Legibility and Conspicuity Performance of Dry and Wet Beads on Paint and Reflective Sheeting License Plates Under Low-Beam Illumination at Night

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Results of five similar but independent field studies investigating the nighttime legibility and conspicuity of two different types of reflective license plates under low-beam illumination are consolidated. In each study reflective sheeting license plates (12 new and 12 used Texas license plates with blue characters on white background) were compared with beads-on-paint reflective license plates [12 new and 12 used Arizona license plates with white characters (beads on paint) on dark red background]. The same set of 48 plates was used in each of the studies. In the legibility studies the license plates were displayed at different distances straight ahead along the longitudinal axis of the experimental car. In the conspicuity studies the plates were displayed either 20 ft to the right or 20 ft to the left of the longitudinal axis ahead of the experimental car. A car providing opposing glare was positioned 200 ft ahead of the experimental car to simulate a tangent section of a two-lane rural highway at night with an opposing car. The studies were conducted with five independent groups of subjects. Twenty subjects were used to determine the nighttime legibility (75 ft) and conspicuity (550 ft) of dry license plates in Study 1, and 12 subjects each were used in the remaining four studies. Studies 2 and 3 investigated the legibility of both dry and wet license plates, respectively, at 50, 75, and 100 ft. Study 4 investigated the conspicuity of wet license plates at 550 and 750 ft, and Study 5 investigated the conspicuity of dry license plates at 750 ft. The results of the legibility studies (Studies 1, 2, and 3) indicate that the dry reflective sheeting plates consistently performed slightly better than the dry beads-on-paint plates. Furthermore, the wet reflective sheeting plates provide considerably better legibility performance when compared with that of the wet beads-on-paint plates. The conspicuity results (Studies 1, 4, and 5) indicate a consistent slight to considerable advantage of the dry or wet reflective sheeting license plates over the dry or wet beads-on-paint plates depending on the display location (left or right) at 550 and 750 ft. All these performance differences were statistically significant at the 0.05 level. In general the results of this investigation suggest that the reflective sheeting design is a much more robust product design when compared with the beads-on-paint design, because it will retain a much greater degree of legibility and conspicuity performance under adverse conditions such as opposing car glare or wetness of the plates.

The following literature review was initially prepared for a license plate evaluation study conducted for the Arizona Department of Transportation (*1*). Reflectorized license plates have been in use for many years to help the driver in the initial detection, recognition, and identification of stationary or moving vehicles on or off the roadway, especially at night. Fricker (*2*) specified several functions of license plates and considered license plates as static visual displays. Some of the functions of license plates (*2*) are that the license plate is an indication that the vehicle was properly registered at the time the plate was issued, it is the most specific means of identifying vehicles involved in accidents for law enforcement agencies and witnesses, and the reflectorized plate is an important item for nighttime traffic safety officials. Larimer (*3*) pointed out some common motoring situations in which reflective license plates have been shown to operate effectively. These are the delineation of parked cars prevalent in residential areas, the warning of damaged, stalled, or parked and unlighted cars and trucks on the road and shoulders of rural roads, supplementary warning of a car's presence for motorists approaching from the rear at a higher relative speed, effective protection in case of taillight failure unknown to the motorist, and positive delineation of approaching "one-eyed" vehicles by indicating the relative position of the vehicle on the road. A number of studies have been conducted to establish the visibility and legibility distances of reflectorized and nonreflectorized license plates made of different materials. Larimer (*3*) studied the visibility of reflectorized license plates at night under conditions of rain, mist, snow, and glare. He concluded that vehicles equipped with reflectorized license plates are visible up to a distance of 1,000 ft and that an increase in the reflective brightness of the plates increases the visibility distance. In the case of opposing headlights (glare), he concluded that plates capable of reflecting 5 cp per incident footcandle on average provide the minimum brightness for a requisite warning at 50 mph. The new reflective plates typically reflect 20 cp per incident footcandle, and the new beads-on-paint plates typically reflect 2 cp per incident footcandle.

Improvements in plate visibility due to reflectorization were shown by many other studies. Wortman (*4*) evaluated reflectorized license plate materials using legibility and visibility distances as criteria, among others. Wortman concluded that there are no significant differences between the legibility distances of plates made of different materials and stated that it is doubtful that an improvement in the reflective materials would increase the legibility distances. In the case of visibility it was concluded that plates with light-colored backgrounds yielded the best visibility distances, all of which provide adequate stopping distance, and that reflectorization of the legend only does not provide for safe stopping distances at speeds associated with modern highways. However, in general Wortman's data show that plates with reflective sheeting can be detected at greater distances than plates with beaded legends. In another study

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Israelsen and Canfield (*5*) evaluated the legibility of reflectorized license plates in a rainfall simulator under dry and varying degrees of rainfall conditions. They compared legibility distances of plates (new and used) made of beads-on-paint material, reflective sheeting, and new paint and concluded that reflective sheeting plates could be read from farther than the corresponding beads-on-paint plates under all conditions, with the margin increasing under rainfall conditions. They also concluded that the legibility of used beads-on-paint plates fell substantially below that of painted plates under wet conditions, whereas reflective sheeting plates maintained a significant advantage under all conditions tested. Stoke and Simpson (*6*) compared the legibility and visibility of enamel and reflectorized license plates and concluded that the reflectorized license plate makes a vehicle more readily seen and recognized than a vehicle with conventional enamel license plates. Olson and Sivak (*7*) conducted a field study on the nighttime legibility of license plates to investigate the effect of factors such as background reflectivity, legend contrast, approach direction, and vehicle lights. They concluded that fully reflectorized license plates provide superior legibility compared with that of plates in which only the legend is reflectorized [these results are in agreement with the findings of Israelsen and Canfield (*5*)]. Furthermore, for the range of materials tested they concluded that the higher the luminance of the plate the better the legibility provided. In summary they suggested that fully reflectorized plates provide improved legibility under both new and worn conditions.

One of the most comprehensive studies on license plates was conducted by Baerwald et al. (*8*) in which they evaluated the legibility of reflectorized license plates made of five different materials under various conditions of reflectorization, color combinations, and width and spacing of numerals. Their conclusions were that there appears to be no appreciable difference in the legibility of the various types of materials used to reflectorize the plates and that on the average the legibility of reflectorized plates was increased by 28 percent when compared with that of the nonreflectorized plates. They also concluded that on the basis of visibility reflectorized license plates may have contributed to a slight reduction in the total number of nighttime accidents. In a study of reflectorized materials for license plates, Post et al. (*9*) concluded that (a) a background of reflectorized sheeting can provide about an 11-fold increase in reflectivity when compared with that of light beaded legends on a dark background and (b) plates with light beaded legends and dark paint backgrounds provide about a 14-fold increase in reflectivity compared with that of plates with dark painted legends and light backgrounds. Zwahlen (*10*), on the basis of the results of a field study, indicated that in roadway situations such as in horizontal curves where reflective targets could become visible for the first time in the periphery of a driver's visual field, appropriate increases in the reflectivity of a target must be made to ensure timely detection.

The general conclusion, although disputed in a few studies, is that reflectorization of any kind improves plate legibility and visibility. However, the other question is whether reflectorization of license plates helps in the reduction of nighttime accidents. Several studies have addressed the relationship between reflectorized plates and nighttime traffic crashes. Vanstrum and Kontour (*11*) studied the effect of reflectorized license plates from an accident reduction point of view in Tennessee and on careful analysis concluded that there was a significant accident reduction that could be attributed to the introduction of reflective sheeting license plates. Campbell and Rouse (*12*) conducted a study to assess the effect of reflectorized license plates on rear-end collisions at night. For this purpose they made a comparison of reflectorized and nonreflectorized vehicles during a 6-week transition period (transition from enamel to reflectorized plates) in 1966 and concluded that reflectorized plates are effective in reducing nighttime rear-end collisions. In contrast to all the studies that considered accident reduction, Stoke (*13*) concluded that there was no statistically significant difference between the numbers of nighttime rear-end collisions and crashes of vehicles equipped with reflectorized license plates (475 accidents) and those of vehicles with nonreflective license plates (497 accidents). Stoke's study, however, was critically discussed by Sacks and Vanstrum (see reference *13*), Kleinknecht and Hicks (*14*), and Hulbert and Burg (*15*), and many questions regarding the experimental design and the interpretation of results published by Stoke were raised. Henderson et al. (*16*) reviewed, summarized, and integrated the available body of data concerning vehicle conspicuity including engineering analyses and other analytical studies, as well as experimental data from laboratory, simulation, and field studies. In all the authors reviewed five studies and stated, "All the five studies are subject to methodological problems and present interpretation difficulties." They also stated, "A statistically significant but not an overwhelming safety benefit can be associated with the reflectorized plates."

Some of the legibility studies mentioned agree in the aspect that there is no significant improvement in the legibility distance of dry, clean license plates owing to the use of different reflective materials such as beads on paint and reflective sheeting. However, as stated earlier the study of Israelsen and Canfield (*5*) showed a significant improvement in the legibility distances for the plates made of reflective sheeting materials under all conditions (dry and varying degrees of rainfall) when compared with those for the beads-on-paint plates or plates with new paint. Zwahlen (*17*) pointed out that most of the visibility studies indicate a reduction in the accident rate because of reflectorization [a study by Stoke (*13*) indicated that the reduction observed was not significant] and argued that if the reflectivities of the license plates used in those studies had been higher the results would have been more positive. Zwahlen (*17*) concluded that reflective license plates with higher specific intensity levels consistently increase the conspicuity of a car parked along a highway at night in a statistically and practically significant manner.

These studies on legibility and visibility represent diverse approaches to examination of the same problem and provide legibility distances that appear to be higher than one could expect under realistic driving conditions. This could be because of factors such as the lack of a windshield and therefore the lack of the effect of windshield transmittance (which has a slight distance-reducing influence) in studies in which no experimental cars were used, the use of license plates with numerals only (no letters), the probable use of characters with larger heights, widths, spacings, and other legibility-enhancing characteristics, the probable use of meaningful combinations of numbers (i.e., 234 789, etc.), the use of highly trained and fairly efficient subjects such as highway patrol personnel and police, the differences in visual capabilities of the subjects used, the differences in background-legend color combinations, the differences in the position of the observer, larger (unlimited) exposure times, and more and longer opportunities for learning. Moreover, the studies involve field and laboratory measurements and range in complexity from elaborately controlled studies to fairly superficial efforts. None of these studies by itself can be considered to be complete and definitive, and the methodology of each one can be faulted in one way or another. Despite this, taken collectively these studies provide a convincing and consistent picture of the clear superiority

of reflectorized plates over conventional painted-only plates from the standpoint of both legibility and visibility. Therefore, any study dealing with the comparison of conventional painted-only plates with reflectorized plates would most likely only further strengthen previous established results. However, a carefully controlled and realistic (close to real-world conditions) nighttime license plate study investigating visibility and legibility performance would be beneficial in establishing any superiority that might exist among the reflective materials (beads on paint versus retroreflective sheeting) being used in the United States. Therefore, it was the objective of the study described here to determine the nighttime legibility and conspicuity performances (conspicuity under opposing glare) of embossed new and used license plates made of retroreflective sheeting and reflective beads on paint (white characters reflectorized only).

METHOD

Experiments

This paper is a summary of five separate but similar experiments conducted to assess the nighttime legibilities and conspicuity performances of both new and used, dry or wet Arizona (beads-on-paint) and Texas (retroreflective sheeting) license plates at different distances. Table 1 provides a summary of the five experiments.

Subjects

A total of 68 young, healthy college students (39 males and 29 females; average age, 20.5 years) participated in the studies. All the subjects had a valid driver's license with an average driving experience of 4.1 years. None of the subjects had any past accident history, although a few of them had moving traffic violations. All the subjects tested, using a Bausch and Lomb vision tester, had visual acuities ranging from 20/17 to 20/25 (corrected vision if applicable) and normal contrast sensitivity, as determined by using the Vistech contrast sensitivity charts. Study 1 used 20 subjects, and the other four studies used 12 subjects each as a sample population. In Study 1 the 20 subjects were 10 males and 10 females with an average age of 20.5 years. Their average driving experience was 3.5 years, and they had visual acuities ranging from 20/17 to 20/25. In Study 2 the 12 subjects were seven males and five females with an average age of 21.7 years. Their average driving experience was 4.5 years, and they had visual acuities ranging from 20/17 to 20/25. In Study 3 the 12 subjects were six males and six females with an average age of 20.6 years. Their average driving experience was 4.5 years, and they had visual acuities ranging from 20/17 to 20/22. In Study 4 the 12 subjects were eight males and four females with an average age of 21.0 years. Their average driving experience was 4.7 years, and they had visual acuities ranging from 20/17 to 20/25. In Study 5 the 12 subjects were eight males and four females with an average of 22.2 years. Their average driving experience was 4.3 years, and they had visual acuities ranging from 20/20 to 20/25.

Experimental Site and Apparatus

The experiments were conducted on an old unused airport runway (75 ft wide and 1,500 ft long) located on the outskirts of Athens, Ohio. A two-lane state highway with moderate traffic runs parallel (about 200 ft away) to the runway. A number of luminaires, a few illuminated advertising signs, and other light sources were within the field of view, especially in the left half of the field of view.

For the legibility experiments a 1981 Volkswagen Rabbit with H6054 headlamps was the experimental car in Study 1, a 1987 Audi Coupe GT with H9004 headlamps was the experimental car in Study 2, and a 1985 Toyota Corolla with H6054 headlamps was the experimental car in Study 3. In each legibility study the license plates were displayed at 50, 75, and 100 ft or at 75 ft straight ahead along the longitudinal axis of the experimental car. Figure 1 provides a diagram of the experimental site and the setup for the legibility experiments.

For the conspicuity experiments the same Volkswagen Rabbit with H6054 headlamps was used as the experimental car in Studies 1 and 5. In Study 1 a 1983 Nissan Stanza with H6054 beams (low-beam operation) was used as the car providing opposing glare, and

TABLE 1 Summary of Legibility and Conspicuity Experiments

LEGIBILITY				
Study #	# Subjects	Distance (ft)	Condition	Experimental Car/Beams
1	20	75	Dry	1981, Volkswagen Rabbit/H6054
2	12	50, 75, 100	Dry	1987, Audi Coupe GT/H9004
3	12	50, 75, 100	Wet	1985, Toyota Corolla/H6054

CONSPICUITY					
Study #	# Sub.	Dist. (ft)	Condition	Expt. Car/Beams	Glare Car/Beams
1	20	550	Dry	1981, Volkswagen Rabbit/ H6054	1983, Nissan Stanza/ H6054
4	12	550, 750	Wet	1987, Ford Taurus/ H9004	1984, Dodge Omni/ H6054
5	12	750	Dry	1981, Volkswagen Rabbit/ H6054	1990, Ford Escort/ H6054

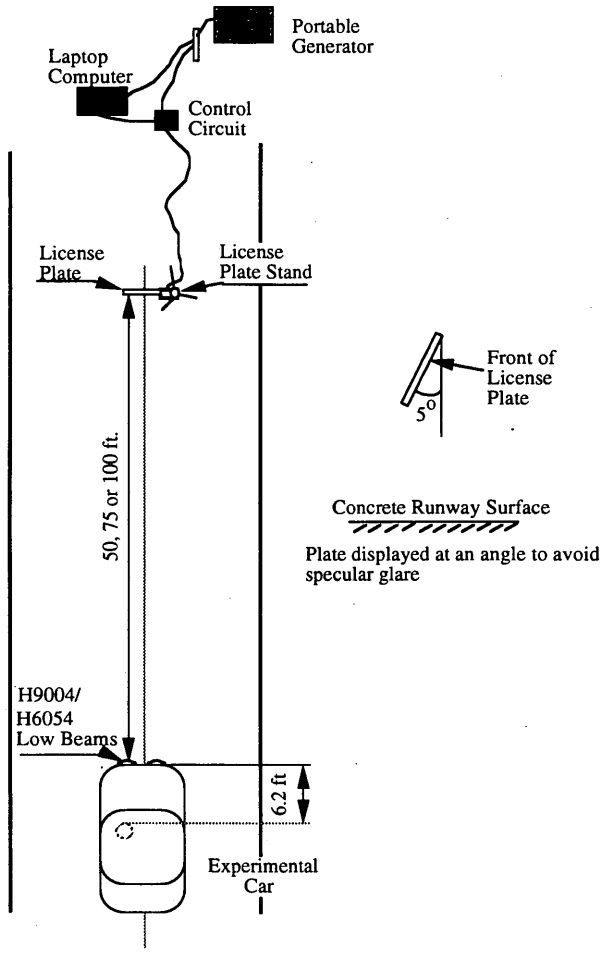

FIGURE 1 Setup for nighttime legibility experiment.

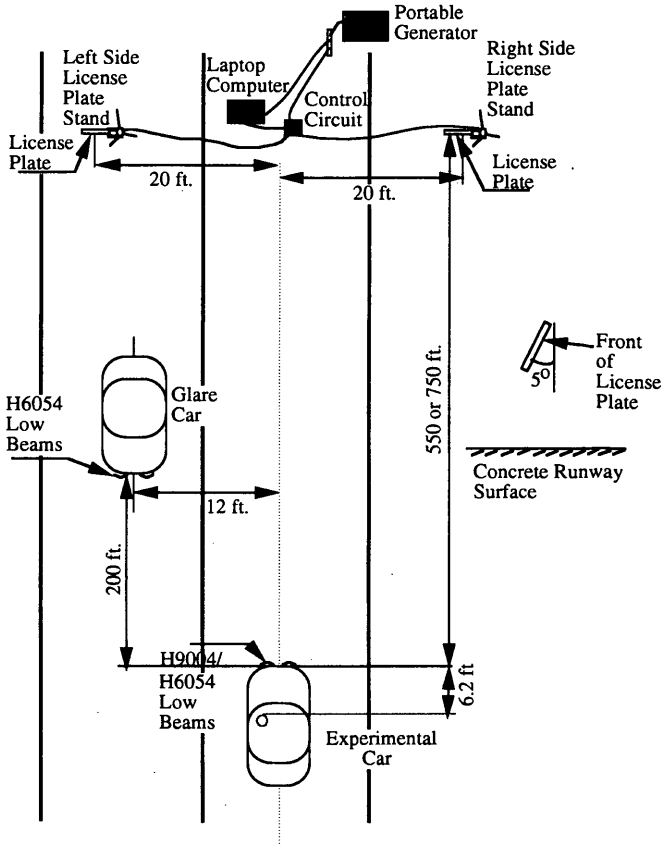

FIGURE 2 Setup for nighttime conspicuity experiment.

for Study 5 a 1990 Ford Escort with H6054 beams (low-beam operation) was used as the car providing opposing glare. A 1987 Ford Taurus with H9004 headlamps was used as the experimental car in Study 4, and a 1984 Dodge Omni, again with H6054 headlamps (low-beam operation), was used as the car providing opposing glare. In each study the license plates were displayed at 20 ft to the left and right of the longitudinal axis of the experimental car, and the opposing car providing opposing glare was always positioned 200 ft ahead and 12 ft to the left of the experimental car's longitudinal axis. Figure 2 provides a diagram of the experimental site and setup for the conspicuity experiments.

Three portable stands (to rotate the license plates along the horizontal axis into an exposed position and to rotate the license plates back into a nonexposed position) on which to mount the license plates were designed and fabricated. Figure 3 provides the typical setup for one license plate display stand. Each stand consisted of an adjustable base, a 4-ft-long vertical iron tube (diameter = 1.25 in.) that could be screwed into the base, and a sliding collar that could be slid onto the vertical tube and tightened at any height with a wing screw. A direct current motor was fixed to one side of the sliding collar, and the shaft of the motor was extended to fit a bracket that was capable of holding both new license plates and license plates that were slightly bent. An electronic circuit was built to control the motors via a computer. A computer program (written in C language

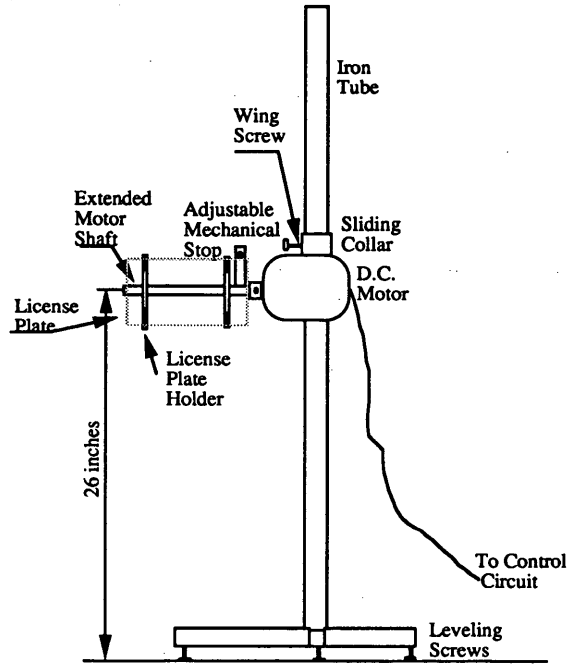

FIGURE 3 License plate display stand.

for a Zenith laptop 8088 PC, 10-MHz clock speed) allowed the experimenters to rotate the proper plate into view for a fixed amount of time specified by the computer program. An adjustable mechanical stop was also provided to stop the license plate at any desired angle to the horizontal plane to expose it to the subject sitting in the experimental car. The computer and the control circuit were powered by a portable generator. A total of 48 plates were tested in the experiments. They consisted of four groups of plates (Arizona old, Arizona new, Texas old, and Texas new), and there were 12 license plates in each group. Four 5-W walkie-talkies were used as communication devices between the experimenters sitting in the car with the subject and the experimenters operating the computer and changing the plates.

Specimen License Plates

All nighttime legibility and the conspicuity experiments used the same 12 license plates of each type: Arizona old (AO), Arizona new (AN), Texas old (TO), and Texas new (TN). All the license plates had three numbers and three letters; the group of three letters appeared first in all cases except for the TO plates, on which the group of three numbers appeared first. The Texas plates had blue characters on a white background and were made of reflective sheeting, and the Arizona plates had white beads-on-paint characters on a dark red painted background. The results obtained from the experiments conducted by Neu (*18*) and Kuntz (*19*) were used in the computer generation of license plate character sets, which had an average difficulty level of legibility for the three letters and the three numbers on each new license plate. Therefore, some letters and numbers were not considered in the computer generation because they were either too easy or too hard to read. From the randomly generated registration numbers, all meaningful combinations (e.g., BOY 567) were eliminated and the new plates (TN, AN) were manufactured from the remaining combinations. The used Texas and Arizona plates were selected from a set of 40 and 34 plates, respectively. These used plates had issue dates from 1981 to 1989, but only 12 plates each issued from 1985 to 1989 were selected (60-month lifetime requirement by some state traffic agencies) such that they met as best as possible the legibility selection criteria mentioned for the new plates. Figures 4 and 5 show the 12 individual license plates that made up the TN and TO and the AN and AO license plate groups. The average character height on the Arizona license plates was 2.86 in., the average character width was 1.23 in., and the average stroke width was 0.35 in. At a viewing distance of 50 ft plus 6.2 ft this character height results in a visual angle of 14.6 min of arc. At a viewing distance of 75 ft plus 6.2 ft this results in a visual angle of 10.0 min of arc. At a viewing distance of 100 ft plus 6.2 ft this results in a visual angle of 7.7 min of arc. The average height on the Texas license plates was 2.74 in., the average character width was 1.22 in., and the average stroke width was 0.33 in. At a viewing distance of 50 ft plus 6.2 ft this character height results in a visual angle of 14.0 min of arc. At a viewing distance of 75 ft plus 6.2 ft this results in a visual angle of 9.7 min of arc. At a viewing distance of 100 ft plus 6.2 ft this results in a visual angle of 7.4 min of arc. The Arizona license plates had an approximately 4.4 percent taller character height compared with the character height of the Texas license plates. Therefore, assuming that all other legibility factors were equal, one would expect that the characters on the Arizona license plates should have been very slightly easier to read than the characters on the Texas license plates. One plate of each type was selected at random from each group, and photometric measurements were made with the CapCalc computer-controlled photometric measurement system for both the nighttime legibility (at a 75-ft distance) and the conspicuity (550- and 750-ft distances, 20 ft to the left and right) experimental arrangements. A description of the CapCalc system is given by Zwahlen et al. (*20*). Table 2 lists the character luminance, the background luminance, and the average luminance of the license plates.

Experimental Design

A randomized block experimental design was used for all of the nighttime legibility and conspicuity experiments. Two separate but identical experiments were run for both legibility and conspicuity experiments, with one using dry license plates and the other using wet license plates to determine if this was a critical factor and if one group of plates would respond better than the other group under such an adverse condition. The dependent variable in the nighttime conspicuity experiments was the detection of the displayed license plate (randomly presented either on the left side or on the right side). The dependent variables in the nighttime legibility experiments were the correct reading of each number (three in a group) and each letter (three in a group) on the license plate. For the nighttime legibility experiments the main independent variables were the license plate material (two levels; Arizona with white beads-on-paint letters on a red painted background and Texas with blue letters on a white background using reflective sheeting) and the age or condition of the license plates (two levels; new and old or used). For each subject in the legibility experiments the license plate material and the age were balanced in such a way that each of the resulting combinations of material and age (four combinations) were displayed exactly once in a random order for every four exposures (block), thus giving a total of 24 presentations for each license plate type (12 license plates and two replications each) accounting for a total of 96 responses from each subject. For the nighttime conspicuity experiments the main independent variables were the license plate material (two levels; Arizona with white beads-on-paint letters on a red painted background and Texas with blue letters on a white background using reflective sheeting), the display position (two levels; left ahead, subjected to considerable opposing low-beam glare, or right ahead, subjected to a fairly low amount of opposing low-beam glare), and the age or condition of the license plate (two levels; new and old). The resulting combinations of material, position, and age (eight combinations) were displayed exactly once in a random order for every eight presentations (block; four similar combinations at each display position), thus accounting for a total of 96 responses from each subject (showing each of the 12 license plates once on each side, two replications, 12 blocks with eight presentations).

Experimental Procedure

Written instructions were given, and the subjects were given two to three trial presentations before the real experiment started. This allowed them to be somewhat dark adapted and to be familiar with the experimental procedure. Two experimenters sat in the back seat of the car; one recorded the responses of the subject, whereas the other one was in constant communication with the experimenters at the license plate stand via the walkie-talkies. Six experimenters were used to conduct the nighttime conspicuity and legibility ex-

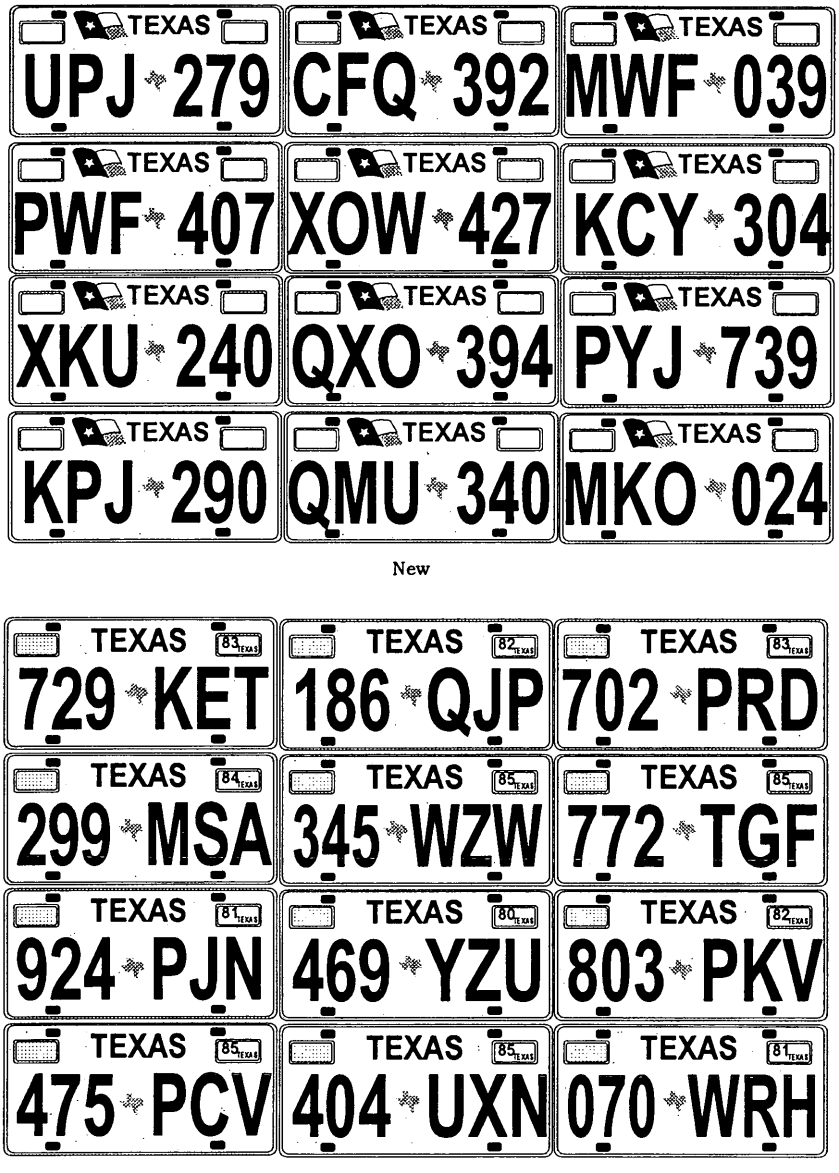

FIGURE 4 Old and new Texas license plates used in experiments.

periments, and each subject took about 1 to 1.5 hr to go through the entire experiment. Completing the vision test and the subject questionnaire took another 30 to 45 min. The subjects were instructed to read out the characters on the plates and say "blank" if they could not discern any particular character and press the horn as soon as they were ready for the next plate to be presented.

For both the nighttime legibility and conspicuity experiments the plates were presented in a random order mentioned in the experimental design section for a duration of exactly 2 sec, which was also computer controlled. The following is an explanation for choosing the 2-sec exposure time. Road and traffic information is obtained by drivers by making a continuous string of discrete eye fixations. According to a work by Zwahlen (*21*) most eye fixations, when driving at night on a straight, level section of a highway last from about 0.1 to 0.8 sec; a few eye fixations may last as long as about 2 secs. While driving on a highway drivers do not have unlimited time to look out for targets or to read license plate information. The maximum eye fixation duration of 2 sec should therefore be a fairly conservative choice for the exposure time.

The nighttime legibility experiments were conducted with the license plates being displayed at distances of 50, 75, or 100 ft or at 75 ft measured from the front of the experimental car (81.2-ft legibility distance for the 75-ft distance). Some state traffic agencies require that licenses plates must be legible at 100 ft during daytime, but no requirement for nighttime legibility was found. The license plate stand was positioned in a manner so that the vertical center of the license plate was exactly along the longitudinal axis of the experimental car with the low beams, and the license plate holder was fixed in such a way that the horizontal center of the license plate was at a height of 26 in. above the ground. This height was the average height (measured from the ground to the horizontal center of the license plate) of 30 rear license plates measured on 30 vehicles

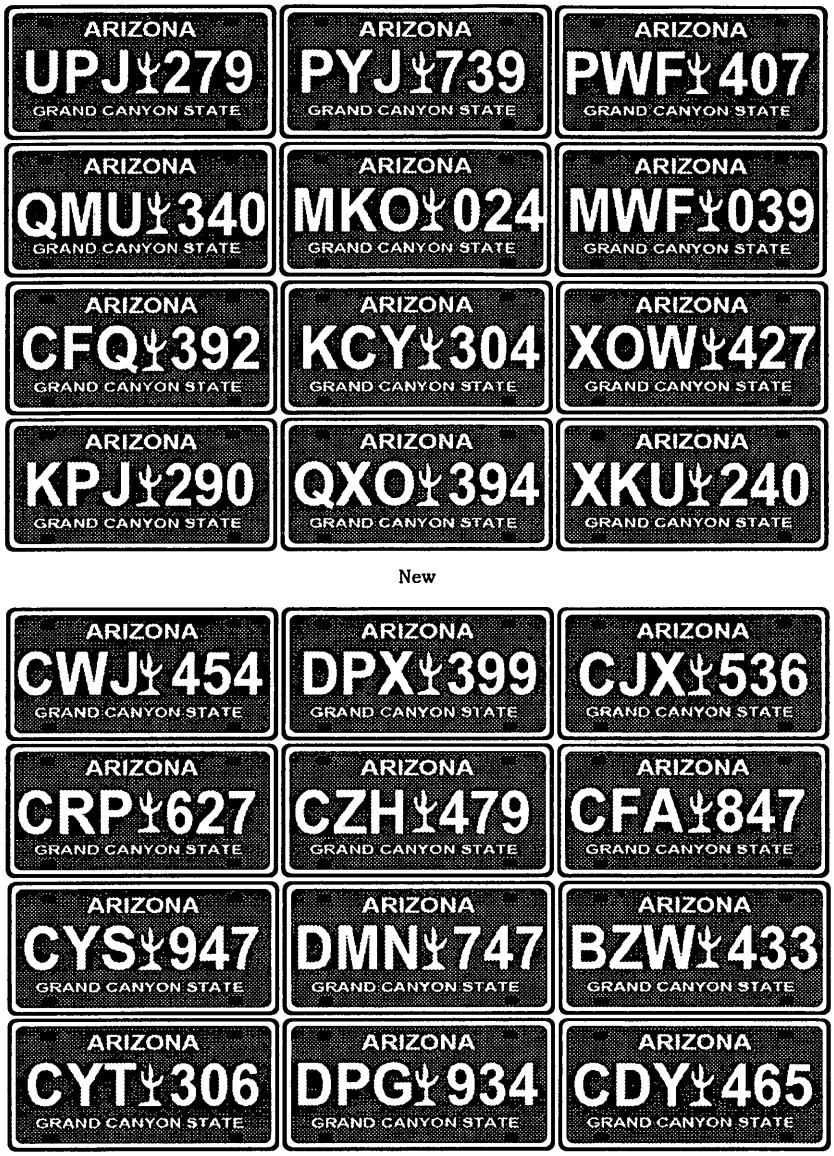

FIGURE 5 Old and new Arizona license plates used in experiments.

chosen at random in a parking lot. For the experiments testing the license plates under the wet condition, the plates were dipped in a pail of water just before being placed in the license plate stand and being presented.

For the nighttime conspicuity experiments the experimental car was moved to a distance of 550 or 750 ft away from the two stands. Some state traffic agencies require that all license plates must provide visible reflectivity at a minimum distance of 550 ft when using standard low-beam headlights. The 550-ft distance incidentally is equivalent to the stopping sight distance for a design speed of 55 mph on wet pavements (22). The 750-ft distance was chosen as the minimum decision sight distance for a design speed of 50 mph. The time between the nighttime legibility and the conspicuity experiments, or vice versa, gave the subjects a rest period of about 5 to 10 min. A car providing opposing glare (low beams) was positioned to the left of the experimental car such that the front-to-front distance between the cars was 200 ft and the longitudinal axis-to-axis distance was 12 ft (typical two-lane rural highway dimensions). There are many occasions on a two-lane highway driving situation when a motorist approaches a car providing opposing glare and must also be able to detect a retroreflective target ahead of his or her car in due time. The distance of 200 ft for the opposing car was selected arbitrarily. The two stands were positioned at either 550 or 750 ft ahead of the experimental car at a distance of 20 ft to the left and 20 ft to the right from the longitudinal axis of the experimental car. The subjects were instructed to respond by saying "left" or "right" indicating the position at which they could see a license plate being displayed in a given trial. The experimenter operating the computer (the left or right position at which the plate would be displayed was computer controlled) would count 1,2,3, . . . in the walkie-talkie after the first, second, third, . . . plates were displayed, so that the experimenters sitting in the car with the subject would know that

TABLE 2 Approximate Luminances for License Plates Used in Experiments

Plate Type	Experiment/ Distance	Luminance (cd/sq. m)		
		Character	Background	Average
TN	Legibility/75 ft.	120	300	210
TO	Legibility/75 ft.	50	230	160
AN	Legibility/75 ft.	60	5	25
AO	Legibility/75 ft.	50	2	20
TNL	Conspicuity/550 ft	------	------	4
TOL	Conspicuity/550 ft	------	------	2
ANL	Conspicuity/550 ft	------	------	<0.5
AOL	Conspicuity/550 ft	------	------	<0.5
TNR	Conspicuity/550 ft	------	------	30
TOR	Conspicuity/550 ft	------	------	10
ANR	Conspicuity/550 ft	------	------	3
AOR	Conspicuity/550 ft	------	------	3
TNL	Conspicuity/750 ft	------	------	4
TOL	Conspicuity/750 ft	------	------	1
ANL	Conspicuity/750 ft	------	------	NM
AOL	Conspicuity/750 ft	------	------	NM
TNR	Conspicuity/750 ft	------	------	20
TOR	Conspicuity/750 ft	------	------	6
ANR	Conspicuity/750 ft	------	------	<1
AOR	Conspicuity/750 ft	------	------	NM

TN - Texas New, TO - Texas Old, AN - Arizona New, AO - Arizona Old
L (left side of driver) and R (right side of driver) denote the position of display location.

NM - Not Measurable Using CapCalc ----- Not Applicable

a license plate was displayed in the case that the subject missed seeing the license plate.

After the legibility or conspicuity experiments were finished an exit interview was conducted with each subject to find out if there were any difficulties during the experiments that could have affected the subject's performance in any way. The data for a few subjects were excluded because they were not wearing the prescribed contact lenses or glasses or they experienced problems with their contact lenses during the experiment. Two sets of data collection forms were prepared for each subject, one for the experimenter noting down the responses of the subject in the car and the other one for the experimenters changing the license plates at the stands. The mechanical stop was adjusted in all experiments such that the plates were leaning forward at an angle of about 5 degrees to avoid specular glare.

RESULTS AND DISCUSSION OF RESULTS

Legibility

An analysis of variance (0.05 significance level) on the recognition of all characters, letters only, and numbers only for the legibility experiment conducted at 75 ft (Study #1) was conducted. When the recognition of all characters on a license plate and the letters only was considered, both material and age of the license plates were statistically significant factors for Texas license plates and the new plates performed better. When the recognition of the numbers only was considered, the age of the plate was no longer statistically significant, but the material by age interaction was statistically significant. The cause for this interaction is that the subjects read the numbers easier on the TO plates, which can be attributed to the fact that the numbers appear first on the TO plates. At the 75-ft distance (81.2-ft viewing distance) both the TO and the TN license plates performed better than either type of Arizona license plates in terms of the total number of characters recognized. It was expected that numbers would be read more easily than letters, and Figure 6 shows that this was the case for the Arizona license plates, even though the group of numbers appeared last on the Arizona plates. However, for the TN plates the letters were read just as well as the numbers at 75 ft. This leads to the conclusion that the legibility must be greater for the TN license plates for the subjects to recognize the letters correctly to the same degree as the numbers. This comparison cannot be made for the TO plates since the numbers appeared first and thus were read with a greater accuracy.

An analysis of variance conducted on the results of Studies 2 and 3 indicated that the license plate design (material), the age, and the distance were all statistically significant. Figure 7 shows the percentages of characters recognized at 50, 75, and 100 ft for each group of dry license plates. For the legibility at 50 ft all groups of license plates showed above 90 percent character recognition, with

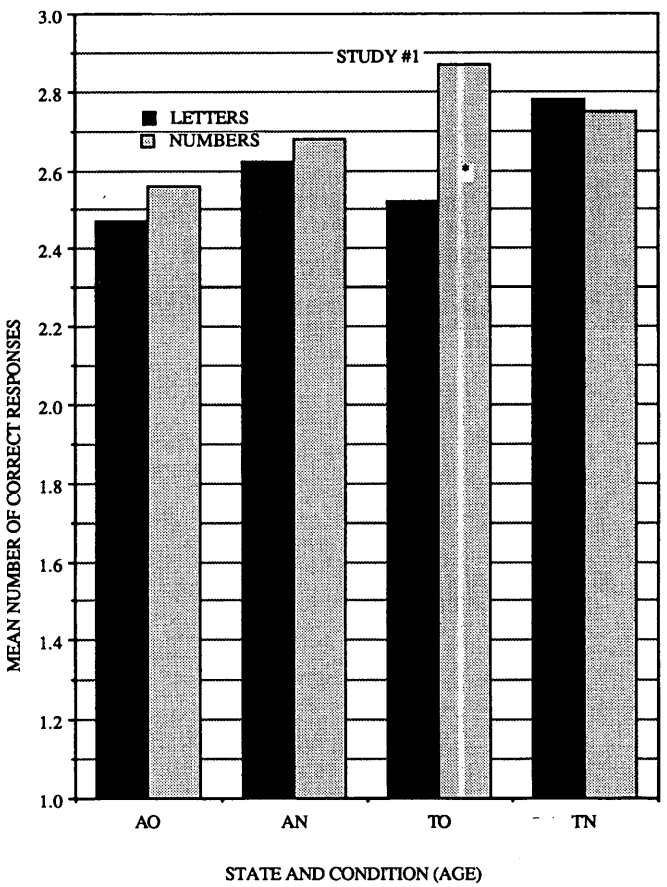

FIGURE 6 Legibility of dry AO, AN, TO, and TN license plate numbers and letters at 75 ft as mean number of correct responses (Study 1; 20 subjects). (For TO plates numbers come first.)

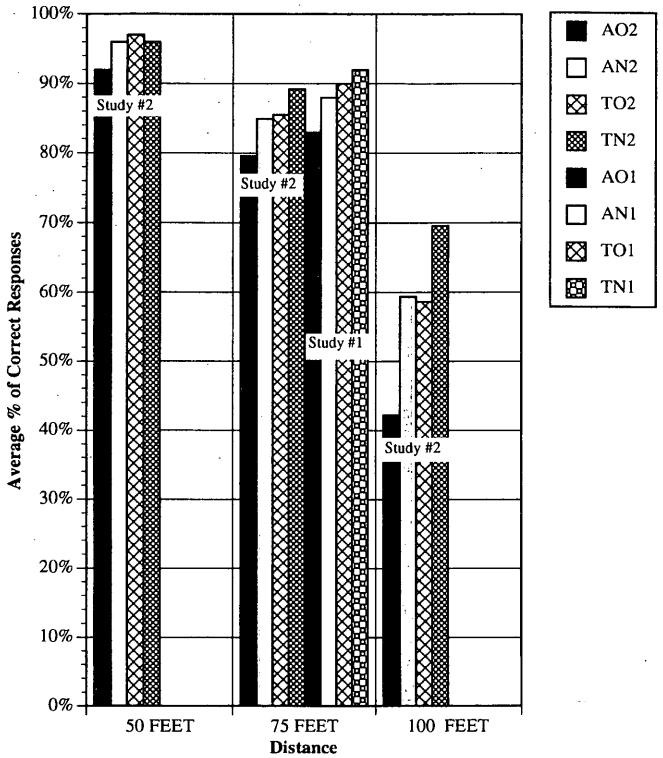

FIGURE 7 Legibility of dry AO, AN, TO, and TN license plate at 50, 75, and 100 ft as average percent correct recognition of characters. Study 2: AO2, AN2, TO2, and TN2 at 50, 75, and 100 ft (12 subjects). Study 1: AO1, AN1, TO1, and TN1 at 75 ft (20 subjects).

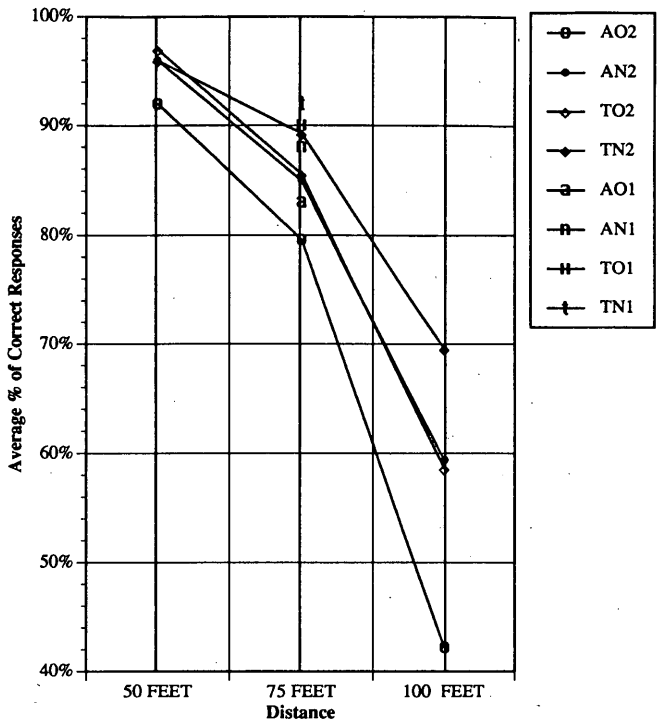

FIGURE 8 Legibility of dry AO, AN, TO, and TN license plates at 50, 75, and 100 ft as average correct response for character recognition. Experiment 2: AO2, AN2, TO2, and TN2 at 50, 75, and 100 ft (12 subjects). Experiment 1: AO1, AN1, TO1, and TN1 at 75 ft (20 subjects).

the AN, TO, and TN license plates performing about equally well. When the distance was increased to 75 ft (81.2-ft viewing distance), the Texas license plates still performed at or above 90 percent character recognition, and the AN and AO license plates dropped to 88 and 83 percent character recognition, respectively, in Study 1 (Study 2 shows almost the same results for 75 ft, but with about a 5 percent drop in the correct response percentage for each type of license plate). With an additional increase in distance to 100 ft a sharp decrease in legibility was observed for all plates, especially for the AO plates. The TN license plates performed significantly better than the rest of the plates at 100 ft, with about a 70 percent character recognition, the AN and TO license plates dropped to about 59 percent recognition, and the AO license plates dropped to about 42 percent character recognition. Figure 8 shows the average percentage of correct responses for each license plate as the distance is increased from 50 to 75 to 100 ft.

Figure 9 shows a comparison of legibility performance for wet and dry license plates at 50, 75, and 100 ft. It is apparent that the wet Texas license plates performed much better than the wet Arizona plates. The wet Texas license plates retained 80 percent or more character recognition, whereas the wet AN and AO license plates fell to 64 and 42 percent character recognition, respectively, at 75 ft. At 50 ft the Texas license plates were not affected by the wet condition, whereas the AN license plates were affected slightly and the AO license plates were affected significantly by the wet condition. At 100 ft the effect of the wetness of the license plates on legibility was even more pronounced. The performance of wet Texas license plates fell about 20 percentage points at 100 ft when compared with the performance of dry Texas license plates at 100 ft, with TN and TO falling to 50 and 42 percent recognition levels, respectively, whereas the Arizona license plates fell about 30 percentage points to a 30 and 10 percent recognition levels for AN and AO, respectively.

Conspicuity

An analysis of variance (0.05 significance level) was conducted on the results for the conspicuity experiment at 550 ft (Study 1) and the conspicuity experiment at 750 ft (Study 5). It was observed that the license plate design (material) and the plate display position (left and right side) factors were highly statistically significant. It is interesting to note that the license plate design (material) by position interaction was also highly statistically significant. This suggests that one license plate design displayed on the left side performed significantly better than the other. It can be seen from the following figures that the Texas license plates were affected considerably less than the Arizona license plates for the left display position. The same result is true for the 750-ft distance. The age factor was slightly statistically significant (alpha = 0.01) for 550 ft, from which one may infer that the new license plates performed only marginally better than the used license plates at 550 ft. However, at 750 ft the age factor was highly significant, indicating that at longer distances the older age of the plates decreased conspicuity.

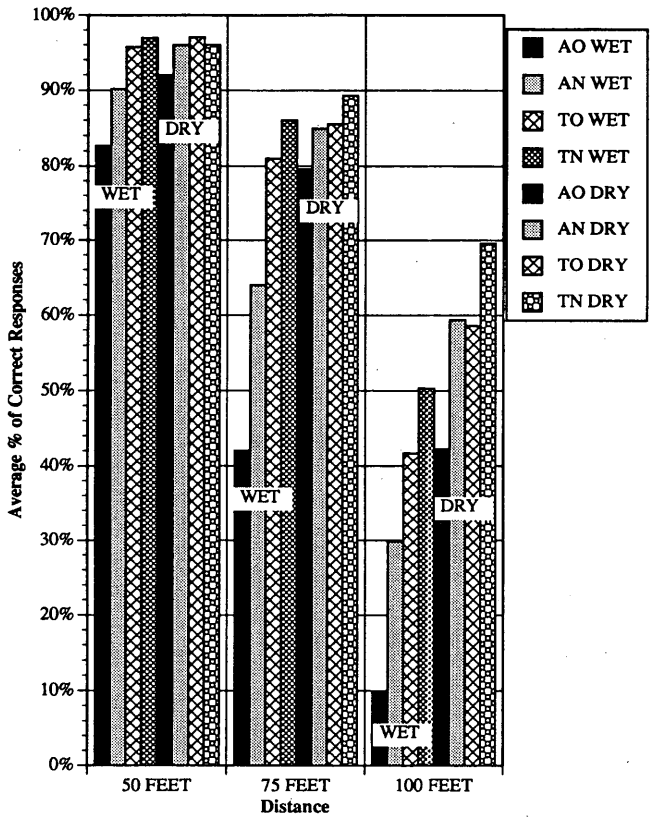

FIGURE 9 Comparison of legibility performance of dry (Study 3; 12 subjects) and wet (Study 3; 12 subjects) AO, AN, TO, and TN license plates at 50, 75, and 100 ft.

An analysis of variance conducted on the results of Study 4 also indicated similar statistically significant differences. Figure 10 shows the detection responses of both wet and dry license plates for both left and right positions at 550 ft. It can be seen from Figure 10 that the level of detection of all plates under the dry condition was 90 percent or more for the right side, with the Texas license plates performing slightly better than the Arizona license plates. However, on the left side the difference between the license plate designs (materials) is much more apparent even under dry conditions. The level of detection of Texas license plates on the left side was still maintained at 88 percent or more under the dry condition, whereas the level of detection of the AN license plates dropped to about 55 percent and that of the AO license plates dropped to about 48 percent. Detection of the Texas license plates was maintained at a level of 90 percent or more for the right side even under wet conditions. The Arizona license plates showed the worst performance, with 22 percent detection for the AO license plates and about 10 percent detection for the AN license plates under the wet condition. However, the level of detection of Texas license plates also showed a fairly sharp drop under the wet left side, but level of detection of the TN license plates was still maintained at over 45 percent (TO 20 percent), and the level of detection of both the new and used Arizona license plates fell to under 11 percent.

Figure 11 shows results similar to those shown in Figure 10 but at 750 ft instead of 550 ft. Again, all of the dry license plates except for AO plates performed reasonably well for the right side, being detected at a level of 90 percent or more. For the left side the dry Texas license plates again performed well at more than 90 percent detection, whereas the dry Arizona license plates fell to under 11 percent detection as opposed to almost 50 percent detection at 550 ft. The wet Texas license plates still performed at more than 90 percent detection for the right side and 70 percent detection for the left side, whereas the Arizona license plates fell to under 6 percent de-

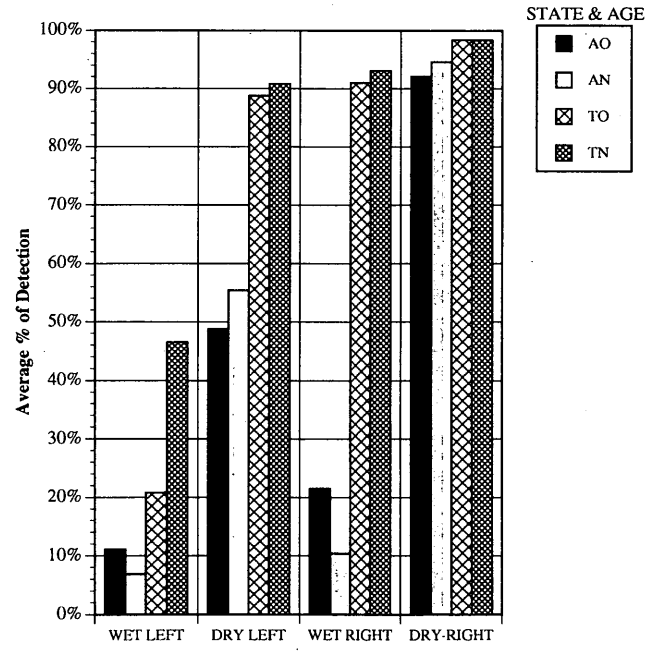

FIGURE 10 Conspicuity of wet (Study 4; 12 subjects) and dry (Study 1; 20 subjects) AO, AN, TO, and TN license plates at 550 ft for left and right positions as average percent detection.

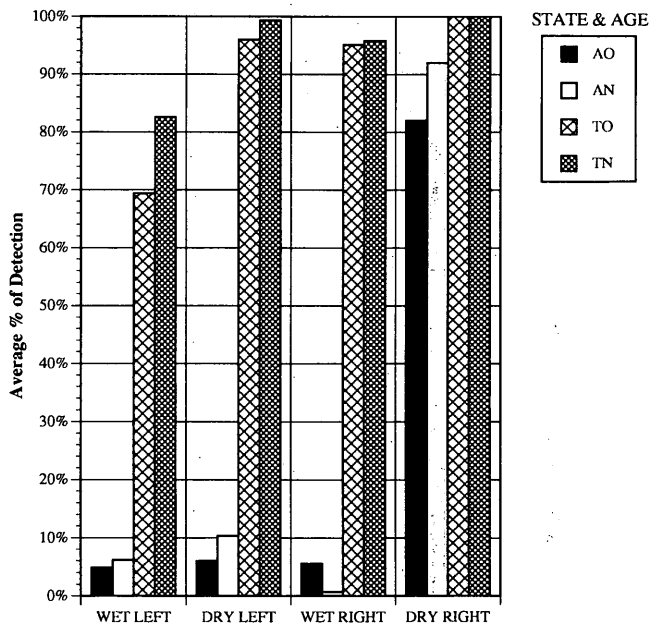

FIGURE 11 Conspicuity of wet (Study 4; 12 subjects) and dry (Study 5; 12 subjects) AO, AN, TO, and TN license plates at 750 ft for left and right positions as average percent detection.

tection for the right side and 7 percent detection for the left side. Figure 12 shows the average percentage of detection for the license plates at 550 and 750 ft for the dry condition, and Figure 13 shows the same data for the wet condition. The Texas license plates performed better in both wet and dry situations at 750 ft than at 550 ft since the license plate locations in the subject's visual field displayed at 750 ft are closer to the foveal region of the subjects than are the license plates displayed at 550 ft, which need to be detected at somewhat larger peripheral angles. This trend is more apparent for the license plates displayed on the left side, with detection rising to more than 95 percent for the dry condition (Figure 12; 750 Left) and almost 70 percent for the wet condition (Figure 13; 750 Left). This trend was not shown for the Arizona license plates since their brightness is not sufficient enough to be detected easily at 750 ft. In all the cases with the dry license plates at 750 ft the Texas license plates (TN, TO) almost always retained 90 percent detection levels. Figure 13 indicates that the wet AO license plates performed better than the wet AN plates. This can be attributed to the presence, usually, of two reflective stickers (reflective sheeting material indicating renewal and expiration information on the license plates) on the AO license plates. Photometric measurements made on wet Arizona plates confirmed that there is little loss in the luminances of the wet AO license plates when compared with the luminances of the dry AO license plates, whereas there is a larger luminance difference between wet and dry AN plates.

Observation and entrance angles for the driver side and the passenger side beams of the experimental car were calculated for both the nighttime legibility and conspicuity experiments by using an existing interactive computer program, and the values are listed in Table 3. The glare source spatial angle between the opposing driver-side beam and the left-side license plate position for the 550-ft conspicuity experiment was 0.66 degree, and it was 1.16 degrees for the 750-ft conspicuity experiment. The glare source spatial angle between the opposing driver-side beam and the right-side license plate position for the 550-feet conspicuity experiment was 4.72 degrees, and it was 4.15 degrees for the 750 ft conspicuity experiment. The glare source spatial angle between the opposing passengers-side beam and the left license plate position for the 550-ft conspicuity experiment was 1.6 degrees, and it was 2.12 degrees for the 750-ft conspicuity experiment. The glare source spatial angle between the opposing passenger-side beam and the right-side license plate position was 5.7 degrees for the 550-ft conspicuity experiment, and it was 5.13 degrees for the 750-ft conspicuity experiment.

For the 550-ft conspicuity distance for the left-side position (−20 ft) of the license plate with the H6054 low-beam pattern for the opposing car at 200 ft (12 ft to the left) the veiling luminance according to the Stiles-Holladay veiling luminance formula (*23*) is 3.56 fL (both beams). The 98 percent illumination threshold value according to the data of Blackwell (*24*) and an assumed background luminance of 0.03 fL is 3.68×10^{-6} fc. The corresponding values for the right-side position (20 ft) of the license plate and at the 550-ft conspicuity distance are 0.10 fL and 0.12×10^{-6} fc. For a 750-ft conspicuity distance for the left-side position of the license plate the corresponding values are 1.27 fL and 0.74×10^{-6} fc, and for the right-side position of the license plate at the 750-ft conspicuity distance the corresponding values are 0.12 fL and 0.08×10^{-6} fc. Looking at the veiling luminance and 98 percent threshold values and the average luminances of the license plates in Table 2, it is not surprising that the left-side conspicuity results are considerably lower when compared with the right-side results.

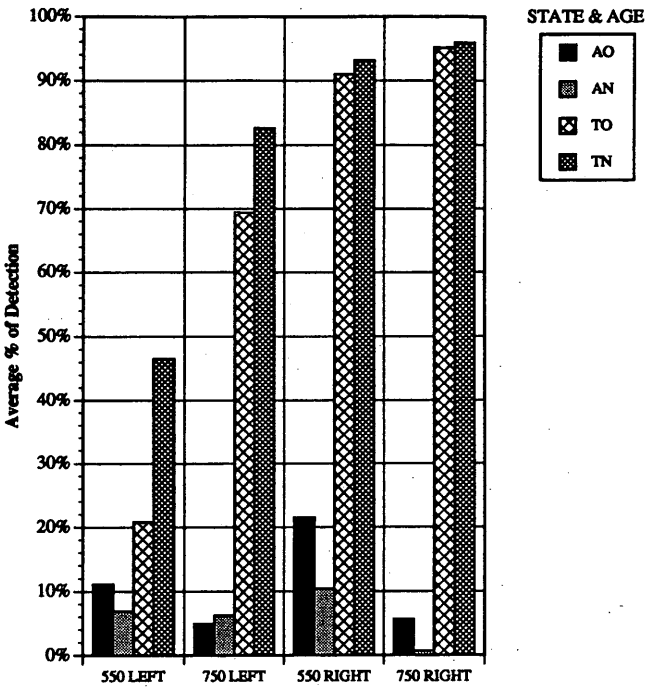

FIGURE 13 Conspicuity of wet AO, AN, TO, and TN license plates at 550 and 750 ft for left and right positions as average percent detection (Study 4, 12 subjects).

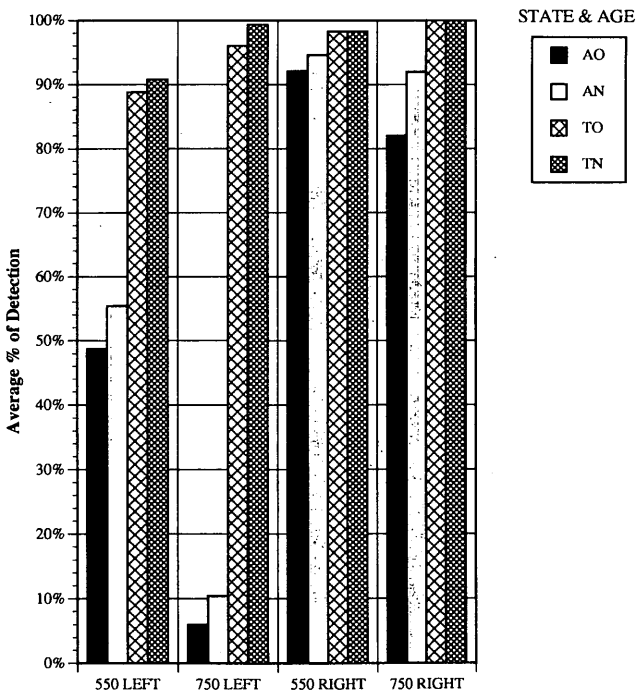

FIGURE 12 Conspicuity of dry AO, AN, TO, and TN license plates at 550 and 750 ft for left and right positions as average percent detection (Study 1, 20 subjects; Study 5, 12 subjects).

TABLE 3 Observation and Entrance Angles of License Plates Used in Experiments

Experiment	Light Source	Lateral Distance (ft)	Longitudinal Distance (ft)	Observation Angle (degrees)	Entrance Angle (degrees)
Legibility	D.S.beam	0	50 (56.2)	1.85	5.17
Legibility	P.S. beam	0	50 (56.2)	3.43	5.17
Legibility	D.S.beam	0	75 (81.2)	1.25	5.04
Legibility	P.S. beam	0	75 (81.2)	2.33	5.04
Legibility	D.S. beam	0	100 (106.2)	0.95	4.99
Legibility	P.S. beam	0	100 (106.2)	1.77	4.99
Conspicuity	D.S. beam	-20*	550 (556.2)	0.17	5.34
Conspicuity	D.S. beam	20	550 (556.2)	0.19	5.47
Conspicuity	P.S. beam	-20*	550 (556.2)	0.35	5.47
Conspicuity	P.S. beam	20	550 (556.2)	0.31	5.34
Conspicuity	D.S.beam	-20*	750 (756.2)	0.13	5.18
Conspicuity	D.S.beam	20	750 (756.2)	0.14	5.25
Conspicuity	P.S. beam	-20*	750 (756.2)	0.25	5.25
Conspicuity	P.S. beam	20	750 (756.2)	0.23	5.18

D.S. beam = Driver Side beam P.S. beam = Passenger Side beam
Reference axis of license plate is directed 5 degrees downward

* The negative sign indicates that the position of the license plate is to the left ahead of the driver.
Height of the center of license plate from the ground = 2.17 ft (26")
Height of light sources (left and right low beams) from the ground = 2 ft (24")
Distance between the centers of the two light sources = 3.33 ft (40")
Longitudinal horizontal distance from a driver's eye position to the light sources = 6.2 ft (74.4")
Lateral horizontal distance from a driver's sagital plane to the longitudinal axis plane of the car = 1.075 ft (12.9")
Height of a driver's eyes from the ground = 3.6 ft (43.3")

CONCLUSIONS

The available literature on the conspicuity and legibility of reflectorized license plates has been reviewed. With regard to legibility some of the studies showed no appreciable difference between reflective sheeting-type license plates and beads-on-paint-type license plates, whereas others did show a difference favoring reflective sheeting. With regard to visibility or conspicuity the literature review indicates that compared with nonreflectorized and painted-only license plates, beads-on-paint license plates doubled vehicle detection distances, whereas reflective sheeting increased the detection distances by seven times.

Most of the studies that have attempted to study the direct safety benefits of fully reflectorized license plates (reflective sheeting only because beads-on-paint-type license plates have not been tested) have shown a reduction in night-time accidents, most notably night-time rear-end and parked car accidents; this reduction appears to be associated with the use of reflective sheeting on the license plate. Only one of the studies (*13*) indicated that this reduction in accidents is not statistically significant, but there were differences of opinion in the interpretation of those results. It is important to note that even with the great care used to rule out other variables it is difficult to quantify accident reduction effects; however, positive safety results appear to have been achieved with reflective sheeting license plates.

All experiments and testing conditions have been designed to test the conspicuity and the legibility performance of Texas (reflective sheeting) license plates and Arizona (beads on paint) license plates under somewhat close to real-world conditions. For both legibility and conspicuity, the retroreflective sheeting material of the Texas license plates performed better than the beads-on-paint design of the Arizona license plates, and these differences are statistically significant at a significance level of 0.01. It should be realized that the two plates are slightly different in other aspects such as color (Texas license plates are blue characters on white; Arizona license plates are white characters on dark red) and are appreciably different in the amount of reflective material on the plate (both the background and the characters on the Texas license plates are reflective; only the white characters on the Arizona license plates are reflective). Less area and the less inherent brightness of the beads-on-paint system notably affect the conspicuity results.

The conspicuity experiments at the 750-ft distance could also be useful, since this longer distance represents the lower value of the decision sight distance range [for a design speed of 50 mph (*22*)]. Looking at the results of the study it can be observed that at these longer decision sight distances the Texas reflective sheeting license plates show an even better performance than that at 550 ft and a drastically greater conspicuity performance than the Arizona plates for wet condition and the left-side display position.

It can be expected that there exists a rather close relationship between plate age and ultraviolet exposure and possible losses in reflectivity due to UV exposure. If there is in fact a large effect (decrease in reflectivity) due to UV exposure, the used Arizona and the used Texas license plates (in use from 1 to 5 years) would be expected to show a fairly large decrement in both legibility and conspicuity performances. However, looking at the results of the study there appears to be very little loss in terms of the conspicuity and legibility (more so for conspicuity) performances between new and used Texas license plates, whereas there exists a somewhat larger but still relatively small decrement between the new and used Arizona license plates. This would indicate that the beads-on-paint design might be slightly more susceptible to ultraviolet exposure and age than the reflective sheeting design. The effect of road contamination (dirt and road grime) could not be explicitly evaluated since there exist no standards or fixed procedures that can accurately quantify the level of contamination, and moreover, such an additional investigation was beyond the scope and financial resources of the study. It is, however, expected that dirt and road grime would affect both of these license plate types in a similar manner, and therefore one could expect that dirty reflective sheeting license plates would always provide a moderately to highly superior conspicuity and legibility performance when compared with equally dirty beads-on-paint license plates, depending on the environmental conditions.

The results of the study agree with those of Israelsen et al. (*5*) in that as adverse environmental factors are added to the experiment the superiority of the reflective sheeting becomes even more apparent. Although there was a significant advantage of the reflective sheeting license plates in the legibility experiments, their advantage was even more pronounced in the conspicuity experiments. It can be tentatively concluded that the reflective sheeting design is a much more robust product design compared with the beads-on-paint design since it retained a much greater degree of legibility and conspicuity performance under adverse conditions such as the presence of glare from an opposing car in the conspicuity experiments and wetness of the plates. It should also be noted that the results obtained in the study and the conclusions drawn are based on the performance of young, alerted, not mentally loaded, healthy, and in many ways ideal subjects. It can be expected that the performance differences between reflective sheeting and beads-on-paint license plates will most likely be greater and even more significant if visually impaired or elderly drivers are considered.

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