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COOPERATIVE
RESEARCH

RAINFALL AND VISIBILITY--THE VIEW FROM BEHIND THE WHEEL

in cooperation with the
Department of Transportation
Federal Highway Administration

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16. Abstract

The factors influencing wet weather accidents are complex, a fact readily ignored by many who would blame tire pavement friction for all our wet weather problems. A factor of significance is visibility, as influenced not only by rainfall intensity but to a great extent by traffic speed. This interim report presents a limited number of direct visibility observations and develops a framework useful in interpreting these data to determine the influence of reduced visibility on the operation of motor vehicles. Information from the literature shows the low probability of high intensity rainfalls. Conclusions concerning the hazard of passing maneuvers during rainfall of 1 in./hr. or more and the need to reduce speed under wet weather conditions are also presented.

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RAINFALL AND VISIBILITY--THE VIEW FROM BEHIND THE WHEEL

by

Don L. Ivey, Eero K. Lehtipuu,
and Joe W. Button

Research Report Number 135-3

Research Study Number 1-10-70-135

Definition of Relative Importance of Factors
Affecting Vehicle Skids

Sponsored by

The Texas Highway Department

in Cooperation with the

U. S. Department of Transportation
Federal Highway Administration

February 1975

TEXAS TRANSPORTATION INSTITUTE
Texas A&M University
College Station, Texas

SUMMARY

The influence of visibility on traffic safety has been implied by surveys of high frequency wet weather accident sites which were conducted as another part of this study. It was apparent that visibility in concert with undiminished traffic conflicts and speed played an important part in accident frequency. The achievement of the following objectives was considered necessary in order to develop appropriate measures to counteract this negative influence on traffic safety.

1.t The determination of the frequency, duration and intensity oft rainfall in the state of Texas.t

2.t The determination of the effect of different intensities of rainfall on driver visibility.t

It is shown that some degree of rainfall takes place approximately 6% of the time* but that high intensity rainfalls are comparatively rare. An intensity of one inch per hour or more takes place less than 0.06% of the time.

An approximate equation was developed for driver visibility which depends on the intensity of rainfall, the vehicle speed and the cyclic frequency of the windshield wipers. The options open to the highway engineer in designing for rainfall are shown to be limited and conclusions are reached concerning the possibility of disallowing passing during rainfall and enforcing reduced speeds. It is shown that traffic speeds in excess of 45 mph are unsafe when passing maneuvers are performed during rainfalls of 1 in./hr.

*6% in Central Texas (Probable variation of from 1 to 10% across thet State).

IMPLEMENTATION

A basis is presented whereby traffic engineers can logically select a "design" rainfall intensity based on the probability of a given event. Based on these "design" rainfalls, appropriate traffic speeds and/or maneuvers can then be determined for specific roadways and geographic areas. These determinations can be made using the visibility equation which was developed. Further use of the "design" rainfall concept is suggested in selecting appropriate combinations of cross slope, texture and runoff length to prevent significant water accumulation on highway surfaces.

Information developed in this report is appropriate to justify reduced traffic speeds during periods of rainfall or to attack proposals for increased traffic speeds. The point is apparent that many skidding accidents are caused by reduced visibility augmented by inappropriate traffic speeds which go together to produce situations which require extreme skid inducing maneuvers.

ACKNOWLEDGMENTS

This study represents one phase of Research Study No. 1-8-70-135, "Factors Influencing Vehicle Skids," a continuing study in the cooperative research program of the Texas Transportation Institute and the Texas Highway Department in cooperation with the Federal Highway Administration.

DISCLAIMER

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I. INTRODUCTION

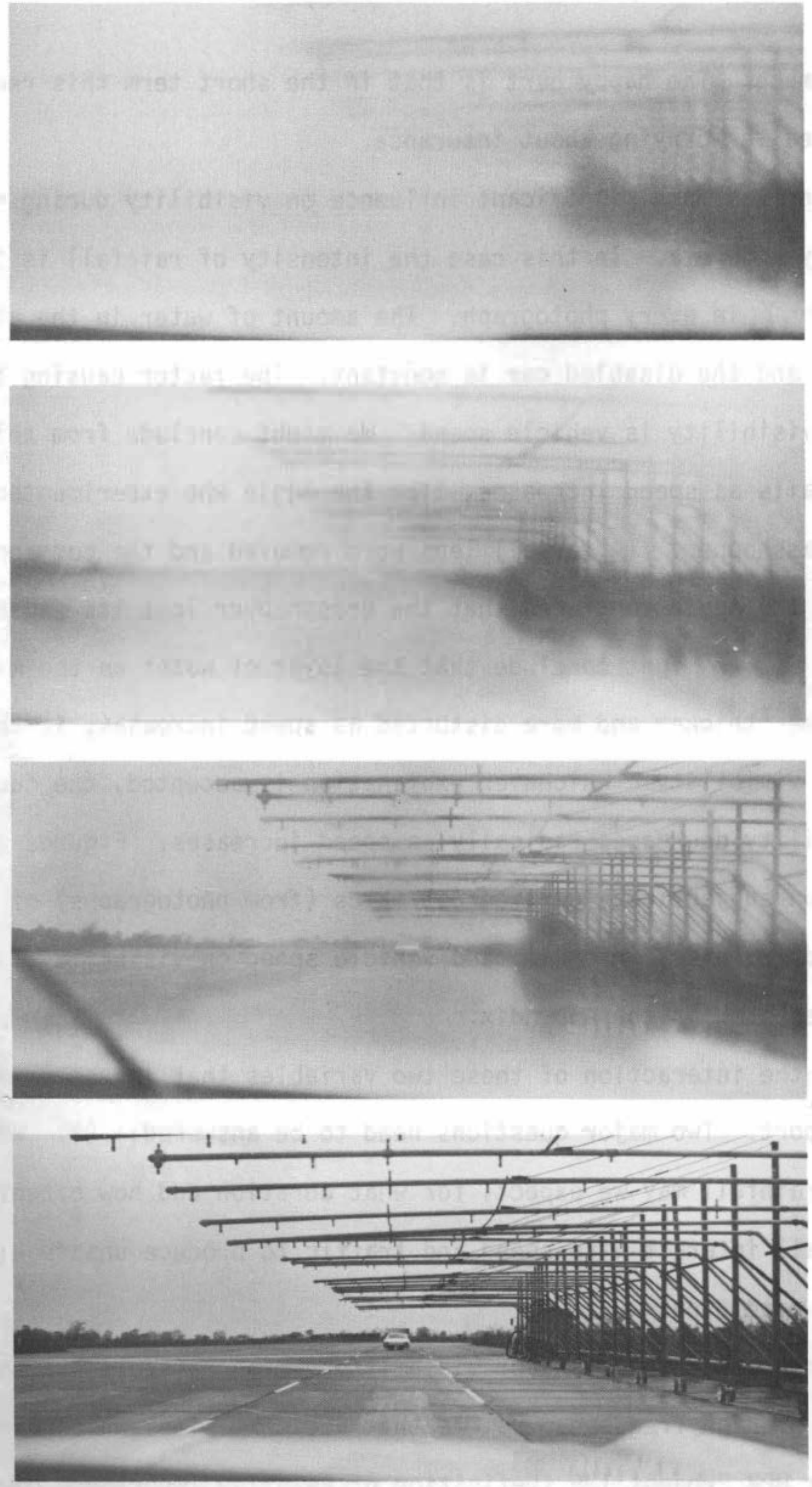
Sight -- that most versatile, adaptable, complex and satisfying of our senses. Its relation to what we call beauty and the ingenious nature of its functions have caused mystics to call it the proof of a supernatural controlling intelligence and anthropologists to marvel that it could evolve, even in the herculean period of five hundred million years.

> *"Time and death and the space between the stars remain the substance of evolution and of all that we are."*
>
> Robert Ardrey

Like all our senses it is taken for granted as long as it functions properly. The shape of our corneal lenses changes automatically to allow clear view of objects from 7 cm. to many miles, the iris contracts or dilates automatically in response to the intensity of light; and when darkness comes, a comparatively slow but still automatic change takes place whereby "visual purple" is generated in the retina and the rod nerves take over the sensing task from the cone nerves. And these are only the relatively simple reactions we can easily observe. A chain of automatic responses, orders of magnitude more complex, lie below the surface of direct observation in the electronic and chemical functions of our central nervous system.

Switching now from the marvels of the human eye to some of its shortcomings, there is one characteristic which severely limits its reliability in certain highway environments. That is, the eye does not directly perceive physical objects, it responds only to particles or waves of light which penetrate its lens, then it relies on the central nervous system to interpret the pattern of stimuli produced by the impinging light. The brain infers the existence of an object from the implications of light waves. Therefore if anything causes the light to change in pattern between the object and the eye the inference made by the brain will be changed, or at least made more difficult. Such is the case when the air is full of particles of water in the space between an object and an eye. Each light wave undergoes refraction (change in direction) every time it traverses a boundary between air and water. Each refraction distorts the pattern received by the eye. Enough refractions will prevent reception of any discernable image at all.

But enough of this discussion trespassing on the realms of the mystic, the anthropologist and the psychophysicist. What does this mean to the driver of a motor vehicle? In a discussion of visibility above all subjects, it may be easier to show than to tell. Figure 1 shows the view, as recorded by a camera, from a vehicle traveling 60 mph in the rain. In this case the rain is produced artificially by an overhead pipe system. From bottom to top the rainfall intensity (I) varies from zero to 4.4 inches per hour and comparative visibility (V) varies from 100 to 5 percent. A disabled vehicle 260 ft. ahead is quite obscured even in the lowest significant rainfall presented in Figure 1. Even if the driver sees the disabled vehicle at this point he will have less than 3 seconds to interpret, decide on an appropriate response and either stop his vehicle or swerve to miss the disabled vehicle. Although this seems critical, it is by no means the most critical condition, since a passing maneuver initiated in the presence of an oncoming vehicle would represent a much more hazardous situation. For most of the driving population this is not enough time. (It is enough time to say briskly, "Is my insurance paid up?") Obviously in the conditions of high rainfall intensity the driver will not have time



I = 4.4 in./hr.
V = 5%

I = 2.7 in./hr.
V = 20%

I = 1.4 in./hr.*
V = 55%

I = 0 in./hr.
V = 100%

FIGURE 1. INFLUENCE OF RAINFALL INTENSITY ON VISIBILITY
(Vehicle Speed-60 mph, Rainfall Distance Ahead -160 ft, Objective Vehicle Distance- 260 ft)

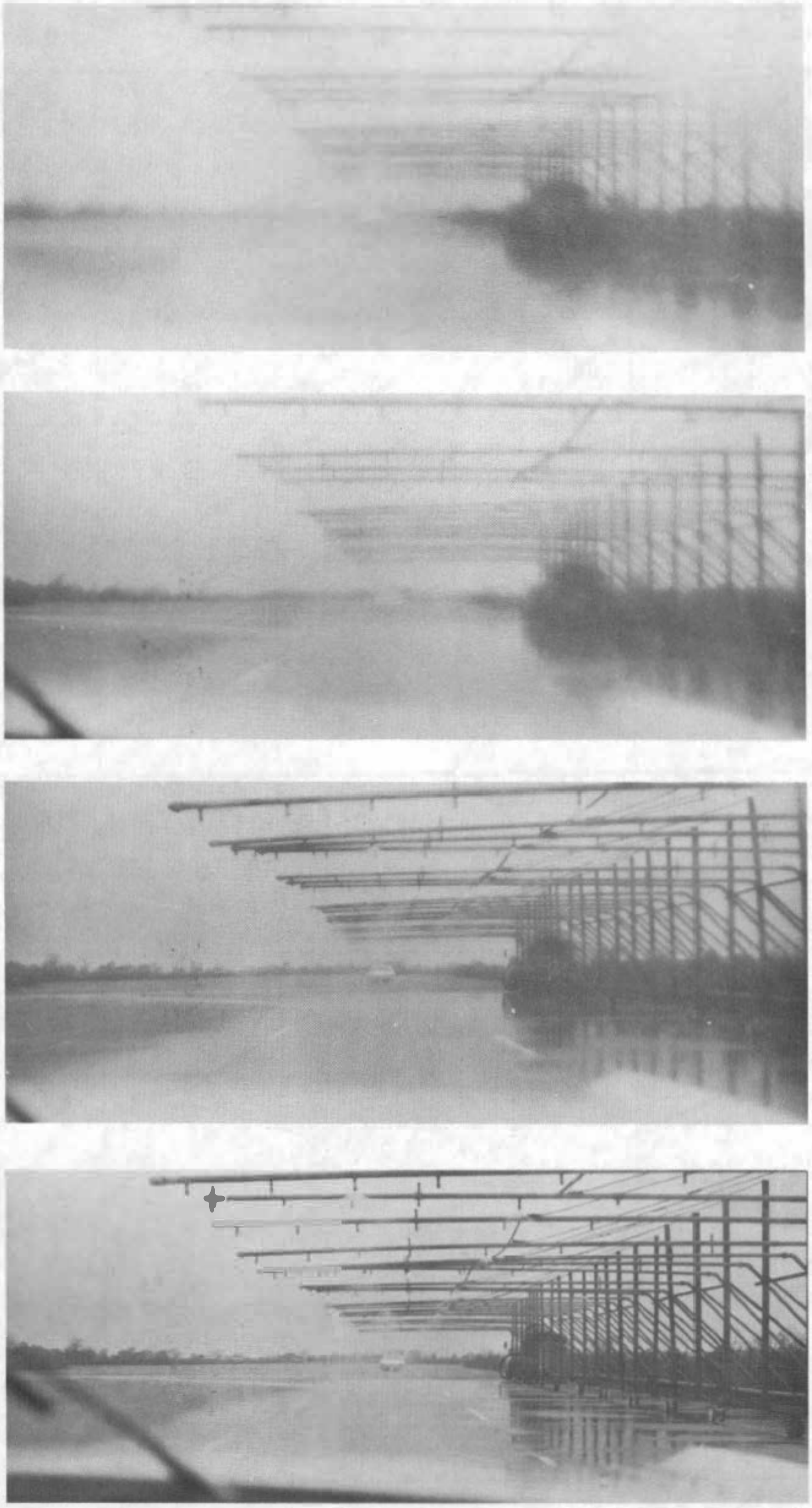
*Extrapolated for illustrative purposes.

to say as much. The happy part is that in the short term this reduces the time devoted to worrying about insurance.

But an even more significant influence on visibility during rainfall is shown by Figure 2. In this case the intensity of rainfall is the same (2.7 in./hr.) in every photograph. The amount of water in the air between the driver and the disabled car is constant. The factor causing the radical change in visibility is vehicle speed. We might conclude from this that our eyesight fails as speed increases, like the Aggie who experimented with the hopping grasshopper. (After all legs were removed and the command to jump was given, the Aggie concluded that the grasshopper lost its sense of hearing.) Or, we might conclude that the layer of water on the windshield, which becomes thicker and more distorted as speed increases, is the cause of reduced visibility. Whichever explanation is accepted, the fact remains that visibility decreases radically as speed increases. Figures 3 and 4 are based on subjectively derived estimates (from photographs) of the influence of rainfall intensity and vehicle speed on visibility. The experiment is presented in the Appendix.

It is the interaction of these two variables that is the primary thrust of this report. Two major questions need to be answered: (1) What intensities of rainfall may we expect, for what duration and how often? (2) How does rainfall interact with speed and traffic to produce unsafe highway visibility conditions?

The importance to safety of visibility during rainfall has been implied by surveys of high frequency, wet weather accident sites which are continuing under HPR Project 135 (Definition of Relative Importance of Factors Affecting Vehicle Skids). During these surveys it became increasingly apparent that visibility, in concert with undiminished traffic conflicts, and speeds must play an important part in causing accidents at sites having



v = 60 mph
V = 20%

v = 50 mph
V = 30%

v = 30 mph
V = 55%

v = 0
V = 85%

FIGURE 2. INFLUENCE OF SPEED ON VISIBILITY
(Rainfall Intensity-2.7 in./hr., Rainfall Distance Ahead -160 ft, Objective Distance Ahead - 260 ft)

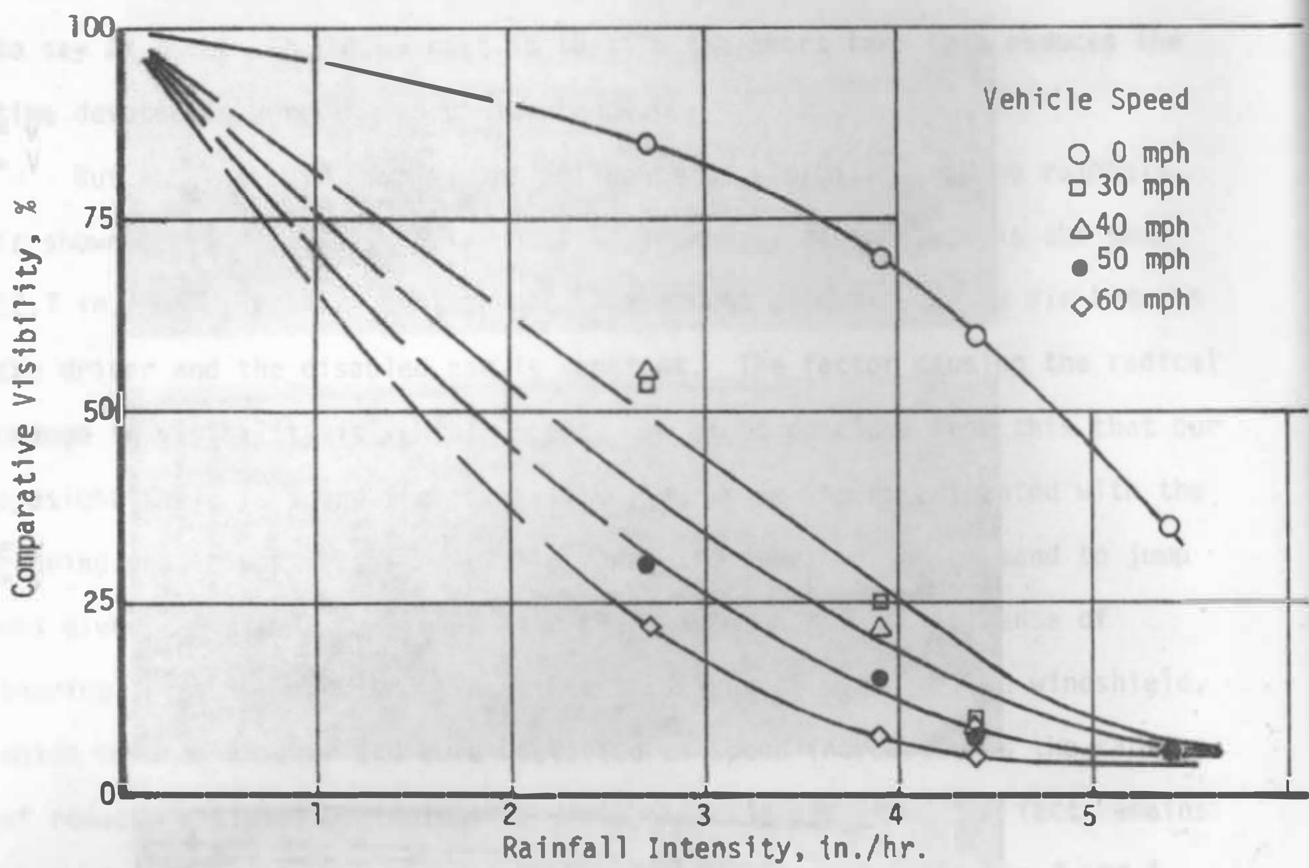


FIGURE 3. PHOTOGRAPHIC ESTIMATE OF VISIBILITY vs. RAINFALL INTENSITY

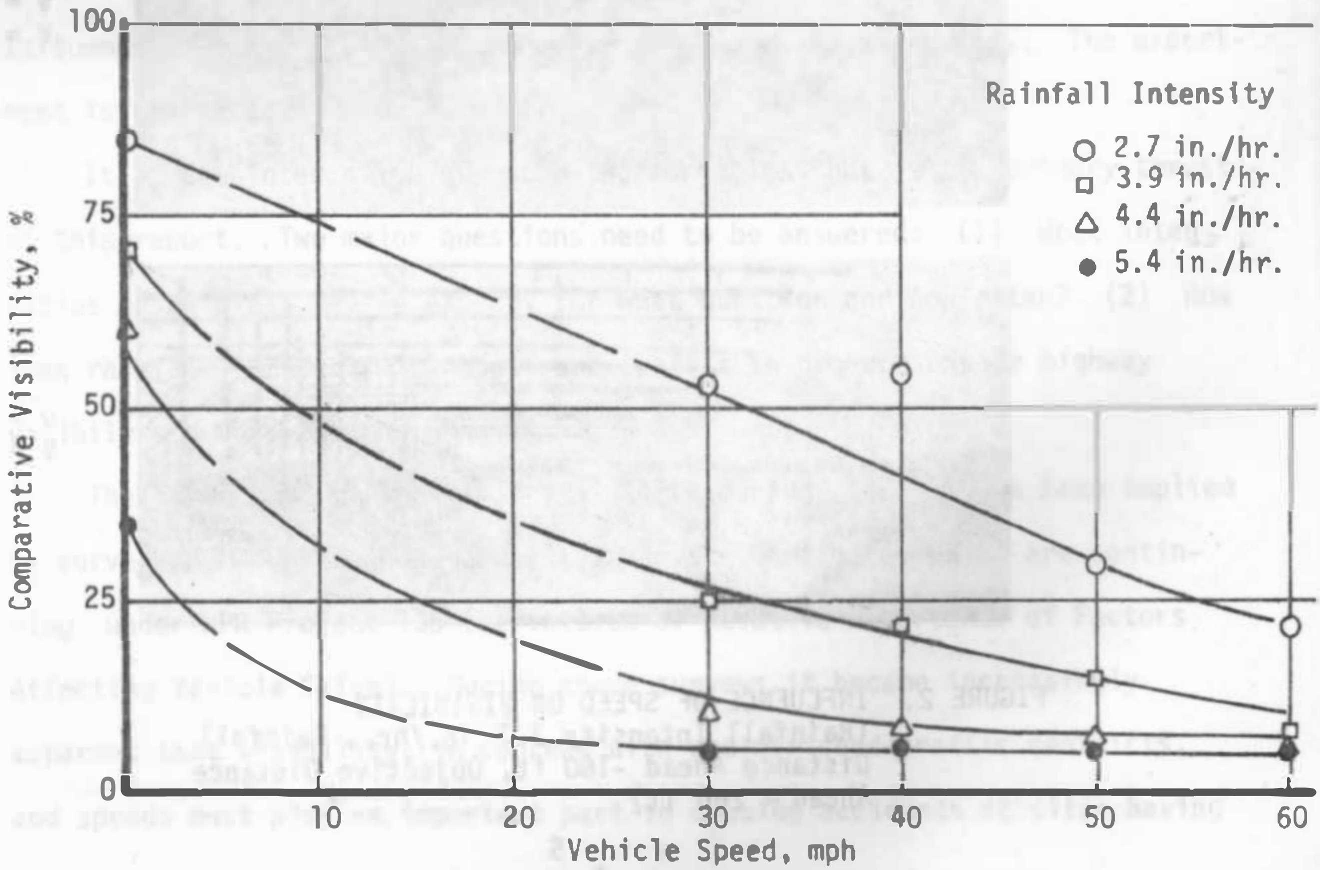
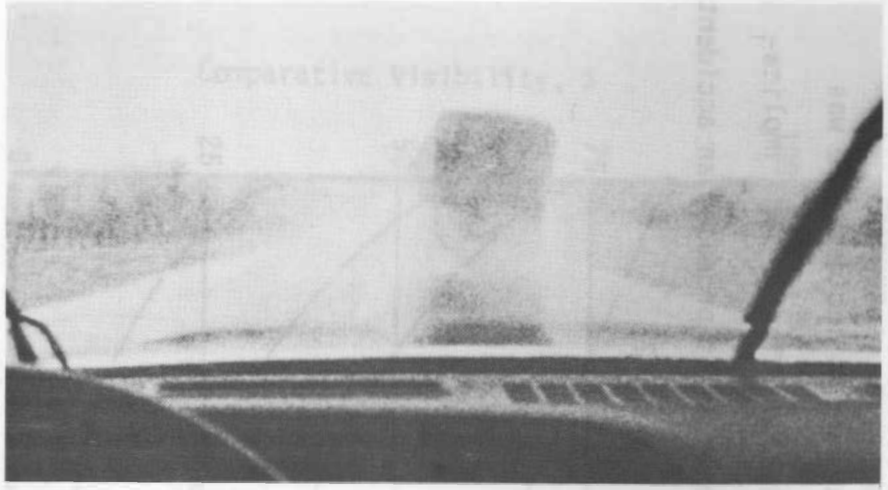


FIGURE 4. PHOTOGRAPHIC ESTIMATE OF VISIBILITY vs. VEHICLE SPEED

what would seem to be ideal geometric, drainage and pavement surface characteristics. The potential for accident causation was illustrated even more vividly by firsthand observation of traffic while filming scenes for the recently released film, "War on Wet Weather Accidents". Some examples taken from this film are shown in Figures 5 and 6. The incompatibility of traffic speeds during rainfall when some vehicles slow down, in appropriate response to reduced visibility, while others proceed at the speed limit further compounds the problem.

Objective evaluation of wet weather visibility is necessary in order to govern the operation of motor vehicles and to apply appropriate criteria for sight distance in highway geometrics and for traffic control devices. The subjective evaluations applied by law enforcement agencies are almost invariably applied after-the-fact in accident situations as a justification for specific actions. Obviously if a man had an accident, he was traveling at a "speed excessive for prevailing conditions". The implication is that one is driving inappropriately only if it produced an accident. It is producing accidents. What can be done about it?



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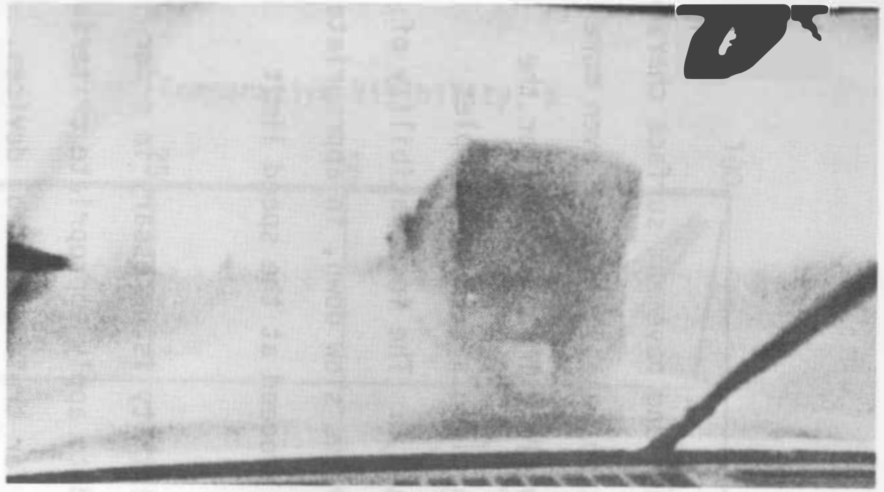

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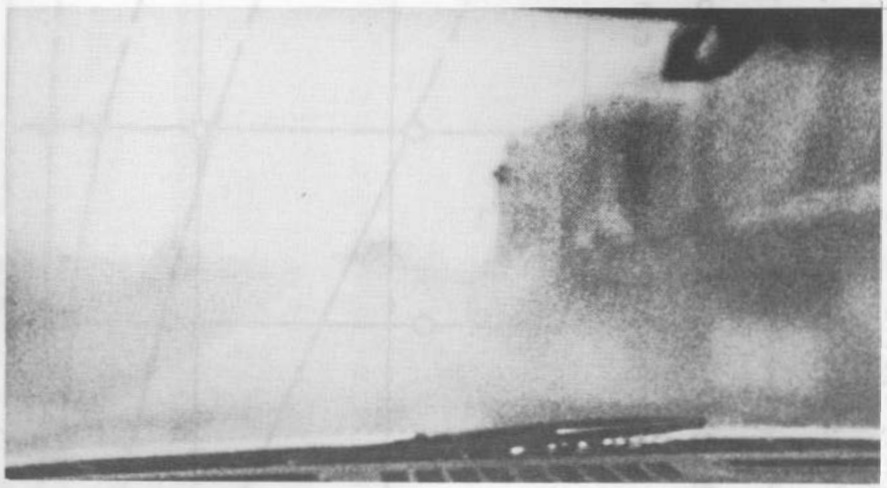

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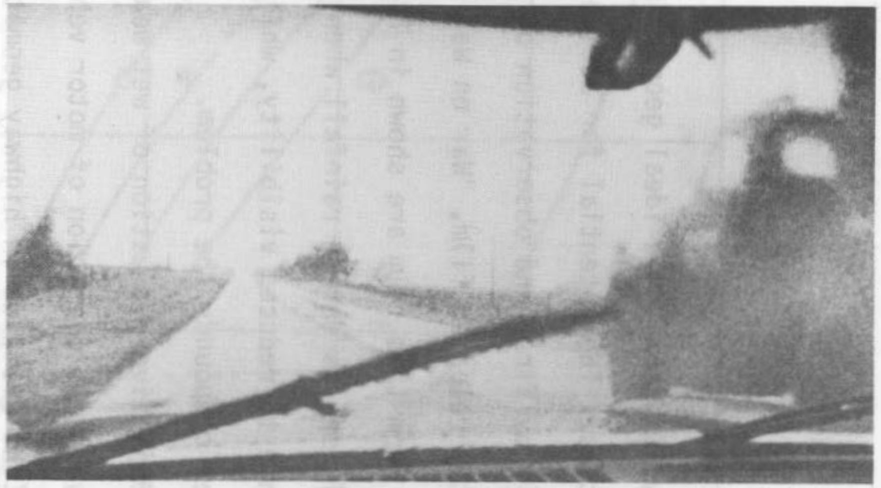

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FIGURE 5. VIEW PASSING A TRACTOR-TRAILER RIG (Light Rainfall, Two Lane State Highway, Truck Speed Approximately 50 mph.)

FIGURE 6. PHOTOGRAPHS OF DRIVER'S VIEW IN VERY LIGHT RAINFALL

II. THE PROBABILITY OF DRIVING IN THE RAIN

Multimillion dollar buildings are not designed for the highest wind ever recorded. (They may be designed for the highest wind which would be expected in a 100-year interval.) Bridges are not designed for the largest trucks ever constructed. (The weight of trucks which may pass over a specific bridge may be limited by law.) Similarly it is not reasonable to design highways and motor vehicles for the highest possible intensities of rainfall in combination with undiminished traffic speeds. What should be determined is the probability of rainfall of given intensity. The possibility of design changes should be considered only if that probability is high enough to be of real significance to society.

To obtain precise information regarding this probability, rainfall intensities as a function of time divided in intervals as small as one minute would have to be recorded at many different geographic points for a period of years. The development of data of this scope does not seem economically feasible. Thus reliance must be placed on rational predictions made from significantly less comprehensive data. In most cases, observations are available on the basis of the total amount of rain falling in a one-hour interval. However, in certain metropolitan sites the U.S. Department of Commerce has made more definitive measurements. Selected measurements made in Texas will be used to answer the following specific questions:

1. Over what period of time does rainfall occur during a typical year?
2. Over what period of time does the rainfall rate exceed certain levels during a typical year?

As representative of Texas, comprehensive data for Austin and Ft. Worth are available for 1973 and 1971, respectively. The average annual rainfall for Texas varies from 57 inches in Beaumont to 8 inches in El Paso. In 1973 Austin had a total rainfall of 35.06 inches, slightly greater than the long-term mean value which was 33.23 between 1933 and 1972. In 1971 Ft. Worth had 36.26 inches, again slightly greater than the long-term mean from 1933 to 1972 of 31.81. Figure 7 illustrates the representative nature of these Central Texas cities. Table 1 gives a breakdown of minutes of precipitation time by months for Ft. Worth and Dallas during the years stated. The values are based on hourly data from Local Climatological Data, Annual Summary with Comparative Data for Dallas and Ft. Worth and the approximations that rainfall during every "rain hour" took place an average of 50 minutes and that rainfall during every "trace hour" took place for 30 minutes. The difference is that most of the hours with measurable amounts of water ran successively; hence in most cases only the first and last hour are shorter than 60 minutes. This results in a higher average value of 50 minutes as compared to the 30 minutes for the "rain trace hour".

According to these estimates the yearly totals were from 5 to 7.5% of the total time. Drivers were in the rain, assuming a uniform distribution of driving time throughout the year, from one thirteenth to one twentieth of their total driving time. During certain critical months (see Austin in January 1973) drivers were exposed to rainfall one eighth of the time that they were driving. If the assumption is made that the time of precipitation is proportional to the yearly amount of precipitation, exposure values for major Texas cities could be computed as the following:

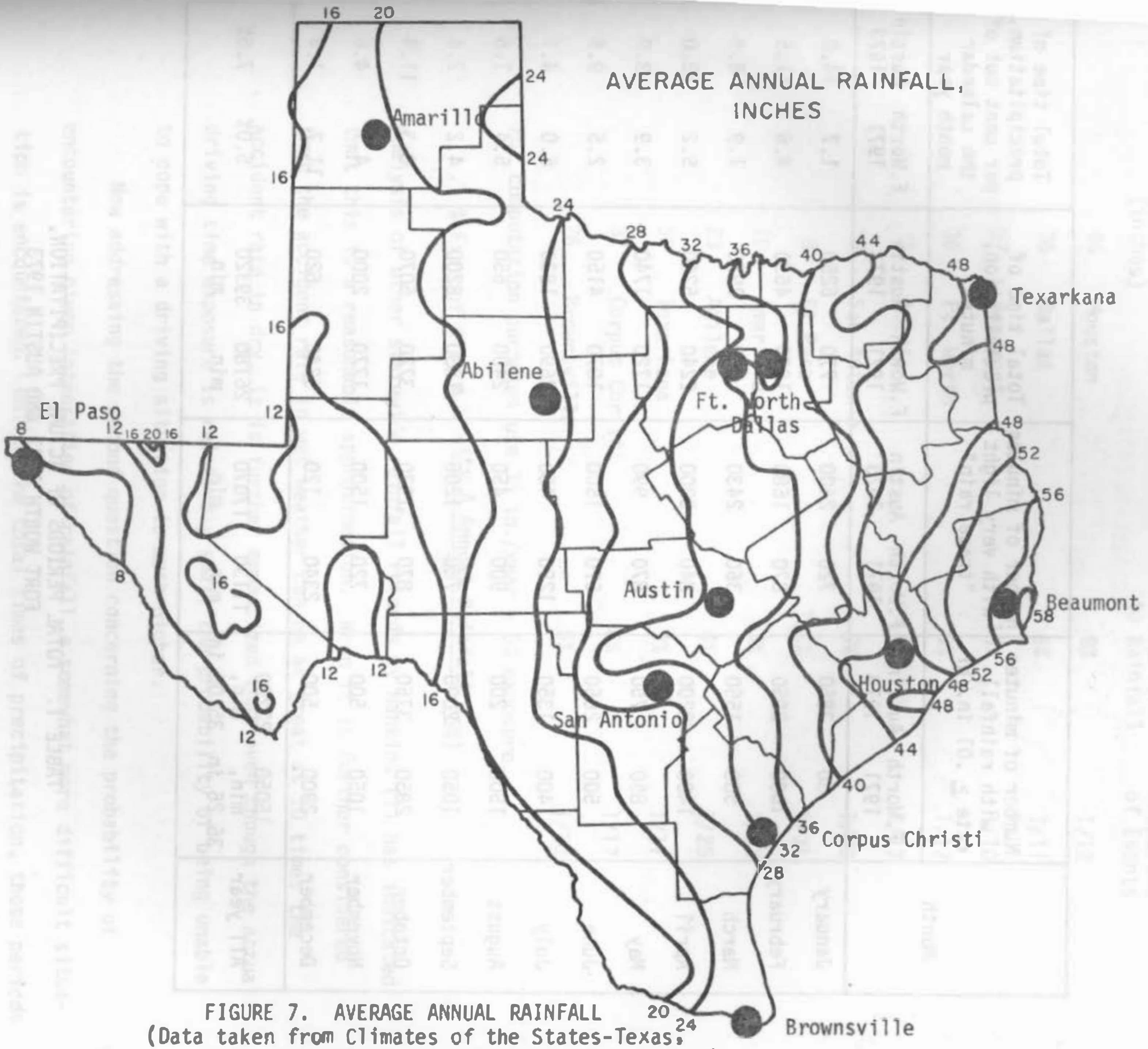

FIGURE 7. AVERAGE ANNUAL RAINFALL
(Data taken from Climates of the States-Texas, February 1960, U.S. Dept. of Commerce-Weather Bureau)

Month	Number of minutes with rainfall rate ≥ .01 in./hr.		Number of minutes with very light "trace rain"		Total time of precipitation, minutes		Total time of precipitation, per cent out of the calendar month year	
	F.Worth 1971	Austin 1973	F.Worth 1971	Austin 1973	F.Worth 1971	Austin 1973	F.Worth 1971	Austin 1973
January	50	3850	720	2400	770	6250	1.7	14.0
February	1000	2950	870	1680	1870	4630	4.6	11.5
March	500	1550	360	2430	860	3980	1.9	8.9
April	1400	2200	840	3000	2240	5200	5.2	12.0
May	850	750	870	990	1720	1740	3.9	3.9
June	500	2650	570	1500	1070	4150	2.5	9.6
July	1400	1350	1290	480	2690	1830	6.0	4.1
August	1500	200	900	450	2400	650	5.4	1.5
September	1050	2000	780	1200	1830	3200	4.2	7.4
October	2850	3750	870	1320	3720	5070	8.3	11.4
November	1050	500	720	1500	1770	2000	4.1	4.6
December	2900	500	2340	120	5240	620	11.7	1.4
All year	15050 min, 36.26 in	22250 min, 35.06 in	11130 min	17070 min	26180 min	39320 min	5.0%	7.5%

TABLE 1. TOTAL PERIODS OF ACTUAL PRECIPITATION, FORT WORTH 1971 AND AUSTIN 1973

Total Yearly Rainfall (inches)		% Exposure to Rainfall	Proportion of Events
46	Houston	8%	1/12
36	Dallas	6%	1/11
57	Beaumont	10%	1/10
36	Ft. Worth	6%	1/17
33	Austin	6%	1/17
30	San Antonio	5%	1/20
8	El Paso	1.4%	1/71
19	Amarillo	3%	1/33
23	Abilene	4%	1/25
50	Texarkana	9%	1/11
32	Corpus Christi	6%	1/17
26	Brownsville	5%	1/20

For computation purposes use 35 in./year = 6% exposure.

$$\therefore \text{ \% Exp. of City A} = \frac{\text{City A Annual Rainfall}}{35} (6\%)$$

Analysis of other statewide rainfall records by Hankins (1) has indicated that this is a reasonable approximation. When it is further considered that the accident rate in wet weather can be as great as 10 times the accident rate in dry, it is further emphasized that even though the actual driving time exposure is relatively small the probability of being unable to cope with a driving situation is much higher.

Now addressing the second question concerning the probability of encountering given intensities of rainfall, a somewhat more difficult situation is encountered. Unlike the total times of precipitation, those periods exceeding certain intensities are not as easily determined. As a starting point there are the hourly tabulations of rainfall equalling or exceeding 0.01 inch, but obviously the rainfall intensity during these hours was subject to wide variation.

The search for detailed observations of the variation of rainfall intensity throughout the duration of specific rain periods was not successful. One obvious reason is that most available instrumentation is not very precise for observation periods of less than 5 minutes. However, in contrast to the shortage of analyses of individual rainfalls, there are extensive data available on the total rainfall observed during different maximum rainfall time periods, beginning with maximum 5 minute rainfall values ranging to the maximum values for periods of several hours. The United States Weather Bureau (2) gives the data presented in Table 2 for rainfall periods of various durations.

Duration of Rainfall Minutes	Maximal Amount of Rain Compared with One Hour Value	Maximal Intensity of Rainfall Compared with One Hour Value
5	0.29	3.48
10	0.45	2.70
15	0.57	2.28
30	0.79	1.58
60	1.00	1.00

TABLE 2. MAXIMUM RAINFALL INTENSITY VARIATIONS WITHIN ONE HOUR

Thus, for high variability rainfalls, the most critical 5-minute period within a one-hour rain period can be estimated as having an intensity 3.48 times the mean intensity for the entire hour. The second heaviest 5-minute period can be calculated from the mean value for 10 minutes (2.70). This intensity is calculated to be 1.92 times the mean intensity of the entire hour. The whole distribution thus becomes:*

"First" period of 5 minutes:	3.48 times the hourly average
"Second" - " -	1.92 - " -
"Third" - " -	1.44 - " -
"Fourth" to "Sixth" - " -	0.88 - " -
"Seventh" to "Twelfth" - " -	0.42 - " -

Distributions close to this one can be obtained from other sources. (2,3) It is possible, however, to construct a smooth curve through the 5 minute interval bar graph distribution. This more natural distribution is of interest since it is likely that the maximum intensity during an hour significantly exceeds the mean of the maximum 5-minute period. The proposed graphical solution is shown in Figure 8. As a unity base line example, a one-hour rain produces a total amount of precipitation of one inch. The average intensity is thus 1 in./hr. Drawing a smooth curve through the intensity/time relationships set forth above and interpolating for each minute yields the following minute-based distribution:

*The attributes "first", "second", etc., do not refer to the temporal sequence of time but to the order of magnitude.

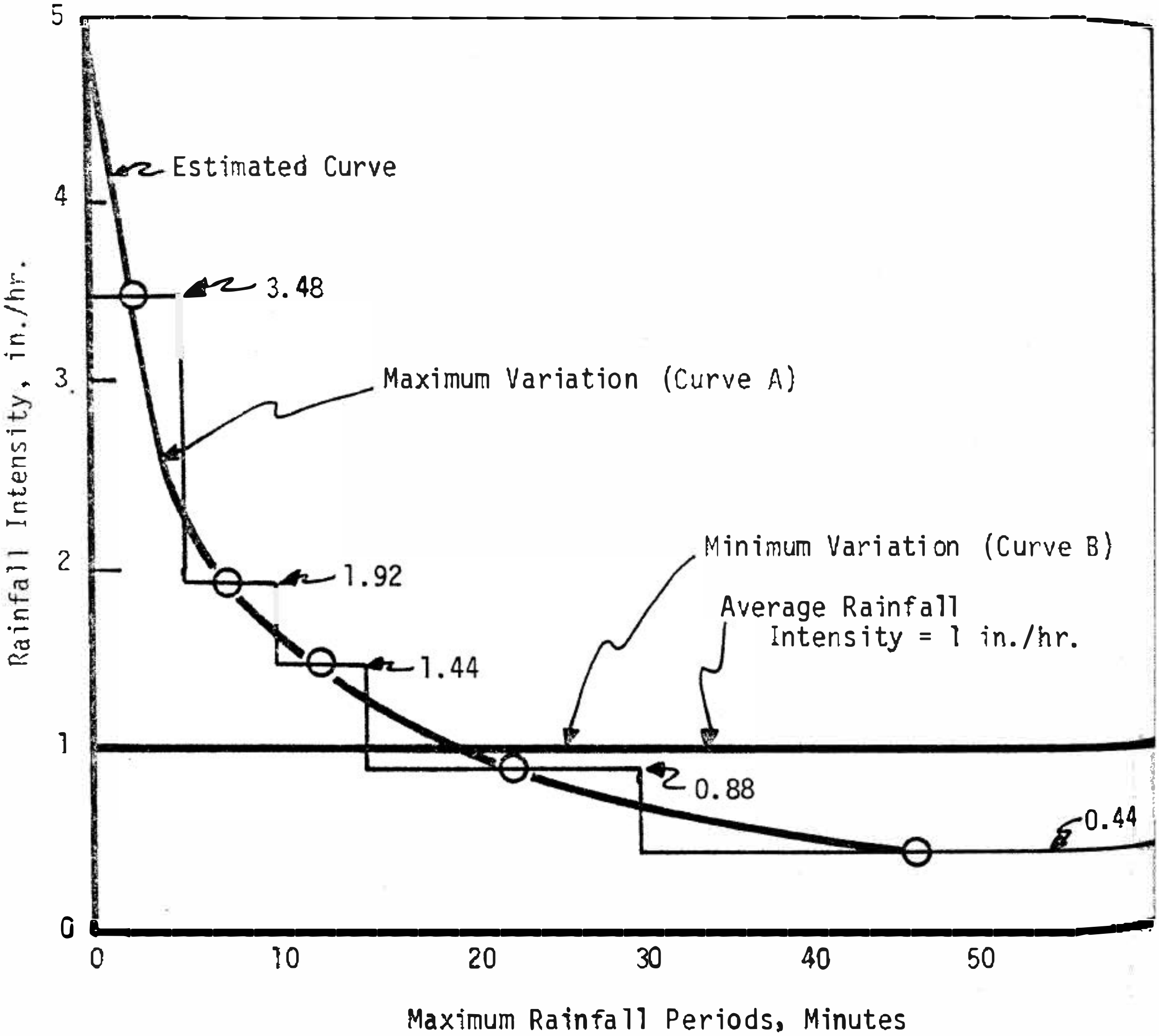

FIGURE 8. GRAPHICAL SOLUTION OF
RAINFALL DISTRIBUTION PATTERN

1st heaviest minute:	4.8 in./hr.	
2nd	- " -	4.0 - " -
3rd	- " -	3.4 - " -
4th	- " -	2.8 - " -
5th	- " -	2.4 - " -
6th	- " -	2.2 - " -
7th	- " -	2.0 - " -
8th	- " -	1.9 - " -
9th	- " -	1.8 - " -
10th	- " -	1.7 - " -
11th to 15th	- " -	1.5 - " -
16th to 25th	- " -	1.0 - " -
26th to 40th	- " -	0.5 - " -
41st to 60th	- " -	0.4 - " -

(Mean equals 1.00 in./hr.

A distribution like this may be assumed to represent the maximum variation that would occur within one hour. A minimum variation is represented by the horizontal line at the one inch per hour level in Figure 8. The intensity distribution of most rains would lie between these low probability extremes.

To elaborate further on intensity distribution, the maximum distribution results shown can be applied to the 1971 Ft. Worth and the 1973 Austin data. Since the hourly rainfall values are available, each value was analyzed separately to obtain the intensity time data given by Table 3.

Rainfall Intensity in./hr.	Fort Worth, 1971		Austin, 1973	
	Time Exceeding Given Intensity (max)* Minutes	Time Exceeding Given Intensity (min)** Minutes	Time Exceeding Given Intensity (max)* Minutes	Time Exceeding Given Intensity (min)** Minutes
0.25	2206	2460	1972	2040
0.50	828	840	910	900
1.00	289	120	319	300
2.00	58	0	107	0
4.00	6	0	22	0

*Computed using maximum variation (Curve A, Figure 8)
**Computed using minimum variation (Curve B, Figure 8)

TABLE 3. TOTAL TIME OF RAINFALL EXCEEDING CERTAIN THRESHOLD INTENSITIES

As seen in Table 3, when intensities less than 2 in./hr. are considered, even the extremes of intensity variations yield similar totals of rainfall time when certain threshold intensities are exceeded. The choice of the form of the distribution thus seems to be of relatively minor importance. However, since maximum variation is the more conservative, it will be considered in the following discussion. For example at Austin in October 1973 there was one hour when 1.97 inches of rain fell. Obviously there were some minutes within the hour when there was an intensity of 2 in./hr. or more; the suggested maximum variation distribution gives 15 minutes exceeding 2 in./hr. intensity. Using the time periods of Table 3, the minutes of rainfall exceeding certain intensity values may be calculated. The results are shown in Table 4.

It is quickly obvious that the exposure of traffic to high intensity rainfall in the Central Texas area is very small, even when the maximum variation data are used. The time of exposure to rainfalls of greater than one inch per hour intensity is less than five hours per year. Interpretation of the meaning of this table with respect to safety will be attempted in greater detail after other questions concerning the effect of different rainfall intensities on visibility are answered.

III. THE THEORY OF VISIBILITY AS INFLUENCED BY RAIN

Any object can be detected by the human eye only if its brightness (luminance) differs significantly from that of its background. The contrast (C) can be expressed simple by Eq. (1):

$$C = \frac{B_o - B_b}{B_b} \tag{1}$$

where C = contrast

B_o = brightness of the object (e.g. in foot-lamberts)

B_b = brightness of the background (e.g. in foot-lamberts)

The object must have some threshold contrast value, differing from zero, to be discerned by the human eye.*

To deal briefly with theoretical aspects of the visibility during rain, the generally accepted theory of Koschmieder (4) may be used in which the horizontal viewing distance is coupled with the apparent contrast according to Eq. (2):

$$C_R = C_0 e^{-\sigma S} \tag{2}$$

where C_R = apparent contrast of the object seen from a distance R

C_0 = inherent contrast of the object seen from a short distance

e = base of natural logarithms

σ = atmospheric extinction coefficient

S = viewing distance

*If some glare effect from external light sources is present, Eq. (1) takes the form $C = \frac{B_o - B_b}{B_b + B_{dvb}}$ where B_{dvb} is the so-called disability veiling brightness. This glare may be present in sunshine as well as in artificial light but is rarely present during daytime rainfall.

Rainfall Intensity in./hr.	Total Time Minutes/Year		Percentage of Time	
	Fort Worth 1971	Austin 1973	Fort Worth 1971	Austin 1973
$\geqq 0.25$	2206	1972	0.42	0.38
$\geqq 0.50$	828	910	0.16	0.17
$\geqq \underline{1.00}$	<u>289</u>	<u>319</u>	<u>0.06</u>	<u>0.06</u>
$\geqq 2.00$	58	107	0.01	0.02
$\geqq 4.00$	6	22	0.001	0.004

TABLE 4. DURATION OF CERTAIN THRESHOLD INTENSITIES FOR ONE YEAR

To calculate the viewing distance (S) from Eq. (2), an appropriate value for contrast (C_R) must be used. It may vary from 0.008 to 0.06 (5) although for aviation purposes a rather conservative value of 0.055 is used. (6) The inherent contrast (C_0) of dark objects equals -1. The substitution of .055 for C_R and -1 for C_0 allows calculation of the distance (S) by Eq. (2).

$$\text{Visibility} = S = \frac{\ln \frac{1}{C_R}}{\sigma} = \frac{\ln \frac{1}{0.055}}{\sigma} = \frac{2.9}{\sigma} \qquad (3)$$

With these factors constant the visibility depends only on the extinction coefficient (σ) which has the inverse dimension of length (e.g. 1/ft.).

During rainfall the extinction coefficient is mainly dependent on the rain droplet size and the droplet spacial density, the combination of which affects the water content of a unit volume of space. However, tests show that the median droplet size can be expressed in terms of rainfall intensity and σ can then be expressed as a function of rainfall intensity. Atlas (7) has compared data from several sources and presents Eq. (4) to express the relationship between rainfall intensity and extinction coefficient.

$$\sigma = 0.25 \cdot I^{0.63} \qquad (4)$$

where σ = extinction coefficient (1/km)

I = rainfall intensity (mm/hr.)

If Eq. (4) is converted into the units of feet, inches and hours it becomes Eq. (5):

$$\sigma = 5.85 I^{0.63} \times 10^{-4} \qquad (5)$$

where σ = extinction coefficient (1/ft.)

I = rainfall intensity (in./hr.)

Combining Eqs. (3) and (5), the following formula for the visual range can be derived:

$$S = \frac{4950}{I^{0.63}} \tag{6}$$

where S = visibility (ft.)

I = rainfall intensity (in./hr.)

Wilson (8) has compared Eq. (4) with another formula by Poliakova and empirical data which was developed jointly by a weather bureau station and an aviation center in Atlantic City, New Jersey. All three sources are in excellent agreement. The empirical data are best fit by Eq. (7):

$$S = \frac{4550}{I^{0.68}} \tag{7}$$

Eqs. (2) through (7) are useful for static observations of large daytime targets without intervening substances other than raindrops. Experimental data were obtained from thunderstorms, probably without noteworthy fog or haze. Eq. (7) is plotted in Figure 9. Now considering highway traffic, the visibility range of interest is limited to approximately 2500 ft. which is required for safe passing on high-speed two-lane highways. Compared with visual ranges in aviation and general meteorology, this is a relatively small distance. If Eq. (7) were directly applicable, visibility restrictions approaching 2500 ft. would require a rainfall rate of about 2.4 in./hr. The study of rainfall probability indicated that intensity is quite rare. Similarly, a stopping sight distance visibility of 600 ft. would require a rain shower of about 20 in./hr. which has not occurred since the days of Noah. However, there are additional factors which cause substantially smaller rainfall intensities to reduce the automobile driver's visibility. These factors further degrading the visibility of a driver are listed below.

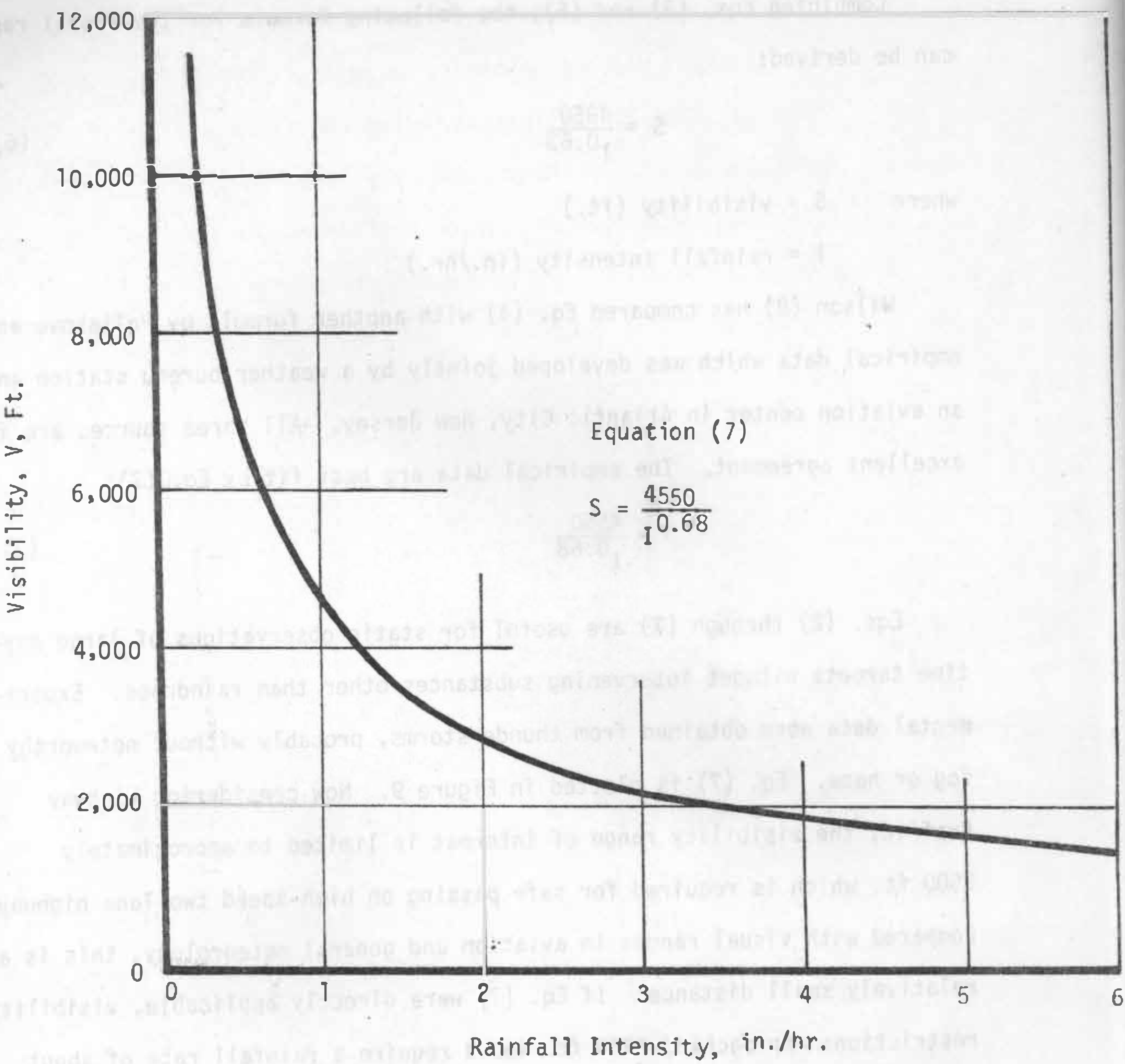

FIGURE 9. METEOROLOGICAL VISIBILITY
AS A FUNCTION OF RAINFALL INTENSITY

1. The accumulated layer of water on the windshield. The thickness of this layer depends primarily on rainfall intensity, vehicle speed, windshield inclination, wiper condition and wiper operating speed. It is probably the nonuniformity of the water layer that accounts for a major part of the visibility reduction.
2. The spots, scratches and other defects of the windshield.
3. The size, color and reflective nature of the target* and background.
4. Traffic interactions. Other vehicles will create additional concentrations of water in the immediate area, and their presence may distract the driver from the observation task, thus increasing reaction time.

These factors illustrate the need for specific visibility tests from inside an automobile. There may also be a significant effect due to different levels of illumination, although Eqs. (6) and (7) seem to indicate the meteorological visibility is dependent only on rainfall intensity. For these reasons specific visibility tests from inside an automobile were considered necessary, although it will be seen that appropriate arrangements with natural phenomena were somewhat cumbersome to make.

*"Target" is used in this chapter to mean the object from which visibility distance is determined.

IV. EXPERIMENTAL VISIBILITY TESTS

The objective of the experiments was to determine the visual ranges from inside an automobile during natural rainfalls. The following guidelines were observed.

1. Different targets. Targets were selected to be representative of possible highway obstacles. Three typical objects were chosen: (a) the rear end of an ordinary light grey car; (b) a toy dog, 15 in. long, with grey fur; and (c) a small unpainted plywood box, 6 in. by 6 in. As a tie to subsequent investigations, a "standard" target was prepared to serve as the fourth object.* This standard target was a 3 ft. by 3 ft. wooden board painted flat black and set in a vertical position.
2. Different levels of illumination. According to the previous hypothesis, the outside illuminance was always measured in order to determine whether this factor influenced visibility.
3. Two observers. One observer would be active as a reference throughout the test series.
4. One test car, a 1968 Plymouth sedan. The wiper speed was 48 cycles per minute.
5. One pavement, concrete. The influence of pavement color is recognized. However, at this stage tests have included only the comparatively light color concrete pavement.

The investigation was conducted at the Texas A&M Research Annex on a former airfield runway with a total length of 7,000 ft. The four targets

*In fact, there are no standard daytime targets in use.

were positioned close to the one end of the runway. All of them were put on the same line perpendicular to the runway length but on different lanes, 25 ft. apart. The runway was marked by distance signs at 20 ft. intervals starting at the target site. By this means the distance to the targets could be easily determined from a moving car.

The procedure to determine visibility distance was to approach one of the targets at a constant speed from an initial distance of 6,000 ft. As soon as the observer (the driver) was able to distinguish the "foreign" obstacle" on the roadway he notified the test monitor by shouting, "I see that Ausdrucksmittle" (or whatever noun seemed appropriate). The monitor then recorded the distance at which the momentous event occurred. This was the visibility in feet. The car was then stopped and backed to the position of the visibility observation, and two other factors were measured: (a) the outside illuminance and (b) the brightness (luminance) of the target as well as its background. The latter measurements were intended to define the threshold contrast at the position of first observation. Prior to the test run a rain gauge was placed on the runway. After the first target was observed the test was repeated on another target lane. If the rain continued, the driver and the monitor changed places and the entire procedure was repeated. The rain gauge was observed between each test to disclose significant intensity variations.

Illumination was measured by a Gossen photographic lightmeter. This meter was easily used and was of sufficient accuracy. The instrument was kept in a transparent plastic bag to prevent wetting during the measurements.

Brightness (luminance) was measured by a Spectra Pritchard Photometer mounted in the test vehicle. (For particulars see TTI Research Report 75-3 by N. E. Walton and N. J. Rowan, pp. 6 to 11.) Unlike the use of the lightmeter, brightness measurements are time consuming, and were not determined for all observations.

Rainfall intensity was defined by stop watch and rain gauge. A plastic rain gauge with a 4 in. diameter funnel was not appropriate for closely spaced observations. A larger water-collecting funnel, 12 in. in diameter, was constructed. Even this gauge was not sensitive enough to measure rapid changes in the rainfall rate. The intensities observed denote mean values over a range from five to fifteen minutes.

During the winter and spring of 1974 five test series were completed. The most important relationship, visibility versus rainfall intensity, is presented in Figures 10 and 11. Despite the small number of data points, estimated curves have been drawn to give a tentative idea of the relationship. The preliminary data do follow the shape of Eq. (1) and the shape of the curve predicted from photographic evidence (Figure 3). Because the data are so limited, no attempt has been made to show the effect of illuminance. These values are shown in parentheses beside the observed points.

The approximate curves that have been passed through the data points in Figures 10 and 11 indicate the following about the influence of rainfall.

1. The rear of an unlighted vehicle is relatively easy to perceive at distances which are apparently always outside the range of required stopping distance. However, there is insufficient

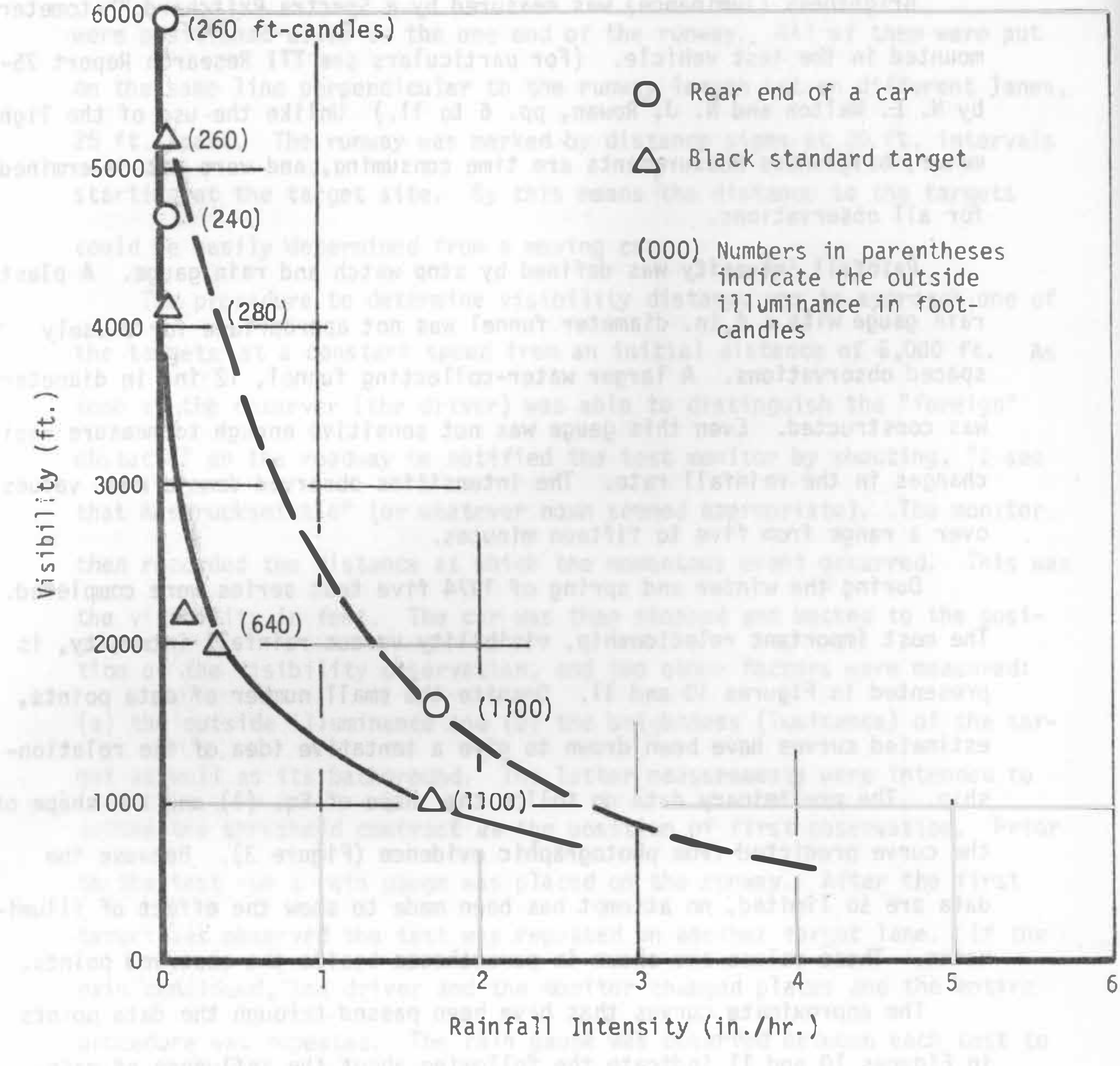

FIGURE 10. VISIBILITY VS. RAINFALL INTENSITY WITH THE REAR OF A GREY AUTOMOBILE AND A BLACK STANDARD BOARD AS TARGETS. (Driving Speed, Approximately 40 mph)

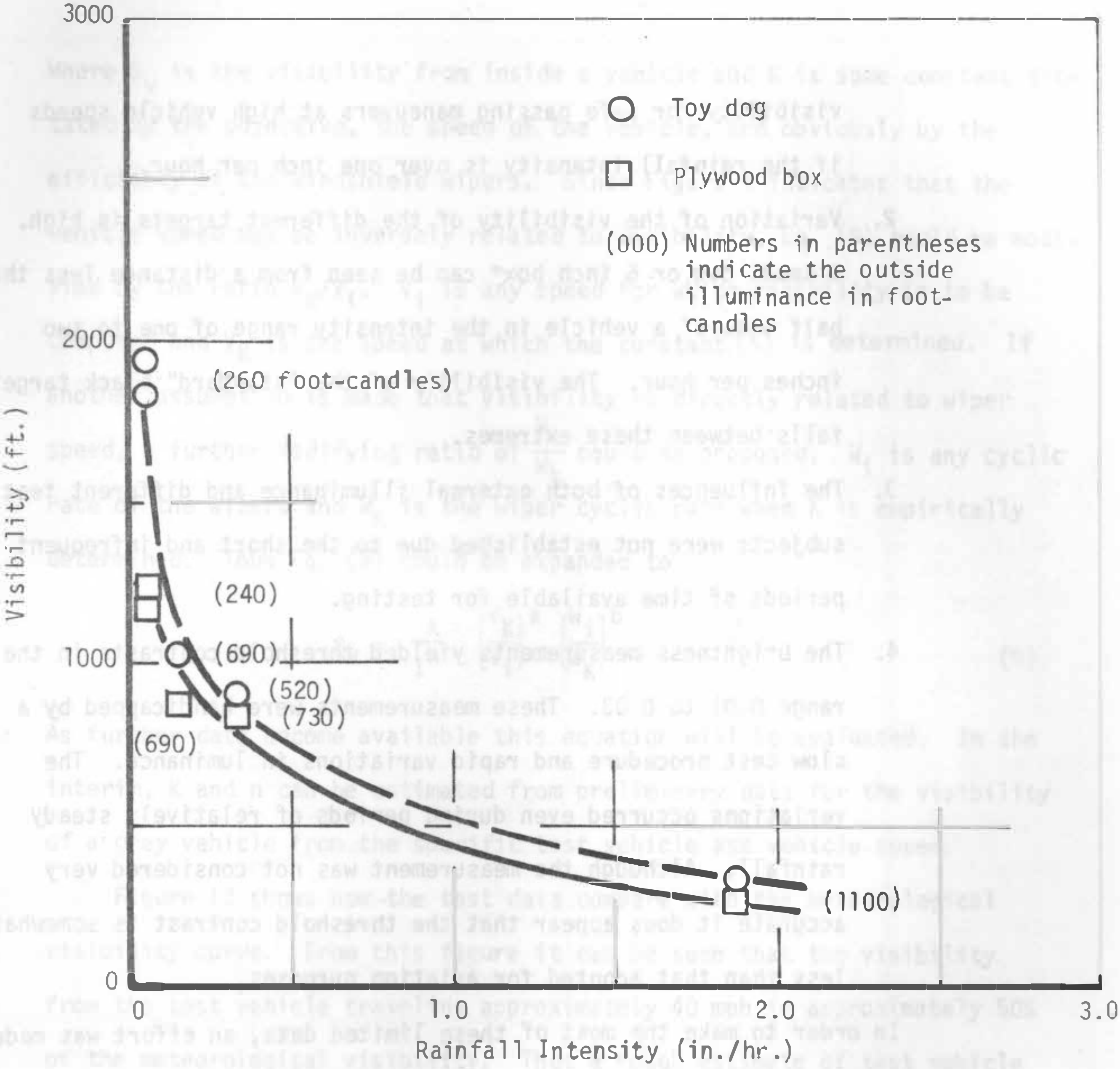

FIGURE 11. VISIBILITY VS. RAINFALL INTENSITY WITH A SMALL TOY DOG AND PLYWOOD BOX AS TARGETS. (Driving Speed, Approximately 40 mph)

visibility for safe passing maneuvers at high vehicle speeds if the rainfall intensity is over one inch per hour.

2. Variation of the visibility of the different targets is high. A small dog or 6 inch box* can be seen from a distance less than half that of a vehicle in the intensity range of one to two inches per hour. The visibility of the "standard" black target falls between these extremes.

3. The influences of both external illuminance and different test subjects were not established due to the short and infrequent periods of time available for testing.

4. The brightness measurements yielded threshold contrasts in the range 0.01 to 0.03. These measurements were handicapped by a slow test procedure and rapid variations in luminance. The variations occurred even during periods of relatively steady rainfall. Although the measurement was not considered very accurate it does appear that the threshold contrast is somewhat less than that adopted for aviation purposes.

In order to make the most of these limited data, an effort was made to express visibility as a functional relationship involving the major variables. Considering the shape similarity of the curve in Figure 9 and the curves in Figures 10 and 11 the following equation, of the form given by Eq. (7), was considered.

$$S_V = \frac{K}{I^n} \tag{8}$$

*The 6-inch height is assumed for measuring stopping sight distances on crest vertical curves (pg. 147, AASHO).

Where S_V is the visibility from inside a vehicle and K is some constant dictated by the objective, the speed of the vehicle, and obviously by the efficiency of the windshield wipers. Since Figure 4 indicates that the vehicle speed may be inversely related to visibility, Eq. (8) could be modified by the ratio V_K/V_i. V_i is any speed for which visibility is to be computed and V_K is the speed at which the constant (K) is determined. If another assumption is made that visibility is directly related to wiper speed, a further modifying ratio of $\frac{W_i}{W_K}$ could be proposed. W_i is any cyclic rate of the wipers and W_K is the wiper cyclic rate when K is empirically determined. Thus Eq. (8) could be expanded to

$$S_V = \frac{K}{I^n} \left(\frac{V_K}{V_i}\right)^a \left(\frac{W_i}{W_K}\right)^b \tag{9}$$

As further data become available this equation will be evaluated. In the interim, K and n can be estimated from preliminary data for the visibility of a grey vehicle from the specific test vehicle and vehicle speed.

Figure 12 shows how the test data compare with the meteorological visibility curve. From this figure it can be seen that the visibility from the test vehicle traveling approximately 40 mph is approximately 50% of the meteorological visibility. Thus a rough estimate of test vehicle visibility is

$$S_V = \frac{2275}{I^{0.68}}$$

which in effect means that K should be estimated at 2275* for the test data presented. Allowing for different speeds, the preliminary estimate for visibility is

*The gross nature of our estimates would quickly lead to the use of a rounded value of 2000 for K.

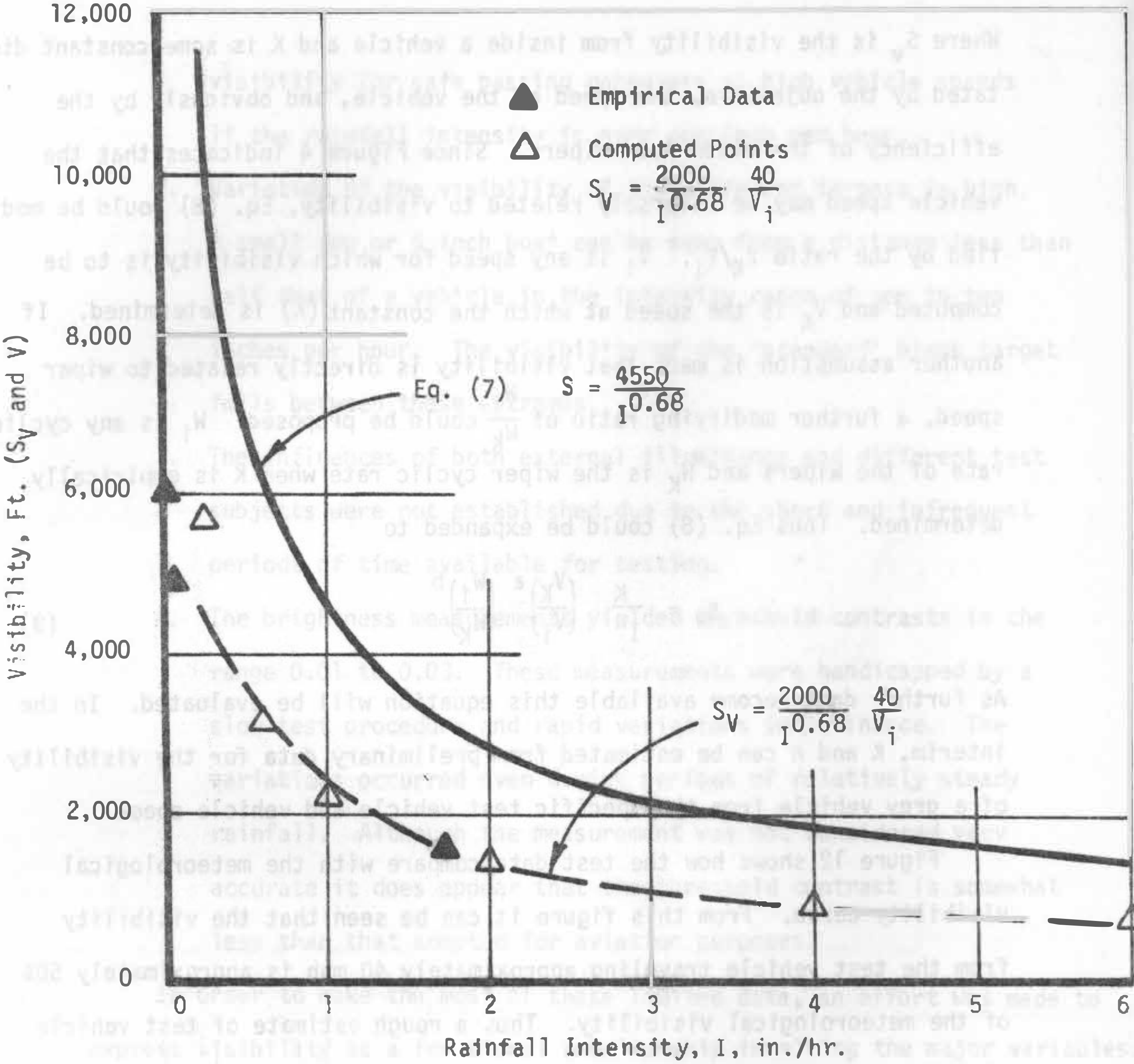

FIGURE 12. COMPARISON OF METEOROLOGICAL VISIBILITY, S, WITH HIGHWAY VISIBILITY, S_V, AT 40 MPH

$$S_V = \frac{2000}{I^{0.68}} \; \frac{40}{V_i} \tag{10}$$

which is plotted in Figure 12. The speed of 40 mph is inserted for V_K since it is the speed used for the estimate of K. Obviously this equation would not be of value at speeds less than 20 mph and probably not less than 30 mph since at 20 mph the visibility S_V would approach the meteorological visibility. Further, it is probable that this equation overestimates the visibility for values of I greater than 2 in./hr. an area for which we have no data, but also one of extremely low occurrence probability. Although the exponent of 0.68 is probably not very accurate for driver visibility, there are presently insufficient data to propose a change, especially since 0.68 seems to do a reasonable job in the real interest range which is below 2 in./hr.

Using this equation, a series of curves can be constructed to estimate the visibility of different objects under a range of rainfall intensities. This was done for the grey vehicle and is shown in Figure 13. Choosing the 70 mph curve it is shown that passing distance becomes less than that recommended by AASHO for rainfall intensities greater than 0.3 in./hr. It is further shown that a rainfall of 2.2 in./hr.is required before the AASHO stopping distance criterion is violated. But what is the probability of driving in rainfalls of these intensities? This question was approached in Chapter II and will be tied to visibility and speed in the next chapter.

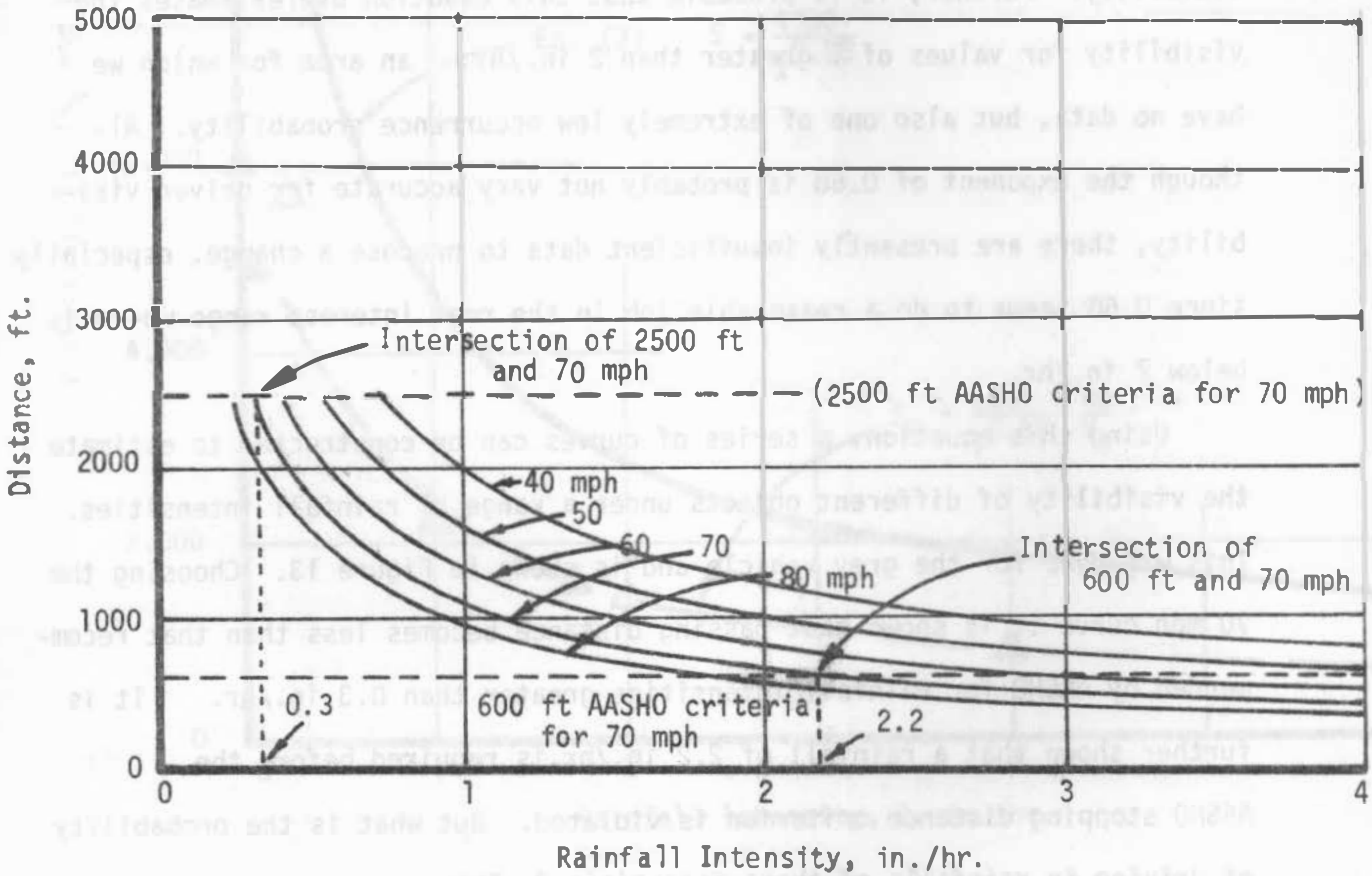

FIGURE 13. DRIVER VISIBILITY INFLUENCED BY SPEED AND RAINFALL INTENSITY (REAR OF GRAY VEHICLE)

V. CONCLUSION

In the preceding chapters data and concepts were presented which will allow the development of preliminary criteria to reduce the danger of accidents due to marginal visibility.

First, the following question should be answered. What rainfall intensity should be considered in designs? Figure 14 summarizes the information developed in Chapter II about the probability of rainfall. The frequency curve at the top of Figure 14 illustrates that rainfall is comparatively rare, about 6% of the total time in Central Texas, with higher rainfall intensities rapidly becoming so rare as to be insignificant. The lower part of the figure estimates the percentage of time that rainfall of less than the indicated intensity would occur. Thus if the highway engineer designs for 1/4 in./hr. the design should be adequate 99.6% of the time. If the design rainfall of 1 in./hr. is selected there will be less intense rainfall 99.95% of the time, or more intense rainfall for 1.2 hours every 100 days. If an economic justification were attempted it is likely that design for even this probability is not justified and would certainly not be justified for the extremely low probability of intensities greater than 1 in./hr.

But what can the highway engineer do to "design" for these occurrences? With respect to wet weather skid resistance there is obviously a great deal that can be done, but with respect to visibility there are not many obvious steps that seem appropriate. One step that is appropriate is to design excellent surface drainage to relieve the problem of vehicle generated spray, but even this is an indirect effect of the rainfall and its influence on visibility.

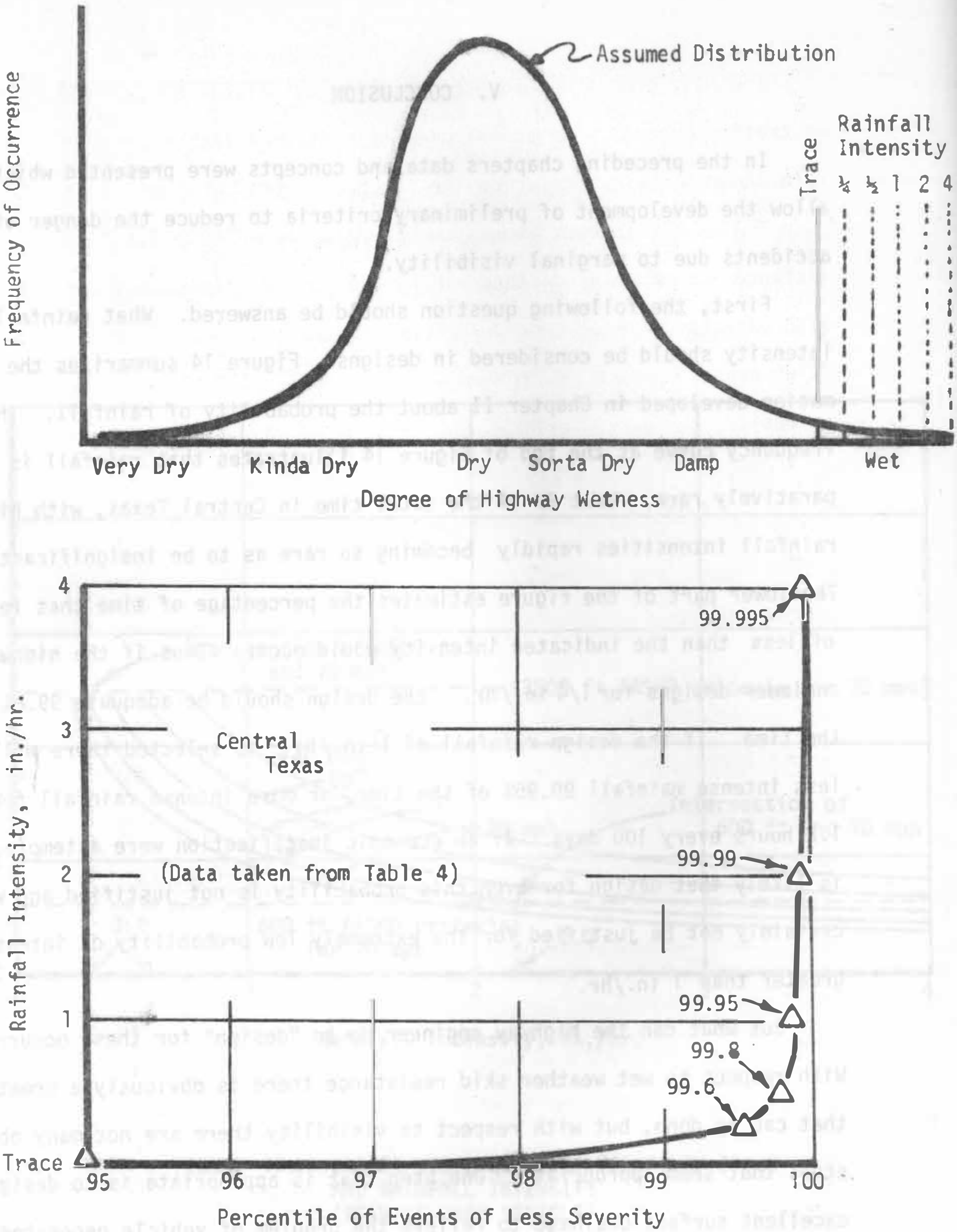

FIGURE 14. PROBABILITY OF RAINFALL IN CENTRAL TEXAS

The most promising and economically justifiable approach seems to be traffic control. As an example it is assumed that an intensity of 1 in./hour is selected for design purposes. Eq. (10) then reduces to $S_V = \frac{80,000}{V_i}$. This equation is compared to the AASHO policy for passing distance and stopping distance in Figure 15. It shows that a conflict with passing distance occurs at speeds above 45 mph. Thus two possibilities are presented: (1) drivers should not pass during rainfall of this intensity or (2) speeds should be reduced.

Obviously these two possibilities are not within the purview of the highway engineer but within that of the Legislature. Since engineers have a considerable influence on laws that are passed concerned with traffic management, the information contained in this report may be used as part of the justification for any traffic control law or as one factor in opposition to the return of legal traffic speeds to pre-1974 levels.

Although no data was presented in this report, it is apparent from the experience of the project staff in filming wet weather highway scenes that the visibility of an oncoming vehicle is greatly extended for an opposing driver if the headlamps of the oncoming vehicle are on low beam. The point is that the use of headlamps on low beam by all vehicles would be of value during daylight rainfall. The current Texas law specifying headlamp use reads:

> *"Every vehicle upon a highway within this State at any time from a half hour after sunset to a half hour before sunrise and at any other time when, due to insufficient light or unfavorable atmospheric conditions, persons and vehicles on the highway are not clearly discernible at a distance of one thousand (1,000) feet ahead shall display lighted lamps and illuminating devices as hereinafter respectively required for different classes of vehicles, subject to exceptions with respect to parked vehicles, and further that stop lights, turn signals and other signaling devices shall be lighted as prescribed for the use of such devices."*

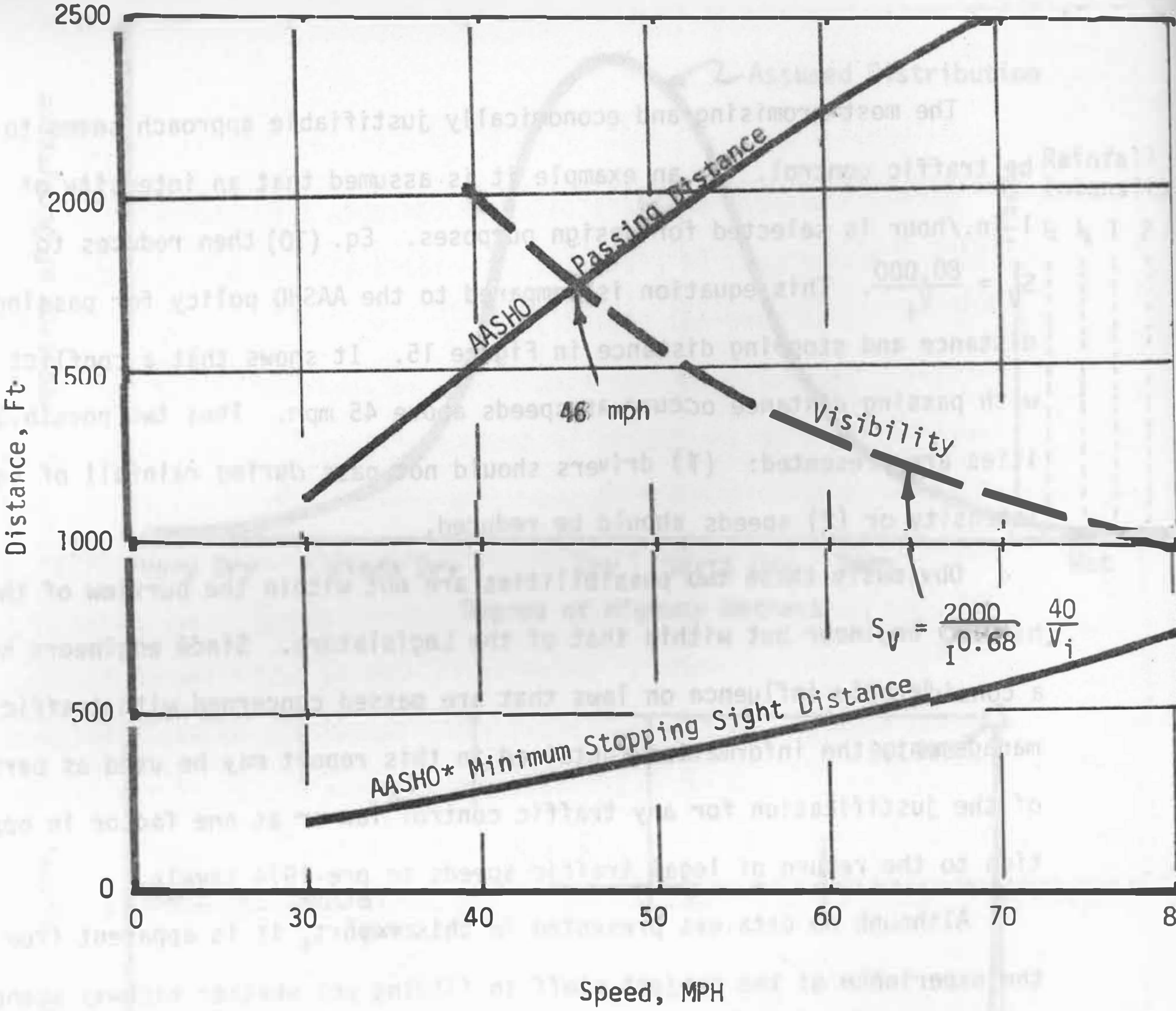

FIGURE 15. COMPARISON OF AASHO STOPPING AND PASSING SIGHT DISTANCE WITH VISIBILITY AT RAINFALL INTENSITY = 1 IN./HR.

*A Policy of Geometric Design of Rural Highways, 1965, Table III-1, pg. 136, Figure III-2, pg. 143.

Although this would seem to cover much of the rainfall period, the specification of 1000 ft. visibility is not easily understood and is rarely if ever enforced. An alternative would be to require that a vehicle display lighted headlamps whenever the windshield wipers are in use due to rainfall.

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APPENDIX

VISIBILITY WITH THE RAINFALL SIMULATOR

Objective and Scope

The objective of this experiment was to indicate the influence of rainfall intensity, vehicle speed, and windshield wiper rate on visibility for the driver of an automobile. This was accomplished by photographing a particular object from inside the automobile while driving through artificially produced rainfall.

Equipment

An overhead pipe and nozzle system was used to artificially produce the rainfall. The test apparatus is shown in Figure 16. The rainfall simulator is 185 feet in length and has 32 spray bars 25 feet long. Each spray bar contains seven nozzles. For this experiment all the nozzles were closed except two on alternating spray bars and one on all other spray bars. A 5000 gallon tank truck equipped with a pump was used to supply the system with water. Water pressure was monitored at the manifold of the rainfall simulator. Rainfall intensity was determined by locating four rain gages under the rainfall simulator for a measured period of time and averaging the results. The relationship between rainfall intensity and water pressure was recorded in order that the conditions might be easily reproduced. The test vehicle was a 1968 Plymouth sedan. The object photographed was the rear hull of a 1966 Buick which had been painted flat white. (The hull was used for safety purposes, to reduce damage in the event of impact by the test vehicle.) Photographic equipment consisted of a model 100 Rapid Omega camera using black and white film.

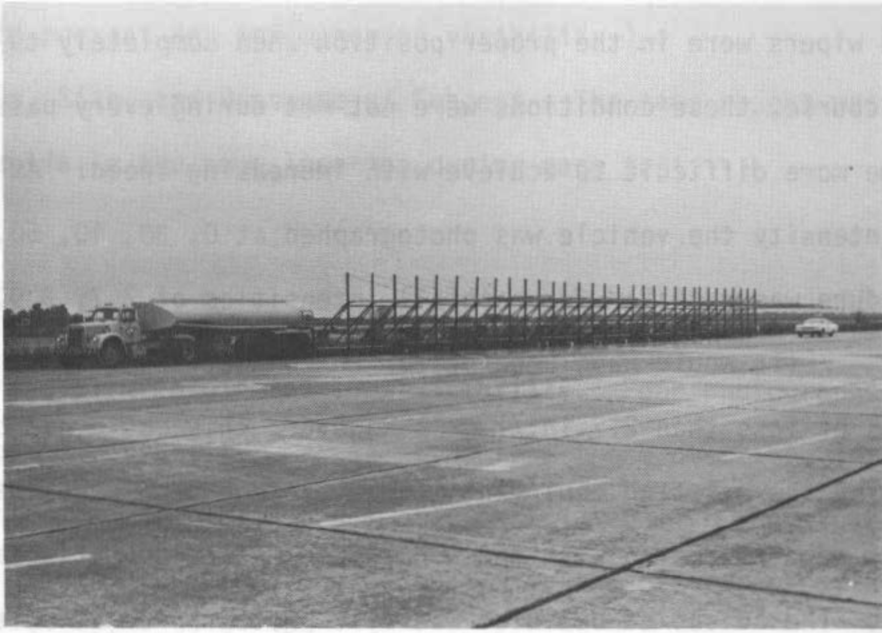


FIGURE 16. RAINFALL SIMULATOR, TANK TRUCK, AND TEST VEHICLE

Procedures

As the test vehicle passed under the rain simulator, the "disabled vehicle" was photographed; providing that the windshield wipers were in the proper position. The disabled vehicle was photographed when the test vehicle had passed about 20 to 30 feet into the artificial rainfall. The windshield wipers were in the proper position when completely to the left side. Of course, these conditions were not met during every pass, and they became more difficult to achieve with increasing speed. At a specific rainfall intensity the vehicle was photographed at 0, 30, 40, 50, and 60 mph. This procedure was repeated for rainfall intensities of 2.7, 3.9, 4.4, and 5.4 in./hr. (It would have been better to conduct these tests at rainfall intensities of less than 2.7 in./hr. However, this could not be accomplished using the existing equipment without introducing undesirable effects.) These tests were conducted with the windshield wipers operating at 48 cycles per minute. The "disabled vehicle" was also photographed at selected conditions of speed and rainfall intensity with the windshield wipers operating at 35 cycles per minute.

Rainfall intensity, vehicle speed, and windshield wiper rate were not the only parameters that affected visibility. However, the other parameters were stabilized by the following methods:

Illumination - All visibility tests were conducted on an overcast day. A light meter indicated only minor changes in illumination throughout the testing period.

Clarity of the Windshield - The windshield was kept clear of fog or any other foreign matter.

Rainfall Droplet Size - The rainfall simulator provided uniform droplet size distribution when operating within the pressure range of this experiment.

Visual Acuity of the Observer - The observer was a Model 100, Rapid Omega camera with black and white film. The shutter speed and f-stop were essentially the same during all tests. (All film received identical processing to prevent any influence on visibility.)

Color, Size, and Distance of Subject - The same object was photographed from essentially the same location during each test.

Results

A photograph of the "disabled vehicle" from the stationary test vehicle with no rainfall represented 100% visibility. Four photographs displaying a wide range of visibility were selected from those described in the previous experiment. Ten people, not directly associated with the experiment, individually compared the four photographs with the one representing 100% visibility, and estimated a value of visibility in percent for each photograph. They were instructed to use their own judgment as to what constitutes visibility. Generally, visibility was defined by the participants as the overall clarity of the objectives within the photograph with special emphasis on the ability to see the "disabled vehicle". The results were averaged, and these five photographs were used as the "standards" to estimate values of comparative visibility for all the other photographs obtained in this experiment.

Figure 17 clearly illustrates the reduction in comparative visibility with increased rainfall intensity and/or vehicle speed. For these photographs the windshield wipers were operating at 48 cycles per minute.

Rainfall Intensity, in./hr.

2.7 in./hr. | 3.9 in./hr. | 4.4 in./hr. | 5.4 in./hr.

Vehicle Speed, mph

0 mph

30 mph

60 mph

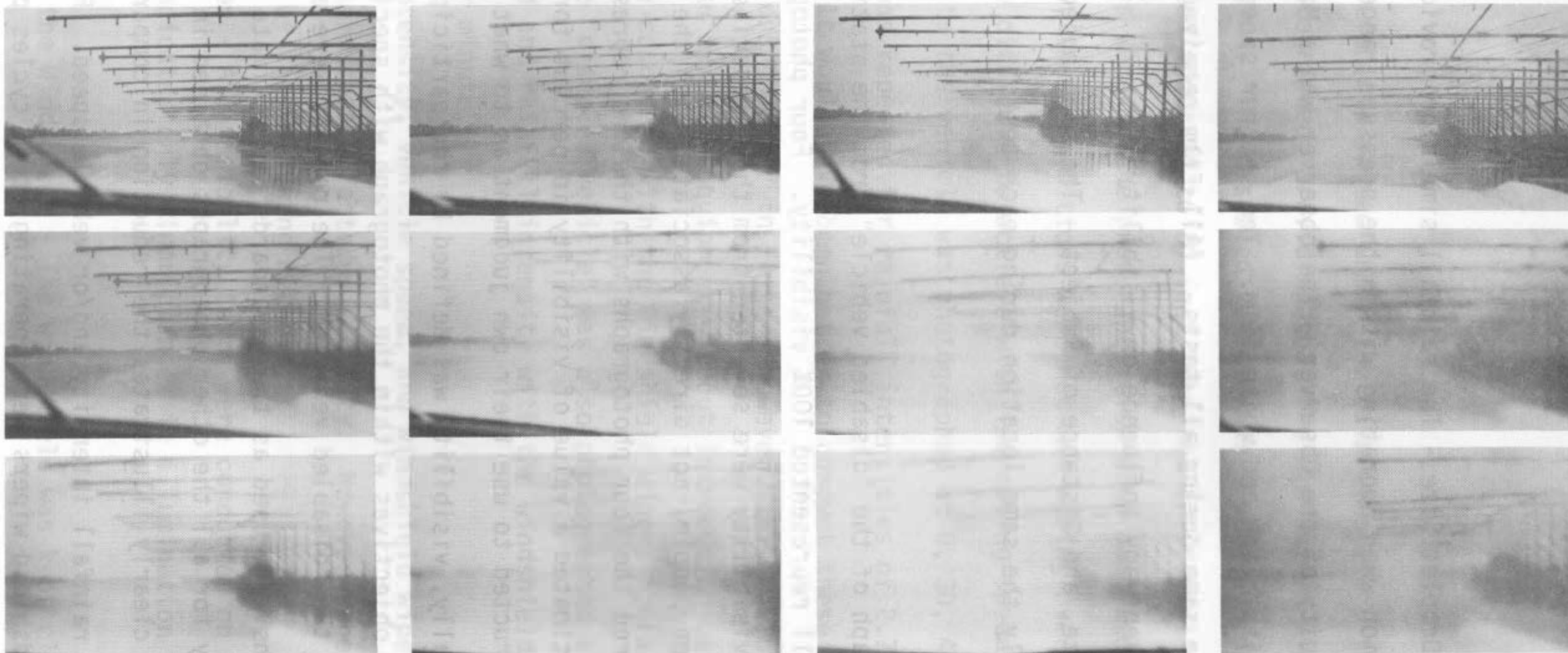


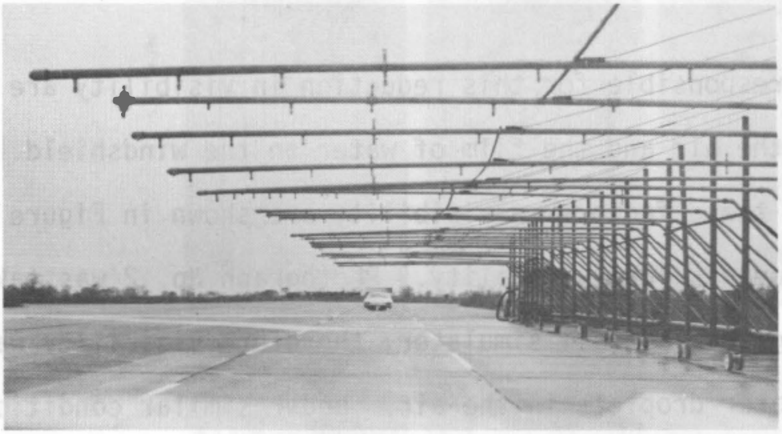
FIGURE 17. INFLUENCE OF VEHICLE SPEED AND RAINFALL INTENSITY ON VISIBILITY

The two factors responsible for this reduction in visibility are the droplets of water in the air and the film of water on the windshield. The cumulative effects of these factors on visibility are shown in Figure 18. Photograph No. 1 represents 100% visibility. Photograph No. 2 was taken just prior to entering the rainfall simulator, therefore visibility was reduced only by the water droplets in the air. Under similar conditions, photograph No. 3 was taken just after entering the rainfall simulator, therefore visibility was reduced by the water droplets in the air and the water layer on the windshield.

As the windshield wiper rate is decreased, so is visibility. This is due to a greater accumulation of water on the windshield between passes of the wiper blade. Figure 19 shows the variation in comparative visibility at two different windshield wiper rates.

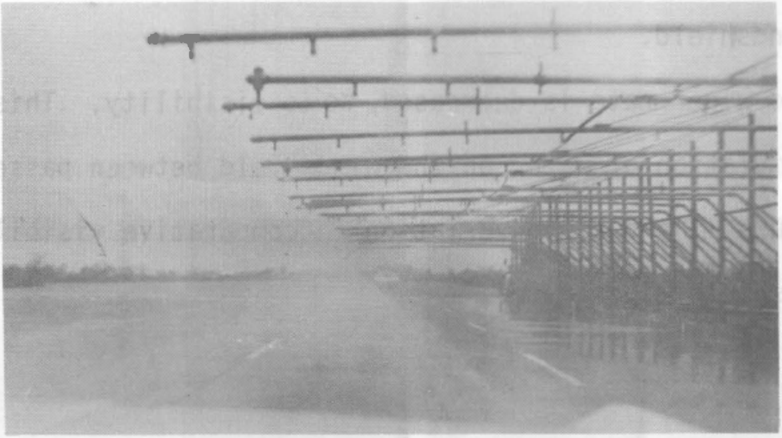
Conclusions

The values of comparative visibility presented in this report relate only to the particular situation described. The visibility in these photographs is not only dependent on the three parameters considered but also on color and size of the subject, distance to the subject, illumination, water droplet size distribution, windshield clarity, and probably others. However, it is obvious from the results presented herein that visibility decreases drastically with increased rainfall intensity and/or vehicle speed, and that visibility is further reduced when using the lower windshield wiper rate.



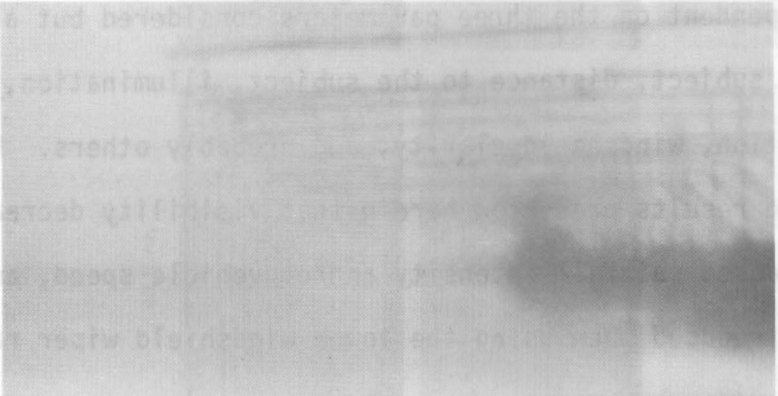
v = 0 mph
I = 0 in./hr.
Dry Windshield
V = 100%

1.



v = 60 mph
I = 4.4in./hr.
Dry Windshield
V = 55%

2.



v = 60 mph
I = 4.4 in./hr.
Wetted Windshield
V = 5%

3.

FIGURE 18. CUMULATIVE EFFECTS OF WATER DROPLETS IN THE AIR AND WATER LAYER ON THE WINDSHIELD

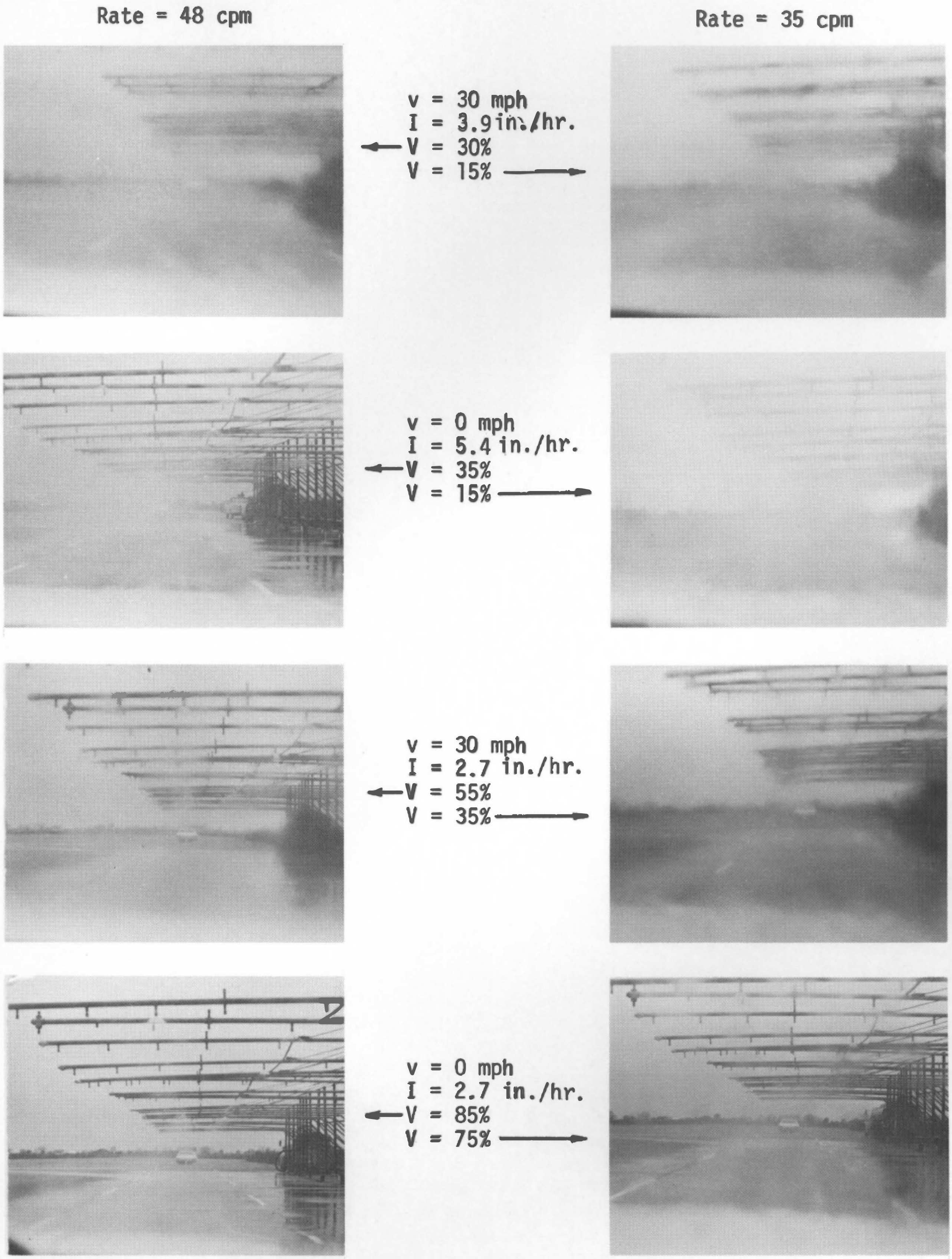


FIGURE 19. INFLUENCE OF WINDSHIELD WIPER RATE ON VISIBILITY