.

Abstract

The 9222 vehicles in the CPIR3 data set were examined for evidence that would indicate whether tinted windshields cause or prevent accidents. Windshield-tint condition was known for 4185 vehicles, and these were almost evenly split between clear and tinted windshields.

The proportions of tinted windshields among these accident vehicles were smaller than those for U.S. produced vehicles of comparable model years. Weighted least squares regressions showed that the proportion of drivers having tinted windshields increases as age increases, but that there are no statistically significant differences between daytime and nighttime conditions. It was concluded from the regression analyses that the data do not support the hypothesis that older drivers are negatively influenced at night with tinted windshields.

It was also found that tinted windshields are associated with a variety of driver and vehicular variables believed to influence accident risk. Because of these uncontrolled, confounding variables, and because of methodological limitations associated directly with the CPIR file, it is not possible to isolate the influence of windshield tinting in accident causation or prevention. A controlled study is needed to make such a determination.

This paper reports that little evidence exists to support either the hypothesis that tinted windshields cause automobile accidents or the hypothesis that they prevent accidents. The author states that too many uncontrolled and confounding variables existed in the data as a result of the various methods used in accident reporting. Therefore, caution should be used when drawing any inferences from this report.

Freedman, M., Zador, P., and Staplin, L. (1993). Effects of reduced transmittance film on automobile rear window visibility. *Human Factors, 35(3)*, 535-550.

Abstract

Deeply tinted window glass transmits less light than less deeply tinted glass and therefore reduces driver visibility. The task of looking through the rear window for hazards before backing a car was simulated in a laboratory setting with five targets (car, bicyclist, pedestrian, child, and debris) shown to drivers (ages 18-55, 56-75, and 76+) at various combinations of luminous transmittance of the windows and luminance (brightness) contrast of the targets. Analyses showed that the frequency of correct target detection varied by target. The car was always detected, but detection probability decreased with reduced luminous transmittance for the child and roadway debris targets. For the bicyclist, pedestrian, child, and debris targets, detection probability decreased with lower luminance contrast and for older age groups. The results suggest that the safety of backing maneuvers is compromised for all drivers at the darkest tinting levels studied. This is particularly true for elderly drivers for tinting levels darker than the 70% minimum luminous transmittance required by federal standards.

This research examined whether reduced transmittance of automobile windows degrades visibility of low and medium contrast hazards that are likely to be found to the side and rear of passenger cars.

Independent Variables

Transmittance. Four sets of 6 mm thick plate glass side and rear windows, professionally tinted, were used. Subjects also observed the targets without glass to simulate 100% transmittance. Levels of transmittance were presented to all subjects in descending order.

Panel number	Transmittance (%)
1-no panel	100
2	69
3	53
4	36
5	22

Contrast. Five targets were presented as scaled-perspective slide images: a bicyclist, a pedestrian, a seated child, a vehicle, and an 18 cm high object representing highway debris. Two levels of contrast were present for each target. These high and low contrast values were obtained by varying clothing and colors on the targets. One contrast level varied from 0.67 to 0.90 and the other level varied from 1.67 to 3.76. Contrast was defined as $L_O - L_B/L_B$. For each trial, as well as between trials, an average background luminance of 1.26 cd/m^2 was present, designed to simulate twilight.

Target	Target contrast (%)
Car	0.73 , 3.76
Bicyclist	0.90 , 2.38
Pedestrian	0.72 , 2.02
Child	0.79 , 2.88
Debris	0.67 , 1.67

Age. Three age groups were examined (see *Subjects*).

Dependent Variables

Target recognition, detection and response latency. Fifty target trials and 50 distractor trials, randomly ordered, were presented for each subject at each transmittance level. Image size represented separation distances as well as viewing angles that would simulate potential conflicts of a driver backing out of driveway onto a street.

Subjects were seated in a simulated vehicle cab with a single driver's seat, with interior and window dimensions that were similar to a common midsize American sedan. Slide projectors presented target images on projection screens over the background luminance. Between trials, subjects looked at a red LED light until a verbal instruction of "ready" was given, asking subjects to check whether or not it was safe to perform the driving maneuver. When a subject detected the presence of a person or object, he or she was asked to push a response button as soon as possible, and describe what was seen and where it was located.

Targets were presented to the rear of the simulated car, and with the exception of the seated child and debris, were also presented in the two zones located to the sides of the simulated car. While each trial was presented in a unique location within each search area, all presentations of a given target were of equal visual angular size, so as to simulate being situated on a common arc within in the search area.

Responses were coded in one of three ways: *full recognition* indicated that the subjects detected the target, indicated the correct location, as well as the correct identification of the target. *Detection* indicated that the subject detected the presence of the target, indicated the correct location, but was not correct in identifying the target. Finally, *incorrect* responses included false alarms and missed detection. Stimulus duration lasted a maximum of 10 s. For each test, subjects were asked to respond with as much certainty as they would in actual driving conditions.

Subjects

A total of 48 subjects participated in the study. Twenty-three of the subjects were female, and 25 were male. Each subject had 20/40, or better, static visual acuity and a valid driver's license. The age distributions of the subjects are outlined below.

Age group	Male	Female	Mean age
18-55	11	13	37.5
56-74	7	5	68.9
75-90	7	5	79.8
TOTAL	25	23	62.6

Results

Due to several critical procedural errors in the design of the experiment and its apparatus, approximately two-thirds of the data that the authors originally intended to collect had to be discarded. The data that remained provided the following findings:

1. The probability of detection was largely dependent upon the target.
2. Contrast and transmittance, as well as transmittance and age, interact nonlinearly in their effects on detection probability.
3. The condition of low contrast with the pedestrian target caused the largest decreases in visual performance.
4. Decrements in detection probability caused by reduced transmittance were greater for older subjects than for younger subjects, and were greater for lower contrast targets when compared with higher contrast targets.

The authors comment that these results provide some evidence that the safety of backing maneuvers may be reduced significantly in cars with tinting treatments that decrease rear window transmittance to a level of 53% or less. Furthermore, they state that older drivers may experience a regular and large increase in the risk of not detecting low-contrast objects when window transmittance is reduced below the current 70% federal standard.

Drivers (of all ages) made incorrect responses at all levels of tinting below the current standard, even for response times of up to 10 s.

Critique

The authors comment that the subject group of ages 18-55, consisting of 24 subjects, was combined for convenience in analyzing the data. It would seem that comparison of data from young, middle-age, and older people would have been more informative than grouping all of the subjects 55 and under together.

Subjects seemed to have a difficult time with some of the tasks, experienced procedural confusion, and often were said to press the response button before detecting targets. To make matters worse, many of the targets were projected in places that could not be seen by the subjects (see below). By commenting that subjects had insufficient practice, the authors indicated that they did not complete enough pilot testing before beginning, resulting in the omission of results.

The results that were omitted were a major portion of the study. In the paper, the authors commented that targets displayed for side-rear-window viewing were often obscured by A, B, or C pillars of the simulated vehicle. Because the targets were often obscured, the authors treated side-window presentations as distracter stimuli and did not analyze those results further.

The trials were presented in descending order of transmittance. It is unclear as to why the authors chose this method of presenting transmittance levels. The authors stated it was partly for convenience (as they did not have to change the window panels for each trial), as well as to permit the subjects to adapt more slowly to the ambient illumination level. Subjects were only dark adapted for 5 minutes, which is a rather short period of time given the low level of ambient illumination. Targets did not appear to be illuminated by back-up lights. Thus, the simulated vehicle did not contain all driving conditions present in everyday driving.

Because testing did not include all combinations of the independent variables, the authors could not show actual detection probabilities. The model estimates that are given are based only on those combinations examined, leaving to question the validity of the model. In addition, while the authors stated that they collected response latency data they do not report these results.

Haase, O., Helmers, G., Schneider, W., and Timmermann, A. (1989). *Vision impairment by worn windshields during night time driving* (SAE Technical Paper Series No. 890686). Warrendale, PA: Society for Automotive Engineers.

Abstract

The paper examines the role that the condition of the windshield plays in night-time accidents. It draws attention to the fact that windshields are subject to wear during the life of the car. An instrument is presented, the stray light analyzer, which measures the stray light caused by these defects. Field tests show that badly worn windshields reduce the distance at which objects on the road can be seen by the driver. A procedure to collect data on night-time accidents is proposed that may allow an estimate of the percentage of night-time accidents that could be avoided by keeping windshields clean and the benefits in terms of saved lives that can be gained by replacing windshields when they reach a certain amount of wear.

This article discusses the effects of stray light produced by windshield damage and wear. Although it is a good overview on the effects of stray light, it does not present any new research related to this topic.

Haber, H. (1955). Safety hazard of tinted automobile windshields at night. *Journal of the Optical Society of America, 45(6)*, 413-419.

Abstract

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, 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 of 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.

This article is an early analytical attempt to understand the relationship between seeing distance and target contrast, and how target contrast is reduced through the use of windshield tinting. However, no experimental results are provided.

Heath, W., and Finch, D. M. (1953). Effect of tinted windshields on nighttime-visibility distances. *Highway Research Board Bulletin, 68*, 1-15.

Abstract

In the past several years there have been developments in the glazing of motor vehicles that may affect the visibility distances of roadway obstacles. These developments have been made primarily to provide a glass which is effective in reducing radiant-heat transmission into a vehicle. Chemical compositions, usually utilizing iron, are employed so the glass will absorb a large quantity of infra-red radiation. The changes made to reduce the heat transmission of the glass also reduce the transmission of light in the visible region if the glass is to be at all effective, since most of the heat of the sun is radiated in the visible spectrum. In general, the absorption of infra-red radiation causes the transmittance for safety windshields to be reduced from values in the order of 87-1/2 to 89-1/2 percent for standard safety plate to values in the order of 71 to 73 percent for heat-absorbing and tinted safety plate with using a tungsten filament light source at a color temperature of 2,848 K.

In addition to increasing the heat absorption of the glass itself, other changes have been made in the plastic sheets used to laminate the safety glass. Tinted colors are used in order to increase the comfort of daytime driving. Some of the tinted plastic laminations have a uniform density while others have a graduated density with greatly reduced transmission in a narrow band at the top serving to reduce sky glare.

State officials faced with the problem of approval of safety glass have had to appraise the effect of various glazing materials on the safe operation of motor vehicles. The usual basis for such appraisal is tests made in accordance with American Standards Association specifications (1). The test normally made on the glazing materials cover the physical factors of strength, stability, quality, and light transmittance. The tinted and heat-absorbing glass produced by the principal manufacturers and now on the market have been found to conform to the ASA Safety Code.

The subject in question is the effect on visibility distances of safety glass having a light transmittance that has been purposely reduced to approximately the ASA minimum of 70 percent. Is the present minimum an adequate requirement, or is it so low as to increase the hazards of night driving when windshields barely meeting the specification are used in place of presently available safety glass having greater light transmission properties?

Experiment One

Independent Variables

Transmittance. Two windshields were employed in the experiment. The first was untinted with a transmittance of 89% measured perpendicular to its surface, and the second was tinted with a transmittance of 71%. When mounted in the test vehicle, the levels of transmittance for the untinted and tinted windshields were 86% and 69% respectively. The slope of the windshield was 45°.

Target. Targets consisted of a wide variety of items including boxes, boards, and buckets. The characteristics of these targets, the number of items presented, and where they were located varied across subjects. This variation was not controlled.

Dependent Variables

Detection (seeing distance). The subjects' task was to press a button when they detected a target, and press the button a second time when the test vehicle passed the target. The test vehicle traveled at a rate of 80 kph in the right lane of a closed, two-lane highway. Targets were placed along the right-hand side of the road. When subjects pressed the response button, marks were made on a continuous paper tape that was driven via connection with the vehicle's transmission. Measurements of seeing distance were transcribed from the paper tape, and readings were reliably made to within 1.5 m. Dimensions of the targets, but no reflectance characteristics, are provided. Data collection took place at night, although the level of illumination provided by the moon varied across nights when different subjects participated. Low-beam headlamps were the primary source of target illumination.

Subjects

Three persons participated in the first experiment. Two persons wore eyeglasses (one pair was green-tinted), and the third had normal vision without correction. No additional information regarding subject characteristics is provided.

Results

The authors calculated the arithmetic mean and standard deviations for seeing distances for each windshield for all targets. Because the targets varied across subjects, the results are generalized. Differences in seeing distance for each of the targets were compared within-subject for the two levels of windshield transmittance. However, the authors report that the size of the standard deviations and the small number of observations on which they were based makes their computation unreliable.

While mean seeing distances were greater in most instances for the tinted windshield than for the clear, no reliable trend was observed across all targets. It was also reported that there was no significant difference in seeing distance associated with having conducted testing on separate nights when different phases of the moon resulted in varying levels of ambient illumination. The authors state that the level of experimental error associated with subjects' pressing the button to indicate the location of targets contributed to the inconclusive nature of the results.

Experiment Two

Independent Variables

Transmittance. The same levels as in the first experiment were examined in the second experiment.

Dependent Variables

Detection (seeing distance). The same task that was employed in the first experiment was used in the second. However, in this experiment all targets were identical. Targets were 30.5 x 28 cm boards, covered with gray cardboard, having a 26% reflectance. The test vehicle drove in the left-hand lane of the same, two-lane highway, and the targets were placed in the center of the right-hand lane. In addition, the vehicle speed was slowed to 65 kph for this experiment.

Subjects

The same three subjects from the first experiment took part in the second experiment.

Results

While the authors note some difficulty associated with the roadway surface that resulted in different targets being illuminated by varying portions of the headlamp beam, the general trends of the results suggest that seeing distances were greater for most targets when the windshield was clear. In the end, the authors state that it is not feasible to assign a percentage of difference in seeing distance associated with the use of the two levels of transmittance. Furthermore, no consistent relationship between transmittance and seeing distance could be shown. However, the authors state that the tinted windshield appeared to cause a reduction in seeing distance for night driving. Triggs (1988) reported that a subsequent analysis of these results was performed, and that an analysis of variance found significant differences to exist between the tinted and untinted windshield. Triggs also reported a significant interaction between windshield tinting and the direction the vehicle drove (east vs. west bound).

Critique

Because of to the absence of control for both dependent and independent measures, the findings of this report are of little more than anecdotal use by current standards. However, considering when it was performed, this research provided early insight into the difficulties surrounding the question of windshield tinting. Much of the variance observed was likely the result of the experimental methodology selected. Requiring subjects to press a response button in order to indicate not only when the target was detected but also when it was passed certainly introduced much of the variance into the results. In addition, the paper tape mechanism used to record subject responses was only accurate to within a range of 1.5 m. Finally, the number of subjects was small.

Helmers, G., and Lundkvist, S.-O. (1988). *Detection distances to obstacles on the road seen through windscreens in different states of wear* (Final Report, No. 339A). Linkoeping, Sweden: Statens Vaeg-och trafikinstitut.

Abstract

The importance of windscreen wear for driver visibility in vehicle lighting has been studied. Windscreen wear is related to the straylight level of the windscreen. Light measurements of straylight levels in windscreens were carried out by a special instrument and by a laboratory method. Detection distances in vehicle lighting to targets on the road were studied in a series of full-scale experiments. In these experiments opposing situations between two vehicles on the road were simulated. The windscreens were exchanged between trials.

Through a series of experiments this research examined the effect of stray light levels of windshields on detection distances for obstacles.

Independent Variables

Stray light. Four windshields that produced varying levels of stray light resulting from wear, and one null case, were examined. Stray light was assessed using the Straylight Index (SLI) defined by Timmerman and Gering (1986).

Stray light level	Windshield condition	SLI value
1	New	0.36
2	Worn	1.08
3	Worn	1.75
4	Very Worn	3.04
5	null	0.00

Target luminance. Three targets that were 0.4 m^2 and covered with woolen cloth were examined. Targets varied in color and luminance factor. However, it is not clear what luminance factor represents. The authors state that targets were viewed at levels of ambient illumination corresponding to nighttime driving in rural areas. Furthermore, no additional light sources were present in the visual field, with the exception of lights from an opposing stationary vehicle.

Target	Color	Luminance factor
1	Black	0.03
2	Dark Gray	0.07
3	Light Gray	0.18

Glare. Four levels of glare from a stationary, but opposing, vehicle were examined. The headlights of the experimental vehicle were correctly aimed, with a vertical misaim of + 0.05°.

1. Weak parking lights (no disturbing stray light luminance)
2. Glaring low beams (misaimed 1.5° high)
3. Correctly aimed low beams
4. Correctly aimed high beams

Independent Variables by Experiment

Experiment 1. Two levels of stray light (SLIs of 0.36 and 0.00) and two levels of glare (1 and 2) were examined. All targets had a luminance factor of 0.07. There were four repetitions per subject.

Experiment 2. Two levels of stray light (SLIs of 0.36 and 3.04), two levels of glare (1 and 2) and all three levels of luminance factor were examined. There were four repetitions per subject.

Experiment 3. Three levels of stray light (SLIs of 0.36, 3.04, and 2.50) and all four levels of glare were examined in this experiment. All targets had a luminance factor of 0.07. There were four repetitions per subject.

Experiment 4. All four levels of stray light and two levels of glare (1 and 2) were examined. All targets had a luminance factor of 0.07. There were four repetitions per subject.

Dependent Variables

Detection distance. Subjects were asked to drive down the center of their lane at a constant speed and press a hand-held push button device as soon as they detected a target. Targets were always located to the right of an imaginary roadway edge. To provide subjects with incentive, the fee that subjects received was reduced by a set amount for each button press for which there was no target. The only marking on the roadway was a nonreflective center line.

Subjects

A total of 14 subjects participated in the study, 12 students and 2 employees at the Swedish Road and Traffic Research Institute, the ages of which are outlined below. Subjects were not visually screened, and were accepted if they reported having normal vision, with or without correction. Some subjects participated in more than one of the experiments. Three subjects participated in each of the first three experiments, all in one car at the same time with an additional driver and experimenter. During the fourth experiment, 3 groups of 3 subjects participated, resulting in a total of 9 subjects. No detailed information was given as to how all 14 subjects fit into the overall experimental design (i.e., some subjects must have participated in more than one experiment).

Age group	Number
22-26	12
34	1
49	1

Results

Experiment 1. The results of this experiment indicated that driving with a new windshield introduces a small reduction in visibility as compared to driving with no windshield at all. Detection distance to the targets detected through the new windshield was reduced to 97% of the no windshield condition when the glare source was only from parking lights. When the glare source was from the misaimed low beams, detection distance was reduced to 98% of the no windshield condition.

Experiment 2. The results of this experiment showed a general tendency for stray light produced by worn windshields to cause a considerable reduction in detection distance. This tendency was seen for both the parking lights and glaring low beams, for all three levels of target luminance. The reductions in detection distance for opposing low beams tended to be larger when compared with opposing parking lights, as was the case for dark targets when compared with bright targets.

Experiment 3. A considerable reduction in detection distance was observed for two levels of stray light when compared to that produced by the new windshield. There were small, if any, differences in detection distance between high levels of stray light. There was a tendency for detection distances to be shorter when large amounts of stray light and glare were present.

Experiment 4. When presented graphically, the results indicate that the curve for the detection distance of each windshield has the same rank order as the SLI values of these windshields. Another important result was that the relative detection distance was found to be linearly related to the mean SLI values of the windshields.

A within-subjects analysis of variance found significant main effects for levels of stray light, target luminance, and glare. Furthermore, stray light and target luminance were significant for each level of glare. A strong interaction was found in the opposing glare condition. The difference between windshields was found to increase with a decrease in distance between the vehicles.

The authors indicated that more research needs to be done to verify these results, as they felt that the data collection was not large enough to establish a generalized linear relationship between the stray light level and the decrement of detection distance found in experiment 4.

Overall, these experiments indicated that worn windshields, when compared with new windshields, caused a decrease in visibility of 9% to 25%. Furthermore, linear relationships existed between the windshield's stray light level and the decrement in detection distance.

The author's hypothesis was indeed confirmed with the results of this study. The decrease in visibility of 9% to 25% is large enough to cause some difficulty in perceiving obstacles in the road. Furthermore, the authors comment that a reduction in the output from the headlights by 50% and 80% reduces low beam visibility by about 10% and 25% respectively, indicating that a decrease in visibility of 9% to 25% is a large decrease indeed.

Finally, the authors commented that this reduction in visibility, especially when combined with other factors, such as windshield dirt, rain, inside film, tint, and large windshield angles, might result in unacceptable reductions of driver visual performance they suggest that further research needs to be done to study these issues more completely.

Critique

All but two subjects were young (22-26 years of age). It would be interesting to see if older drivers would give similar results. In addition, it was not clear where subjects sat; with a driver it would seem difficult for four people to sit in the front seat of a car and get similar views.

Huber, G. (1988). *Physical characteristics of heat absorbing glass and their influence on the driver* (SAE Technical Paper Series No. 885052). Warrendale, PA: Society for Automotive Engineers.

Abstract

The characteristics of heat-absorbing glass for passenger cars are described with regard to climate perception and visibility of the driver, both of which are important aspects of active safety. Such modern types of glass reduce the transparency to heat and at the same time maximize light in the visible spectrum. To be in a position to quantify the advantages and disadvantages in the visible spectrum as regards transparency, dazzling, reflectance and diffused light, practical road test runs were carried out on the same public roads under different conditions in light and climatic environmental. The tests comprised physicotechnical, physical, and psychological data with regard to driving behavior of and strain on the drivers. The results confirm the predominance of advantages of heat absorbing glass and provide indications as to optimizing the side and rear windows by increasing the degree of heat-absorbing.

This research sought to confirm possible positive benefits of heat-absorbing glass for passenger cars by examining its influence on driving behavior and the physiological state of the driver.

Independent Variables

Transmittance. Three vehicles, with different windows in each, were used in the study. With the exception of the window transmittance, the three test vehicles were identical. Subjects drove the vehicles in realistic traffic conditions and were not informed of the aim of the study or the type of windshield present. Subjects drove a total of 12 times, four each per transmittance level. One vehicle was equipped with a clear glass windshield, a second with a heat absorbing windshield, and the third was equipped with a heat absorbing windshield, side and rear windows. The percentage light transmittance of the windows for each vehicle is shown in the table below.

Car	Windshield	Side front	Side rear	Rear
1	89	90	90	90
2	81	74	74	74
3	81	74	60	40

Environmental conditions. Four environmental conditions were examined: brightness, heat, dusk, and darkness. Each subject drove each level of transmittance under each of the environmental conditions. This combination resulted in 12 drives per subject along a standardized route.

Dependent Variables

Operational variables. Four operational variables (vehicle control measures) were obtained for each transmittance and environmental condition combination:

- vehicle speed
- longitudinal acceleration
- transverse acceleration
- steering angle

Stress indicators. During each drive, four physiological measures were obtained. Physiological data were used to assess the stress a driver experienced and, ultimately, whether or not a driver felt safe while driving.

- heart rate
- skin temperature
- breathing rate
- muscular tension

Behavioral adaptation. Subjects were assessed for adaptation to traffic in the following areas. However, it is unclear how these dependent measures were assessed.

- directional stability
- checking for danger
- signaling
- merging
- observing cyclists
- adaptation to other vehicle's speed
- appropriate speed
- jeopardizing safety
- interaction
- rear-view mirror observation
- observing exterior mirror

Driving behaviors. Each subject was assessed in the following areas of driving behavior. Again, it is unclear how these dependent measures were assessed.

- starting off
- overtaking
- accelerating
- lack of confidence
- incidents
- emotional signals
- observing regulations
- peripheral activities
- consideration of pedestrians and cyclists
- lateral distance to other road users
- lateral distance to other obstacles
- braking
- negotiating intersections
- distance to forward vehicle
- making use of opportunities
- anticipation
- observing following traffic
- tension
- driving style

Subjects

Fifteen subjects participated in the experiment. No additional information about the subject population is provided.

Results

The authors report that the physiological data indicate the stress of driving is lower with heat-absorbing windows than with clear windows during daylight hours. However, in the dusk environmental condition, the breathing rate of drivers did indicate a higher level of stress. On the basis of the behavioral data, the author concludes that vehicles with heat-absorbing glass promote a more controlled driving style than clear glass. The behavioral data was broken down into five factored groups in order to describe the driving behavior of the subjects involved in the study. These groups were:

- Driving dynamics: starting off, braking, accelerating
- Consideration: distance to forward vehicle, lateral distance to other road users and obstacles, consideration for pedestrians and cyclists, observing to regulations
- Driving skills: overtaking, lack of confidence, negotiating intersections, making use of opportunities
- Emotion: tension, peripheral activities, emotional signals
- Overall assessment: driving style, incidents, drive quality

The author states that these five groups allowed for a breakdown of drivers into good and poor driver categories. The data were said to indicate a significant increase in consideration by poor drivers when operating vehicles equipped with heat absorbing glass. No statistical analyses are provided.

The author reported that environmental conditions significantly affected some behavioral variables. Drivers showed less response to other drivers after dusk. Directional stability was worse when driving at night, as was adapting to speeds of surrounding vehicles. No-fault conflicts tended to occur on bright, sunny days. Furthermore, drivers watched for cyclists during the day more than during dusk and nighttime hours. However, no statistical analyses are provided.

Overall, the author suggests that the results indicate a reduced level of strain on drivers with the use of heat absorbing glass. The author states that because heat-absorbing windows eliminate light stimuli that drivers find disturbing, there is improved information processing. No strong disadvantages were found in terms of driving stress or quality with heat-absorbing windows.

Critique

It is unclear how behavioral measures were taken, how they were analyzed, and how variables were used to characterize drivers. In other words, what qualifications were needed to characterize a driver as good or poor? Many of the behavioral factors are based upon personal judgment, and it is unclear what criteria the experimenter used in determining driver visual performance. The study made use of different environmental conditions, but makes little note of how these conditions were characterized. The authors do not mention time of day or illuminance values to characterize dusk, brightness, or darkness. Did brightness constitute daylight from sunrise to sunset? The route is said to be standardized but not fully explained, the 15 subjects were reported to be balanced by age and gender (but it is not clear how they were balanced), and the actual method of data collection is not clearly explained.

Hurst, W. S., and Scroger, M. G. (1974). *Influence of windshield tint on the temperature in automobile passenger compartments* (Final Report, No. DOT HS-801 282). Washington, DC: U.S. Department of Transportation, National Highway Traffic Safety Administration.

Abstract

The effect of tinting in the glass of windshields on the air temperature in automobile passenger compartments was investigated. Measurements were performed with two nearly identical vehicles, one equipped with tinted windshield glass and one equipped with clear windshield glass. All other glass in both vehicles was tinted. Tests were performed statically, with the cars parked facing south, and dynamically, with the car's driver at approximately 80 km/h. In the static tests, the interior air temperatures as determined by liquid-in-glass thermometers were typically 2 to 3° C cooler in the vehicle with the tinted windshield. In the dynamic tests, the differences in the interior air temperatures were smaller, typically about 0.5 to 1.5° C. The interior air temperature differences determined with thermocouples varied with the thermocouple position. The differences typically ranged from a negligible amount (less than 1° C) to about 6° C; temperature differences as large as 16° C were observed on the car dash.

This research examined the effect of windshield tinting on air temperature in automobile passenger compartments.

Independent Variables

Transmittance. Two new windshields were used in this experiment. One windshield was clear, and the other was tinted. However, no information about the transmittance or rake of the windshields is given. Two identical cars were used, and all window glass in the sides and rear of each car was tinted. Air conditioning was not used during any of the tests.

Dependent Variables

Temperature. A large number of thermocouples and thermometers were placed at various locations within the car to measure the temperature throughout the automobile. Two voltmeters were used to measure the thermocouples, and each thermocouple was measured using the same voltmeter throughout the experiment to ensure consistency in measurement. Temperature measurements were made every 10 minutes.

In two static tests the cars were faced towards the south. In the dynamic tests, the cars traveled southeast (at 80 kph) for approximately 90 minutes, and then northwest, again at 80 kph, for 90 minutes. The weather for the static and dynamic tests was virtually the same across all days, as shown in the following table.

Day (test)	Weather condition
Day 1 (static)	thin and light high clouds with sunny skies
Day 2 (dynamic)	thin and light high clouds with sunny skies
Day 3 (static)	very clear skies and strong sun with cool breeze
Day 4 (dynamic)	very clear skies and strong sun

Results

Overall, the interior temperatures measured in the car with the tinted windshield were lower than that for the car with the clear windshield. However, the interior air temperature differences measured in the dynamic tests were less than those for the static tests. Air leaks inside the car were suggested as being a main factor in this finding, opening one vent at 80 kph reduced interior temperatures by 5° C.

In dynamic tests, differences in temperature between the two cars generally ranged from 0.5° to 1.5° C. These differences were lower than in the static tests, in which temperature differences between the two cars were 2° to 3° C.

The maximum difference in temperature as indicated by the liquid-in-glass thermometers between the cars was 3.7° C for the static tests and 1.5° C for the dynamic tests. Thermocouple readings often showed a greater difference depending on their placement in the car and whether or not they were in the path of direct sunlight.

Thermocouples placed in direct sunlight indicated higher temperature readings than those placed out of direct sunlight. A 5° to 8° C temperature difference was found for thermocouples placed in sunlight on the seat of the car, and up to a 16° C difference for thermocouples placed on top of the dashboard.

Critique

Only two windshields were used, one clear and one tinted. The results of the study clearly showed that the tinted window caused a decrease in interior automobile temperatures, though the level of benefit varied dramatically depending upon the testing condition. This research would have benefited significantly from an examination of various window transmittance levels in order to determine how percentage transmittance influences interior car temperatures. Unfortunately the authors do not even state the transmittance characteristics of the two windshields examined, nor do they report the windshield rake.

While this research was conducted under "worst-case" conditions, on hot and sunny days, there would also be a benefit in carrying out similar tests under different weather to examine the changes in the benefits of tinting with seasonal variation.

Keßler, F. R. (1993). Light diffusion characteristics and visibility interferences in automobile windshields. In A. G. Gale, I. D. Brown, C. M. Haslegrave, I. Moorehead, and S. Taylor (Eds.), *Vision in Vehicles IV* (pp. 69-78). Amsterdam: North-Holland.

Abstract

Soiling and/or deterioration of automobile glazing causes stray light by transmission or reflection. Stray light impairs the driver's environmental perception. The art and degree of perception interference depends strongly on the stray light characteristics. Wide-angle diffusion (angle of deflection over 2 degrees) is especially discussed.

Following some practical remarks, the possibility of characterizing the stray object by means of characteristic parameters is discussed. Some quantitative relations based on a theoretical treatment of the problem are given.

The principles of two systems for measurement and analysis of diffusion characteristic are presented together with some typical results. One system uses stationary equipment which is base on the scanning principle. The other instrument involved is a mobile probe for stray light which is used directly on the vehicle.

This paper addresses the problems of stray light generated by soiling and surface defects of windshields. The author presents information on the physics of stray light and suggests that an understanding of light diffusion through windshields can be arrived at through modeling. The author states that:

- The origins of light diffusion can be understood by means of physical models.
- The model parameters are suitable for characterizing the light diffusion.
- That two systems have been developed to analyze the light diffusion.

However, this paper does not discuss the any investigations related to the effects of stray light or windshield wear on driver visual performance.

Merritt, J. O., Newton, R. E., Sanderson, G. A., and Seltzer, M. L. (1978). *Driver visibility quality: an electro-optical meter for in-vehicle measurement of modulation transfer (MTF)* (Final Report, No. 1780-1). Goleta, CA: Human Factors Research, Inc.

Abstract

In order to provide a practical means for developing and monitoring standards of driver visibility quality, an electro-optical MTF meter was designed and delivered to NHTSA. Tests were conducted with Landolt ring targets to relate human vision to meter readings, under various types of optical degradation (windshield fogging, icing, dirt film, etc.); there was excellent agreement between meter readings and visual test measures, confirming that the visibility quality meter (VQM) can stand in as an "average observer" to determine if visibility quality meets minimum requirements. The VQM is a rugged and simple solid-state device with an oscilloscope display of image luminance cross-section; image contrast values are read directly from the display for determination of MTF (i.e., contrast transmittance). The large body of visual contrast-sensitivity data available in the literature can be directly related to VQM readings, thus providing visibility standards for targets of a given size, shape, distance, luminance, and viewing condition. Further research with driving-specific visual tasks is required, however, to directly link the VQM and driver visibility requirements. Significant findings include: (1) a relatively simple optical meter can be used for in-vehicle measurement of contrast degradation and optical distortion; (2) since the MTFs in question are decreasing monotonic functions of spatial frequency, it is sufficient to test at just one spatial frequency representing finer detail to ensure adequate visibility for all detail larger than the test frequency; this makes compliance testing procedures very straightforward; (3) driver visibility is limited more often by contrast degradation than by inadequate resolution, since many of the driver's visual tasks involve relatively very large objects; (4) the MTF for veiling luminance is equal at all frequencies, permitting very simple measurement.

This paper describes the development and use of a device, the Visibility Quality Meter (VQM), to measure the modulation transfer of automotive windshields. The authors state that inadequate target contrast, rather than insufficient image resolution, is frequently the limiting factor in driver visual performance through windshields. The test of human visual capabilities performed by the authors was intended to validate the VQM measurement device, rather than to substantiate the relative importance of target contrast over resolution.

Independent Variables

Windshield MTF. Sixteen windshield samples, with various MTF characteristics, were examined by subjects. Several of these samples had simulated fogging, some had varying levels of simulated melting ice, and still others had simulated cigarette smoke and/or dirt. One level of windshield MTF served as a control, and was a clean and clear windshield. No information regarding the windshield transmittance characteristics is provided.

Target size. Eight target sizes were examined. All targets were Landolt rings that varied from a Snellen acuity of 20/25 to 20/200. The equivalent target sizes in cycles per degree (cpd) were reported to be between 24 and 3.

Dependent Variables

Threshold contrast. Subjects were asked to adjust the luminance contrast for a series of Landolt rings until the target contrast reached threshold visibility. All targets were viewed against a background of fixed illumination (322 cd/m^2). Subjects determined the threshold contrast for all 16 levels of windshield MTF using most of the levels of target size. For some levels of windshield MTF either the range of target size or luminance contrast available were not sufficient to reach threshold contrast.

Subjects

Ten subjects, seven men and three women, participated in the experiment. Subjects had a minimum static visual acuity of 20/25, both near and far, although most had better than 20/20 vision. Subject age ranged from 27 to 46 years. The authors reported that subjects were highly motivated and interested in participating, and that the level of motivation translated into consistency in their results. No additional information of the subject population is provided.

Results

Measures of windshield contrast transfer, determined via contrast threshold for subjects, were compared with measurements made with the visibility quality meter for each of the levels of windshield MTF. The authors reported that contrast transfer and windshield MTF, as measured by the VQM meter, were significantly correlated ($r^2 = 0.94$). The authors state that these results support the validity of the VQM meter as related to human visual contrast sensitivity.

Critique

While this study validates the VQM metering system, it does not address the relationship between automotive windshield MTF, or transmittance, and driver visibility of realistic targets in a dynamic driving environment. However, the results do demonstrate that increasing levels of contrast are required for drivers to detect objects through windshields of degraded quality. Unfortunately, it is difficult to relate the levels of windshield MTF used in this study to actual driving applications.

Owens, D. A., Sivak, M., Helmers, G., Sato, T., Battle, D., and Traube, E. C. (1992). *Effects of light transmittance and scatter by windshields on nighttime visual performance* (Technical Report No. UMTRI-92-37). Ann Arbor, MI: The University of Michigan Transportation Research Institute.

Abstract

A laboratory study investigated the effects on night vision of windshield transmittance and light-scattering properties in relation to the effects of reduced contrast, glare, night myopia, and age. Three groups of subjects included: (1) ten elder drivers, (2) ten younger drivers who were susceptible to low levels of night myopia, and (3) ten younger drivers who were not susceptible to night myopia. Visual acuity of all subjects was measured for high- and low-contrast targets viewed through five windshields with and without glare that simulated opposing low-beam headlights at 50 m distance. To assess night myopia, visual accommodation of younger subjects was measured objectively under each of the ten windshield-by-glare conditions while they viewed four realistic low-luminance targets. The transmittance of three clean windshields, with different tints and rake angles (ranging from 45° to 75° from the vertical) varied from 0.86 to 0.43. Two additional conditions were created by mounting a dirty windshield at rake angles of 45° and 75,° which produced light transmittances similar to two of the clean windshields but now with a higher degree of light scatter.

The main results are as follows: (1) Reduced transmittance of clean glass elevated low-contrast resolution thresholds by 0.09 log units, but had no effect on high-contrast thresholds. (2) Light-scatter of dirty wind-shields elevated low-contrast thresholds to unmeasurable levels. (3) Glare elevated low-contrast thresholds by 0.18 log units. (4) Resolution thresholds were 0.28 log units higher for low-contrast than for high-contrast targets. (5) Thresholds for low-contrast targets were 0.31 log units higher for elder than for younger subjects. (6) Tests of accommodation showed significant increases of night myopia with glare and reduced target luminance, as well as a tendency toward greater night myopia for higher luminance targets with the dirty windshields as compared with the clean windshields. (The accommodation data were inconclusive, however, because few subjects had substantial levels of night myopia.) It was concluded that low windshield transmittance due to rake angle and tint has a significant detrimental effects on the visibility in nighttime driving, but these effects are small relative to those of light-scatter from high levels of dirt and wear.

Independent Variables

Transmittance/light scatter. Four separate windshields were used to create five viewing conditions. The dirty windshield condition consisted of a uniform film of dirt, simulated insect smears, and some natural wear that produced light scatter. The same windshield was used for the two "dirty" conditions by varying the rake. The author's intent was to examine the total effect of reduced transmittance resulting from a combination of tinting and rake, as opposed to the individual contributions. All transmittance measurements were made parallel to the line of sight at the various rakes. Windshields were positioned 91 cm from the subject's eyes.

Glass	Transmittance (%)	Rake (degrees from vert.)
clear/clean	86	45
blue/clean	65	65
gold/clean	43	75
clear/dirty1	64	45
clear/dirty2	37	75

Age and susceptibility to night myopia. The subject population was divided into three groups of ten persons each according to age and susceptibility to night myopia. Susceptibility to night myopia was based upon measures of the subjects' dark focus. Measures of dark focus were not made for older subjects.

Subjects	Age range	Dark focus values
Elder Group	62-78 (mean = 69.9)	NA
NearYoung Group	20-34 (mean = 25.5)	0.49 D to 1.64 D
FarYoung Group	20-34 (mean = 25.5)	-0.80 D to 0.40 D

Glare. Two levels of glare were presented, glare or no glare. The glare source was produced using a slide projector with a reduced aperture such that the beam of light was projected toward the subject, 2° to the left of the visual targets. The intensity of the glare source was adjusted to 0.7 lx at the subject's eye, and was stated to be comparable to the glare produced by U.S. low-beam headlamps.

Target contrast. Two sets of photographic transparencies were projected onto a large screen located 7.9 m from the subject. One set of stimuli was used to assess visual acuity (Bailey-Lovie charts) and a second set was used to assess accommodation (speed-limit sign and pedestrians).

Visual acuity task: The center columns of letters from Bailey-Lovie charts were presented to subjects. The stimuli included two levels of contrast (L_{max} - L_{min}/L_{max} + L_{min}), 0.9 and 0.1, as projected upon the screen. The size of the projected letters covered a range of visual acuity from 20/6 to 20/400, or -0.5 to 1.3 log minimal angle of resolution (MAR) in steps of 0.1 log MAR. Luminance values for these stimuli ranged from 0.87 to 1.26 cd/m^2, or a surface reflectance of 8% to 12% for an illumination level of 33 lx (civil twilight).

Accommodation task: Four photographic transparencies of realistic objects from a nighttime road environment were shown for the accommodation task. This task was only performed by the younger subjects (NearYoung and FarYoung Groups). The scenes on the transparencies were of a speed-limit sign and a pedestrian. The pedestrian scene was presented at three levels of contrast. In the projected scene the pedestrian wore white clothing, and neutral density filters were used to produce luminance levels of 11, 0.9, and 0.09 cd/m^2 (simulated clothing reflectances of approximately 100, 10, and 1% respectively for a 35 lx illumination).

Dependent Variables

Visual acuity. Visual acuity tests were performed using an ascending method-of-limits procedure. Threshold measures of MAR (minimum angle of resolution) were defined as the visual angle of the critical detail of the smaller of two correctly identified letters from a Bailey-Lovie chart.

Accommodation. Measures of accommodation and pupillary dilation were measured with a Canon R-1 autorefractor.

Subjects

See *Age and susceptibility to night myopia* (above).

Results

A table, similar to that below, was used by the authors to summarize variables with statistically significant effects on visual resolution performance as determined through analysis of variance. The values given in the table represent main effects averaged across other variables.

Variable	Range tested	Target contrast	Change in log threshold (MAR)	Change in Snellen ratio
Transmittance*	0.86 - 0.43	low	0.09	20/73 to 20/89
Age of the observer*	26 - 70 years (means)	low	0.31	20/62 to 20/126
Glare*	0 - 0.7 lx	low	0.18	20/65 to 20/98
Target contrast	0.9 - 0.1		0.28	20/42 to 20/80
Light scatter†	clean & dirty	high	0.34	20/38 to 20/84

*These data are for low-contrast stimuli and clean windshields only.

†These data are for high-contrast thresholds measured with glare through clean windshields with transmittance of 0.65 and 0.43, and dirty windshields with transmittance of 0.64 and 0.37. Low-contrast thresholds for the dirty windshields exceeded the range of measurement.

The authors report that over the ranges tested, age, glare, target contrast, and light-scatter had greater effects on resolution performance than did transmittance. Light-scatter produced the largest effect, age and contrast had slightly smaller effects, and glare had an intermediate effect. Relatively speaking, the effect of windshield transmittance was small, but significant for low-contrast stimuli. The authors suggest these results indicate that the effects of light scatter from dirt or wear are more troublesome than those due to reduced windshield transmittance.

Tests of visual accommodation showed that, for susceptible individuals, reduced target luminance and glare exacerbated night myopia. While there were increases in night myopia for bright targets when viewed through dirty windshields, there was no effect of windshield transmittance on night myopia. The authors caution, however, that the results are inconclusive because subjects exhibited only small levels of night myopia.

Critique

Of primary interest in this study was the effect of the total light transmitted through a windshield on driver visual performance. Consequently, no effort was made to separately control for the effects of transmittance per se, rake angle, or spectral sensitivity.

Rompe, K., and Engel, G. (1984). *The influence of scattered light in windshields on driver's vision during night driving.* SAE Paper #840385. Warrendale, PA: Society of Automotive Engineers.

Abstract

The investigation was carried out with a driving simulator, where 20 subjects had the task to drive in a passenger car on a synthetic, curved road which was displayed on a screen. The subjects could steer the car on the road with the steering wheel and by using the accelerator and the brake pedal they had free choice of the driving speed. Besides driving, the subjects had to detect visual signals at various defined contrasts to the surrounding field and to confirm detection. The number of right answers and the reaction times were taken as measure of the influence of scattered light on driver's vision through four different windshields with haze levels of 0.2, 1.5, and 4.9% and a green tinted windshield with a haze level of 0.2%.

This research examined the influence windshield haze, target contrast, subject age, and glare on target recognition, reaction time, and driving speed in a simulated driving task.

Independent Variables

Haze. Windshield haze was artificially created by introducing a series of small impacts on the glass that were said to be evenly distributed over the surface of the windshield.

Haze	Transmittance of light (%)	Transmittance of energy (%)
0.2 +/- 0.1 (green)	79	58
0.2 +/- 0.1 (clear)	88	79
1.5 +/- 0.6 (clear, aged)	NA	NA
4.9 +/- 1.0 (clear, aged)	NA	NA

Contrast. Four levels of luminance contrast were examined, while the target background luminance was held constant at 0.3 cd/m^2. Glare was introduced using one 100 cd/m^2 source. This source was aimed only at one side of the windshield (the driver's side).

	Number of target presentations	
Luminance ratio	Left side	Right side
2:1	7	7
4.6:1	7	8
21:1	7	4
149:1	4	6

Age. Four age groups were examined.

Age group	No. of subjects
25 - 35	6
36 - 45	6
46 - 55	6
55 - 65	2

Dependent Variables

Target recognition. A square visual target, with an opening on one of four sides (random), with a constant presentation duration of 2 s was presented. The subtended visual angle of the target is not given by the authors. Targets were presented a total of fifty times either to the left or right of the roadway center. Target presentation locations were fixed, and positioned directly above the simulated horizon.

Reaction time. Reaction time was defined as the time a subject took to correctly identify the location of the opening in the target, and press a button that corresponded to the location of the opening.

Driving speed. Driving speed was not well defined. This variable is believed to be the rate at which the simulated roadway was presented, and was under the control of the subjects via an "accelerator" pedal.

Subjects

A total of 20 subjects participated in the study. The age distribution of the subjects is outlined above. All subjects were stated to have normal vision, although criteria are not provided. No other information related to the subject population was provided.

Results

Target recognition, which varied as a function of contrast sensitivity, was best with clear windshields (i.e., there was no haze) but decreased with increasing amounts of haze. Furthermore, subjects appeared to adapt their driving speed in a simulator to compensate for the losses experienced in acuity that resulted from the introduction of windshield haze. However, reaction time to the task remained fairly constant across all levels of haze. No statistical analyses are provided.

Critique

The researchers mistakenly report the task to be that of contrast sensitivity, and while they varied the target contrast, the task was more similar to that of a Landolt-ring, visual-acuity task. The authors did not provide information related to the viewing distance of the target, whereby preventing the reader from inferring the level of difficulty associated with the task. Instances of the subject detecting the target in the visual field were considered incorrect if the subject failed to identify the location of the opening in the square target. In addition, in presenting the stimuli the levels of target contrast, as well as the target location, were not balanced. No statistical analyses are presented.

While the authors report that the levels of contrast examined were determined in preliminary tests, and selected in such a way that the lowest contrast level was just visible and recognizable, subsequent levels of contrast were several orders of magnitude larger. The results show evidence of a ceiling effect such that only two of the four target contrast levels produced any reduction in recognition, and no apparent change in response time. Again, no statistical analyses were performed by the authors.

No criteria are specified for identifying the visual capacities of the subjects. The authors simply state that subjects' vision was checked using a device for determining licensure in Germany, and that "subjects proved to be suitable." In addition, based upon a sample size of only two for the oldest group, the authors concluded that age had no apparent influence on subject's ability to perform the task.

As for the presence of the glare/dazzling source of light on the left side of the target area, the authors state only that stimuli presented on the left were more severely effected by haze than those presented on the right. However, for targets presented on the right side of the target area, the influence of windshield haze was only slightly detectable, even at the lowest levels of contrast.

Rompe, K., and Engel, G. (1987). *The influence of windshields with lower light transmission in driver's vision during night driving.* SAE Paper #870062. Warrendale, PA: Society of Automotive Engineers.

Abstract

The influence of reduced light transmission of the windshield had been tested under night driving conditions with a driving simulator and the disadvantages of spectacles had been pointed out. When the luminous density ratio of the objects on the road went to very low values the risk of accidents grew rapidly with low light transmission windshields or haze effects of already 1.2% on normal tinted shields. The coincidation of low level light transmission and haze effects in the results shows a possibility to denominate limits for the use of aged windshields and now acceptance for the use of low light transmission windshields at least for spectacle wearing drivers.

This research examined the influence of windshield light transmittance, target contrast, subject age, eye glasses, and glare on target recognition, reaction time, and driving speed in a simulator.

Independent Variables

Windshield	Transmittance of light (%)	Transmittance of energy (%)
Clear	89.0	83.0
Green	76.4	58.0
Green	58.0	44.0
Gray	40.0	33.0
Green*	77.4	49.0

Transmittance and haze. The windshields listed below were placed in front of the subjects in alternating sequences, inclined at 55° from vertical. Every subject was reported to have made one test with each windshield.

*indicates there was a haze level of 1.2% on this windshield only

Contrast. Four levels of luminance contrast were examined, while the target background luminance was held constant at 0.3 cd/m^2. Glare was introduced using one 100 cd/m^2 luminance source. This source was aimed only at one side of the windshield (the driver's left side).

Luminance ratio	Number of target presentations	
	Left side	Right side
2:1	7	7
4.6:1	7	8
21:1	7	4
149:1	4	6

Age. Four age groups were examined. All subjects were male. Twenty of the subjects wore eyeglasses, twenty did not. All subjects were classified as having "normal" vision.

Age group	Normal sighted	Spectacle wearers
25 - 35	6	6
36 - 45	6	6
46 - 55	6	6
55 - 65	2	2

Dependent Variables

Target recognition. A square visual target, with an opening on one of four sides (random), with a constant presentation duration of 2 s, and an average interval of 8 s. The subtended visual angle of the target is unknown. Targets were presented a total of fifty times on either the left or right side of roadway center. The locations of targets were in fixed positions, directly above the simulated roadway horizon.

Reaction time. Reaction time was defined as the time a subject took to correctly identify the location of the opening in the target, and press a button that corresponded to the location of the opening.

Driving speed. Driving speed was not well defined. Subjects appeared to choose a speed that they felt was a relative velocity between the motor vehicle and projected road. This variable is believed to be the rate at which the simulated roadway was presented, and was under the control of the subjects via accelerator and brake pedals.

Subjects

A total of 40 subjects participated in the study. The subjects' age distribution is outlined above. Twenty subjects were stated to have normal vision, although criteria are not provided. An additional twenty subjects wore eye glasses. Subjects' vision was tested with a device used for determining driving licensure in Germany, and were determined "to be suitable" to participate in the study. No other information related the subject population is provided.

Results

This research confirms an earlier study by the authors, using some of the same conditions, with subjects having normal vision for both the percentage of right answers as well as reaction time. As in the earlier study, the authors reported that target recognition was best with clear windshields. They also found that eyeglass wearers had distinct disadvantages during night driving when compared with subjects who did not wear eyeglasses. These disadvantages occurred even though subjects' daylight, as well as twilight, visual capacities were almost identical. For contrast level 1 (a luminance ratio of 2:1 and luminance of the visual signal of 0.61 cd/m^2), there was a 20% reduction in correct responses, a 5 km/h reduction in speed, and a reaction time increase of 0.05 s for eyeglass wearers when compared with subjects who did not wear eyeglasses.

Glare effects were found to be more pronounced for eyeglass wearing drivers, and resulted in more errors and longer reaction times. The authors report that the influence of the glare source depended upon the location in which the targets were presented. Specifically, the ability of subjects to detect targets on the left were severely diminished by the presence of the glare relative to targets presented on the right. Reaction time was fairly constant across transmittance of windshields, with the exception of the 40% transmittance that caused a significant increase in reaction time. Finally, a decrease of light transmittance to 58% or less proved difficult for eyeglass wearing drivers during night driving conditions. No statistical analyses were provided.

Critique

As in their earlier study, the researchers mistakenly report the task to be that of contrast sensitivity, and while they varied the target contrast, the task was more similar to that of a Landolt-ring visual-acuity task. Furthermore, the authors failed to provide information related to the viewing distance of the target, thereby preventing the reader from inferring the level of difficulty associated with the task. Instances of the subject correctly detecting the targets in the visual field were considered incorrect if the subject failed to identify the location of the opening in the square target, but was able to identify the location of the target in the visual field. No statistical analyses were presented.

The authors explain that subjects performed one test with each windshield, but it was unclear what "one test" signified. Furthermore, it was unclear why the authors felt that a learning process would be eliminated simply due to the inclusion of 50 visual signals for each windshield. The authors state that "the presentation program was identical for each windshield" but do not state whether any parts of the presentation program were in randomized or blocked order. The authors mentioned that the 30 visual signals were balanced on the left or right respectively, per windshield, per contrast, per age group. However, the number of presentations shown in the report are not balanced for left and right presentations of the four contrast stages. The number of presentations varied from 4 to 8 for each contrast level and each side.

No criteria are specified to identify the visual capacities of these subjects. The authors simply state that the subjects' vision was checked using a device used for determining licensure in Germany, and that "the subjects proved to be suitable." Despite a sample size of only two for the oldest group, the authors concluded that age had no apparent influence on subject's ability to perform the task.

The authors mention that "enhanced speed delivers a higher percentage of right answers" but only vaguely define speed as it is used in the study to be "relative velocity between motor vehicle and projected road." It is difficult to determine how this speed effect comes about, and how it is controlled. It is unclear if all subjects experience similar speeds for comparison, or if this result comes about from each subject's own speed preferences.

Roper, V. J. (1953). Nighttime seeing through heat-absorbing windshields. *Highway Research Board Bulletin*, *68*, 16-30.

Abstract

The glass used in heat-absorbing windshields currently available transmits 18 percent less light than ordinary windshields. This reduction in light transmission led to concern about the possibility of a serious reduction in nighttime-seeing distances, which are barely sufficient, at best.

Tests were conducted on an airstrip, using two identical cars equipped with sealed-beam headlamps. Ordinary and heat-absorbing windshields were interchanged in the two cars. Observations were made while driving at 40 mph., half with each type of windshield. Seeing distance observations were made both against the glare of an approaching car and when the road was clear.

A summary of these observations shows an average reduction in seeing distance of not quite 6 percent for driving with no approaching vehicle and an average reduction of 2 percent when approaching another car on a straight, level road over a distance of almost a mile.

For the most critical portion of the seeing-distance curve, the last 500 ft. before meeting an approaching car, results show the same seeing distances through ordinary and heat-absorbing windshields. This may be explained by the slight reduction on brightness of the approaching headlamps as offsetting the reduction in brightness of the obstacles under observation. Both reductions are caused by the 18 percent additional absorption of light by the heat-absorbing glass.

As a result of these data, it may be argued that unless the driver does practically all of his driving at night, the daytime benefits to be derived from the heat-absorbing glass windshield offset the small reduction in seeing distance at night. This reduction averaged 3 percent over the entire seeing-distance curve obtained in the tests reported as a result of the investigation.

Independent Variables

Transmittance. Two levels of windshield transmittance were examined. The first, referred to by the author as the clear windshield, had no heat-absorbing treatment applied. Although never specified, on the basis of examination of the spectral transmittance, an overall transmittance value for this windshield appears to be about 88%. The second level of windshield transmittance examined, referred to as the heat-absorbing windshield, is reported by the author to be 18% less than the clear windshield.

Visual acuity. Two levels of visual acuity were examined, 20/20 and 20/40. Persons with 20/20 visual acuity were given the task of driving the test vehicle, while those with 20/40 visual acuity were front-seat passengers in the same vehicle.

Dependent Variables

Seeing distance. Seeing distance was defined as the distance at which subjects could detect the presence of a 406 mm square target, with a reflectance of 8%, placed at the right edge of the roadway as the test vehicle traveled at a rate of 64 km per hour. Out of the 12 targets used, 11 were gray and one was red. Thirty observations per target were obtained for each of the subjects for both levels of windshield transmittance (2,880 observations of seeing distance).

A closed airport runway was used to simulate a roadway, and testing was only conducted on clear, moonless nights. Subjects used one of two switches to record, via a paper-tape recorder, when they detected a target. Two test vehicles were on the "roadway" at the same time, and approached each other from opposite directions. The first four targets were viewed with the vehicles high-beam headlamps, while the remaining were viewed using low-beam patterns.

Subjects

A total of four subjects were used, two of which had 20/20 and two of which had 20/40 visual acuity. No additional description of the subjects is provided.

Results

The results are provided in the table below. Each cell is representative of the seeing distance, in meters, for 30 observations. The author reported that "there appears to be no significant difference in the comparative results" between the two levels of visual acuity examined, although there existed "considerable variation" between subjects to see the targets. However, no statistical analyses of this difference are reported.

The author reported that the loss in seeing distance associated with the heat-absorbing windshield was minimized when the vehicles opposed each other, especially within a distance of 914 m, in part due to a reduction in glare that counteracted the reduction in target brightness. For the portion of the test where the reported seeing distances were the shortest, and could therefore be considered most critical, there was very little difference in seeing distances between the two levels of transmittance. The author reported an average reduction in seeing distance for the heat-absorbing windshield of 2% when vehicle headlamps were opposing each other, and 5.7% for clear roadway once the vehicles had passed (i.e., once the headlamps of one vehicle did not effect the other).

Critique

While a sufficiently large number of observations was made per subject, the degree of variability associated with individual subject differences suggests that it would have been useful to test more subjects. Furthermore, despite having reported visual acuity as an independent variable no statistical analyses were reported. A reader's interpretation of the results from this study could have been enhanced were additional information regarding the experimental apparatus provided (i.e., headlamp beam pattern descriptions and the windshield rake). Finally, only two levels of transmittance were examined, and the absolute transmittance values of the windshields are not stated by the author.

Southall, D., and Burnand, M. (1991). An investigation of the visual effects of electrically heated windscreens in Jaguar cars. In A. G. Gale, I. D. Brown, C. M. Haslegrave, I. Moorehead, and S. Taylor (Eds.), *Vision in Vehicles III* (pp. 117-123). Amsterdam: North-Holland.

Abstract

This study investigated drivers' subjective responses to driving cars fitted with wired screens, and undertook laboratory tests of visibility under night-time driving conditions to examine any effects due to reflection by the wires of light from oncoming headlamps, and any effects due to light transmission and obscuration under daytime reduced visibility (fog and snow).

Only 6 out of 20 drivers noticed the wires during a 2 hour drive and only 1 complained of reduced visibility. The wires did not lead to visual discomfort nor any measurable effect on visibility during night time on simulated snow/fog driving conditions.

This research examined whether cars equipped with electrically heated windshields that contained wires inside the glass would affect a driver's visibility during normal or inclement weather.

Road Trials

Independent Variables

Windshield. Electrically wired windshields and normal windshields were examined. Four cars were used in the experiments, two Jaguar sedans and two Jaguar sports cars. One car of each type was fitted with a wired windshield, and the other with a normal windshield.

Dependent Variables

Visibility. Subjects drove the cars over a standard test route. Each driving session lasted 1.5 to 2 hours, beginning at dusk and ending under nighttime conditions. Subjects were asked to identify instances of reduced visibility.

Visual acuity. Measures of driver's visual acuity were made with subjects looking through the two different windshields.

Visual fatigue and discomfort. Subjective ratings of tiredness, soreness, dryness of the eyes, headaches, as well as neck and shoulder pain were made by subjects after driving the cars equipped with the two different windshields.

Subjects

Twenty subjects participated in the experiment. No additional information about the subject population is provided.

Results

Of the 20 subjects participating in the experiment, only six stated that they noticed the wires imbedded in the electrically heated windshield, and only one subject reported any visibility problems associated with its presence. Three of 20 subjects stated that they would not want a heated windshield in their cars. There was no measurable change in subjects' visual acuity associated with the use of the electrically heated windshield, nor was there any increased rating of fatigue or discomfort. No statistical analyses are reported.

Visibility Under Nighttime Driving

Independent Variables

Windshield. An electrically wired windshield and a normal windshield from a Jaguar XJ6 were examined. Windshield rake was 35°. The order of windshield presentation was balanced.

Target. Three miniature model cars were used as targets. The models (a police car, taxi, and sedan) were presented in random order. Targets were not to scale.

Dependent Variables

Acuity. A standard Snellen acuity test was given to subjects under both levels of the windshield condition.

Target identification (detection distance). The subjects' task was to identify a low visibility target that was viewed against a glare source. The glare source represented an oncoming vehicle, and was offset by 4° from the simulated roadway centerline. Subjects conducted ten trials for each of the target/windshield combinations. The performance measure was the distance at which subjects could correctly identify the target.

Subjects

No information related to either the number of subjects or their characteristics was provided.

Results

There was no significant reduction in visual acuity associated with the electrically heated windshield. The results of the target identification task are provided in the table below. On the average, targets had to be 3.4% closer to subjects in order that they be correctly identified, although the authors reported that this difference in distance was not practically significant. No statistical analyses are provided.

Target	Taxi		Police car		Sedan	
Windshield	Normal	Wired	Normal	Wired	Normal	Wired
Average Distance*	261	250	259	253	253	244
Lowest Detection	225	173	187	195	204	190
Highest Detection	287	270	290	290	268	265

*All mean viewing distances are in cm.

Visibility Under Snow/Fog Conditions

Independent Variables

Windshield. An electrically wired windshield and a normal windshield from a Jaguar XJ6 were examined. Windshield rake was 35°. The order of windshield presentation was balanced.

Dependent Variables

Target identification. The subjects' task was to identify low contrast targets of both fine and coarse detail.

Subjects

No information related to either the number of subjects, or their characteristics, was provided.

Results

The authors only state that the wires imbedded into the heated windshield are not likely to reduce a driver's ability to detect obstacles under conditions of fog or snow. No statistical analyses are provided.

Critique

In general, too little quantitative information is provided. No statistical analyses are reported, and all of the conclusions are presented in general terms.

Stackhouse, S. P., and Hancock, P. A. (1992). *The evaluation of vehicle window tint density on target detection capability* (Final Report), Human Factors/Ergonomics Consultants.

Conclusion

The current NHTSA rule requires 70 percent of incident light to be transmitted through the vehicle's glazing. However, the rule does not state the amount of light which must reach the driver's eyes through side and rear windows. That is, if the luminance of the scene outside the side and rear windows was 1.0 candela per square meter, then 70 percent of this or 0.7 candelas per square meter will reach the driver's eyes if the driver is facing the rear or side windows. However, if the outside luminance was 0.01 candelas per square meter then the luminance for the driver would be only 0.007 candelas per square meter. The former case is adequate for detecting realistic targets while driving a vehicle but the latter case is clearly not adequate for safe driving.

From this example it is clear that one can conceive of circumstances where 70 percent glazing transmissivity jeopardizes traffic safety. However, for these cases we can confidently state that no one should attempt to drive in near darkness (0.007 candelas per square meter). The safety issue here perhaps relates to the use of headlights and not to the use of tinted film.

If we assume that 1.0 candela per square meter falls within the range of luminance values known as dusk or twilight, then the 70 percent transmissive glazing yields a luminance of 0.7 candelas per square meter at the driver's eyes. If we consider the data plotted in Figure 12, the compilation of d' values from all experiments, then we see that target detection performance d' values at luminances between 0.1 and 0.25 candelas per square meter are already in the "data limited" or asymptotic range as shown in Figure 13.

Thus we can state that at outside scene luminances of 1.0 candela per square meter, target detection performance would be very good when luminance has been reduced to 0.1 to 0.25 candelas per square meter by window transmissivities of 10 to 25 percent. That is, the point "A" of Figure 13. lies somewhere between 10 and 25 percent transmissivity. Increasing the luminance at the driver's eyes by either increasing outside scene luminance or increasing window transmissivity (decreasing film tint density) or both would cause little or no improvement in target detection performance. This finding pertains to all four experiments and includes the very low luminance conditions of the See-In Experiment and the divided attention of the drivers in the three simulation experiments.

Based on the results of the experiments reported here, target detection performance would not be improved by increasing side and rear window transmissivity to values greater than 30 percent. The 30 percent transmissivity for side windows was obtained by applying a tinted film of 36 percent transmissivity to windows of 84 percent transmissivity. Similarly the rear window, with a transmissivity of 78 percent, was covered by a 36 per cent film to yield a total transmissivity of 28 percent. The glazing tint and rear window rake angle values are typical of most cars on the roads today. This suggests that tinted films of 36 percent transmissivity can be applied to side and rear window glazing without an effect on traffic safety. For the experiments reported here, this leaves a margin of safety since the location of the point "A" of Figure 13. is well below the luminance resulting from application of 36 percent film.

While many factors enter into decisions about traffic safety, the results of these experiments strongly show that realistic targets can be successfully detected in ecologically valid circumstances under very low luminance conditions.

This research examined, for near worst-case but realistic conditions, the safety threshold for the use of tinted films on all glazing except windshields. Two experiments were carried out by the authors. The first experiment examined the effect of transmittance on older subjects' ability to perform driving maneuvers. The second experiment examined the effect of transmittance on subjects' ability to detect the presence of a gun placed on an automobile seat.

Object Detection (Driving Simulation) Experiment

Independent Variables

Driving maneuvers and targets. Three different driving maneuvers were examined in a driving simulator: lane-changing, left-turn, and reversing-to-park. Each of the three maneuvers was treated as a separate experiment. For each of the maneuvers three target conditions were used for the purpose of examining detection. The combinations of maneuver and targets are provided in the following table.

	Maneuver		
	Left-turn	Lane-changing	Reverse-to-park
Target	Adult Pedestrian	Sedan	Child
	Tricycle	Mini-Van	Tricycle
	No Target	No Target	No Target

Transmittance. Three levels of tinting were examined: 21%, 36%, and 51% transmittance. The films were professionally installed and free of bubbles or blemishes. Once the films were applied to the windows of the experimental vehicle, photometric measurements of transmittance were performed perpendicular to the glazing surface. The resulting transmittance values are provided in the following table.

	Transmittance (%)			
	No film	21% film	36% film	51% film
Front-side window	83	17	30	42
Rear-side window	83	17	30	42
Rear window	84	17	30	43

Glare. Half of the trials in the object detection experiment included the use of a set of headlamps that represented a car that was following the simulated vehicle. Two halogen headlamps on high-beam were used to illuminate the interior of the of the simulated vehicle. The interior rear-view mirror was left in the daylight position. The table below provides the luminance, reflected from the rear-view mirror, towards the drivers' eyes.

Film/transmittance	Light reflected (lx)
No film	204.4
51% film	104.4
36% film	37.7
21% film	7.5

Dependent Variables

Target detection. This research employed signal detection theory (SDT), and as such required subjects to identify the presence, or absence, of the previously described targets in the simulated path of the vehicle.

Subjects

Subjects in the object detection experiment ranged in age from 55 to 79 years (mean 64.4). There were 17 subjects, three of whom were female. All subjects had corrected 20/40, or better, static visual acuity, and were licensed drivers.

Results

The authors treated each of the maneuvers as separate experiments, and as such report the results for each of the maneuvers separately.

Left-turn. The authors reported marginal decreases in detectability of targets, and slight increase in response bias, associated with low levels of luminance. Increases in luminance resulted in non-linear increases in detectability. When plotted against target contrast, subject response bias was virtually unaffected and detection increased only slightly with increasing levels of target contrast.

Reverse-to-park. Increases in luminance resulted in increases in detectability, and a slight increase in response bias was associated with low levels of luminance. When plotted against target contrast, subject response bias was slightly higher for low contrast targets as opposed to those of high contrast, and detection increased with increasing contrast.

Lane-changing. Results from the lane-changing maneuver differed from those of the pervious maneuvers. The authors reported elevated detection performance for subjects under lower levels of luminance and target contrast than had been previously reported. Furthermore, the general trend of increased detection and decreased response bias associated with increasing contrast was not strictly observed. The authors reported a fairly non-monotonic relationship between levels of detectability and increasing levels of luminance and contrast.

See-In Experiment

Independent Variables

Transmittance. The same levels of tinting that were examined in the Object Detection Experiment were used.

Transmittance (%)	Background luminance (cd/m^2)	Target contrast
0.84	0.04	-0.8
0.44	0.03	-0.8
0.30	0.02	-0.8
0.18	0.01	-0.8

Dependent Variables

Target detection. Again, the authors employed signal detection theory (SDT), and as such required subjects to identify the presence, or absence, of a target that was located inside a vehicle with windows of various levels of transmittance. The target was a pistol, and distracter items included a purse, paper bag, coffee mug and leather glove. The target could appear on either the front or rear seats. Subjects "looked into" the vehicle at a distance of 2 m from the car, 3m from the actual target.

Subjects

Subjects in the see-in experiment ranged from 20 to 40 years in age (mean 28.8). There were 23 subjects, 11 of whom were female. The age range for subjects in this experiment was selected to be representative of that for law enforcement personnel. All subjects had corrected 20/40, or better, static visual acuity and were licensed drivers.

Results

The authors reported that subjects were sensitive to changes in the experimental conditions, such as variations in tinting level, and that these variations affected their ability to detect the presence of the pistol as well as their bias to say whether they detected the pistol. Subjects' ability to detect the presence of a pistol was elevated by increased levels of illumination, and increased levels of decision bias were observed for low luminance conditions.

Critique

While this work is an extensive and complex study, it is not well documented. The authors state that the purpose of this report was to determine the safety threshold for the use of tinted films under near worst-case conditions, yet that threshold is never clearly identified. The detection criterion selected to define acceptable visual performance in the signal detection task was not justified. Further problems result from the manner in which values of luminance and contrast were defined. Because slides of real items were used as targets, actual levels of luminance and contrast varied between the target and background. This variation was stated by the authors as being difficult to describe. Unlimited viewing time for the experimental task might not validly represent real-life tasks of interest. In the "see-in" experiment, the viewing distance (3m) might be considered unrealistically long. The results for one independent variable (the use of headlights from the rear to produce added illumination and glare) were not reported.

Timmermann, A., and Gehring, G. (1986). *Field measurements of windshield surface wear* (SAE Technical Paper Series No. 861361). Warrendale, PA: Society of Automotive Engineers.

Abstract

An instrument is described which permits the measurement of scattered light on windshields in cars in full daylight. It presents the intensities of the scattered light as a diagram and calculates two indices, which can be associated with the most prominent types of wear, i.e. impact of small stones and wiper damage.

The instrument is easy to operate and permits inspection of a large number of windshields in a short time. Measurements on 700 vehicles indicate a linear increase in wear due to impact of small stones with mileage and a more-than-linear increase of wiper damage. Vehicles of identical mileage can have very different values depending on the type of use.

In this paper the authors discuss and describe considerations for the design of a device to measure surface wear on automotive windshields. On the basis of these considerations, the authors present a device that was field tested on a large number of windshields in Sweden and Germany. The authors do not discuss the impact of windshield wear on driver visual performance.

Triggs, T. J. (1988). Some vehicle design factors that influence driver visual performance. *International Journal of Vehicle Design, 9*(4/5), 542-547.

Abstract

Human Factors considerations have been central to vehicle design rule making for more than twenty years. This topic may be considered under a number of different general areas: Visibility, field of view, design of controls, design of displays, anthropometric considerations, handling characteristics, ride quality, and aesthetics. This paper focuses on issues involving the first two of these. Primary emphasis is given to the question of designing for the visual information that a driver receives from the outside environment. The problem of windscreen light transmission is discussed. A case is made that the requirement for high transmission levels can be justified on both experimental and theoretical grounds. Recent experimental evidence is presented showing a significant decrement in visual performance resulting from the Australian practice of using wire mesh stone guards mounted in front of the windscreen. Finally, data are presented suggesting that car-following distance is influenced by the degree of obscuration caused by the leading vehicle design.

This article is a review of several studies related to driver visual performance, including windshield transmittance. While this paper offers a critique of some previous studies, it does not provide any new analytical or quantitative results.

Waetjen, R., Schiefer, U., Gaigl, A., and Aulhorn, E. (1992). Influence of windshield tint and tilt on recognition distance under mesopic conditions. *German Journal of Ophthalmology, 1*, 424-428.

Abstract

The influence of the angle of inclination and tint of windshields on recognition distance was tested in 94 subjects aged 20-83 years. Both clear and tinted (heat absorbing) windshields were tested. Light transmission (in the vertical position) was 90.3% for the clear windshield and 81.0% for the tinted windshield. The windshields could be set at angles of 0° (vertical), 30°, 50°, and 70° of inclination. The tests were performed at night with low-beam headlights (mesopic conditions). A Landolt ring (diameter 43.5 cm; contrast 1:1.5) served as a test stimulus; it was painted on a disc 87 cm in diameter that could be rotated in steps of 45 degrees. The mean recognition distance without the windshield was 32.2m +/- 5.5m (mean +/- SD). It decreased to 31.0m +/- 5.3m) by using a clear windshield in the vertical position (values for the tinted windshield are shown in parentheses): 30.1m +/- 5.6m (27.9m +/- 5.3m) with a 50 degree angle of tilt, and 28.5m +/- 5.4m (26.9m +/- 5.1m) with a 70 degree angle. The differences between the recognition distances obtained using the various tilts and tints were small but statistically significant (p<0.01 in all cases: Student's paired t-test). Since the performance of the human eye is stressed to it's limits during nighttime driving, our study suggests that extreme tilt of the windshield should be avoided and that option of delivering cars equipped with a heat absorbing but clear front windshield should be provided.

Independent Variables

Transmittance. Two windshields, one tinted and one un-tinted, were used. A third condition, no windshield, was also examined. The untinted windshield (clear) had a transmittance of 90.3%, and the tinted windshield had a transmittance of 81.0%. Measurements were made perpendicular to the windshield surface.

Rake. Four levels of windshield rake were examined: 0°, 30°, 50°, and 70°.

Dependent Variables

Recognition distance (orientation). The subject's task was to recognize and report the orientation of a low-contrast Landolt ring (43.5 cm in diameter with an opening of 8.7 cm). The Landolt target could be presented in eight different orientations. The authors state that this contrast between the target and background were comparable to a darkly clothed pedestrian on an un-illuminated roadway. The target was illuminated only by a set of low-beam halogen headlamps, positioned in accordance with motor vehicle specifications. Luminance values for the target, background, and road surface were 0.03, 0.04 and 0.02 cd/m^2, respectively. The target was located on the right side of an asphalt roadway, and was moved towards the subject in increments of 1 m until the orientation of the target could be correctly recognized.

Subjects

Ninety-four persons took part in this experiment. Subjects ranged in age from 20 to 83 (mean = 48.6, median = 50.5). All had corrected, or uncorrected, static visual acuity of 20/40 or better (mean = 20/18).

Results

Using Student's paired *t*-tests, the authors reported that subjects' recognition distances were significantly shorter for all conditions relative to when no windshield was present. Recognition distances with a tinted windshield were always significantly shorter than those with a clear windshield. Recognition distances were shortened from 6.5 to 8.8% as a result of the introduction of windshield tinting. Both tinting and rake were found to have a significant effect on a subject's ability to detect the Landolt target. A particularly sharp decrease in recognition distance was observed when the windshield rake was greater than 50°. Recognition distances (meters) for no glass, clear windshield, and tinted windshield at differing rakes are presented in the table below.

		Rake° /Tint							
	No glass	0 clear	0 tint	30 clear	30 tint	50 clear	50 tint	70 clear	70 tint
Mean (m)	32.2	31.0	29.0 †	30.5	28.4 †	30.1	27.9 †	29.5	26.9 †
SD (m)	5.5	5.6	5.3	5.7	5.3	5.6	5.3	5.4	5.1

† = Significant differences between means obtained using Student's unpaired *t*-test on individual comparisons ($p < 0.01$).

Critique

Subjects appear to have performed the recognition task in the absence of any additional workload. The subjects were free to concentrate on target recognition, whereas drivers face a considerably heavier workload. The results of this experiment would have been more informative had it been performed in a real, or simulated, driving environment.

Wakely, H., Wolf, L., and Godin, S. (1983). *Optical engineering research on new and used automotive glazing.* (Final Report No. DOT HS-806 690). Chicago, IL: IIT Research Institute.

Abstract

This study was performed to provide a quantitative background for selecting criteria for automotive glazing materials, particularly for transmittance and haze, as these are affected by laboratory tests and road exposures. Experimental designs and data collection protocols were prepared and followed which yielded objective descriptions of the response of new, in-use, and end-of-useful-life glazing materials to environmental exposures & simulations of exposures. Research subject areas included: (1) Transmittance & Haze of Automotive Glazing Presently in Use, (2) Tolerated Obscuration of Glazing in Use, (3) Environmental Effects on Glazing, (4) ANSI Z-26 Tests Effects on Glazing Transmittance & Haze, and (5) Production of a Motion Picture Illustrating the Effects of Increasing Haze on Roadway & Roadside Visibility. The results indicated that drivers often operate vehicles with windshield haze levels exceeding 4%, largely attributable to dirty glazing. Tests based on environmental models indicate Securiflex glazing provides optical qualities equivalent to or exceeding on-road use requirements; Securiflex glazing meets ANSI Z-26 visibility and durability tests, (Tests 3, 4, 16, 17, 18, 19, and 24 - 17 modified to accept a 4% haze increase proposed for glass-plastic glazing) and retained adequate optical qualities (haze & transmittance) to meet present user requirements.

This paper addresses the effects of environmental factors that produce haze and reduced transmittance in automotive windshields. While the authors make extensive quantitative measures of windshield haze and transmittance, no data related to driver visual performance through these windshields is presented.

Weigt, P. F. (1986). Darker glass in the reward field of view. In A. G. Gale, M. H. Freeman, C. M. Haslegrave, P. Smith, and S. P. Taylor (Eds.), *Vision in Vehicles* (pp. 343-353). Amsterdam: North-Holland.

Abstract

Modern car design with large and obliquely mounted glasses results in cars with an uncomfortable climate, which can adversely affect the driver's concentration.

Light transmittance of automotive glazing is regulated by law in most countries, but the rearward field of view is not so clearly defined as the 180 degree forward field of view. Legally required limits for the reflectance of rear-view mirrors are at a minimum of 40 percent due to an EC Regulation. A backlight with 40% light transmission therefore gives a performance in line with the EC Regulation for rear view mirrors.

Normally tinted glasses are offered by glass manufacturers as a solar control glazing. The effectiveness of tinted glass especially green glass and coated green glass is discussed. A proposal to increase the thermal comforts in the car is made by recommending darker tints than normally used.

Darker tints could affect the driver's vision. An investigation was carried out using a driving simulator to determine how drivers react when looking through windshields with various degrees of light transmission in the range of 90% to 40%. A windshield with scattered light produced by surface damages was also investigated.

Results obtained with the driving simulator show that a small amount of scattered light impairs the drivers vision much more than glasses with a normal depth of tint. Dark glasses with a light transmission of 40% can be tolerated in locations in the car where the images normally observed are of high contrast levels.

Independent Variables

Transmittance. Windshields at five levels of luminous transmittance were examined. While the spectral characteristics of the "green" windshields were similar, the "clear" windshield was considerably different.

Glass	Transmittance of light (%)	Transmittance of energy (%)
clear	91	85
laminated (green)	76	58
toughened w/ haze (green)*	77	54
toughened 1 (green)	60	45
toughened 2 (green)	40	31

* approximately 1.5% scatter

Contrast. Four levels of luminance contrast were examined. The author states that "the investigation method" described by Rompe and Engel (1984) was used. It is therefore assumed that the same four levels of contrast, target pattern, and criteria reported by Rompe and Engel were employed in this study. Glare was introduced using one 100 cd/m^2 luminance source. This source was aimed only at one side of the windshield (the driver's side), similar to the method of Rompe and Engel (1984).

Luminance ratio	Number of target presentations Left side	Right side
2:1	7	7
4.6:1	7	8
21:1	7	4
149:1	4	6

Dependent Variables

No clear description of the dependent variables is provided. However, the dependent variables are assumed to be the same as, or similar to, those stated by Rompe and Engel (1984). The author identifies the dependent variables as "percentage of right answers, the reaction time, and the percentage of no answers to the presented targets," but provides no further information.

Subjects

The only information provided regarding the subject population was to state that half of the subjects wore eye glasses, and half did not.

Results

Subjects' ability to perform the task was impaired only when the target contrast level was at its lowest. Specifically, subjects were able to detect the presence of better than 80% of the targets for all but the lowest level of contrast. For all other levels of target contrast the author states that differences in transmittance (91% - 40%) had no effect on subjects' visual performance. Therefore, the author suggests that use of 40% transmittance glass should be permissible "if images of high contrast levels are normally observed through it." No statistical analyses were performed by the authors.

Subject visual performance when viewing targets through the glass with 1.5% scatter was reported as being dramatically effected. The author states that a small amount of scattered light impairs a driver's vision more than the tinting of windshields. However, subjects' ability to detect the presence of targets was only really noticeable when the target was of very low contrast. Again, no statistical analyses were performed by the authors.

No differences between eyeglass wearers and subjects without eyeglasses were reported. No statistical analyses were performed by the authors.

Critique

The author states that the use of 40% transmittance glass should be permitted in the rear of a vehicle, if images of high contrast are normally observed through the rearward view. The author states that the use of 40% transmittance glass in the rear of a vehicle would not be an issue in the daylight (presumably because there would be sufficient light to provide adequate visibility), and at night similar illumination will be provided by the headlights of following vehicles. This fails to address instances of vehicle backing on overcast days, or at night, without additional illumination.

Overall, there is insufficient information included in this paper. It appears almost certain that the same experimental methods that were employed by Rompe and Engel (1984) were repeated in this investigation. Therefore, this investigation likely suffers from the same problems as Rompe and Engel (1984).

Wolf, E., McFarland, R. A. and Zigler, M. (1960). Influence of tinted windshield glass on five visual functions. *Highway Research Board Bulletin, 225*, 30-46.

Abstract

Tinted windshields and side windows in automobiles have been introduced for two purposes: (a) to eliminate a major portion of radiant infra-red energy, and (b) to reduce excessive brightness and glare. The commonly used bluish-green tinted glass has a transmission of 65 to 70 percent, which is similar to that of sunglasses of light shade. At photopic (daylight) luminance levels the absorption of the glass is hardly noticeable. At mesopic (dusk) and scotopic (night) luminance levels a 30 percent reduction in transmission may interfere seriously with vision.

To study the effects of tinted windshield glass on vision at various luminances, tests were performed on (a) dark adaptation, (b) recovery from the shock of a blinding light flash, (c) visual acuity, (d) depth perception and (e) the effects of glare.

Dark adaptation tests showed that when looking through a tinted windshield the thresholds for recognition of a test stimulus were higher than that without an absorptive filter in the light path. The rise in threshold corresponded exactly to the brightness loss produced by the tinted glass.

When the eyes were adapted to low levels of luminance or to complete darkness and were suddenly exposed to a bright flash of light, recovery from the light shock and regaining of the previous sensitivity level was not enhanced by the presence of the tinted windshield glass. The reduction of luminance of a light flash by a tinted windshield was of no advantage, because the same absorption of the windshield also reduced the visibility of a test target.

Visual acuity was reduced slightly by tinted windshield glass. When acuity was measured with targets of small differences in size (Landolt rings) it was found that with the tinted windshield the intrinsic details could be seen only if they are 10 to 20 percent larger than when seen without an absorptive filter in the path of light.

Depth perception was also influence by tinted windshield glass. A 25 to 35 percent loss in depth perception was observed when the test object was seen through tinted windshield glass.

When test targets were identified in the vicinity of a glare source and the ratios of glare luminance / target luminance were determined when the targets are viewed through tinted windshield glass and without the filter, it was found that the ratios remained the same whether tinted windshield glass was in the path of view, or vision was not obstructed by filters.

All tests uniformly showed that with tinted windshield glass in the line of sight the eyes appeared less sensitive by an amount that corresponded to the physical absorption of radiant flux by the filter in front of the eyes. No improvement of vision of any sort was found when tinted windshield glass was used.

This research examined the effects of tinted windshield glass (of approximately 70% transmittance) on subjects' dark adaptation, recovery from light shock, visual acuity, depth perception, and response to glare.

Wolf, E., McFarland, R. A. and Zigler, M. (1960)

Dark Adaptation

Independent Variables

Transmittance/filter. Four levels of transmittance/filter, hence forth referred to as filter, were examined. Three of these four levels were samples of windshield glass, all varying in spectral characteristics but similar in transmittance. One level was a null case. The three windshield samples had transmittance characteristics in the range of 65% to 72%. One level was "bluish," one "brownish," and one "deep yellow" in color. A filter was placed between the test stimuli and the observer after the dark adaptation function was established for a given retinal area. A shutter was used to control presentation times.

Target luminance. A wide range of target luminances were used. Luminance levels varied as a function of stimulus size, stimulus location, surround luminance, and filter level.

Location/surround. Test stimuli were presented in two different locations in the visual field and at two levels of surround lighting. In all, there were only three levels of this variable presented: central stimulation without surround lighting, parafoveal stimulation without surround lighting, and dark adaptation with surround lighting. The stimuli were squares subtending 1.3° in the fovea and 2° in the parafovea. The surround was a 40° field, evenly illuminated. The observer was exposed to a luminance of 5173 cd/m^2 for 10 m before the tests.

Dependent Variables

Threshold dark adaptation time. Each test consisted of stimulus exposure at a specific target luminance level until threshold detection was reached during the process of dark adaptation. Tests were repeated at intervals of every 1 to 1.5 m.

Subjects

No information was given about the subject population.

Results

When a filter was inserted in the path of the stimulus, the dark-adaptation curve obtained was shifted upward 0.16 log units relative to a no filter condition. This indicated that 1.45 times more light was required for threshold recognition when the stimuli were seen through the tinted windshield glass in the absence of surround lighting.

When the stimulus was presented against a surround of 0.32 cd/m^2 the threshold level was from 0.14 to 0.16 log unit higher when a filter was used. The results indicated that the luminance loss produced by a filter's transmittance, rather than its spectral characteristics, was responsible for the reduction in threshold sensitivity. These results were consistent with calculations of physical loss in luminance resulting from the filters. Shifts in dark adaptation of equal magnitude were obtained using filters with different spectral characteristics, but approximately equal transmittance. Therefore, the authors suggest that it is luminance loss produced by the filters rather than their spectral absorption that is responsible for reductions in sensitivity. No statistical analyses are provided.

Recovery from Light Shock

Independent Variables

Transmittance/filter. The same four levels of transmittance/filter that have previously been described were once again examined. For each surround luminance and filter level the following four conditions were presented:

1. Both the shocklight and stimulus were unfiltered.
2. The shocklight was unfiltered and the stimulus was filtered.
3. The shocklight was filtered and the stimulus was unfiltered.
4. Both the shocklight and the stimulus were filtered.

Surround. The target was a square subtending 2° and presented 10° below center. The target was presented against either a black background, a surround luminance of 0.32 cd/m^2, or a surround luminance of 0.032 cd/m^2. The observer was dark adapted for 30 minutes and then exposed to a luminance of 1268 cd/m^2 for 0.04 s. The stimulus was not continuously on, but was presented every 2 s to subjects. In order to simulate two sources of high luminance (i.e., oncoming headlamps), two concave mirrors were used to reflect light from the projector.

Dependent Variables

Recovery time. Recovery time was defined as the time from the end of light shock exposure to the first recognition of the stimulus.

Subjects

No information about the subject population was provided.

Results

Recovery time after light shock was 1.2 to 1.4 times longer when the stimulus was obscured by tinted windshield glass than when no filter was placed in front of the stimulus. The largest increases in recovery time were associated with illuminated target surrounds. This increase in recovery time is proportional to the loss in luminance transmittance in the filters. No statistical analyses are provided.

Mean recovery times from light shock (s)

No filter in front of shock source		Filter in front of shock source	
No stimulus filter	Filtered stimulus	No stimulus filter	Filtered stimulus
26.7	31.1	23.8	27.3

Visual Acuity

Independent Variables

Target size. Charts with 10 sizes of Landolt rings were used. Ring size varied from 1.2 to 4.0 mm. Charts consisted of 25 symbols with gaps appearing in one of four randomly determined positions. The viewing distance was 187 cm.

Ring size	Visual acuity	Ring size	Visual acuity
1	0.068	6	0.230
2	0.076	7	0.303
3	0.085	8	0.342
4	0.096	9	0.390
5	0.114	10	0.455

Luminance. Two levels of luminance were examined. The first level, 0.30 cd/m^2, is in the mesopic range, and the second level, 189.3 cd/m^2, is in the photopic range.

Transmittance. More than one level of transmittance was examined, but the authors do not make it clear as to exactly how many levels of transmittance were used, or what their characteristics were.

Dependent Variables

Target recognition. The subjects' task was to identify the position of the gap in the Landolt rings. The number of correct responses was the performance measure.

Subjects

Twenty-one subjects participated in the mesopic test. Subjects who wore corrective lenses continued to wear them during the test. Twenty subjects participated in the photopic test. No other information about the subject population was provided.

Results

The results indicated that visual acuity was reduced by tinted windshield glass, as subjects were not able, for the most part, to identify gap positions of ring size 9 or 10. When the luminance level was 0.30 cd/m^2, instead of the 189.3 cd/m^2, subjects were less likely to correctly identify the location of the Landolt ring's gap. These results indicated that at both photopic and mesopic luminance levels tinted windshield glass reduced visual acuity. No statistical analyses are provided.

Depth Perception

Independent Variables

Spatial frequency/depth. A Verhoeff stereopter was used. The stimuli were vertical bars of differing widths and depths. Eight different bar positions were examined. Subjects started out at 100 cm from the stereopter, and the distance increased or decreased depending on each subject's ability to recognize depth.

Transmittance. Luminance from the stereopter was varied by use of filters and a diaphragm. Two levels of transmittance were examined, a no filter and a filter condition. The filtered condition used was reported to be a windshield sample of 70% transmittance.

Dependent Variables

The dependent measure is not made explicitly clear by the authors. It appears to be related to the spatial relationship of the vertical bars.

Subjects

Twenty subjects participated in the depth perception study. No other subject information is provided.

Results

Steropsis was reduced from 12.5% to 37.5% when the depth target was viewed through tinted glass. Tests with the Verhoeff stereopter showed a 25% reduction in depth perception when a tinted windshield was placed in the path of vision. No statistical analyses are provided.

Effects of Glare Experiment

Independent Variables

Glare Source. The full luminance of the glare source was 10,312 cd/m^2. Glare was controlled using a series of filters. The filters provided transmittances of 0.0001%, 0.001%, 0.01%, 0.1%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80% and 90%.

Transmittance. Two levels of transmittance, a null case and a 70% transmittance windshield sample, were used to create four conditions.

1. Both the glare source and stimulus were unfiltered.
2. The glare source was unfiltered and the stimulus was filtered.
3. The glare source was filtered and the stimulus was unfiltered.
4. Both the glare source and the stimulus were filtered.

Stimulus location. The targets, Landolt rings, were randomly located in one of three locations (outer, middle and inner circles), separated from the glare source by 3.25°, 2.25° and 1.25° respectively.

Dependent Variables

Target recognition. The subjects' task was to identify the location of the gap in a Landolt ring. The intensity of the glare source was varied to determine threshold detection of the Landolt ring.

Subjects

Thirty-one college students participated in the glare study. No other subject information was provided.

Results

Results of the glare tests are given in the following tables. The first table provides results that the authors regard as "typical" for the entire group. The second table provides results for older subjects (70 years and over). The authors suggest that the reduction of glare by tinted windshields is not helpful in rendering targets more visible in the vicinity of a glare source. No statistical analyses are provided.

Mean of all subjects

Threshold luminances (cd/m²)

	No filter		Tinted windshield	
Circle	No filter in front of glare	Filter in front of glare	No filter in front of glare	Filter in front of glare
Outer	0.26	0.16	0.26	0.16
Middle	0.30	0.26	0.30	0.26
Inner	0.58	0.30	0.52	0.38

Mean of subjects 70 years or older

Threshold Luminances (cd/m²)

	No filter		Tinted windshield	
Circle	No filter in front of glare	Filter in front of glare	No filter in front of glare	Filter in front of glare
Outer	1.86	0.58	1.86	1.86
Middle	3.22	0.99	3.22	3.22
Inner	3.55	3.22	4.71	4.71

Critique

Many aspects of this research were not well defined by the authors; this is particularly true of the description of the subject populations. In certain sections of the research the number of subjects is given, while in others no information is given at all. No distinction is made between subject ages except in the final glare study, where comments are made about different results obtained with the 70-years-and-older subjects. However, no information is provided concerning the number of older participants. No information regarding the visual capabilities of subjects is provided for any of the experiments. No statistical analyses are performed for any of the five experiments conducted by the authors. Despite the absence of quantitative analyses, in each experiment it is reported that the use of window tinting could worsen, but never aid, subject's visual performance.

SUMMARY OF THE LITERATURE

Transmittance

Of the reviewed articles, 15 investigations varied windshield or window transmittance. Ten of those articles reported that reduced levels of transmittance have a negative influence on subjects' ability to identify or detect targets. The level of influence varied considerably across investigations, five investigations described the effect on seeing distance as serious or statistically significant. The existing literature appears to leave little doubt that motor vehicle window transmittance can influence a driver's ability to detect objects/obstacles, particularly in dusk or nighttime conditions. What remains to be determined is the degree of impact specific levels of transmittance have on driver visual performance. Unfortunately, the performance criteria that have been established vary dramatically across investigations. To further complicate the issue, not all researchers have used the same methods for determining light transmittance.

While some researchers report transmittance measures that have been taken normal to the windshield/window surface, others report transmittance values that have been measured parallel to the line of sight at the installed angle. The measurements performed by Owens et al. (1992) indicate that substantial reductions in windshield transmittance result when windshield rakes exceed 60° from vertical. The authors reported a 9% reduction in windshield transmittance for a rake of 60°, relative to 0, increases to a reduction of 12% and 34% for rakes of 65° and 75°, respectively. It has been proposed (NHTSA, 1992) that standards for light transmittance be changed to require measurement at the angle of installation, but as of yet this proposal has not been adopted.

Among the studies to find statistically significant effects associated with the use of reduced transmittance are Derkum (1993), Heath and Finch (1953) (as analyzed by Triggs, 1988), Owens et al. (1992), Rompe and Engel (1987), and Waetjen et al. (1992). The dependent measures in these studies included target recognition and detection, visual acuity, reaction time, and driving speed. One investigation (Wolf et al., 1960) reported negative effects on visual performance of reduced transmittance, but did not include statistical analyses.

While other studies failed to find statistically significant visual performance decrements associated with reduced transmittance, there is some question as to whether the criteria used were sufficiently stringent (Weigt, 1986). Several investigations included levels of tinting that did not span a large range of transmittance values. As a result, the authors report some diminished visual performance, but no statistically significant differences associated with tinting use. Examples of investigations where the examination of a wider range of transmittance would have been beneficial include Doane and Rassweiler (1953), Dunn (1973), Huber (1988), and Roper (1953). Unfortunately, it has not been uncommon for researchers to limit their investigation to transmittance levels of 70% and above. Two recent studies suggest that driver visual performance begins to decline significantly for levels of transmittance below approximately 70% (Derkum, 1993; and Rompe & Engel, 1987). Yet there is considerable variability (and absence of systematic control) in the levels of light transmittance examined and the method of transmittance measurement. Furthermore, the effect of rake on light transmittance has not always been factored into transmittance measurement.

In an attempt to summarize the effects of transmittance on driver visual performance, data from six studies are presented in two figures. Each figure summarizes data from one of two types of tasks that subjects were expected to perform. These data were obtained through visual inspection of published figures or results provided in the studies. These six studies, of the thirty-three reviewed, were selected on the basis of similarity in the tasks performed and the ability to ascertain quantitative results.

Figure 1 presents data from two target recognition experiments conducted by Rompe and Engel (1987) and Weigt (1986). In both of these studies the target was a variation of a Landolt ring, and subjects were instructed to identify the location of the ring's gap (orientation) while target contrast and transmittance were varied (only results for the mean contrast level from subjects reported to have normal vision are presented in Figure 1). A best-fitting line was determined independently for each of the studies.

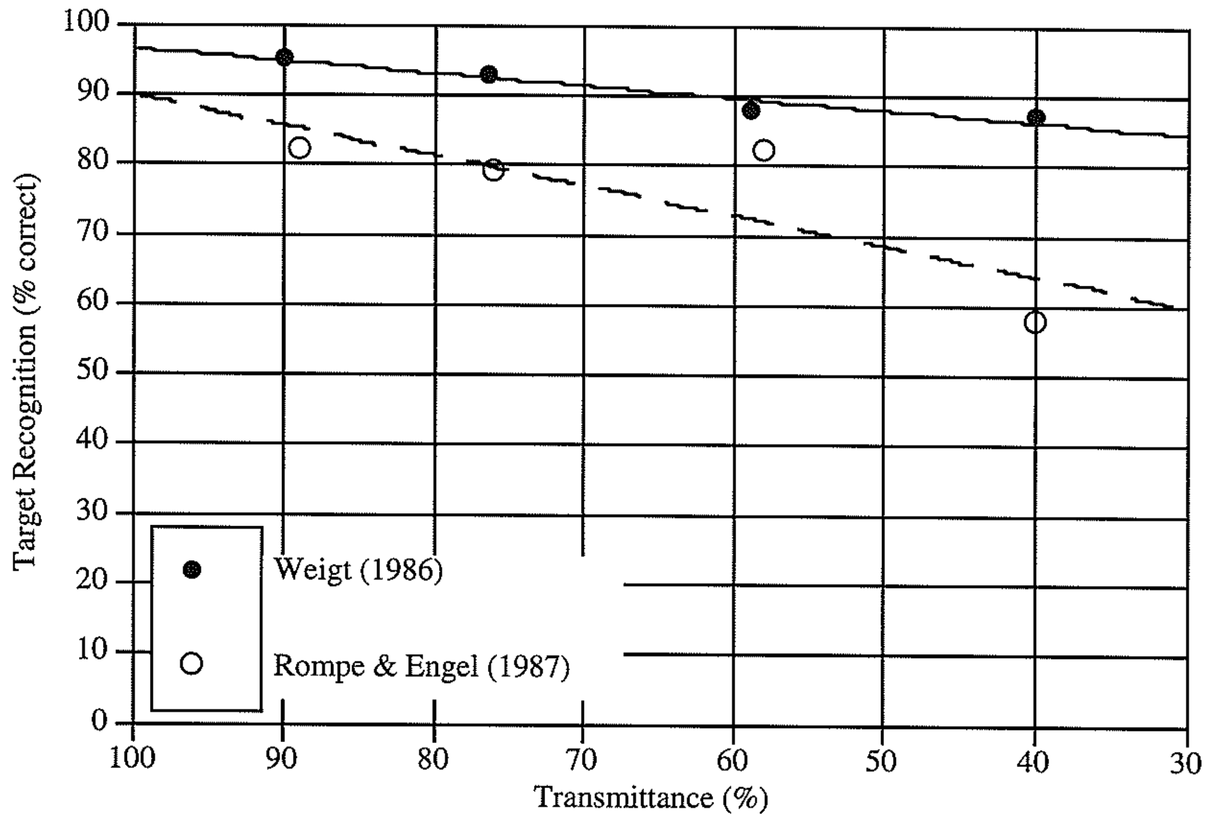

Figure 1. A comparison of results from studies using Landolt-like tasks to examine the relative effects of windshield transmittance on driver visual performance. Data are only for the mean contrast level, from subjects reported to have normal vision.

An examination of Figure 1 reveals that the slope of the best-fitting line for the Weigt study was not as steep as the slope observed in the study by Rompe and Engel. The results of the study by Rompe and Engel suggest roughly a 50% reduction in transmittance, from 100%, will produce a 20% reduction in driver visual performance for a Landolt-ring task. The results of the study by Weigt would suggest that less than a 10% reduction in visual performance would be observed under similar conditions.

Figure 2 presents data from seeing-distance experiments conducted by Derkum (1993), Doane and Rassweiler (1953), Heath and Finch (1953), and Waetjen et al. (1992). In each of these studies the task was to determine the effect of windshield transmittance on seeing distance for a wide variety of objects. Target contrast was held constant while windshield transmittance was varied in the study conducted by Derkum (only the results from conditions without glare are presented). The target in the Derkum study was a Landolt ring that was moved towards subjects until they could identify its orientation. In the study conducted by Doane and Rassweiler, target reflectance, headlamp type, headlamp aim, and windshield transmittance were all varied, although not systematically, resulting in four separate conditions. The results from all four experimental conditions are represented in Figure 2. Heath and Finch also examined several different conditions, all of which are independently represented in Figure 2. In the study by Waetjen et al., variations in transmittance were accomplished though a combination of luminance transmittance (tinting) and windshield rake variations.

In order that the data from the four studies could be presented in the same figure, some normalization of the data was performed. The results were recomputed such that changes in seeing distance were reported in percent change in seeing distance as a function of windshield transmittance ($[distance_x/distance_{maximum}]*100$). A best-fitting line was determined independently for each of the four studies.

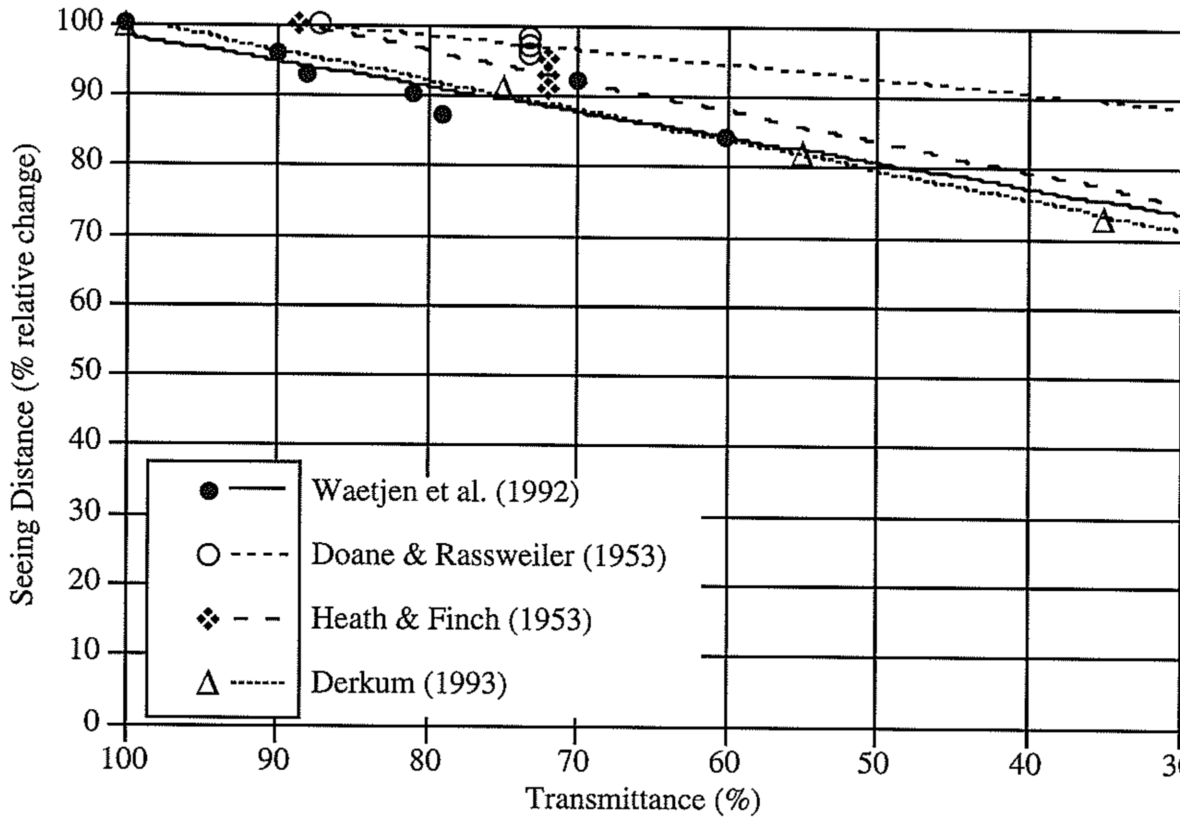

Figure 2. A comparison of results from studies using seeing distance to examine the relative effects of windshield transmittance on driver visual performance. Data are from selected conditions of each study (See text).

An examination of Figure 2 reveals that the normalized results from the studies performed by Waetjen et al., Heath and Finch, and Derkum are very similar in the slope of their best-fitting lines. The slope of the best-fitting line for the Doane and Rassweiler study was not as steep as that observed in the other three studies. The results of the work by Waetjen et al., Heath and Finch, and Derkum suggest that a 50% reduction in transmittance, from 100%, will produce approximately a 20% reduction in driver visual performance for a seeing distance task. The results based upon the work of Doane and Rassweiler suggest roughly a 10% reduction in visual performance under similar conditions.

Striking similarities were observed in the effect of windshield transmittance on driver visual performance, independent of the task, in the studies performed by Derkum (1993), Heath and Finch (1953), Rompe and Engel (1987), and Waetjen et al. (1992). Specifically, the slopes of the best-fitting lines are very much alike. Similarity is also seen in the results of the Doane and Rassweiler (1953) and Weigt (1986) studies. On the basis of this assembly and re-examination of previously reported data, it appears that a reduction in transmittance by 50%, from 100%, can produce a reduction in driver visual performance, independent of task, on the order of 10-20%. However, because much of the data was obtained through visual inspection of published figures this statement should only be treated as a generalization of the combined results.

Dirt

Two of the reviewed articles examined the effects of dirt on driver visual performance through windshields (Allen, 1974; and Owens et al., 1992). Allen reported that dirt contributed to reducing driver visual performance, particularly under conditions of glare. Similar results were reported by Owens et al., who stated that light scatter resulting from dirt significantly reduced driver visual performance. Owens et al. also reported that light scatter resulting from dirt had a larger effect on visual performance in an acuity task than age, glare, target contrast, or transmittance. However, these researchers did not quantify the levels of windshield dirt examined.

Glare

No research was located that addressed the effects of veiling glare resulting from reflection off the dash board. However, six of the reviewed articles examined the effects of glare from oncoming vehicles on driver visual performance through tinted windshields or windows (Allen, 1974; Derkum, 1993; Helmers & Lundkvist, 1988; Owens et al., 1992; Stackhouse & Hancock, 1992; and Wolf et al., 1960). There was substantial variation in the approaches taken by different investigators.

Allen varied the distance of the glare source from the observer. He reported that the closer the glare source was to an observer, the shorter the observer's detection distance was with dirty or scratched windshields. Derkum examined the effect of glare at various levels of transmittance and reported that glare, versus no glare, significantly affected target recognition. Helmers and Lundkvist varied the type of glare source, both in intensity and spectral composition, and reported that glare resulted in increased levels of stray light from worn windshields. In turn, the increased levels of stray light resulted in decreased detection distances. Owens et al. reported that glare had a dramatic effect on visual acuity, particularly for persons susceptible to night myopia. Stackhouse and Hancock do not thoroughly discuss the influence of glare in their experiment, other than to say that tinted films do not improve target detection by reducing the effects of glare. Wolf et al. reported results similar to those of Stackhouse and Hancock.

The results appear to indicate that reduced-transmittance glazing does not aid driver visual performance in the presence of oncoming glare. However, these investigations do suggest that glare has a substantial effect on driver visual performance when windshields are worn (scratched) or dirty as a result of the stray light produced.

Privacy

No literature that specifically addressed the influence of windshield transmittance on occupant privacy was located. Only the “see-in” experiment reported by Stackhouse and Hancock (1992) indirectly examines the issue of privacy. The authors state that subjects were sensitive to changes in the level of tinting, and that the same variations effected their ability to detect the presence of the pistol. This result suggests that reduced transmittance windows provide some level of privacy within a vehicle.

Reflectance

No literature related to the influence of windshield reflectivity on driver visual performance was located.

Spectral Properties

Of the articles reviewed, none specifically examined the effects of reflectance or spectral properties on driver visual performance or driving performance. Only the article by Dain et al. (1993) discusses the potential for combined luminance transmittance and spectral transmittance effects of windshields, sunglasses, and contact lenses. However, no quantitative data related to driving performance or sight distance is presented. Nonetheless, Dain et al. conclude that a reduction in luminous transmittance associated with the combined use of tinted contact lenses, sunglasses and tinted windshields presents a risk to drivers. However, Dain et al. readily admit that the level of risk is difficult to demonstrate.

Target Characteristics

A number of the articles reviewed do not justify the levels of target contrast, reflectance, or size examined. Still others failed to report any stimulus characteristics at all. Early studies, like that of Heath and Finch (1953), did not seem to recognize, or at least emphasize, the importance that target contrast and reflectance have on driver visual performance.

Several of the reviewed studies employed static visual acuity tasks as performance measures when examining the effects of transmittance. Previous attempts to correlate static visual acuity with driving performance (i.e., accident records) have generally not been successful (Leibowitz, 1993). Leibowitz has suggested that possible alternatives to static visual acuity testing are contrast sensitivity (either static or dynamic), visual field, night vision, glare recovery and visual persistence.

Only a few of the articles reviewed reported systematically varying target contrast (Freedman et al., 1993; Owens et al.; 1992, Rompe & Engel, 1987; and Weigt, 1986). These investigations reported that a driver's ability to detect a target was either strongly or significantly dependent upon the level of target contrast. However, none reported the influence of target contrast as a function of target eccentricity (i.e., its location in the visual field).

Wear

Six of the reviewed articles examined the effects of windshield wear on driver visual performance (Allen, 1974; Derkum, 1991; Helmers & Lundkvist, 1988; Owens et al., 1992; Rompe & Engel, 1984, 1987). Allen (1974) reported that windshield wear contributed to reducing driver visual performance under conditions of glare. Derkum (1991) examined 28 windshields in various conditions of wear, and reported moderate-to-high negative correlations between measurements of scattered light and visual acuity. Two studies by Rompe and Engel (1984, 1987) showed that target recognition is reduced, and driving speed decreased, in response to stray light produced by worn windshields. Helmers and Lundkvist (1988) reported that stray light produced by worn windshields resulted in significant reductions in driver visual performance (9% to 25%). Owens et al. (1992) also found light scatter from worn windshields to significantly affect driver visual performance.

Overall, the research suggests that windshield wear produces stray light which reduces driver visual performance, particularly in the presence of glare. One investigation has suggested that the influence of stray light from dirty or worn windshields has a greater effect on driver visual performance (and therefore driving performance) than target contrast, glare, age, or windshield transmittance (Owens et al., 1992). However, the levels of windshield wear examined were frequently not quantified, and those researchers who did quantify wear used dissimilar measurement techniques.

Conclusions

While the quality of the existing research is not particularly strong, there is sufficient evidence to conclude that motor-vehicle windshield and window transmittance have a significant effect on driver visual performance. While moderate reductions in interior vehicle temperatures can be attributed to window tinting (Hurst & Scroger, 1974), there is no evidence to support the use of tinting to reduce the effects of oncoming glare on seeing distance (Stackhouse & Hancock, 1992; Wolf, McFarland, & Zigler, 1960), and no data exist on the effect on discomfort glare. However, on the basis of a re-examination of previously reported data, it appears that transmittance has a linear effect on driver visual performance, with a reduction in transmittance levels from 100% to 50% resulting in a reduction in visual performance of 10-20%. Because the effect of transmittance on visual performance does not produce any obvious departures from linearity (i.e., there is no clearly defined level of transmittance at which visual performance deteriorates dramatically), the establishment of transmittance regulations must be based upon a criterion of acceptable driver visual performance. If a driver visual performance criterion can be defined, then corresponding levels of windshield and window transmittance can be identified.

Summary Table of the Reviewed Literature

Author	Type of study	Independent variables	Dependent variables
Allen (1974)	experimental (static & dynamic)	- dirt - glare - wear	- target detection - target recognition
Boyce and Gu (1992)	model	- age - luminance - traffic scenario - transmittance	- reaction time - visibility level
Clark (1993)	review		
Cunningham (1993)	review		
Dain et al. (1993)	theoretical		
Derkum (1991)	experimental (static)	- rake - target contrast - wear	- acuity - preference
Derkum (1993)	experimental (dynamic in lab)	- glare - target format - transmittance	- target recognition
Dietzel (1991)	review & theoretical		
Doane and Rassweiler (1953)	experimental (dynamic)	- headlamp aim - target reflectivity - transmittance	- seeing distance - target recognition
Dunipace et al. (1974)	model		
Dunn (1973)	experimental (static)	- age - target type - transmittance	- detection distance
Filkins (1979)	statistical research	- transmittance	- accident rate
Freedman et al. (1993)	experimental (simulation)	- age - target contrast - transmittance	- resp. latency - target detection - target recognition
Haase et al. (1989)	review		
Haber (1955)	theoretical		
Heath and Finch (1953)	experimental (dynamic)	- transmittance	- seeing distance
Helmers and Lundkvist (1988)	experimental (dynamic)	- glare - stray light (wear) - target luminance	- detection distance
Huber (1988)	experimental	- environmental conditions - transmittance	- behavioral adapt. - driving behavior - operational variab. - stress indicators
Hurst (1974)	experimental (dynamic)	- transmittance	- temperature
Keßler (1993)	review & theoretical		
Merritt et al. (1978)	experimental	- modulation transfer function - target size	- threshold contrast
Owens et al. (1992)	experimental (static)	- age - dirt - glare - night myopia - target contrast - transmittance	- accommodation - acuity

Author	Type of study	Independent variables	Dependent variables
Rompe and Engel (1984)	experimental (simulation)	- age - contrast - wear	- driving speed - recognition - reaction time
Rompe and Engel (1987)	experimental (simulation)	- age - contrast - haze - transmittance	- driving speed - recognition - reaction time
Roper (1953)	experimental (dynamic)	- acuity - transmittance	- seeing distance
Southall and Burnand (1991)	experimental (static & dynamic)	- electric vs. non-electrically heated wind-shields	- acuity - fatigue and discomfort - target ident.
Stackhouse and Hancock (1992)	experimental (simulation)	- glare - maneuvers & targets - transmittance	- target detection
Timmermann and Gering (1986)	review		
Triggs (1988)	review		
Waetjen et al. (1992)	experimental (static)	- rake - transmittance	- seeing distance - target recognition
Wakely et al. (1983)	review		
Weigt (1986)	experimental (simulation)	- target contrast - transmittance	- reaction time - target recognition
Wolf et al. (1960)	experimental (static)	- glare - spatial frequency - stimulus location - target luminance - target size - transmittance /filter	- dark adaptation - recovery time - target recognition

STATE REGULATIONS ON MOTOR VEHICLE WINDOW TINTING

Motor-vehicle window-tinting regulations across states in the U.S. are extremely inconsistent and often confusing. To say that there is little uniformity is an understatement. From outlawing windshield tinting altogether to allowing it without regulation, very little common ground currently exists between states concerning the regulation of after-market tinting. The following is an overview of state regulations regarding tinted automotive glass [compiled from the American Automobile Association *Digest of Motor Laws* (1994)].

While some states have detailed regulations, many states are simply vague. For example, regulations in New Mexico allow windshield tinting as permitted by local restrictions. Therefore, while one level of tinting is legal in one municipality, it is possible to drive a few miles and find the same tinting to be illegal in another. In Nevada, tinting is permitted except for application to the windshield, but there are no limits given as to how much tinting can be applied to other windows. Many other states restrict use, but do not clearly specify the limits. In Arizona, for example, tinting is legal within prescribed limits, but the limits do not appear to have been specified.

Other states have regulations that are harder to define. In North Carolina, for example, regulations are pending, but it is not clear when a decision will be made. Hawaii has relaxed regulations, allowing after-market tinting on any window so long as the light transmittance is no less than 35% (plus or minus 5%). Therefore, the minimum permissible transmittance level is 30%. In Missouri the regulations state that after-market tinting may be illegal, unless the tinting meets state requirements and is only on the rear windows. Finally, in Indiana, tinting is legal only when tested on 1/8th inch clear glass and solar reflectance of light is found to be no greater than 25% measured on the nonfilm side with light transmittance of at least 35% in the visible light range.

Some states allow tinting, but with so many restrictions that it often may not be worth the trouble to install. For example, tinting is permitted in Texas on some vehicle windows and on front side doors with approved glass material only. In addition, tinting of any density can be applied to rear windows of vehicles with two outside mirrors, and any vehicle that is a 1988, or newer, model must have a safety inspection that requires only approved tinting material on side windows. Florida's regulations are lengthy and specific; of note is a regulation which states that if a window is not transparent, two side mirrors must also be present. Side windows in Florida cannot have less than 28% light transmittance, and windows behind the driver cannot have less than 15%.

Difficulty arises when traveling between states. Some state regulations specify rules for both in-state and out-of-state residents, while others do not specify whether regulations apply to nonresidents. For example, New Hampshire residents are prohibited from tinting their own vehicles' windshield or windows to the left or right of the driver, but there are no specific laws regulating out-of-state vehicles. In contrast, Delaware's requirements apply directly to out-of-state vehicles. Delaware permits only the rear window and rear side windows to be tinted, but the light transmittance must be a minimum of 70% and the vehicle must have two outside mirrors.

Medical exemptions are allowed in many states, but not in all. Even when exemptions are allowed, once again regulations differ across states. In Illinois and Iowa, medical reasons that warrant increased tinting beyond state regulations are allowed with certification only. Michigan requires a letter to be in the possession of the driver using the words *medical necessity* if there is tinting applied to the windshield or front side windows. Pennsylvania prohibits tinting completely except for medical exemptions, while Oregon and Rhode Island prohibit after-market tinting without exception.

If a generalization can be made about the consistency of state regulations, it is be that many states do not allow after-market tinting on windshields or side windows to the right and left of the driver.

When tinting is allowed, especially tinting that is placed on the rear window and rear side windows, the most common regulation is to have a light transmittance of at least 35%. Some states, such as Maine, Minnesota, and Louisiana require 50% light transmittance, while others, such as Nebraska and Oklahoma, will permit 20% light transmittance on some windows. Overall, however, a minimum of 35% light transmittance is common for rear and rear side windows. While few states allow windshield tinting, states will often allow tinting material on the top 10.2 cm to 15.2 cm.

After-market tinting regulations are inconsistent, confusing, and lack specificity in some states. As a result, it is difficult to implement, or enforce, state regulations given that drivers are not well informed. Many drivers will enter states where after-market tinting is illegal from states where tinting is legal.

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