Effect of Ambient Lighting and Daytime Running Light (DRL) Intensity on Peripheral Detection of DRL

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Daytime running lights (DRLs) have been proposed to reduce the frequency and severity of traffic accidents by enhancing the conspicuity of vehicles to other drivers. DRL regulations have been enacted in several countries and are being considered in the United States. Although various studies of DRL effectiveness have been conducted, only one has included the range of ambient illumination conditions encountered in the United States. The project reviewed methodologies appropriate for the study of DRL effectiveness and conducted a study of DRL effectiveness under a wide range of ambient illumination. A peripheral detection experiment was conducted in which subjects responded to a DRL test vehicle approaching at a 20-degree peripheral angle while the subjects were performing a central attention task. DRL intensities were 0, 200, 400, 800, and 1,600 cd. Ambient illumination levels varied from about 11 000 to more than 110 000 lx (1,000 to 10,000 fc). Only the 1,600-cd intensity resulted in a statistically significant increased peripheral detection distance. Improved peripheral detection distance was limited to ambient illumination levels below 43 040 lx (4,000 fc). The mean improvement in detection distance for 1,600-cd intensity and ambients less than 43 040 lx (4,000 fc) was about 75 m (247 ft), or about 3 sec of driving time at 88 km/hr (55 mph).

Daytime running lights (DRLs) for automobiles and motorcycles have attracted the attention of the traffic safety community for many years as a means of increasing the daytime conspicuity of vehicles to other road users (*1–7*). Several European countries have required DRLs for a number of years (*8,9*), Canada has recently implemented a DRL requirement (*10,11*), and the European Economic Community is considering a uniform DRL requirement (*12,13*). The U.S. Department of Transportation has conducted various DRL studies to assess the applicability of DRLs to the U.S. environment (*14–16*).

A substantial amount of DRL research has been conducted, including studies of accident experience before and after DRL implementation (*8,9,17,18*), fleet studies in which DRL-equipped vehicles have been compared with non-DRL-equipped vehicles (*19–21*), observational studies in which observers have made judgments of various DRL configurations (*22*; D.W. Moore, DRL tests in various U.S. cities, SAE Lighting Committee Correspondence, 1985–1986), and experimental tests of DRL performance using detection distance or other performance measures (*15,16,23–29*).

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However, this body of work includes only a few experimental studies that provide quantitative relationships among DRL parameters such as intensity, environmental parameters such as ambient illumination, and performance measures such as detection distance or conspicuity.

The issue of DRL effectiveness as related to ambient lighting levels is especially important for DRL use in the United States and other countries that have a significant amount of territory at lower latitudes and, therefore, higher ambient illumination levels than encountered in most European countries. For instance, Sweden and Finland, which pioneered DRL application, have typical ambient levels about one-tenth those of the United States. Only one study studied DRL performance over an ambient range that is typical of the U.S. environment (*15*).

DRL EVALUATION METHODOLOGIES

The predominant experimental and observational methodologies used in DRL evaluation have been judgment or comparison techniques, decision making, central detection, and peripheral detection.

DRL judgment studies, in which the effectiveness of various DRL configurations are ranked or rated by observers, tend to be conducted under uncontrolled conditions and cannot provide quantitative performance measures that can be used to evaluate DRL accident reduction potential.

Gap acceptance studies and similar decision-making approaches pose methodological problems and can be very difficult to conduct, especially when one is attempting to measure gap acceptance behavior of unsuspecting drivers. However, such studies may be extremely useful for evaluating DRL effectiveness in a more natural situation than is provided by the typical controlled experimental task.

DRL central visual detection studies are of limited value because of the very long DRL detection distances typically found for direct viewing of DRL-equipped vehicles. However, some conditions will exist in which improved central detection due to DRL is relevant (e.g., driving under glare conditions or when the other vehicle is viewed against masking backgrounds).

Peripheral detection studies were judged to be the best technique for relating DRL conspicuity (i.e., initial noticeability of the other vehicle) to ambient illumination and DRL intensity. However, performance is sensitive to the peripheral angles at which targets are presented, central task demands, and deviations of observers' gaze direction.

DRL PERIPHERAL DETECTION EXPERIMENT

The purpose of the experiment was to determine DRL peripheral conspicuity as a function of ambient illumination and DRL intensity. A secondary purpose was to examine the effectiveness of DRL as a function of driver age.

Test Site and Subject Station

The test site was a concrete taxiway at the Camarillo airport (Ventura County, California) that was about 15 m (50 ft) wide. It provided a straight east-west "roadway" of more than 762 m (2,500 ft). A connecting ramp at the far end of the runway provided a turn-around area for the test vehicle. The terrain surrounding the taxiway was essentially flat, with low mountains in the far background.

Six subject chairs were located in a line at the east end of the test area. The DRL vehicle approached the subject station from the west. The central task display was located at a 20-degree angle to the north of the vehicle path and at a distance of about 16 m (53 ft) from the subjects' station. The peripheral angle deviation from the nominal 20 degrees for the two end subjects was less than 1 degree at a distance of about 150 m (500 ft). The experimenter's station was behind the subject station.

An overview of the test area configuration is given in Figure 1.

Method

Groups of six subjects were run simultaneously. The DRL vehicle started each trial from a distance of 762 m (2,500 ft) or greater and approached at 40 km/hr (25 mph). The data collection period started when the vehicle was 701 m (2,300 ft) from the subject station and ended when it was 38 m (125 ft) away.

Central Task

The central task display used six vehicle lamp assemblies 12 cm (4 in.) in diameter (Grote Type 5064 with Type 1156 32-cd lamps), three with red lenses and three with amber lenses. Five of the lamps were mounted around the edge of a circular panel 0.73 m (2 ft) in diameter and the sixth was mounted in the center. One light at a time was flashed in random sequence with a timing of about 0.5 sec on, 0.5 sec off. The subjects' task was to count (silently) only the yellow flashes. The light flashes were easily visible under all lighting conditions. Subjects wrote down their flash count at the end of each run on a score sheet.

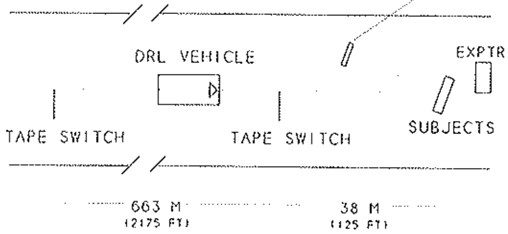

FIGURE 1 DRL test area configuration (not to scale).

DRL Detection Task

Each subject was provided with a quiet response switch and was instructed to press the switch when the vehicle could be seen out of the corner of his or her eye during a trial. Subjects were instructed to respond to any aspect of the vehicle that would lead them to believe another car was approaching if they were actually driving.

Experimental Plan

Twenty-four subjects were used, divided into four subgroups, each consisting of three "old" and three "young" subjects. Each subgroup was run for two half-day periods: a morning and an afternoon period. Two subgroups were run morning first, and the other two were run afternoon first. Thus, the entire set of runs required four days.

Each half-day run was divided into four blocks of runs. Each block consisted of 10 runs, with 2 runs at each of the five DRL intensity levels. The sequence of intensity levels was randomized within each block (with the constraint that each level was to occur twice). A run took 3 to 4 min, so an entire block required 30 to 40 min. A rest period was taken between blocks. The amount of time between when subjects were alerted to the start of each run and when the DRL vehicle actually started was varied to avoid subjects' basing responses on the time from when they were first alerted.

As all subjects in each age group received all DRL intensity conditions, intensity was a within-group variable. Age was a between-group variable. The basic design is a repeated measures design in which each subject received repeated trials at each level of DRL intensity.

Independent Variables

Independent variables were as follows: (a) DRL intensity: 0, 200, 400, 800, 1600 cd (each lamp of a two-lamp system), (b) ambient lighting environment, and (c) age: younger (18 to 30 years) and older (55 years and older).

Several measures of the ambient lighting environment were recorded: (a) horizontal illuminance (HILLUM) measured in footcandles, (b) vertical illuminance (VILLUM) measured in footcandles, (c) sky luminance (SKYLUM) measured in foot-Llamberts (fL), and (d) road luminance (ROADLUM) measured in foot-Llamberts.

Ambient lighting conditions were varied by testing on selected days (for example, on overcast days to obtain lower ambients) and because successive runs under the same DRL intensity conditions occurred throughout the day and, therefore, under a range of ambient conditions.

Photometric Measurements

HILLUM was recorded at the end of each run. VILLUM, SKYLUM, and ROADLUM were recorded about 12 times each test day, from just before the first run to just after the last run. Illuminance was measured with a Minolta T-1 illuminance meter with a cosine-corrected sensor. Luminance was measured with a Minolta LS-100 luminance meter with a circular 1-degree field of view. Sky luminances were taken just above the horizon terrain along the path of the DRL vehicle. Road luminances were measured with the 1-degree field approximately centered at a point about 150 m (500 ft) west of the subject station.

Dependent Variables

Dependent variables were (a) DRL vehicle distance for the peripheral detection task, and (b) amber light count for the central task.

Procedures

A subject group arrived at the test site at about 7:30 a.m. for a morning test period and at about 1:30 p.m. for an afternoon test period. On the first test occasion, printed instructions were handed to the subjects and read to them while they were asked to read along.

Emphasis was placed on the importance of paying attention to the central task, not looking to the side during or between test runs, and maintaining a consistent detection criterion in regard to DRL vehicle detection responses. Subjects were instructed to respond as soon as they became aware of an approaching "vehicle," but they were not instructed to respond to any particular aspect of the approaching vehicle.

Several practice trials were given before the first test trials. Subjects were given the opportunity to ask questions or make comments after each practice trial.

A bonus award was given for the most accurate flash count over each block of 10 trials in order to encourage motivation for the flash-count task and to generally increase subject interest in the overall test situation. Subjects were paid a base amount of $180 for participation in the two half-day sessions plus an additional $10 for the most accurate flash count.

Subjects were encouraged during the rest periods to comment on any difficulties they had in following procedures and to indicate after each trial if they thought that they responded inappropriately.

Apparatus

DRL Vehicle and Test Lamps

The test vehicle was a 1984 Volkswagen Rabbit fitted with a black plywood panel 0.38 × 1.4 m (1.25 × 4.5 ft) mounted vertically in front of the grill. The DRL lamps were mounted behind and flush with circular cutouts in the panel. The lamps were clear Types 4412 (SAE J-583) 27.5 cm (5.25 in.) in diameter and have a nominal H,V intensity of 11,000 cd, a vertical beam width of 6 degrees, and a horizontal beam width of 40 degrees. These lamps were chosen for their relative uniformity of vertical and horizontal beam pattern. The lamp mounting height was 0.67 m (2.2 ft), and their center-to-center distance was 1.2 m (3.6 ft). The Volkswagen Rabbit was painted a flat gray over the areas visible to the subjects to minimize responses to specular reflection. The black panel simulated the dark grill area of many (although not all) cars.

DRL Lamp Calibration and Control

DRL intensity was adjusted by the use of a set of four adjustable resistors for each lamp; power was provided from the vehicle electrical system through a voltage regulator for each lamp. A switch box next to the driver allowed the driver to select lamp intensity.

The lamps were calibrated and the resistors set at the proper values by measuring the illuminance generated on a vertical grid perpendicular to the vehicle longitudinal axis. Details of the calibration and beam pattern are given in the project final report (*16*). Although the lamp intensity decreased slightly as the test vehicle approached the subjects because of the increase in vertical angle at which the lamps were viewed, the estimated intensity difference would be less than 10 to 20 percent.

Test Control and Data Recording

A laptop computer interfaced with a digital/analog input/output device was used to (a) randomly select the sequence of central task lights and control the on/off period of flashes, (b) record the times of tape switch crossings of the DRL vehicle, and (c) record the time of each subject's vehicle detection switch-press.

Subjects

Subjects were recruited from the Ventura County area. The criteria for subject selection were

- Young (18 to 30) or old (55 and older),
- Vision within standards for California driver's license,
- Current driver's license,
- Currently driving at least 4,000 mi/year, and
- Not taking prescription drugs that might affect performance.

The mean age of the old and young groups were 65.7 and 22.5 years, respectively.

DATA ANALYSIS

Detection Distance Conversions

Detection distance was calculated for each subject on each trial by using the times of tape switch crossings and time of subject response, assuming a constant DRL vehicle speed. Analysis of the variation in average speed from run to run indicated that speed variation was likely to be small within a run.

Data Quality and Missing Runs

Extensive data screening was performed to test for data quality. One young subject was a "no-show" and could not be replaced; 31 other cases were lost due to various problems such as admitted inadvertent responses. The final data set consisted of 1,809 data points from 23 subjects.

Data Transformations

Several transformations of the raw detection distance distributions were examined to match statistical test requirements, and various relationships between detection performance and transformations of the photometric data were examined. The latter included various measures of target "contrast" in an effort to examine independent variables that might be better correlated with detection performance than the individual illuminance and luminance variables.

Statistical Methods

Data analysis was complicated by the uncontrolled nature of the ambient illumination conditions. Each group of subjects to some extent experienced a different range and quality of ambient conditions. In general, such confounding was more of a problem for the lower ambient levels, as all subjects were exposed to the higher ambient levels for a number of blocks, but some subjects had much less exposure to the lower levels than did others.

Emphasis was placed on correlational analyses and extensive use of descriptive statistics for overall data examination, in addition to analysis of variance methods.

RESULTS

Photometric Data

The lighting environment during the testing periods can be summarized as follows:

- Overcast conditions occurred during the entire morning on one of the test days and on the early-morning hours on two other test days, resulting in more or less diffuse illumination with relatively low HILLUM values during these test blocks.
- Clear sky with the sun behind subjects illuminating the front of the test vehicle normally occurred by the later morning test blocks.
- Sun more or less overhead to in front of the subjects illuminating the rear of the test vehicle occurred during the afternoon test blocks.

Generally, HILLUM levels were below 11 000 lx (about 1,000 fc) at the beginning of the test day, increased to about 110 000 1x (about 10,000 fc) at midday, and then decreased to about 54 000 lx (about 5,000 fc) at the end of testing.

VILLUM incident on the plane of the vehicle front increased from about 11 000 lx (about 1,000 fc) at the beginning of the morning testing, reached peak values of 86 000 lx (about 8,000 fc) at about 10:00 a.m., and then decreased to about 21 500 lx (about 2,000 fc) at the end of testing. During the afternoon, the vehicle front was in shadow for much of the time.

ROADLUM remained relatively constant at about 10,000 cd/m^2 (about 3,000 fL) after about 10:00 a.m., following an initial rise from about 700 cd/m^2 (about 200 fL) at the beginning of testing.

SKYLUM increased monotonically from about 3,400 cd/m^2 (about 1,000 fL) at the beginning of testing to about 27 000 cd/m^2 (about 8,000 fL) at the end of testing.

HILLUM is shown plotted versus time of day for the 4 study days in Figure 2.

The lighting conditions encountered in this study were complex but typical of viewing in the natural environment.

Central Task Performance

A flash-count error score was formed by subtracting the number of reported flashes from the number of actual flashes for each subject on each trial. The overall error rate was very small; 95 percent of all trials resulted in errors of one count or less. As the flash-count task was judged to be fairly difficult and require concentrated attention, it was concluded that subjects were unlikely to have glanced in the direction of the DRL vehicle to any significant amount. The possibility of such glances cannot be ruled out entirely, as a glance could occur in less than 0.5 sec and as eye movements were not recorded or observed (the experimenter did check for subject head

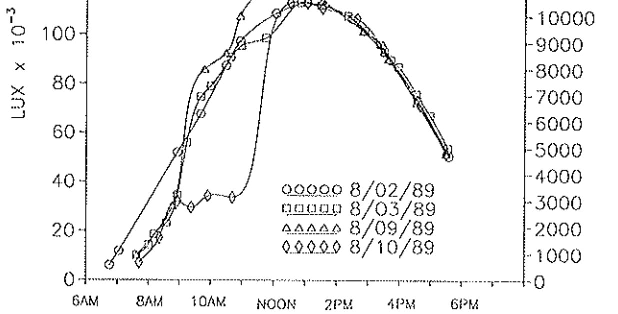

FIGURE 2 Horizontal illuminance versus time of day.

movements during the observations periods, however.) No significant correlations were found between the flash count score and other performance measures.

Detection Performance

General Trends

Mean detection performance across all subjects versus DRL intensity is shown in Figure 3. Both detection distance (DETDIST) and delta detection distance (DELDIST) measures are shown (DELDIST for each case in the detection distance for that case minus the overall subject's mean detection distance for all cases).

The results are shown separately for low ambient trials, that is, HILLUM less than 43 040 lx (4,000 fc), high ambient trials, i.e., HILLUM greater than 43 040 lx, and all trials. (The threshold of 43 040 lx to divide low and high ambients was determined after examination of various groupings of ambient levels for the various photometric measures.)

A mean improvement in DELDIST of about 75 m (247 ft) is shown for the low ambient, 1600-cd condition and about 22 m (72 ft) for the low ambient, 800-cd condition. Only a small trend is shown for improved DELDIST for the high ambient conditions, and only at 1600-cd level.

The same variables are plotted in Figure 4, but with age category as a parameter instead of ambient category. The older subjects show a trend toward better performance than the younger subjects, an unexpected result, that is discussed later.

Analysis of Variance

Three-way analyses of variance (ANOVAs) were run to test the effects of DRL intensity, subject age, and ambient level (categorized into low and high ambient). The ANOVAs were run for DETDIST as well as for three transformations of DETDIST. Transformations were examined as the distributions of DETDIST were found to be nonnormal (skewed in the direction of longer values). The transformations examined were (a) DELDIST, the difference between each DETDIST

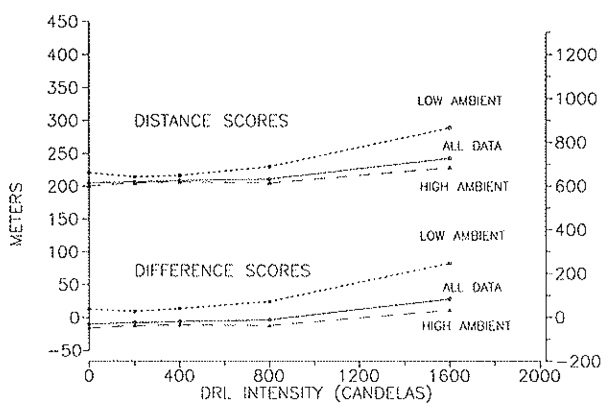

FIGURE 3 Ambient level and detection distance.

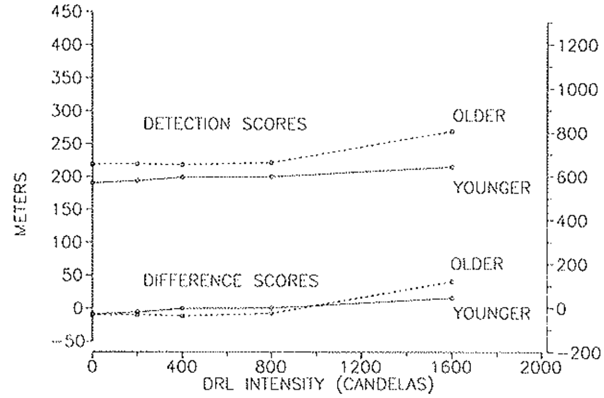

FIGURE 4 Age and detection distance.

score for a subject and that subject's overall mean score; (b) LOGDIST, logarithmic transformation of DELDIST; and (c) DELLOG, the log of each DELDIST subtracted from the mean of the logarithmic transformations of individual scores.

For all measures, DRL intensity and ambient level were significant main factors. Subject age was significant for all measures except DELDIST. Significant interactions were also found for all detection distance measures except for LOGDIST. The presence of interaction terms made the ANOVA results somewhat difficult to interpret. However, the main effects of DRL intensity and ambient level were consistent across all transformations of detection distance scores.

Comparison of Individual Means

Comparison among individual DETDIST and DELDIST means at each DRL intensity were performed separately for the low and high ambient categories. The results indicated that significant improvement with DRL intensity occurred between the 1600-cd case and all other intensities but that no other comparisons were significant.

Comparisons of individual means for DETDIST between low and high ambient levels at each DRL intensity show a significant difference only at 1600 cd. However, significant differences between low and high ambients were found for DELDIST scores at each DRL intensity value. Thus, subjects performed relatively better at the low ambient levels than at the high ambient levels regardless of DRL intensity level.

Regression Analysis

Linear regression functions for DETDIST versus HILLUM are shown in Figure 5 for each DRL intensity. Only the 1600-cd DRL intensity shows an obvious nonzero slope.

Linear regression functions for DETDIST versus DRL intensity categorized into low and high ambients are shown in Figure 6. Little or no trend was found for an increase in mean detection performance for the high ambient condition, but an increase did occur for the low ambient condition.

Summary of Peripheral Detection Distance Results

In summary, DETDIST and DELDIST scores showed effectiveness of DRL at ambient levels below 43 040 lx (4,000 fc)

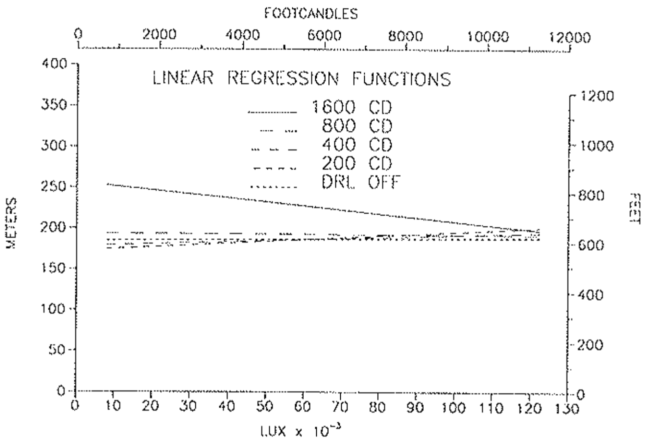

FIGURE 5 Detection distance versus horizontal illuminance.

for DRL intensities of 1600 cd (although a trend toward effectiveness was found at 800 cd).

Relationships Between Detection Performance and Other Photometric Measures

Analyses similar to those discussed were performed to examine the relationship between detection performance and photometric measures other than HILLUM, including various visibility index functions such as ratios of DRL intensity to road luminance and sky luminance. However, no other measure or transformation was found that correlated with detection performance to any greater extent than did HILLUM.

In general, although specification of DRL effectiveness in terms of horizontal illuminance alone might be misleading under some conditions, it was concluded that horizontal illuminance does provide an adequate measure for system evaluation of DRL effectiveness.

Comparison with Other Studies

A study by Kirkpatrick et al. used a range of DRL intensities and a detection task similar to the present study (*15*). Kirkpatrick et al. used a 15-degree angle between a central vision task and the approaching vehicle rather than the 20-degree angle used in this study, and the central task consisted of counting a single flashing light instead of the multiple-light display used in this study. A DRL intensity range of 250 to 2000 cd was used by Kirkpatrick et al.

A comparison of mean detection distance versus DRL intensity for the two studies is shown in Figure 7. The two data sets are remarkably similar, given the many sources of variation in such experimentation. A comparison between the two studies with data categorized into low and high ambients (as defined earlier) also showed general agreement.

Hörberg (*29*) reported a peripheral detection (DRL vehicle at 20 degrees) study under twilight conditions in which illuminance varied from 100 to 2000 lx (about 9.3 to 186 fc). His results showed that a 300-cd DRL enhanced detection below illuminances of about 800 lx (about 74 fc). Because his highest ambient level was several times less than the lowest level typically encountered in the present study a direct comparison is not possible. However, a rough comparison can be made by considering only runs in the present study with HILLUM below 10 760 lx (1,000 fc).

A total of 30 such runs existed: 10 at a DRL intensity of 1600 CD and 5 at each of the other DRL intensities. These data suggest that for HILLUM less than 10 760 lx (1,000 fc), detection was improved at DRL intensities as low as 400 cd, with a large mean increase in detection distance occurring at 1600 cd. Thus, the present results are in agreement with Hörberg at the lower ambient levels.

DISCUSSION OF RESULTS

The experimental task used in this study required detection of the DRL vehicle in the near periphery of the observer's visual field. The 20-degree angle selected is large enough to be outside the visual cone of immediate priority to the driver but still within an area of concern for possible hazards. The nature of the task used emphasizes the role of DRL in attracting attention (conspicuity) as opposed to providing improved perceptual information to the driver once a DRL vehicle is noticed and attended to. Because of the lower probability of detection at a 20-degree angle than at, say, within a 5-degree range, the results of this study will be conservative—

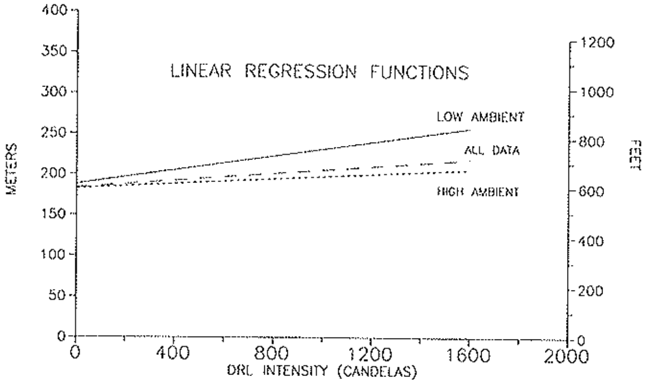

FIGURE 6 Detection distance versus DRL intensity.

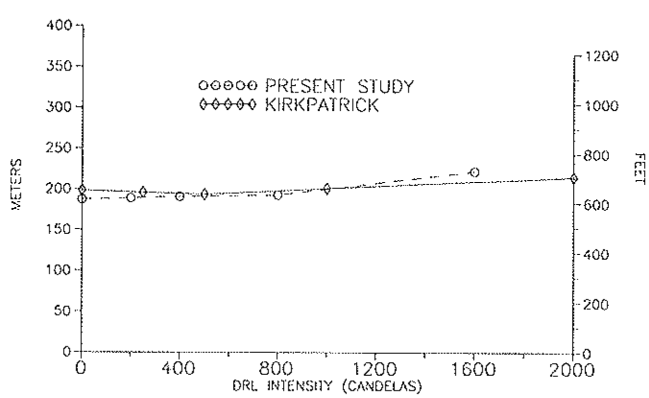

FIGURE 7 Comparison of present study with study by Kirkpatrick et al. (*15*).

that is, DRL intensities and ambient conditions for which DRL proved beneficial in this study will almost certainly enhance conspicuity for comparable conditions in which a DRL vehicle occurs at angles smaller than 20 degrees. Examination of DRL effectiveness at peripheral angles greater than 20 degrees is of interest; the single angle used in this study represented a compromise between including additional viewing angles versus obtaining an adequate number of data points for each DRL intensity.

The subjects' focus of attention on the flashing light task required more concentrated attention than one would expect from a "typical" driver who would normally be scanning the visual scene in front of him or her. Thus, many drivers would have been likely to detect the DRL vehicle at longer ranges or, possibly, at lower DRL intensities than are indicated by these results. However, the attention required in this study is not unlike that needed by a driver in a difficult traffic situation or a driver who is distracted or otherwise occupied by driving or nondriving tasks.

This study did not address the issue of DRL effectiveness for scenarios in which the driver's task primarily involves perceptual and decision-making functions. For example, the issue of DRL usefulness in assisting passing maneuvers in the face of oncoming traffic would involve questions of distance, speed, and time estimation as well as detection of an oncoming vehicle.

The results for age are difficult to interpret given the known degradation in visual performance with age. It was noted during the study that the older age group consisted primarily of professionals who were retired but still active and who appeared to be highly motivated. Thus, motivational factors might have compensated for any decrease in visual function due to age.

CONCLUSIONS

For the DRL intensity levels evaluated in this study, 1600 cd was the minimum intensity required for achieving increased peripheral detection over a range of ambients that are representative of much U.S. driving.

Within the range of DRL intensities studied, DRL was primarily effective for enhancing peripheral detection at lower ambients, although a trend toward improvement does occur at higher ambients.

For the low ambient range and 1600-cd DRL, a mean improvement in detection distance of 75 m (247 ft) was found. This corresponds to about 3 sec at 88 km/hr (55 mph), a substantial amount of additional time for a driver to perceive and respond to a possible hazard.

A horizontal illuminance level of 43 040 lx (4000 fc) appears to be a reasonable division between low and high ambient conditions.

By themselves, the results of this study suggest that 1600 cd should be considered a minimum level for DRL intensity under conditions of higher ambients. However, a final decision as to the appropriate DRL intensities for any geographical area must also consider the amount of accident reduction likely as a function of ambient levels, the distribution of driving miles versus ambient level, possible glare problems at twilight and dawn ambient levels, cost of DRL implementation and maintenance, compatibility with the international standards community, and other trade-offs between DRL benefits and costs.

ACKNOWLEDGMENTS

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