of their actual occurrence, and the reduction in accidents after the installation of automatic warning devices is as expected. The grade crossings that are modified in fiscal year 1976 will provide better data, since three-fourths of them were selected on the basis of the accident-prediction model. During this period, 43 of the 100 most hazardous grade crossings will be modified.

CONCLUSION

The accident-prediction model can be effectively used to develop a grade-crossing improvement program. It identifies groupings of crossings (with or without the accident-history adjustment) that can be expected to experience the most accidents if they are not modified, and the accident experience after modification has been in reasonable agreement with that predicted.

ACKNOWLEDGMENTS

This report could not have been developed without the efforts of G. van Belle, D. Meeter, and W. Farr, who prepared the report, Influencing Factors for Rail-Highway Grade-Crossing Accidents in Florida. In addition, the efforts of Meeter in editing the many rewrites of this report and in providing needed technical assistance are greatly appreciated. Appreciation is also given to Winifred Bailey, who suffered through the typing and editing of the many revisions, and to Wyndal Hand, who assisted with the data.

The changes to the model and the subsequent conclusions as to the sight-distance factors and the effects of gates are those of the author and are not necessarily those of the above-mentioned consultants.

REFERENCES

1. G. van Belle, D. Meeter, and W. Farr. Influencing Factors for Rail-Highway Grade-Crossing Accidents in Florida. Accident Analysis and Prevention, Vol. 7, 1975, pp. 103-112.
2. D. Schoppert and D. Hoyd. Factors Influencing Safety at Highway-Rail Grade Crossings. NCHRP, Rept. 50, 1969.
3. A Policy on Design Standards for Stopping-Sight Distances. American Association of State Highway and Transportation Officials, Sept. 2, 1971.
4. J. B. Hopkins and F. R. Holmstrom. Toward More Effective Grade-Crossing Lights. Transportation Systems Center, U.S. Department of Transportation, Cambridge, Mass., 1975.
5. J. Beauchamp and J. Olsen. Estimates for the Mean and Variance of Lognormal Distribution Where the Mean Is a Function of an Independent Variable. Eastern Deciduous Forest Biome Study, Oak Ridge National Laboratory, Technical Rept. 71-101, 1972.
6. Manual on Uniform Traffic-Control Devices. American Association of State Highway and Transportation Officials and U.S. Department of Transportation, 1971.
7. W. J. Dixon, ed. BMD Biomedical Computer Programs. Univ. of California Press, Berkeley, 1971.
8. J. Coleman and G. Stewart. Accident and Accident-Severity Prediction Equations. Proc., National Conference on Railroad-Highway Crossing Safety, Washington, D.C., 1974.

Publication of this paper sponsored by Committee on Railroad-Highway Grade Crossings.

Visual Performance of Drivers During Rainfall

Ron S. Morris, John M. Mounce, Joe W. Button, and Ned E. Walton, Texas Transportation Institute, Texas A&M University

This paper reports an investigation of the effect of rain on the visual performance of drivers. The degradation of static visual acuity in terms of visual angle, detection probability, and legibility as a function of rain intensity was determined by experiments that used a rainfall simulator that produced artificial rain. The significant findings include the following: (a) Water on the windshield is the primary factor accounting for reduced visual performance, (b) visual degradation in the daytime with windshield wipers in operation appears to be a linear function of the rain rate with normal drop sizes, (c) during nighttime conditions, drop size is a significant factor in reducing visual performance (smaller drops are a more serious problem than is the rain rate), (d) wiper speeds above 50 CPM do not improve visual performance, (e) without windshield wipers, visual performance is reduced to levels that are unacceptable for driving (equivalent to visual acuity greater than 20/200) at rain rates greater than 2.5 cm/h (1 in/h), and (f) the effective rain rate can be determined from the vehicle velocity, the terminal velocity of the drop, the rake angle of the windshield, and the actual rain rate.

The factor of visibility during adverse weather has been largely neglected by the highway transportation industry. There are at least two reasons for this: These are that the problems associated with driver visibility have been underestimated and that objective measurements of the effects of wet weather on the visual performance of drivers are difficult to obtain. Thus, there have been very few developments designed specifically to assist the automobile driver in the performance of visual tasks during adverse weather (1).

EQUIPMENT AND METHODOLOGY

The objective tests used in this research determined the effects of selected, controlled intensities of artificial (simulated) rainfall on the visual performance of drivers relative to visual acuity, target detection, recognition, and legibility. These tests were also designed to assess the improvement to driver visibility afforded by windshield wipers at various cyclic rates. All of the tests were conducted on overcast days to more closely simulate actual rain conditions. To eliminate the effects of wind on the paths of the falling drops, the tests were conducted on days and nights when the wind was less than 8 km/h (5 mph) (2). To establish a feasible relation between the simulated condition and real-world conditions, the rainfall characteristics of the stimulus, i.e., the droplet-size distribution, were evaluated and compared to the characteristics of natural rainfall.

The rainfall-simulator studies used controlled, in-vehicle experimentation with human subjects. An overhead pipe and nozzle system (Figure 1) was used to produce rainfall artificially. The simulator was 56.4 m (185 ft) long and had 32 spray bars 7.6 m (25 ft) long.

All of the observations were made by test subjects from a 1975-model automobile in which the windshield, windshield wipers, and headlights were original vehicle equipment that had been maintained at the recommended specifications. The windshield wipers were modified by adding a 430-W (¼-hp) AC gear motor to replace the original motor. An inverter to supply AC power and a variable speed controller to produce any wipe rate from 0 to 80 cycles/min were placed where operation by the test administrator would be convenient.

VISIBILITY PERFORMANCE

Three basic visibility measures were used in the simulator experiments: (a) visual acuity, (b) legibility, and (c) target detection and identification.

Panels containing Landolt rings of nine different sizes (Figure 2), which could be fastened to a portable backboard in any desired orientation, were used as the standard measure of visual acuity. The sizes of the rings were designed to cover the range of visual acuity from 20/20 to 20/200 when observed from a distance of 45.7 m (150 ft). Standard Manual on Uniform Traffic Control Devices (MUTCD) type D1-1 destination signs were observed by the test subjects to determine the legibility distance (Figure 2). These signs also were placed 45.7 m (150 ft) from the point of observation.

Several targets were used in the detection and identification portion of the experiment. These were

1. Mannequin—upright, male caucasian clothed in a dark gray raincoat;
2. Nonreflective sign—small, single-post sign; and
3. Front or rear of object vehicle—light brown, 1967 sedan with no light display.

EXPERIMENTAL DESIGN ADMINISTRATION

The experimental design was structured into two basic tests, S-1 and S-2. The data collection from tests S-1 and S-2 was divided into two sets of observations based on the type of visual performance required of the subject. The first set included the response related to visual acuity and legibility, and the second set concentrated on target detection and recognition. Each set of observations included both S-1 and S-2 results, i.e., the subject was required to respond from a position outside the simulated rain but viewing through it and then from within the simulated rain. The following variables and criterion measures were used:

Variable or Measure	S-Test
Independent variable	
Rainfall intensity	1, 2
Time (day or night)	1, 2
Glare versus no glare	1, 2
Ambient light	1, 2
Windshield wiper rate	2
Controlled variables	
Interior environment and fogging	1, 2
Target position (separation distance)	1, 2
Subject-vehicle position (separation distance)	1, 2
Glare-vehicle position	1, 2
Target presentation	1, 2
Original equipment windshield wipers and variable speed modification	2
Criterion measures	
Target detection	1, 2
Target recognition	1, 2
Visual acuity	1, 2
Legibility	1, 2

The rain intensity was adjusted and checked before the beginning of each test period. The glare vehicle was positioned (at night) with the visual acuity and legibility signs exactly 45.7 m (150 ft) from the subject vehicle. The artificial rain was begun, and the subject maneuvered the vehicle to a predesignated position (S-1) outside the rainfall. Instructions concerning the desired observations were read to the subject, whose view was then restricted by placing a cardboard shield across the front of the vehicle. The Landolt rings were repositioned, and the destination sign was changed. The shield was removed, and the subject was asked to respond. The test administrator recorded the experiment number, the time, the ambient light (during the day), the glare condition (at night), the rain intensity, the visual acuity, and the legibility (correct or incorrect).

The subject then maneuvered the vehicle to a new position (S-2) within the rainfall. The shield was replaced and a wiper rate was established and recorded. The Landolt rings and the destination sign were reset and the shield was removed. The subject was asked to respond in the same manner as before, and the same data were recorded. This procedure was repeated throughout the range of wiper rates and for both glare conditions. (The Landolt ring orientations, the destination-sign names, and the variations in wiper rates and glare conditions were all presented in random order.) The procedures for administering the tests involving target detection and recognition were essentially the same.

RESULTS

The analysis of the data began with a survey of the simple statistics; those results that appeared promising were then studied by an analysis of variance (ANOVA) and a regression analysis to develop dependencies.

S-1 Tests

The S-1 tests included visual acuity, probability of detection, and legibility measured at various rain rates [2.5, 5.1, 7.6, and 10.6 cm/h (1, 2, 3, and 4 in/h)] under both daytime and nighttime conditions. The simple statistics for visual acuity, measured in minutes of visual angle in daytime and dark conditions respectively, are given below (1 cm = 0.4 in).

	Rain Rate (cm/h)				
Daytime Statistic	0	2.5	5.1	7.6	10.2
Mean	1.058	1.563	1.400	1.972	2.688
Standard deviation	0.243	0.512	0.507	0.580	0.814
Low	1.000	1.000	1.000	1.000	1.000
High	2.000	2.000	2.000	2.500	5.000

	Rain Rate (cm/h)				
Nighttime Statistic	0	2.5	5.1	7.6	10.2
Mean	1.716	2.324	2.367	3.350	7.775
Standard deviation	0.479	0.868	0.482	1.587	2.775
Low	1.000	1.000	1.000	2.000	3.500
High	2.500	4.500	3.500	10.000	10.000

The visual acuity shows a definite increasing trend as the rain rate increases. The average values are plotted as a function of the rain rate in Figure 3. At night there was a large decrease (increase in the minimum visual angle) in visual acuity at higher rain rates although in daylight very high rain rates produced only a minor degradation of visual acuity. Quite obviously, rain does not significantly affect visual acuity if there is no windshield and water interface.

There is a seeming anomaly in the visual acuity at the 2.5-cm/h (1-in/h) rate. The simulator produced a greater proportion of drops smaller than 0.5 mm in diameter at the 2.5-cm/h (1-in/h) rate than at the 5.1-cm/h (2-in/h) rate, which is evidence that the drop size, rather than the rain rate, is the primary factor in reducing visibility (fog being the limiting case). Unfortunately, the net effect is not quantifiable with the data collected, as the variability is so high that any statistically significant effect is masked.

There was no attempt to perform a regression analysis on the S-1 data for visual acuity since the standard deviations showed a variability that increases nonlinearly over the range of rain rates. Also, the drop size must have a marked effect since the values of the standard deviation at the 2.5-cm/h (1-in/h) rate have no relation to the values at the 0 and 5.1-cm (2-in) rates. Consequently, the error variance of the random variable (the visual acuity) violates the requirement of uniformity in a manner that cannot be corrected by weighting, which obviates the validity of a linear regression analysis.

The S-1 day results, however, showed much less variability, and the results of the ANOVA of the visual acuity with the rain rate are shown in Table 1. The F-ratio is clearly significant. The Duncan multiple range test (Table 2) shows that the visual acuity is significantly different from zero for the 7.6 and 10.2-cm/h (3 and 4-in/h) rates and for the 5.1 and 10.2-cm/h (2 and 4-cm/h) rates. The visual acuity in up to 7.6-cm/h (3-in/h) rain rates is not significantly different from that in the clear condition. (The statistic used in the ANOVA tests the hypothesis of equal treatment means, i.e., H_0: $M_1 = M_2 = M_3 = M_4$, by testing the hypothesis of equal variance, i.e., H_0: $\sigma_1^2 \quad \sigma_2^2 \quad \sigma_3^2 \quad \sigma_4^2$. Therefore, the ANOVA results may mean only that the variances were different at the different rain rates. The Duncan multiple range test then relies on the error variance, which is considered uniform from treatment level to treatment level.

The detection tasks showed no perceptible degradation during the daytime rain condition. The nighttime condition, however, showed some interesting results. There was no particular pattern of detection or identification probability with the rain rate. Here, several variables that were not experimentally controlled affect the system. Specifically, although headlight glare would be expected to reduce target identification and detection, it actually increased the probability of detection at the 7.6-cm/h (3-in/h) rate. Not only does rain increase the specular reflection, and hence the disability glare, but the water in the atmosphere also causes increased backscatter, which possibly illuminates the object to be detected (3). Rain size and rate have a confounding effect on visibility that is dependent on the task to be performed.

S-2 Tests

The S-2 tests were conducted in the same manner as the S-1 tests except that the vehicle was in the rain. The most obvious result is the significant effect of water on the windshield. The probability of detecting the sign dropped significantly, and the probability of reading the sign dropped to zero at the lowest level of rain rate (Figures 4 and 5). These figures also show the effect of the windshield wiper; at even the lowest wiper speed the probability of detecting and reading the sign increases.

Under the nighttime condition, the detection of the sign is the same under both the glare and the no-glare conditions. However, the probability of reading the sign behaves anomalously. Under both the glare and the no-glare conditions, the probability of reading at the 2.5-cm/h (1-in/h) rate is less than that for the 5.1 and 7.6-cm/h (2 and 3-in/h) rates. The most reasonable explanation for this phenomenon is that of the drop-size distribution. The improved probability of reading the sign in the glare condition is the result of the illumination of the sign by the backscattered light.

The probability of detecting the individual targets and properly identifying them was essentially the same for all of the rain rates with the use of windshield wipers during the daytime condition. The nighttime condition, however, presented a different picture. The data for the probability of detection and proper identification showed a precipitous degradation between the 7.6 and 10.2-cm/h (3 and 4-in/h) rain rates. The curves in Figures 4 and 5, for the probability of detection and the probability of identification respectively, show the marked improvement of visibility given by windshield wipers. Between the 0 and 2.5-cm/h (1-in/h) rate the probability of detection dropped from almost 1 to less than 0.50. (There are no data points in this range to statistically support a hypothesis regarding the shape of the curve, but the function is probably a negative exponential.)

Thus, glare causes decreased detectability at night and reduces identification even more, although the differences are not significant in these data. The data at the 2.5-cm/h (1-in/h) rate appear to be an artifact but may be explained by the effect of the previous drop size. Apparently, the smaller drop-size distribution causes greater backscatter from both the approaching object and the vehicle, and this backscatter, while illuminating the sign, also causes an increased background illumination that reduces the contrast between the sign and the background.

The simple statistics for the visual acuity data for the S-2 daytime and nighttime simulator studies were calculated and are graphically shown in Figure 6. The improvement in visual acuity with the use of a wiper definitely indicates that water on the windshield is the most significant aspect of rain-reduced visibility. However, changes in the wiper speed have virtually no effect on visual acuity [wiper speeds below 25 cycles/min (cpm) were not investigated].

The design of the S-2 experiment lends itself to a three-way classification ANOVA, which is shown in Table 3. In this analysis, three levels of time (daytime, nighttime, and nighttime with glare), four levels of wiper speed (0, 25, 50, and 75 cpm), and five levels of rain rate [0, 2.5, 5.1, 7.6, and 10.2 cm/h (0, 1, 2, 3, and 4 in/h)] were used. Since no inferences about the population of rates were made, and since the other classification variables were discrete, a fixed-effect model was chosen for the analysis. All of the effects, including the interactions, were significant. The F-ratios were very significant, indicating that visual acuity is degraded

Figure 1. Rainfall simulator.

Figure 2. Landolt ring and legibility sign.

Figure 3. Visual acuity versus rain rate (S-1).

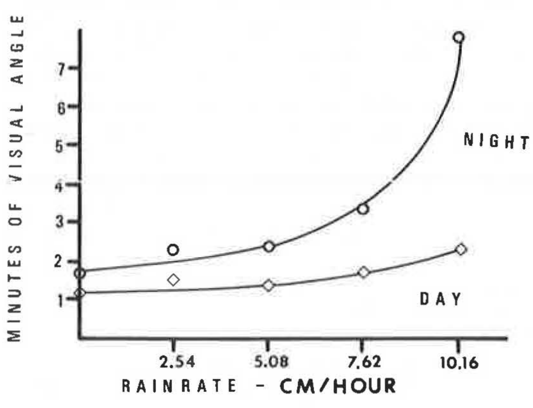


Table 1. Statistical analysis (S-1 day data).

Source	Degrees of Freedom	Sum of Squares	Mean Square	F-Ratio
Rate	4	7.233	1.808	12.056[a]
Error	10	1.500	0.150	—
Total	14	8.733	0.623	—

[a]Significant at the 0.01 level.

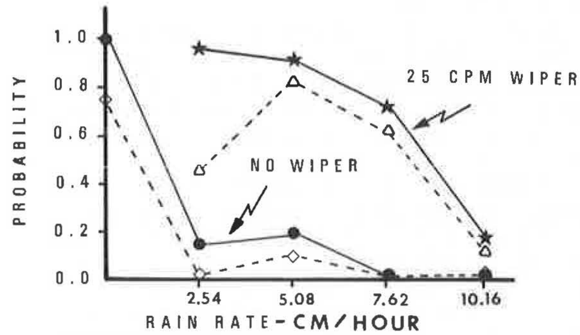
Table 2. Duncan multiple range test (S-1 day data).

Rain Rate (cm/h)	Mean of Visual Angle	Rain Rate (cm/h) 0	2.5	5.1	7.6	10.2
0	1.0	0	0.33	0.66	1.50[a]	1.83[a]
5.1	1.33	—	0	0.33	1.17	1.50
2.5	1.66	—	—	0	0.94	1.17
7.6	2.50	—	—	—	0	0.33
10.2	2.83	—	—	—	—	0

Note: 1 cm = 0.4 in.

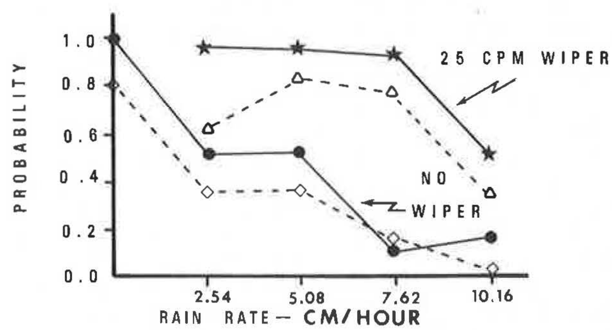
[a]Significant at the 0.05 level.

Figure 4. Probability of detecting the sign (S-2 night).



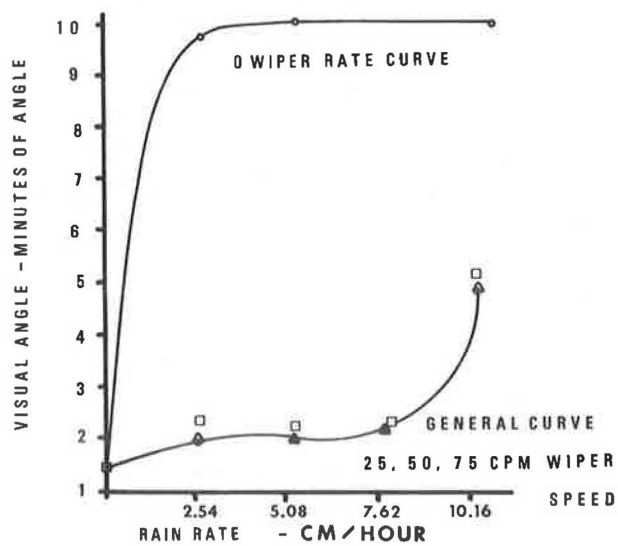
Note: Glare condition shown by dashed line.

Figure 5. Probability of reading the sign (S-2 night).



Note: Glare condition shown by dashed line.

Figure 6. Visual acuity versus rain rate (S-2).



by the time of day, the rain rate, and the wiper speed. The results of a Duncan multiple range test of these data are shown in Table 4. This test shows that the visual acuity at the 0-cpm wiper speed is significantly less than that at the 25, 50, and 75-cpm wiper speeds for all of the rain rates investigated. The differences in visual acuity among the 25, 50, and 75-cpm wiper speeds were either not significant or were barely significant at the 0.05 level. Thus, wiper speeds greater than 25 cpm do not significantly improve visual acuity at rain rates of up to 10.2 cm/h (4 in/h).

Table 3. Analysis of variance (S-2 data).

Source	Degrees of Freedom	Sum of Squares	Mean Square	F-Ratio
Rate	4	1 609.66	402.41	204.27[a]
Wiper speed	3	4 673.87	1557.96	790.84[a]
Time	2	273.38	136.69	69.38[a]
Rate[a], wiper speed	9	2 445.52	271.72	137.93[a]
Rate[a], time	8	432.96	54.12	27.47[a]
Wiper speed[a], time	6	198.44	33.07	16.79[a]
Rate[a], time[a], wiper speed	18	143.36	7.96	4.04[b]
Error	871	1 718.02	1.97	
Total	921	11 495.22	12.48	

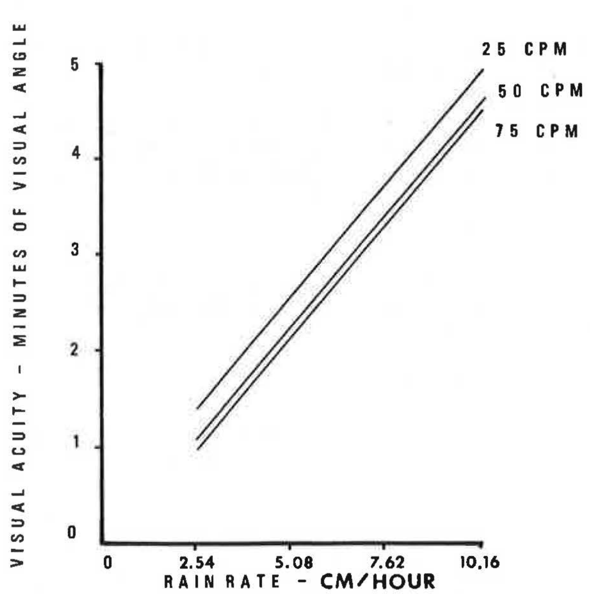
[a]Significant at the 0.0001 level. [b]Significant at the 0.01 level.

Table 4. Duncan multiple range test (S-2 data).

Visual Acuity	V_0	V_{25}	V_{50}	V_{75}
2.5-cm/h rain rate				
V_0 = 9.76	0	7.39[a]	7.76[a]	7.77[a]
V_{25} = 2.37	—	0	0.37	—
V_{50} = 2.00	—	—	0	—
V_{75} = 1.99	—	—	—	0
5.1-cm/h rain rate				
V_0 = 7.98	0	5.71[a]	5.85[a]	7.73[a]
V_{25} = 2.27	—	0	0.14	0.15[b]
V_{50} = 2.13	—	—	0	0.01
V_{75} = 2.12	—	—	—	0
7.6-cm/h rain rate				
V_0 = 9.83	0	5.71[a]	5.85[a]	5.86[a]
V_{25} = 2.40	—	0	0.14	0.15[b]
V_{50} = 2.12	—	—	0	0.01
V_{75} = 2.10	—	—	—	0
10.2-cm/h rain rate				
V_0 = 10.00	0	5.71[a]	5.85[a]	5.86[a]
V_{25} = 5.63	—	0	0.14	0.15[b]
V_{50} = 5.28	—	—	0	0.01
V_{75} = 5.76	—	—	—	0

Notes: 1 cm/h = 0.4 in/h.
V = visual acuity in minutes of visual angle.
[a]Significant at 0.01 level. [b]Significant at 0.05 level.

Figure 7. Prediction of visual acuity at various wiper speeds by the regression equation.



After the data were altered to give visual degradation by improving the absolute threshold angle in clear air, further analysis of the visual acuity data for the S-2 daytime tests by multiple linear regression techniques gave Equation 1.

$$VA = 0.415\,25r + 0.755\,59W_{25} + 0.597\,05W_{50} + 0.584\,86W_{75} \quad (1)$$

where

VA = degradation of threshold visual angle in minutes,

Figure 8. Cross section of vehicle windshield at visual centerline.

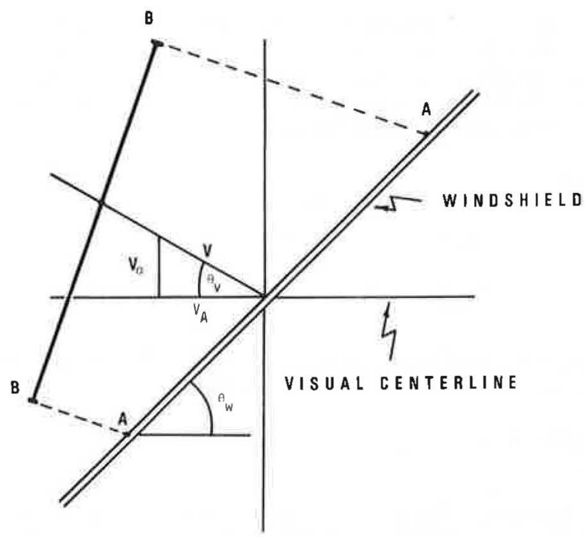
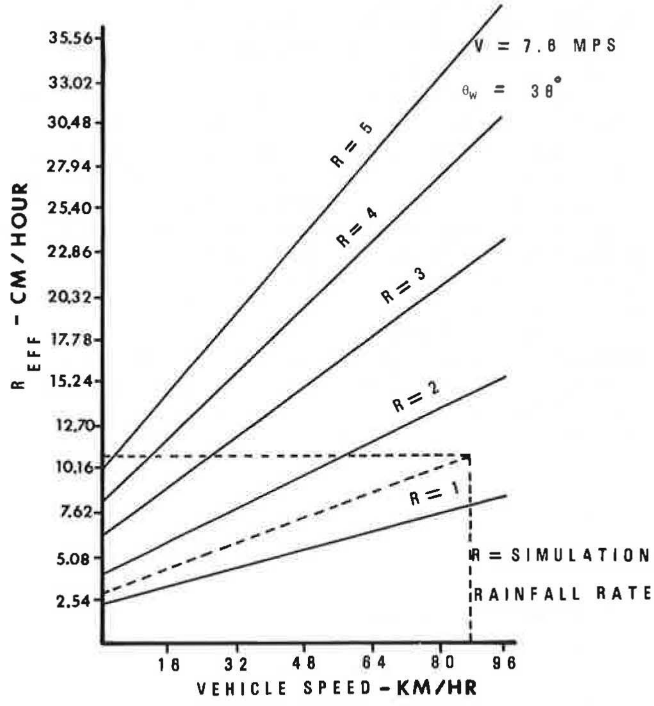


Figure 9. Effective rain rate versus vehicle velocity.



r = instantaneous rain rate, and
W_{25}, W_{50}, W_{75} = one when wiper speed is 25, 50, or 75 cpm respectively and zero otherwise.

The model uses three dummy variables for the three conditions of wiper speed (W_{25}, W_{50}, and W_{75} equal one when the wiper speed is 25, 50, and 75 cpm respectively; otherwise zero). The regression analysis of variance (shown below) shows that the model is highly significant, with a coefficient of multiple regression of 0.914, and that all of the parameters are also highly significant (α = 0.0001).

Source	Degrees of Freedom	Sum of Squares	Mean Square	F-Ratio	Prob>F
Regression			94.41	315.96	0.0001
Rain	1	368.54	368.54	1233.40	0.0001
Wiper rate	3	9.09	3.03	10.14	0.0001
Error	119	35.56	0.299	–	–
Total	123	413.19	–	–	–

The test for the significance of the regression coefficient for wiper speed (shown below) shows that the 75-cpm rate is significantly different from the 50 and 75-cpm rates, which leads to the conclusion that wiper speeds need not be greater than 50 cpm.

Wiper Speed (cpm)	t for $H_0B = 0$	Prob>T
0	9.33	0.0001
25	5.37	0.0001
50	4.24	0.0001
75	4.16	0.0001

Figure 7 shows the prediction of visual acuity at various wiper speeds by the regression equation.

Relation Between Simulated and Natural Rainfall

The vital link relating the simulator studies and natural rainfall is the effective rain rate. That is, the simulator studies involve static tests in which the rain falls directly on the windshield, but in actual driving conditions, the rainfall on the windshield is a function of the vehicle velocity: Simulator rain rates correspond to much lower effective rain rates encountered in the dynamic rain environment.

There is a direct relation between the effective rate of rainfall on the windshield and the vehicle speed, the actual rainfall rate, and the rake angle of the windshield. The effective rate of rainfall on the windshield can be estimated by summing the rates due to falling raindrops and to the forward (horizontal) motion of the vehicle (4). If the effects of the aerodynamics of vehicle design and the raindrops splattering on the vehicle are neglected, and if it is assumed that all raindrops in a given rain are falling straight downward at the same velocity, then the effective rain rate (r_{eff}) is defined as the static rain intensity necessary to produce the same amount of water on the windshield as would be encountered in an actual rain of intensity (r) in a vehicle traveling at velocity (v):

$$r_{eff} = f(r, v_a, v_0, \theta_w) \tag{2}$$

where

r = actual rain rate,
v_a = vehicle velocity,
v_o = terminal velocity of raindrops, and
θ_w = windshield rake angle.

The rain rate is defined as the depth of water falling on a unit area in a given time interval (typically an hour). If the unit area is considered as moving through a stationary, water-filled atmosphere, the relation between r and r_{eff} can be derived. Figure 8 shows the resultant velocity vector for the windshield moving at velocity (v_a) during a rainfall with a terminal velocity (v_o). The magnitude of this vector is given by

$$v = (v_0^2 + v_a^2)^{1/2} \tag{3}$$

and the angle is given by

$$\theta_v = \tan^{-1}(v_0/v_a) \tag{4}$$

Consider the plane unit area $(\overline{BB})$ normal to the resultant velocity vector ($\vec{v}$). The effective rain rate, if that plane moves with velocity (v), is

$$r'_{eff} = (v/v_0)\,r \tag{5}$$

The plane $(\overline{BB})$ projects onto the windshield to form the plane $(\overline{AA})$ Thus, the effective rain rate is r'_{eff} reduced by the ratio of the unit area at $\overline{BB}$ divided by its projection on the windshield. This can be reduced to the ratio of $\overline{BB}$ to $\overline{AA}$ or

$$\lambda = \overline{BB}/\overline{AA} = \cos[90 - (\theta_v + \theta_w)] \tag{6}$$

Since $\overline{BB}$ is a unit area, this reduces to

$$\lambda = \sin\theta_w \cos\theta_v + \cos\theta_w \sin\theta_v \tag{7}$$

or (from Equation 4)

$$\lambda = \sin\theta_w \cos[\tan^{-1}(v_0/v_a)] + \cos\theta_w \sin[\tan^{-1}(v_0/v_a)] \tag{8}$$

The effective rain rate is now given by the following relation:

$$r_{eff} = \lambda r'_{eff} = \lambda[(v_0^2 + v_a^2)^{1/2}/v_0]\,r \tag{9}$$

This becomes (from Equation 8)

$$r_{eff} = \{[v_a/(v_0^2 + v_a^2)^{1/2}]\sin\theta_w + [v_0/(v_0^2 + v_a^2)^{1/2}]\cos\theta_w\}\ (v_0^2 + v_a^2)^{1/2}/v_0 \tag{10}$$

which reduces to

$$r_{eff} = r[(v_a/v_0)\sin\theta_w + \cos\theta_w] \tag{11}$$

The veracity of this relation was checked by investigating the following limiting cases:

1. A windshield with a rake angle of 0 deg at zero velocity (v_a = 0) should have an effective rain rate equal to the actual rain rate. The relation for r_{eff} shows that

$$r_{eff} = r[(0/v_0)\sin 0° + \cos 0°] = r \tag{12}$$

2. A windshield with a rake angle of 90 deg at zero velocity (v_a = 0) should have an effective rain rate of zero (r = 0). The relation for r_{eff} shows that

$$r_{eff} = r[(0/v_0)\sin 90° + \cos 90°] = 0 \tag{13}$$

3. A windshield with a rake angle of 90 deg at velocity v_a should have an effective rain rate of

$$r_{eff} = r[(v_a/v_0)\sin 90° + \cos 90°] = r(v_a/v_0) \tag{14}$$

Thus, as the vehicle velocity increases, the effective rain rate increases. Further, as the terminal velocity decreases, the rain rate increases because the amount of water in the air at any instantaneous time also increases. And at 0-deg windshield rake angle an increase in velocity has no effect on effective rain rate.

Figure 9 shows a plot of effective rain rates versus vehicle speed for selected rainfall rates. This plot makes two significant assumptions: (a) that the vehicle velocity vector and the rainfall were at 90 deg to each other and (b) that the effects of wind could be ignored. The curves show that the rain produced by the simulator accurately reflects rain rates that are typically encountered. For example, to simulate the condition of a vehicle having a velocity of 88 km/h (55 mph) in a rainfall of 3.8 cm/h (1.5 in/h) requires a static rain rate of 10.80 cm/h (4.25 in/h). The dotted lines in the figure show this relation.

CONCLUSIONS

The significant results of this research can be summarized as follows:

1. During rain conditions, the primary factor that reduces visibility is the film of water on the windshield, which impairs vision by reducing the optical resolution. The S-1 studies, when compared to the S-2 studies (no rain on the windshield versus rain on the windshield), demonstrate this point. At a 2.5-cm/h (1-in/h) simulator rain rate [equivalent to a 0.75-cm/h (0.30-in/h) effective rate at 88 km/h (55 mph)], vision through the windshield is reduced to the point that acuity decreases to 10 min of visual arc, which corresponds to a static visual acuity of 20/200. However, the daylight visual acuity through a 10.2-cm/h (4-in/h) simulator rain, with no water on the windshield, produced a visual degradation equivalent to only 2.5 min of visual arc, which corresponds to a static visual acuity of 20/50.

2. The simulator results showed a precipitous decrease in the detection and identification of pertinent targets (i.e., a man or an automobile) between the 5.1 and 10.2-cm (2 and 4-in/h) simulated rain rates.

3. Windshield wipers restore visual acuity to approximately the same level as would be expected if the vehicle remained outside the rain and the driver looked through it. Higher windshield-wiper speeds do not significantly improve visibility at speeds above 50 cpm.

4. A regression model of visual degradation in terms of the increase in threshold visual angle as a function of the rain rate is given by Equation 1.

5. There are significant interactions between rain and the glare from oncoming vehicles.

6. Raindrop size distribution is a significant factor in visibility reduction, especially at low levels of illumination. A concentration of smaller drop sizes, i.e., those less than 0.5 mm in diameter, causes serious visual degradation through reduction of contrast and the decrease in the quality of the texture background.

ACKNOWLEDGMENT

The research reported in this paper was sponsored by the National Highway Traffic Safety Administration. The contents reflect the views of the authors only, who are responsible for the facts and the accuracy of the data presented.

REFERENCES

1. D. L. Ivey, E. K. Lehitpuu, and J. W. Button. Rainfall and Visibility—The View From Behind the Wheel. Texas Transportation Institute, Texas A&M Univ., College Station, Rept. 135-3, 1975.
2. W. E. K. Middleton. Vision Through the Atmosphere. Univ. of Toronto Press, 1952.
3. A. Walvolgel. The N_o-Jump of Raindrops Spectra. Atmospharenphysik ETH, Zurich, 1974.
4. F. A. Berry. Handbook of Meteorology. McGraw-Hill, New York, 1945.

Publication of this paper sponsored by Committee on Visibility.

Computer Program for Roadway Lighting

F. W. Jung and C. Blamey, Research and Development Division, Ontario Ministry of Transportation and Communications

The development of a computer program for the design and evaluation of fixed highway lighting is reported. The program calculates the illuminance, luminance, and disability veiling brightness in each lane at specified grid points on the road surface for regular, straight rows of luminaires, for a straight highway up to six lanes wide. Isoilluminance and isoluminance diagrams can also be obtained. The program can be used as a design tool in the following way: For a chosen road geometry and a selected luminaire type, the designer can determine the performance of a proposed lighting design by calculating the relevant performance measures and comparing the results with the current accepted, or the proposed new standards. Many different designs can be rigorously evaluated in a short time. In conjunction with photometric measurements, the program was used to evaluate the performance of the existing design on the Toronto Bypass. Lighting designs based on calculations of luminance and disability veiling brightness are preferable to those based on illuminance because nighttime visibility is determined by the former rather than the latter.

Modern electronic computer methods are entering the field of outdoor lighting and assisting and improving the design and management of lighting systems. This paper presents a model for a computer program that combines the design tasks of luminaire selection, performance evaluation, and, at a later stage, economic comparison of various alternative systems. The domain of this model is limited to straight, regular systems of roadway lighting, but similar models can be used for other lighting systems, such as parking lots, shopping plazas, or curves and intersections of highways (although the higher costs of developing these programs may be justified only if their potential users join in the effort).

Lighting design by computer methods is cost-effective for two reasons: First, there is a saving in labor costs