UMTRI-2003-36

DAYTIME VEILING LUMINANCE FROM WINDSHIELDS: EFFECTS OF SCATTERING AND REFLECTION

Mary Lynn Mefford
Michael J. Flannagan
Go Adachi

November 2003

DAYTIME VEILING LUMINANCE FROM WINDSHIELDS: EFFECTS OF SCATTERING AND REFLECTION

Mary Lynn Mefford
Michael J. Flannagan
Go Adachi

The University of Michigan
Transportation Research Institute
Ann Arbor, Michigan 48109-2150
U.S.A.

Report No. UMTRI-2003-36
November 2003

Technical Report Documentation Page

<table>
<tr><td>1. Report No.
UMTRI-2003-36</td><td>2. Government Accession No.</td><td>3. Recipient's Catalog No.</td></tr>
<tr><td colspan="2" rowspan="2">4. Title and Subtitle
Daytime veiling luminance from windshields: Effects of scattering and reflection</td><td>5. Report Date
November 2003</td></tr>
<tr><td>6. Performing Organization Code
302753</td></tr>
<tr><td colspan="2">7. Author(s)
Mefford, M.L., Flannagan, M.J., and Adachi, G.</td><td>8. Performing Organization Report No.
UMTRI-2003-36</td></tr>
<tr><td colspan="2" rowspan="2">9. Performing Organization Name and Address
The University of Michigan
Transportation Research Institute
2901 Baxter Road
Ann Arbor, Michigan 48109-2150 U.S.A.</td><td>10. Work Unit no. (TRAIS)</td></tr>
<tr><td>11. Contract or Grant No.</td></tr>
<tr><td colspan="2" rowspan="2">12. Sponsoring Agency Name and Address
The University of Michigan
Industry Affiliation Program for
Human Factors in Transportation Safety</td><td>13. Type of Report and Period Covered</td></tr>
<tr><td>14. Sponsoring Agency Code</td></tr>
<tr><td colspan="3">15. Supplementary Notes
The Affiliation Program currently includes AGC America, Autoliv, Automotive Lighting, Avery Dennison, BMW, DaimlerChrysler, DBM Reflex, Denso, Federal-Mogul, Ford, GE, General Motors, Gentex, Guardian Industries, Guide Corporation, Hella, Honda, Ichikoh Industries, Koito Manufacturing, Labsphere division of X-Rite, Lang-Mekra North America, Magna International, Mitsubishi Motors, Muth, Nichia America, North American Lighting, OSRAM Sylvania, Philips Lighting, PPG Industries, Reflec USA, Reflexite, Renault, Samlip, Schefenacker International, Sisecam, Solutia Performance Films, Stanley Electric, TG North America, Toyota Technical Center USA, Valeo, Vidrio Plano, Visteon, 3M Personal Safety Products, and 3M Traffic Control Materials.
Information about the Affiliation Program is available at: http://www.umich.edu/~industry/</td></tr>
</table>

16. Abstract

Light that is reflected or scattered from a vehicle windshield toward the eyes of a driver creates a veiling luminance that the driver must look through in order to see the roadway ahead. At night, scattered light is probably the dominant contributor to this effect, but for daytime conditions most attention has been given to the component of veiling luminance caused by images of the top of the dashboard seen by specular reflection in the windshield. This study was designed to provide data on real-world values of: (1) the overall veiling luminance that drivers are exposed to under sunny daytime conditions, and (2) the relative contributions to that luminance from specularly reflected and diffusely scattered light. We made photometric measurements of the veiling luminance caused by the windshields of 18 vehicles under sunny conditions. Illuminance on the outer surface of the windshield averaged 88,900 lux, and under those conditions the total veiling luminance from the windshield averaged 561 cd/m^2. Of that total, about 60% was attributable to reflection and about 40% to scatter. Thus, under the conditions examined here, although the contribution from scatter is not negligible, reflection causes the majority of veiling luminance, and measures that would reduce reflected luminance potentially offer substantial benefits. Directions for further research include sampling wider ranges of vehicles and of sun angles, and better quantification of the overall importance of windshield veiling luminance for driver vision in the daytime.

<table>
<tr><td colspan="2">17. Key Words
Windshields, veiling luminance, scattering, reflection, driver vision, daytime, sunlight</td><td colspan="2">18. Distribution Statement
Unlimited</td></tr>
<tr><td>19. Security Classification (of this report)
None</td><td>20. Security Classification (of this page)
None</td><td>21. No. of Pages
14</td><td>22. Price</td></tr>
</table>

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. The current members of the Program are:

AGC America
Autoliv
Automotive Lighting
Avery Dennison
BMW
DaimlerChrysler
DBM Reflex
Denso
Federal-Mogul
Ford
GE
General Motors
Gentex
Guardian Industries
Guide Corporation
Hella
Honda
Ichikoh Industries
Koito Manufacturing
Labsphere division of X-Rite
Lang-Mekra North America
Magna International
Mitsubishi Motors
Muth
Nichia America
North American Lighting
OSRAM Sylvania
Philips Lighting
PPG Industries
Reflec USA
Reflexite
Renault
Samlip
Schefenacker International
Sisecam
Solutia Performance Films
Stanley Electric
TG North America
Toyota Technical Center, USA
Valeo
Vidrio Plano
Visteon
3M Personal Safety Products
3M Traffic Control Materials

Contents

INTRODUCTION

During daytime driving, natural light that is specularly reflected or diffusely scattered from windshields can create a veiling luminance that a driver must look through in order to see the forward scene. Because this luminance is superimposed on that scene, it decreases all of the contrast values in the scene, including the contrasts between objects and their backgrounds, and thereby may decrease the visibility of objects and surfaces that are important for the driver to see. A variety of countermeasures could be used to reduce veiling luminance, including antireflection treatments for windshields, lower-reflectance materials for the parts of the dashboard that are reflected in the windshield, and better maintenance of dirty or pitted windshields. Because these potential countermeasures address different components of veiling luminance, it is important to know the relative contributions of these components to the overall veiling luminance that a driver sees.

The purpose of this study was to provide data on real-world values of: (1) the overall veiling luminance levels that drivers are typically exposed to under sunny daytime conditions, and (2) the relative contributions to those luminance levels from specularly reflected light and diffusely scattered light. For diffusely scattered light, this study was designed to distinguish between light scattered by dirt that can be easily removed from the inner and outer surfaces of the windshield and light that is scattered from the windshield after it has been cleaned. The scattering that remains after cleaning is presumably attributable to a variety of mechanisms, including enduring deposits on the surfaces of the glass, pits and scratches on those surfaces, and scattering centers in the body of the windshield.

To quantify windshield veiling luminance and its components, we selected a limited but reasonably representative sample of vehicles and made photometric measurements of the driver's view through the windshield under daytime field conditions. We made measurements under a range of conditions that allowed us to decompose the overall veiling luminance that a driver would see into separate components corresponding to: (1) scattered light from dirt on the inside of the windshield, (2) scattered light from dirt on the outside of the windshield, (3) the image of the dashboard specularly reflected by the windshield, and (4) residual scattered light from the windshield after it had been cleaned.

The relative contributions of the components of veiling luminance will be different under various ambient light conditions, depending on factors such as sun angle and cloud cover. For this study, we chose a situation in which overall veiling luminance is relatively high but which is not rare: a south-facing vehicle on a day with clear sky and a relatively low sun angle. The contribution to veiling luminance from dirt will clearly depend on things such as time of year (possibly worse in northern areas in the winter when roads are salted) and the maintenance habits of car owners. For this study, we did not attempt to sample the worst conditions of windshield dirt, but rather tried to represent reasonably common levels of dirt. We were careful to ensure that the vehicle owners did not know the full purpose of the study before we measured the dirt levels on their windshields, so that they would have no reason to alter their windshield-cleaning habits before the measurements.

The contributions of specular reflections to daytime veiling luminance have been relatively well studied, and are predictable from such factors as dashboard illuminance, dashboard reflectance, and windshield rake angle (e.g., Edson, 1992; Sauter, Bow, LaDriere, & Parman, 1992; Schumann, Flannagan, Sivak, & Traube, 1996). Likewise, the contributions of scattered light to nighttime veiling luminance have been relatively well studied (e.g., Owens, Sivak, Helmers, Sato, Battle, & Traube, 1992). The relative allocation of attention to these issues in previous research has probably been influenced by a belief that the effects of reflected light on driver vision are dominant in the day and the effects of scattered light are dominant at night, and, indeed, that belief is probably correct. The primary source of reflected veiling luminance is the image of the dashboard seen in the windshield, and the dashboard is normally not strongly lighted at night. Probably the most important exception is when the dashboard is strongly and intermittently lighted by overhead street lights. In many night situations, oncoming headlamps are the only significant sources of veiling luminance, and because of their location they do not strongly illuminate the top of the dashboard, although they are susceptible to scatter by dirt or other scattering elements on or in the windshield.

METHOD

Vehicles

Eighteen vehicles were selected from among UMTRI employee vehicles. The sample included fourteen passenger cars, two light trucks, one minivan, and one SUV. We believe these vehicles are approximately representative of the vehicles found on Michigan roads during late summer. However, the sample should not be considered representative of all vehicles in service on public roads in the United States, encompassing all seasons.

Photometry

Photometric measurements were taken on each vehicle individually. The major elements of the setup are shown in Figure 1. Data collection occurred only on sunny, cloudless days in an UMTRI parking lot. A Photo Research PR-650 spectrophotometer was mounted in the driver's seat of each vehicle at the eye height of an average driver for the appropriate vehicle type (Sivak, Flannagan, Budnik, Flannagan, & Kojima, 1996): 1.11 m above the ground for passenger cars and 1.42 m for the light trucks, the minivan, and the SUV (there was only one minivan and one SUV in the sample). Illuminance from the sun and sky was measured with a Minolta T-10 meter that was placed on the outer surface of the windshield, parallel to that surface, approximately at the point that the line of sight from the spectrophotometer intersected it. A light trap was placed just in front of the vehicle being measured, at the same height as the spectrophotometer and directly in front of it on a line parallel to the main axis of the vehicle. The light trap consisted of a box with a small hole on one side (see Figure 1). The box was flat black inside and had a set of baffles to reduce internal reflections. Thus, measurements were taken from a typical driver's eye location for a line of sight that was straight ahead and level.

The vehicles were all positioned facing directly south. Over all sessions, the sun varied from 22 to 39 degrees above the horizon, and from 29 degrees east of south to 59 degrees west of south.

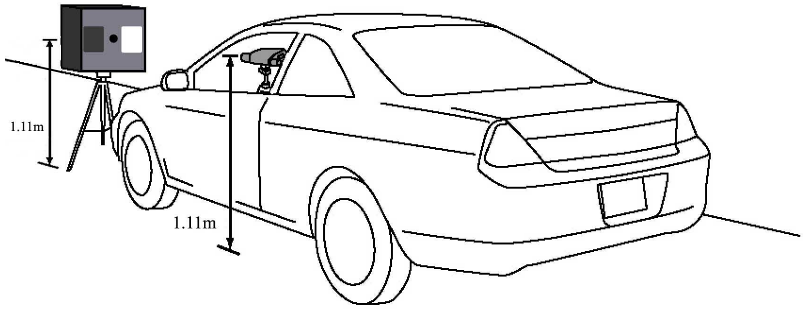

Figure 1. Diagram of the experimental setup. The heights of the spectrophotometer and light trap shown here (1.11 m) were used for passenger cars. The black dot on the box in front of the car represents the opening of the light trap.

Procedure

Photometric measurements were taken under a variety of conditions to allow us to calculate the separate contributions of various sources to overall veiling luminance. After positioning the light trap in front of the vehicle and mounting the spectrophotometer in the driver's seat, an initial luminance measurement was taken. The inside surface of the windshield was then cleaned twice with a household window cleaner and paper towels. A second luminance measurement was then taken. Next, the outside of the windshield was cleaned in the same manner as the inside, followed by a third luminance measurement.

The third luminance measurement thus indicated the amount of veiling luminance observable with a windshield that was clean to ordinary household standards. That luminance can be assumed to be a combination of residual scatter and reflection of the dashboard. In order to determine the amount of veiling luminance attributable to each of those sources, we took measurements that allowed us to determine how much veiling luminance would be measured if the luminance of the reflected dashboard image could be reduced to zero (as could hypothetically be done by placing a perfect black surface on the dashboard). Because reducing the luminance of the dashboard itself to zero or near zero was not practical in the field situation, we took a series of measurements with standard surfaces of varying reflectance placed one at a time on the dashboard.

Luminance measurements were taken through the reflected images of the standards in the windshield. These measurements could then be used to extrapolate to an estimate of the veiling luminance that would be observed if the image of the dashboard could actually be eliminated. The surfaces used included a white standard with reflectance of 0.99 (Photo Research RS-2) and three levels of gray with reflectances for daylight of approximately 0.43, 0.29, and 0.21. (The reflectances of the grays were approximately, but not exactly, spectrally neutral. Because of this, and because of small variations across sessions in the spectral distribution of the prevailing daylight, the actual reflectance values for the gray surfaces used in the analyses described below were based on individual measurements of reflectance for each gray surface in each session, in comparison to the white standard.) The positioning of the white standard is illustrated in Figure 2.

After the measurements from inside the vehicle were completed, the vehicle was moved and the spectrophotometer was placed in the same position in the parking lot that it had occupied inside the vehicle. The small background luminance inside the light trap was then measured directly, without the windshield intervening.

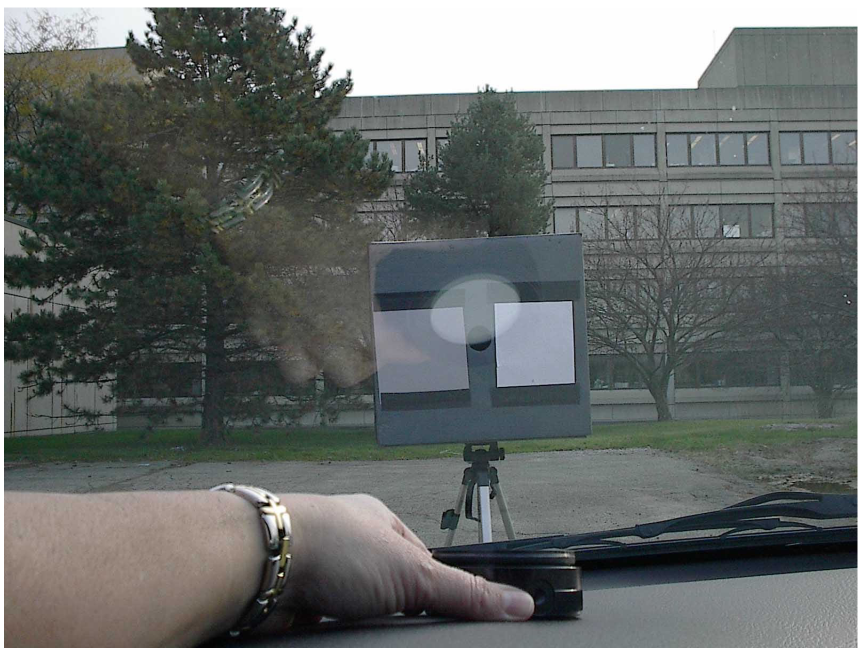

Figure 2. A photograph taken from the position of the spectrophotometer, showing the white reflectance standard being placed on top of the dashboard (the round white image partly overlapping the black hole in the light trap). During measurements, the image of the reflectance standard on the dashboard completely overlapped the hole, and the field of view of the spectrophotometer was within the hole. The gray and white surfaces on the front of the light trap are for calibration measurements not used in the data reported here.

RESULTS AND DISCUSSION

The average sun illumination on the outer surfaces of the windshields was 88,900 lux. Average values for the veiling luminances measured through the windshield initially and after each of the cleaning operations are shown in Table 1. These values have had the small background luminance of the light trap (which averaged 15 cd/m^2) subtracted from them.

The first two lines of Table 2 show the estimates of veiling luminance attributable to dirt on the interior and exterior surfaces of the windshield. As indicated in Table 2, these were calculated simply as differences from before to after each of the cleaning operations.

The third line of Table 2 shows the luminance remaining after both cleaning operations (simply repeating the third line of Table 1), which therefore cannot be attributed to dirt (as least not to dirt that is removed by typical household cleaning). That remaining luminance is further partitioned at the bottom of Table 2 into components attributable to dashboard reflectance and to residual scatter in clean windshields. As indicated in the table, this partitioning was done using a regression model.

The regression model was used to infer what veiling luminance would have been measured if we could have completely eliminated luminance due to the reflectance of the dashboard. The reasoning for this is illustrated in Figure 3, which shows data for one vehicle. The figure shows the regression of the veiling luminance values that were measured through the windshield on the reflectances of each of the corresponding samples that were placed on the top of the dashboard. The vertical-axis intercept (at zero reflectance) thus serves as an extrapolated estimate of the luminance that would be measured with a perfectly black dashboard. A similar regression analysis was performed for each of the 18 vehicles. The fits were extremely good; the R^2 values averaged .998, and the minimum value was .991. The average intercept value for all vehicles was 125 cd/m^2, as shown by the value for "residual scatter" in Table 2. The remainder of the veiling luminance measured through the cleaned windshields, 338 cd/m^2, is thus the inferred luminance attributable to the reflected image of the dashboard.

The absolute luminance values presented in Tables 1 and 2 are valid for the high illumination conditions under which they were collected. However, it is more generally useful to know the effects on veiling luminance relative to illumination. The right column of Table 2 shows the same components in terms of the effect that illumination, measured at the outer surface of the windshield, has on veiling luminance (in cd/m^2/lux). These values were calculated for each vehicle, using the corresponding illuminance values, and averaged to arrive at the values in Table 2. (Our main concern here is to estimate the relative contributions of the various components to veiling luminance. The proportional contributions based on raw luminances are slightly different from those based on the luminance effects adjusted for illumination. This is because the relative contributions of the components varied from vehicle to vehicle and because the illumination levels were higher during some sessions than others. Basing estimates of proportional contributions on the raw luminance values therefore arbitrarily gives effectively higher weight to the data from vehicles that were measured under stronger illumination. Equal weighting, which is the case with the average luminance effects, is more appropriate for this sample of vehicles.) The values for the luminance effect are also presented graphically in Figure 4.

Table 3 shows the proportional contribution of each of the components to overall veiling luminance, based on the luminance-effect values from Table 2. The majority of veiling luminance, under the conditions tested here, was attributable to dashboard reflectance—about 60%. Residual scatter (i.e., scatter that persisted after a reasonable level of cleaning) accounted for about 22%, and scatter from removable deposits accounted for about 18%.

It has been demonstrated that the component of veiling luminance from windshields that is due to dashboard reflectance can be predicted fairly simply from windshield rake angle and from the illumination and reflectance of the dashboard itself (Edson, 1992; Schumann et al., 1996). We performed a multiple regression analysis of the luminance-effect values that were attributable to dashboard reflectance for each vehicle. The predictors were windshield reflectance (calculated from the individual rake angles for each vehicle and assuming a common air-glass index of refraction ratio of 1.5) and dashboard reflectance. The results indicated that, for these vehicles, dashboard reflectance accounted for most of the differences among vehicles in reflected veiling luminance (R^2 for dashboard reflectance as a single predictor was .78), and rake angle was not a statistically significant predictor.

The component of veiling luminance attributed to "residual scatter" could be at least partly due to scattering of light from blemishes on the windshield surface that accumulate over time and distance, such as pits and scratches. We therefore regressed the luminance-effect values of residual scatter for individual vehicles on vehicle mileage. The regression, however, was not significant.

Table 1. Measurements of veiling luminance separated by the cleaning operations.

Measurement	Luminance (cd/m^2)
Initial (a)	561
After inside cleaning (b)	509
After outside cleaning (c)	463

Table 2. Estimated components of veiling luminance. See text for explanation of the column for luminance effect.

Component	Source of estimate	Luminance (cd/m^2)	Luminance effect ($cd/m^2/lx$)
Interior dirt	Table 1 (a – b)	52	.000551
Exterior dirt	Table 1 (b – c)	46	.000516
Remaining (not from dirt)	Table 1 (c)	463	.00499
Breakdown of "remaining"			
Dashboard reflectance	Regression model	338	.00364
Residual scatter		125	.00135

Table 3. Proportional contributions of the components to overall veiling luminance.

Component	Luminance effect ($cd/m^2/lux$)	Proportion of total luminance effect
Interior dirt	.000551	0.091
Exterior dirt	.000516	0.085
Breakdown of "remaining"		
Dashboard reflectance	.00364	0.601
Residual scatter	.00135	0.223
Total	.00606	1.000

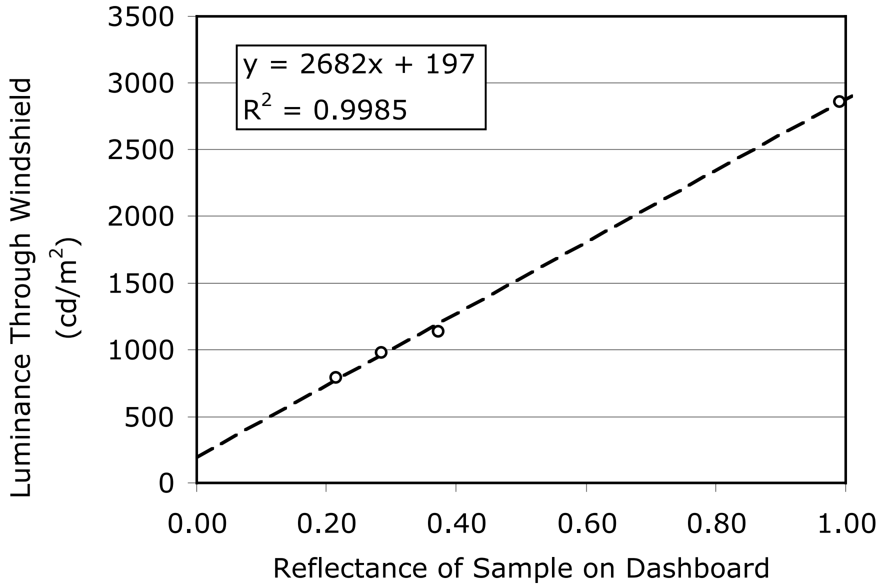

Figure 3. An example of the regression modeling used to separate luminance attributable to dashboard reflection and residual scatter, for a single vehicle. The luminance at the vertical-axis intercept (in this case, 197 cd/m^2) is the estimate of "residual scatter" luminance.

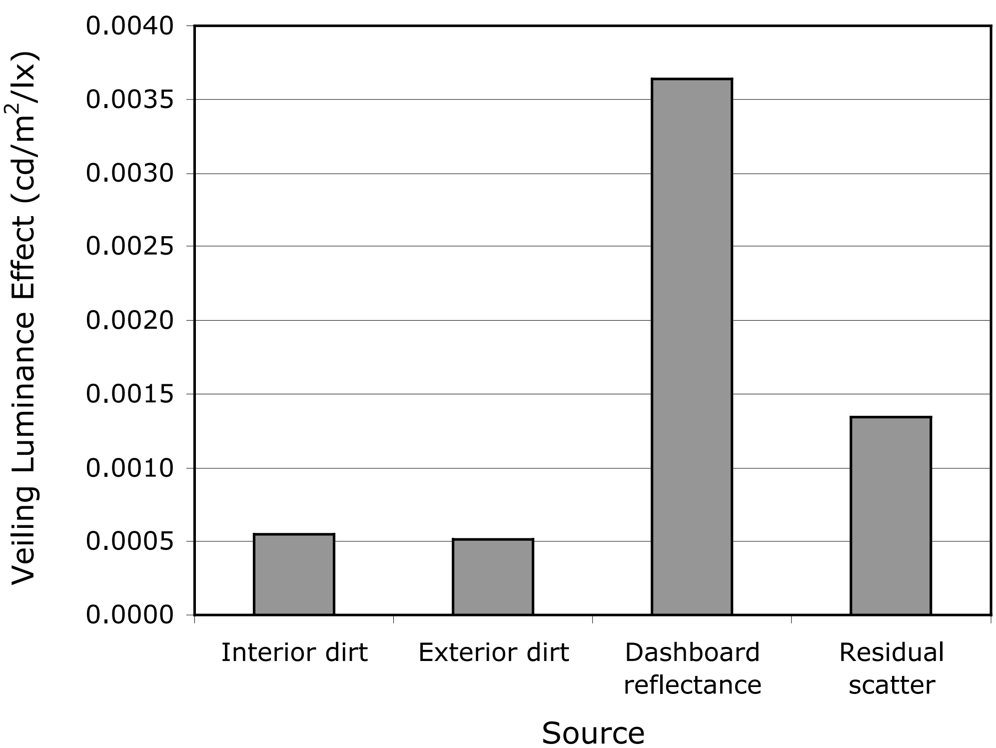

Figure 4. Mean luminance effects (cd/m^2/lux) for the sources of veiling luminance.

SUMMARY AND CONCLUSIONS

These results indicate that, under the conditions tested, about 60% of windshield veiling luminance was attributable to the reflected image of the dashboard. About 40% was attributable to scattered light, including about 18% that was attributable to dirt that could be easily cleaned from the interior or exterior surfaces of the windshield and about 22% that remained after cleaning. Thus, although the contribution from scatter is not negligible, reflection causes the majority of veiling luminance, and measures that would reduce reflected luminance potentially offer substantial benefits. Such measures include glass treatments that reduce reflection from the glass surfaces and low-reflectance dashboard materials. Directions for further research include sampling wider ranges of vehicles and of sun angles, and better quantification of the overall importance of windshield veiling luminance for driver vision in the daytime.

REFERENCES

Edson, L. (1992). *Veiling glare: What factors create it and how to use these factors to predict the performance of a vehicle design* (SAE Technical Paper Series No. 920104). Warrendale, Pennsylvania: Society of Automotive Engineers.

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

Sauter, J. L., Bow, N., LaDriere, M. L., & Parman, S. (1992). *The effects of instrument panel color and windshield angle on veiling glare* (SAE Technical Paper Series No. 920105). Warrendale, Pennsylvania: Society of Automotive Engineers.

Schumann, J., Flannagan, M. J., Sivak, M., & Traube, E. C. (1996). *Daytime veiling glare and driver visual performance: Influence of windshield rake angle and dashboard reflectance* (Report No. UMTRI-96-13). Ann Arbor: The University of Michigan Transportation Research Institute.

Sivak, M., Flannagan, M.J., Budnik, E.A., Flannagan, C.C., & Kojima, S. (1996). *The locations of headlamps and driver eye positions in vehicles sold in the U.S.A.* (Report No. UMTRI-96-36). Ann Arbor: The University of Michigan Transportation Research Institute.