VISIBILITY ASSESSMENT OF REAR LAMPS IN DAYTIME FOG

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Abstract: In dense fog, the visibility of a vehicle's rear lamps is of fundamental importance. However, few studies have addressed the visibility of rear fog lamps in daytime fog. The present study evaluates the contrasts of tail lamps, brake lamps and rear fog lamps. An experiment was performed in 2001 at a parking lot on Mt. Fuji Parkway in Japan. A vehicle equipped with a data-recording system was used as the data measurement station. Luminance, illuminance and transmissivity in fog were simultaneously recorded at intervals of 2 minutes. Three types of tail lamp, three types of brake lamp and two types of rear fog lamp were used, with an observation distance of 50.0 m. The recorded data showed the background luminance in fog to be affected by illuminance and transmissivity in the daytime. A multiple regression model was applied to determine the background luminance. Contrasts were calculated using this model. Tail lamp visibility was low in deep fog in daytime. Under the same conditions, the rear fog lamps had higher visibility than both the tail lamps and the brake lamps. It was found that the rear fog lamps could provide sufficient visibility in daytime fog.

Key Words: Rear fog lamp, Fog, Visibility, Driver, Daytime

1. INTRODUCTION

In Japan, many expressways pass through foggy areas (JH, 2002), and consequently, drivers must contend with hazardous conditions that arise from fogginess. In dense fog, delineators must have adequate visibility in order to provide road geometry cues. Allen et al. reported drivers' visibility requirements for roadway delineation (Allen, 1977). Under the adverse visibility conditions of fog, steering performance can be improved with these measures: by increasing delineation contrast to achieve a longer visual range, and by enhancing the quality of the delineation configuration through increasing the segment-to-gap ratio and decreasing the segment cycle length. In fog, the effect of scattering on roadway delineation is greater than that of attenuation: Scattering reduces contrast and desaturates colors (Shepard, 1996). Heiss,1976 described the effectiveness of various types of lane and roadside delineators as visual aids in fog and proposed that luminous intensity of delineators be made adjustable in order to compensate for the ambient light level and fog density. Hagiwara et al., 1996 conducted an experiment to evaluate the visibility of two types of laser beam as a function of fog density. The results showed that laser beams provided sharp visible lines in dense fog; however, the observation angle was too narrow and the luminance of laser beams was not sufficient for daytime visibility. Hagiwara, et.al., 1998 proposed an illuminated delineator that uses fiber optics (FO delineator. The FO delineator provided sufficient visibility distance in dense artificial fog both in daytime and at nighttime. A highly scattered luminance was not generated in dense artificial fog if the brightness of the FO delineator was maximized.

In the field, numerous warning signs and illuminated delineators are installed at side of the road. However, as some literature indicates, there are doubts as to whether these countermeasures are effective in low visibility conditions. Taniguchi, et.al., 2001 used a questionnaire survey to investigate which is visible to the driver. The main objective of this investigation is to determine what kinds of cue on the road or side of the road are helpful to driving under blowing snow conditions. The results indicated that most drivers answered that rear lamps of the leading vehicle were very helpful for road alignment guidance. Also, illuminated traffic control devices were effective at night.

A review of the literature shows that lighting sources for roadside delineators in fog should be of high intensity and have a low scattering effect. Lights of this kind can improve driver visibility and provide exact information to the driver on the scattering and attenuation conditions of fog. In addition, drivers said that existing lighting sources were not sufficiently visible during hazardous conditions in daytime. High intensity rear lamps could be a major countermeasure to restricted visibility in fog. However, few studies have dealt with the visibility of rear lamps in daytime fog. We carried out field observations to understand how fog affects the visibility of rear lamps in daytime. The objectives were:

1) To estimate the contrast of rear lamps in daytime fog by using a background luminance estimation model with the illuminance and the transmissivity as explanatory variables.
2) To assess the effects of luminous intensity in daytime fog on driver visibility of rear lamps.

2. METHOD

2.1.Experimental Site and Subjects

The experiment was conducted at a parking lot on Mt. Fuji Parkway. The elevation of the parking lot was approximately 1000 m. The main reasons for selection of this location were the frequent occurrence of fog and the availability of straight, paved road. Access to the parking lot was restricted. Observation was carried out from June 24 to 30, 2001, but among the seven days, there was only one foggy day. Therefore, this study used only the data collected from June 27. Four young men (average age: 26 years) participated in the experiment for subjective visibility assessment. All subjects had normal visual acuity and normal contrast sensitivity. All subjects had a valid Japanese driver license.

2.2.Targets

Eight types of rear lamp were investigated: three of brake lamp, three of tail lamp and two of rear fog lamp. The experimental vehicle supplied the power for these devices. Table 1 shows the specifications of these lamps. Luminous intensity of tail lamps varied from 4.5 cd to 16.5 cd; brake lamps, from 60 cd to 153 cd; and rear fog lamps, from 212 cd to 241 cd. Rear fog lamps had over ten times the luminous intensity of tail lamps.

Figure 1 shows the configurations of the eight types of rear lamp. In Japan, white is the most common body color of passenger vehicles. A white board (1.8 m wide x 1.4 m high) simulated the rear of the leading vehicle. All rear lamps were installed on the white board, and were set 0.6 m above the ground. To assess the visibility of the targets in fog, luminance of the fog itself should be measured. However, this measurement requires a fixed black background because the luminance of fog could depend on the characteristics of the background (Hagiwara, et al., 2000). Therefore, a black board (0.9m wide x 1.3m high) was set at left side of the white board. As shown in Figure 2, the background in this study was defined as 0.2 degrees in diameter.

Table 1 Illuminance intensity and size of the eight rear lamps using in this study.

Lamp	(1)sstop	(2)stail	(3)srfog	(4)isstop	(5)istail	(6)rstop	(7)irtail	(8)irfog
Intensity (cd)	153	16.5	241	60	4.5	72.1	5.99	212
Area (cm^2)	186	186	56.5	92.8	92.8	98.9	98.9	63.1
Luminance (cd/m^2)	8226	887	42655	6466	485	7290	606	33597

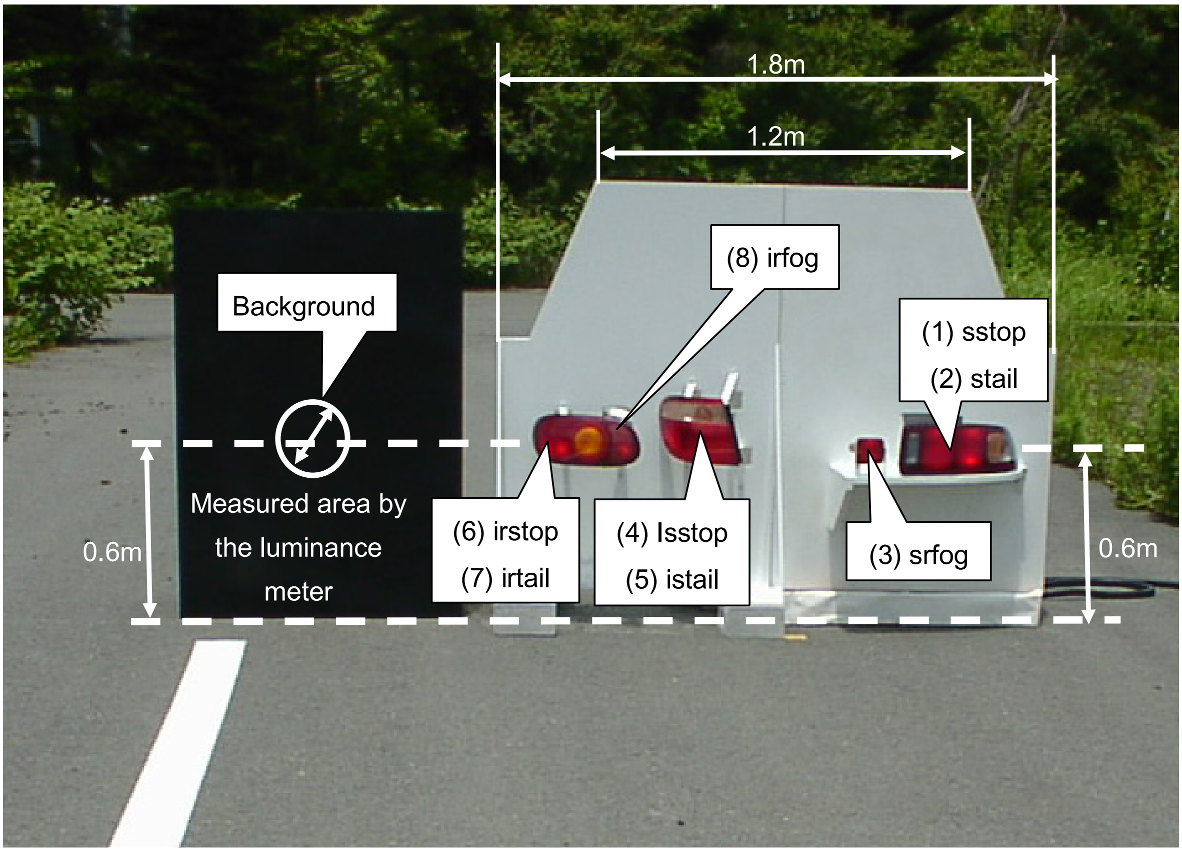

Figure 1. Configuration of eight rear lamps and backgrounds.

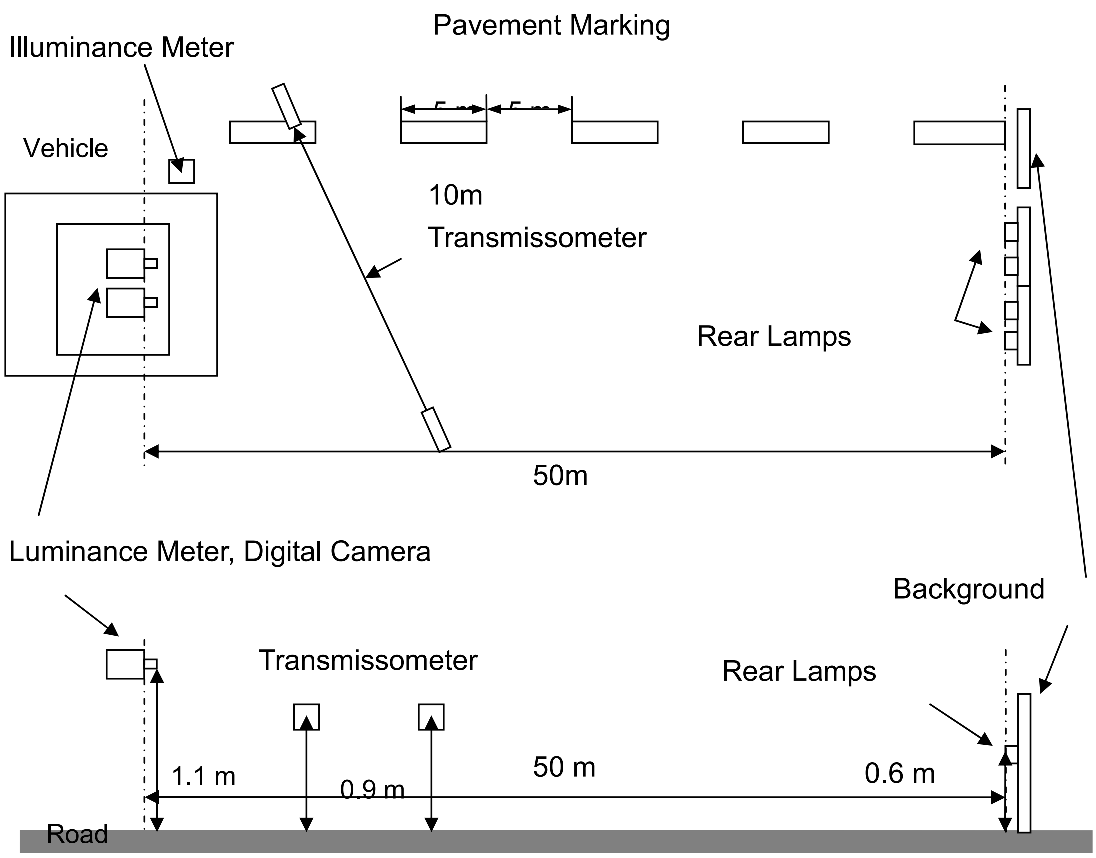

Figure 2. Location of measurement devices at experiment site.

2.3. Measurement devices

Figure 2 shows the locations of measurement devices and rear lamps at the experiment site. A 1985 Toyota Camry with a windshield transmissivity of about 0.8 was used as the data measurement station. Low beams were left on during experiments. A luminance meter, a digital camera and a laptop computer were installed in the vehicle. The experimental vehicle supplied the power for these devices. The luminance meter (Topcon BM-8) measured the luminance of the black board. The viewing angle of the luminance meter was set at 0.2 degrees. The illuminance meter (Minolta T10) was located on the left side of the vehicle, and recorded horizontal illuminance. The digital camera (Canon EOS-DCS3) recorded the still image of targets. A transmissometer shown in Figure 2 was placed diagonally across the measured area. The projector unit and the photometric unit were set 0.9 m above the ground, with a distance of 10 m between them. The direction of these units was adjusted so that the output was 10 volts under clear conditions.

2.4. Data recording systems

Two laptop computers were used to record data and to control lighting of the lamps. Figure 3 shows an overview of this recording system. The two laptops were connected via a wireless LAN. LabView 6.0 was employed to develop this data recording system. The first laptop computer on the Toyota Camry simultaneously recorded the values for luminance, illuminance, and transmissivity. This laptop also controlled the digital still camera. The second laptop was set up in the second vehicle at the side of the white board. This laptop controlled the lighting of eight rear lamps. The cycle for each measurement lasted about 2 minutes. At the beginning of each measurement, the first laptop sends a command via wireless LAN to the second laptop to activate a light. The second laptop then turns one rear lamp on. After a few seconds, the first laptop simultaneously triggers the shutter of the digital still camera and records luminance, illuminance, and transmissivity.

2.5. Subjective visibility assessment of rear lamps

The subjects were seated in the vehicle, where they were first given instructions regarding the regarding glare range due to daytime fog. In the experiment, the first laptop announced the stimulus number through speakers. The duration of each stimulus presentation was 10 seconds, followed by a 2-minute rest period. After looking at the target, the subjects entered a rating on a paper form. Numerical values (1-10) were assigned to scale positions during data analysis in the laboratory.

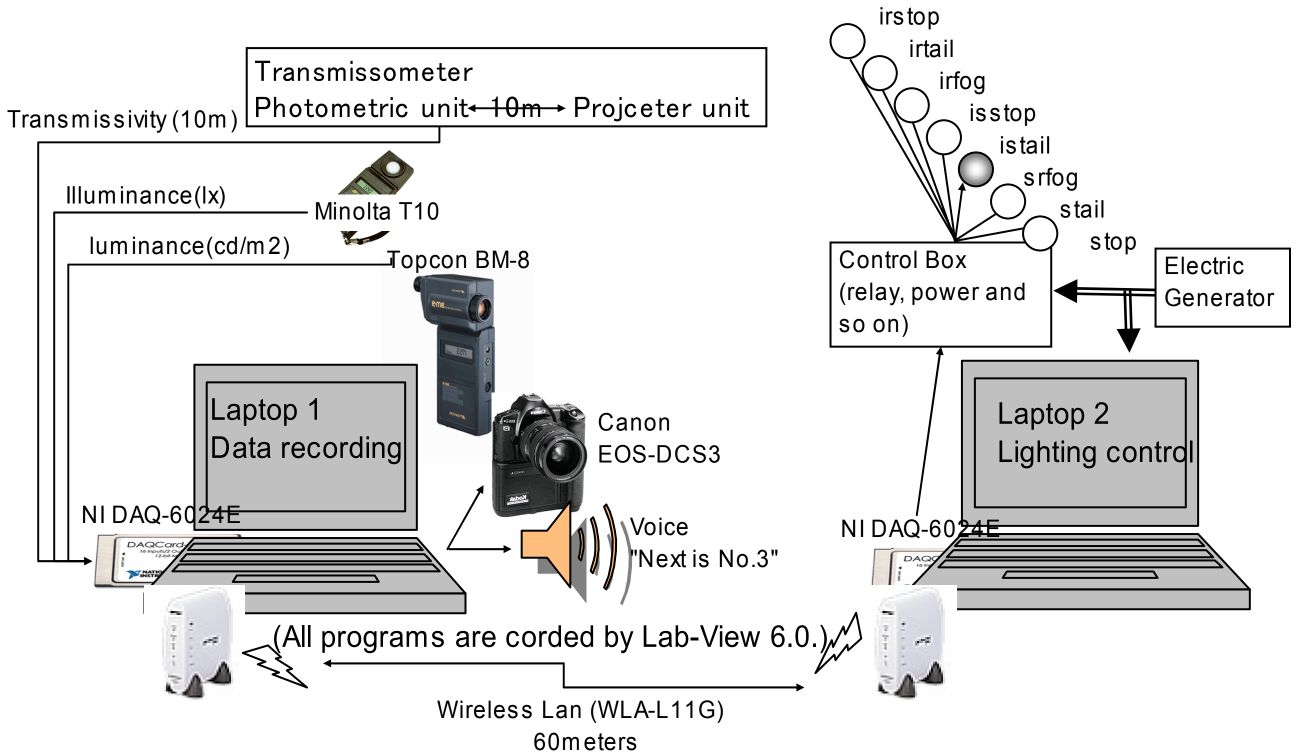

Figure 3 Data recording systems

3. RESULTS

3.1. Selecting Recorded Data

Although the experimental site was monitored around-the-clock from June 26 to 30, only day that had deep fog in the daytime was June 27, from 11 a.m. to 1 p.m. Data analysis focused on data recorded during this time period. Incomplete data, as well as data under clear conditions, i.e. transmissivity less than 5% at 10 m, were removed. Therefore, this study used only 111 data collected from 10:51 to 12:22 on June 27, 2001. Each piece of data includes background luminance (luminance of the black board), illuminance, transmissivity at 10 m, the digital still image, and the subjective visibility assessment of the targets.

Figure 4 indicates 111 data distributed by luminance and transmissivity. Illuminance values ranged from 2,500 lx to 10,000 lx. Transmissivity at 10 m ranged from 30% to 95%. The size of a circle indicates the value of the background luminance. Size increases with background luminance. The background luminance tends to vary inversely with transmissivity. Figure 4 indicates that background luminance tends to increase as illuminance increases.

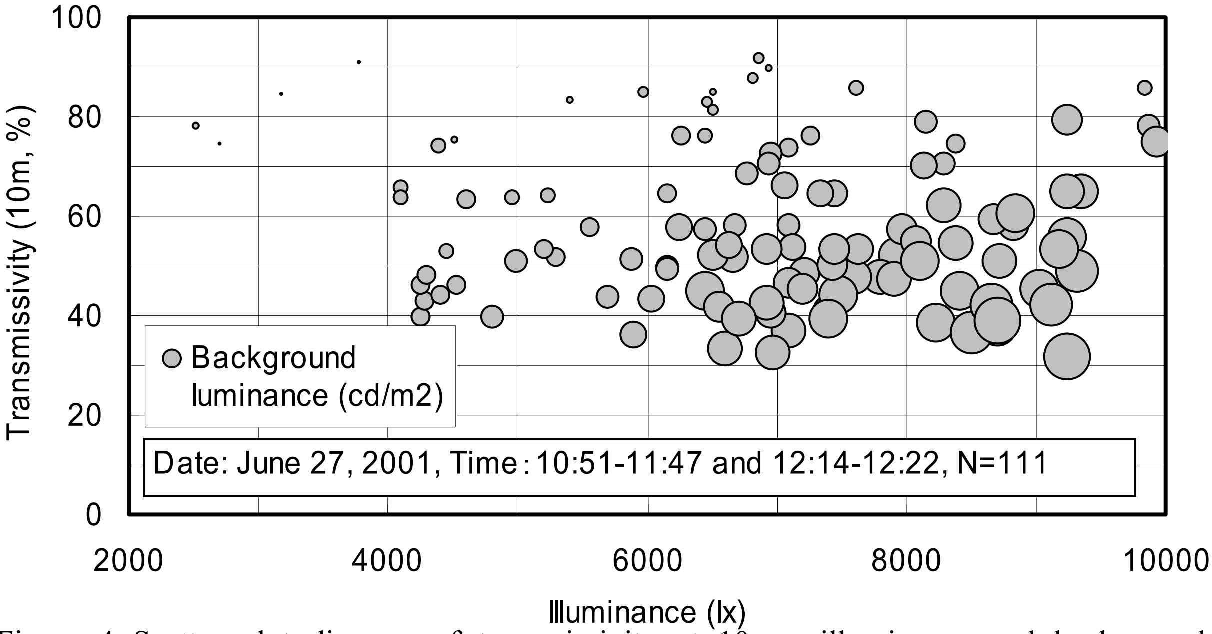

Figure 4 Scatter plot diagram of transmissivity at 10 m, illuminance and background luminance.

3.2. Subjective Visibility Assessment of the Targets

Figure 5 shows the relationship between transmissivity at 10 m and subjective visibility assessment as a function of eight rear lamps. Subjective visibility assessment is an average of the values reported by the four subjects. The maximum is 7 (sufficiently visible), and the minimum is 1 (invisible). Data are plotted in Figure 5 as three groups. Squares indicate subjective visibility assessments for two rear fog lamps; triangles for three stop lamps; and diamonds for three tail lamps.

The subjective visibility assessment value tends to decrease as the transmissivity decreases, for all three types of rear lamps. The subjective visibility assessment value increases with the luminous intensity of the rear lamps. Among the same type of rear lamps, lamps with stronger luminous intensity exhibited larger values. In the case of the rear fog lamps, the subjective visibility assessment value was over 5 for any transmissivity at 10m. Compared with the other two types of the lamps, the downtrend of subjective visibility assessment values as a function of transmissivity was not so sharp for rear fog lamps. In the case of stop lamps, the downtrend of subjective visibility assessment value as a function of transmissivity was almost straight. Under light fog conditions, the stop lamps indicated large subjective visibility assessment value. However, under deep fog conditions when the transmissivity was less than 50%, the subjective visibility assessment was around three. The subjective visibility assessment values of the tail lamps were the lowest among three lamp groups. Under deep fog conditions, the visibility assessment reached the lowest value. The tail lamps were invisible under such conditions.

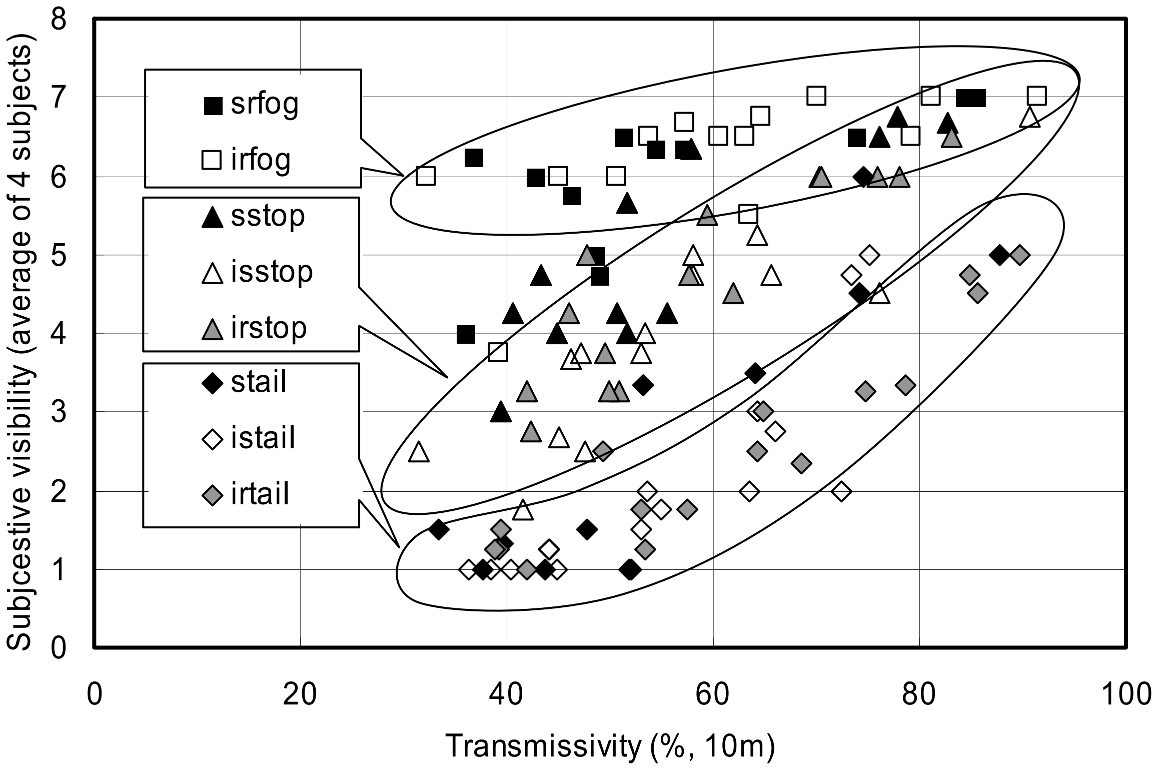

Figure 5 Subjective visibility assessment value versus transmissivity at 10 m as a function of the eight rear lamps.

3.3. Contrast of the targets during fog

The luminance difference and the luminance contrast (referred to simply as contrast) are well known as indexes for visibility performance. In this study, contrast is selected due to the uniformity of the background luminance and daytime conditions. Contrast is usually defined as:

$$Contrast = \frac{|L_T - L_b|}{L_b} \qquad (1)$$

where L_t (cd/m^2) is the luminance of the target and L_b (cd/m^2) is the luminance of the background.

The luminance of the targets could not be measured easily in the field due to the small size of the targets. Hagiwara, et. al., 2000 proposed a method to estimate the contrast under fog conditions without measuring the luminance of the targets directly. In this method, luminance of the rear lamp is the sum of the lamp luminance and the background luminance (luminance of the fog itself). Thus, contrast of the lamp is defined with the equation:

$$Contrast = \frac{|(L_{tf} + L_{bf}) - L_{bf}|}{L_{bf}} = \frac{L_{tf}}{L_{bf}} \qquad (2)$$

where L_{tf} (cd/m^2) is the luminance of lamp in daytime fog and L_{bf} (cd/m^2) is the background luminance in daytime fog.

The luminance of the targets in daytime fog is calculated using the following equation:

$$L_{tf} = \varepsilon \times \frac{I}{A} \qquad (3)$$

where L_{tf} (cd/m^2) is the luminance of lamp in the daytime fog; I (cd) is the luminous intensity of lamp; A (m^2) is the area of lamp; and ε is the transmissivity with respect to the length of the observation path.

Table 1 shows the luminance of all eight lamps without fog ($\varepsilon = 1.0$) calculated by equation (3). The transmissivity was given by the visual range. An equation developed by

Koschmieder, 1942 was used to convert the visual range into the transmissivity and vice versa.

$$\varepsilon = \exp(-\frac{x}{V} \times \ln(1/c_0)) \quad (4)$$

where, ε is the transmissivity; V is the visual range (m); x is the observation distance (m); and c_0 is the threshold contrast (0.02).

In equation (2), luminance of the black board was used as the background luminance. As shown in Figure 4, the illuminance and the transmissivity affected the background luminance. The effect of the transmissivity and the illuminance on the background luminance was modeled via a multiple regression equation. Equation (5) is the result of the multiple regression model in which the background luminance is the objective variable.

$$L_{bf} = -0.09688x1 + 0.000928x2 + 5.760752 \quad (5)$$

where L_{bf} : background luminance (10^2, cd/m^2); x1: transmissivity (at 10 m); and x2: illuminance (lx).

Table 2 shows the results of the multi-regression analysis. T-values of the transmissivity and the illuminance exceeded 10. The coefficient of determination was 0.907. Figure 6 shows the relationship between estimated results and measured results. No distortion can be seen and errors are distributed normally around the center line.

Table 2 Results of the multi-regression analysis.

Correlation coefficient	0.95
Coefficient of determination	0.91
Correction coefficient of determination	0.91
Standard error	0.709086
Number of data	111

	Coefficient	Standard error	t-value	P-value
Constant	5.7607517	0.35	16.2	0
Transmissivity (10m, %)	-0.096882	0.0039	-24.9	0
Luminance (lx)	0.0009276	0	25.1	0

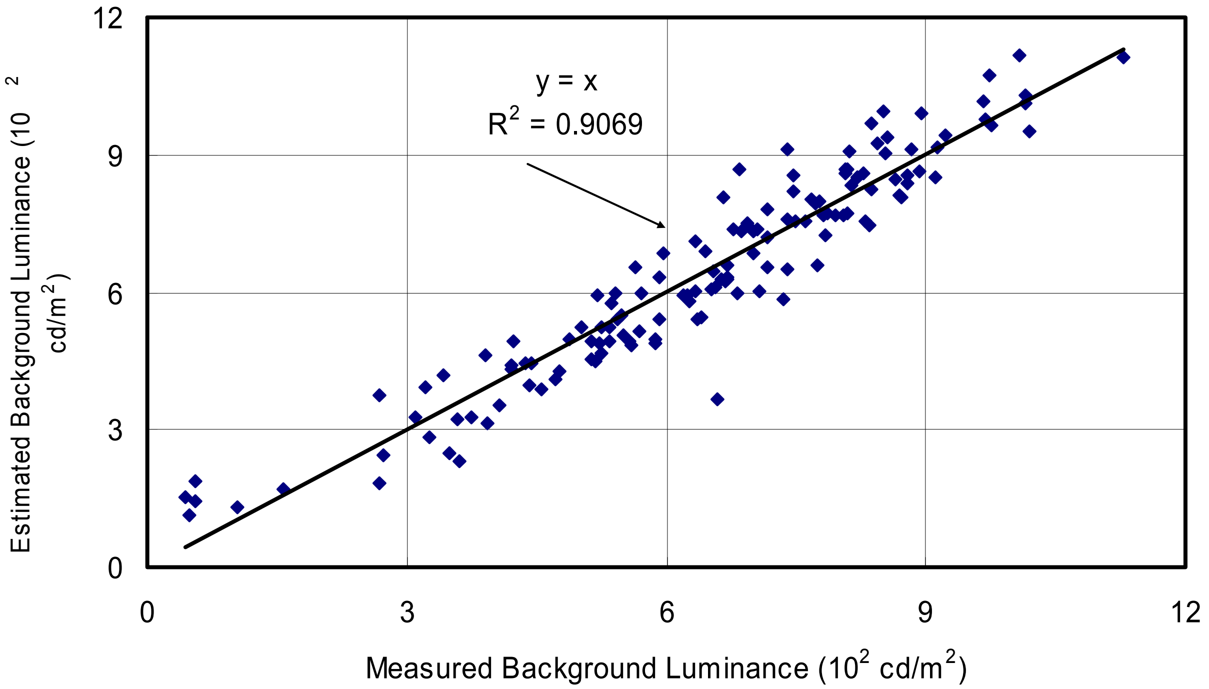

Figure 6 Correlation between measured background luminance and estimated background luminance by the multi-linear regression model in daytime fog.

3.4. Contrast versus subjective visibility assessment value

Figure 7 shows the relationship between the contrast of the eight rear lamps and the subjective visibility assessment values. The contrast of the eight rear lamps was obtained from equation (2). Markers in Figure 7 show the types of rear lamp. When contrast was less than 0.1, the subjective visibility assessment value did not exceed three. These targets were almost invisible. The tail lamps make up a high proportion of these data. When contrast was more than 0.1 and less than 1.0, subjective visibility assessment values ranged from three to six. These targets were not invisible but were not sufficiently visible. The stop lamps comprise a high proportion of these data. When contrast rose above 1.0, subjective visibility assessment values almost equaled sufficiently visible. It was possible that the subjects experienced some glare. These data belonged to the rear fog lamps.

In addition, Figure 7 shows a threshold contrast as a vertical line. Blackwell's threshold contrast, 1946 was used because the background luminance was almost uniform in fog and was close to the adaptation brightness. Threshold contrast is defined as the contrast that is detected with a probability of 50 percent. The threshold contrast is estimated from the visual angle of the target and the background luminance. However, the background luminance did not reveal large effects on the threshold contrast under bright conditions. In Figure 7, the background luminance was fixed, and its value was 100 cd/m^2. The size of the target was determined to be the minimum diameter (0.2m) among the eight rear lamps. The threshold contrast was 0.3.

The rear lamps become visible when the contrast exceeds the threshold contrast. As shown in Figure 7, when the contrast was lower than the threshold contrast, the indicated subjective visibility assessment value was less than 2. Because of this correlation, it may be allowable to assess the visibility of the target by using the contrast calculated by equation (2).

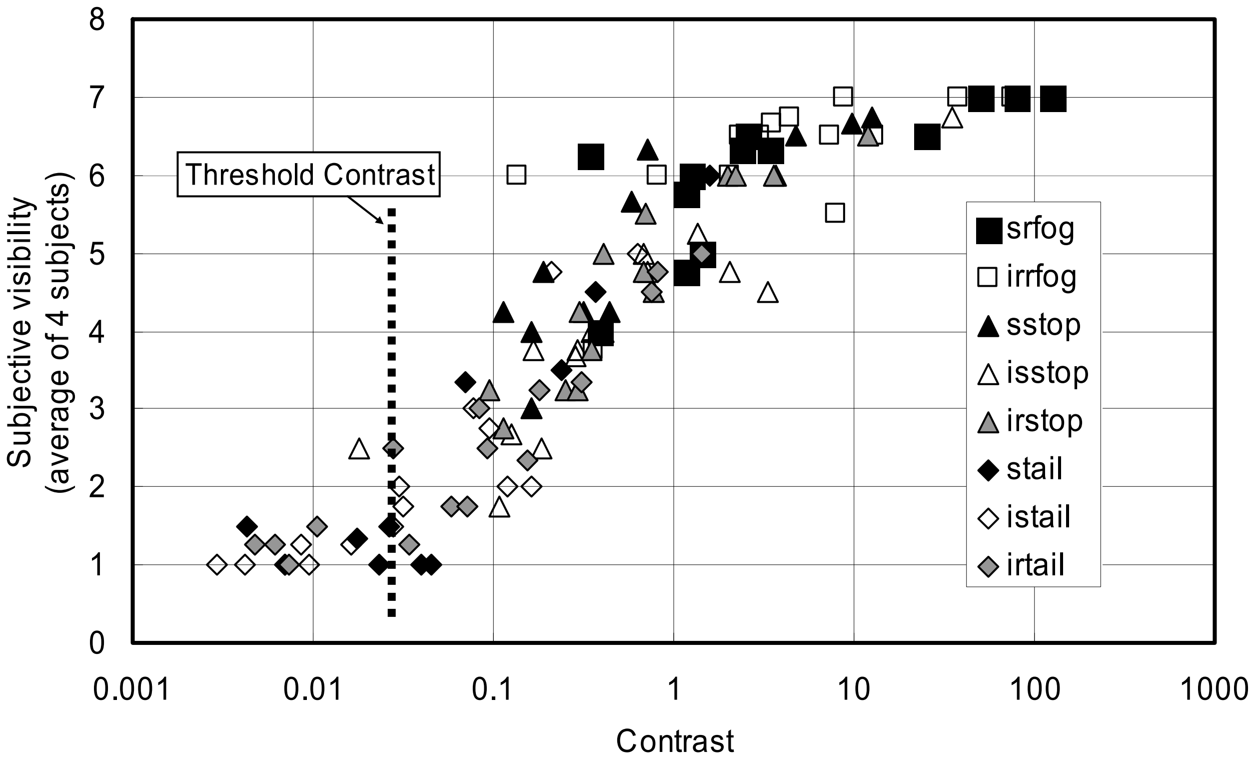

Figure 7 Calculated contrast versus subjective visibility assessment in daytime fog.

3.5. Visibility estimates of rear lamps in daytime fog

This section compares the visibility performance among three types of the rear lamps based on results described in this study. Detectable distance when contrast of the target reaches a critical value is defined as visibility performance of the target. It is reasonable for a critical contrast for detectable distance to be 0.1. The threshold contrast is less than 0.1. However, the drivers could not detect such a low contrast target under real driving conditions. The background luminance was estimated by equation (5). The contrast of the rear lamps was calculated using equation (2) as a function of visual range and observation distance.

Four visibility conditions were assumed for conducting the comparison of visibility performance among the three types of the rear lamps. Visual range varied from 30 m to 200 m. A visual range of 50 m in fog is one criterion for traffic suspension on highways in Japan (JH, 2001). Very low visibility conditions might occur in localized areas before traffic is halted. Next, the visual range of 30 m is added. There were four illuminance conditions; 3000 lx, 5000 lx, 7000 lx and 10000 lx.

Figure 8 shows estimated detectable distances when contrast is 0.1 as a function of the visual range. The plotted marks indicate the eight types of rear lamps. The illuminance condition was 5000 lx. Detectable distance decreased rapidly as visual range decreased. When visual range was less than 50 m, detectable distances of the tail lamps were very short compared with the other two types of rear lamps. The rear fog lamps had larger detectable distances than the stop lamps. Also, detectable distances of the rear fog lamps were more than twice those of the tail lamps. Differences in luminous intensity among the same types of the rear lamp did not manifest large effects on detectable distance.

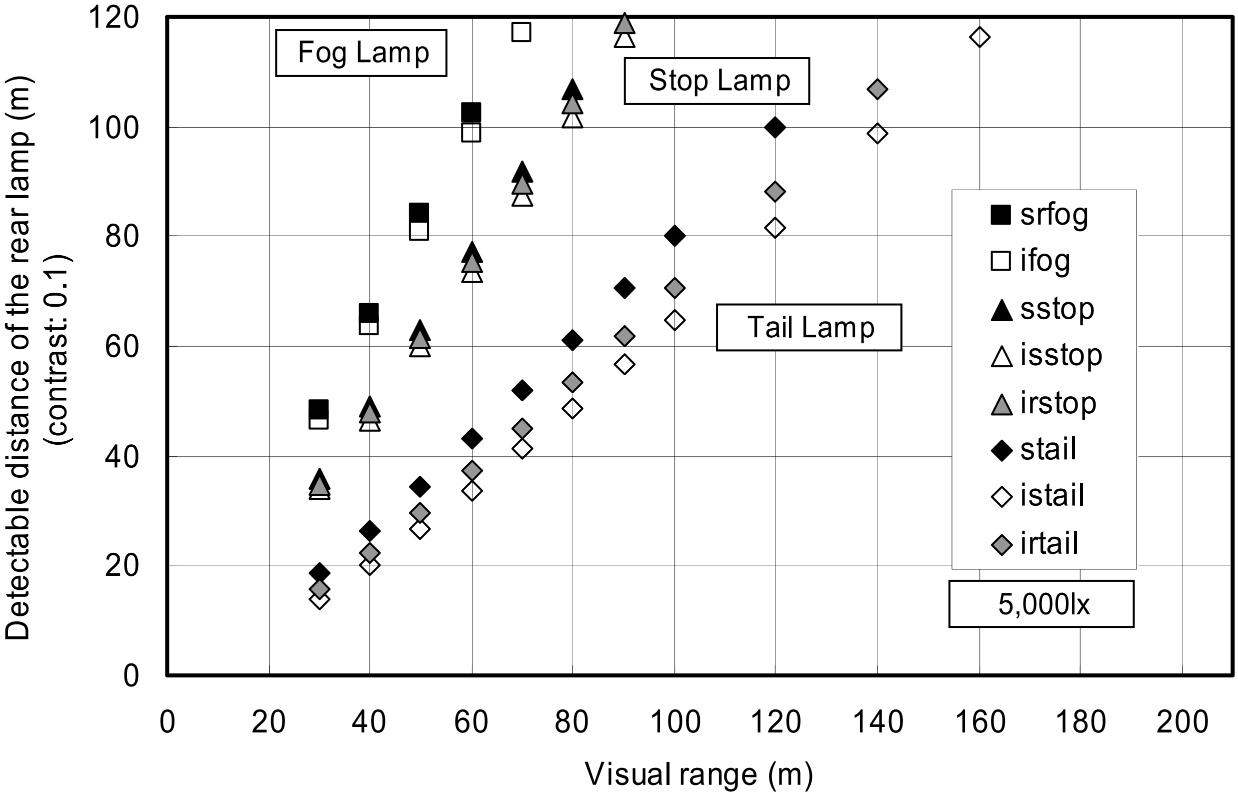

Figure 8 Visual range versus detectable distance calculated by equation (2) when contrast of the rear lamp is 0.1. (visual range: 30 m to 200 m, illuminance: 5,000 lx)

Figure 9 shows the effect of illuminance on detectable distance. As shown in equation (2), illuminance reduces the contrast of the target. Four illuminance conditions were selected. Figure 9 showed the results for the three different types of rear lamp according to slight differences in detectable distance among the same types of rear lamp. Differences in distance among the four illuminance conditions tended to increase as visual range increased. Under low visual range conditions, the effect of difference in illuminance between 10,000 lx and 3,000 lx on detectable distance was almost equivalent to a 20 m difference in visual range. In the case of 10,000 lx, detectable distance of the tail lamp was close to 10 m when visual range was less than 30 m. Under the same conditions, that of the stop lamp was almost 30 m, and that of the rear fog lamp was almost 40 m. The driver might not notice the tail lamp before colliding with the leading vehicle. These differences are thought to be due to the difference in luminous intensity among three rear lamps.

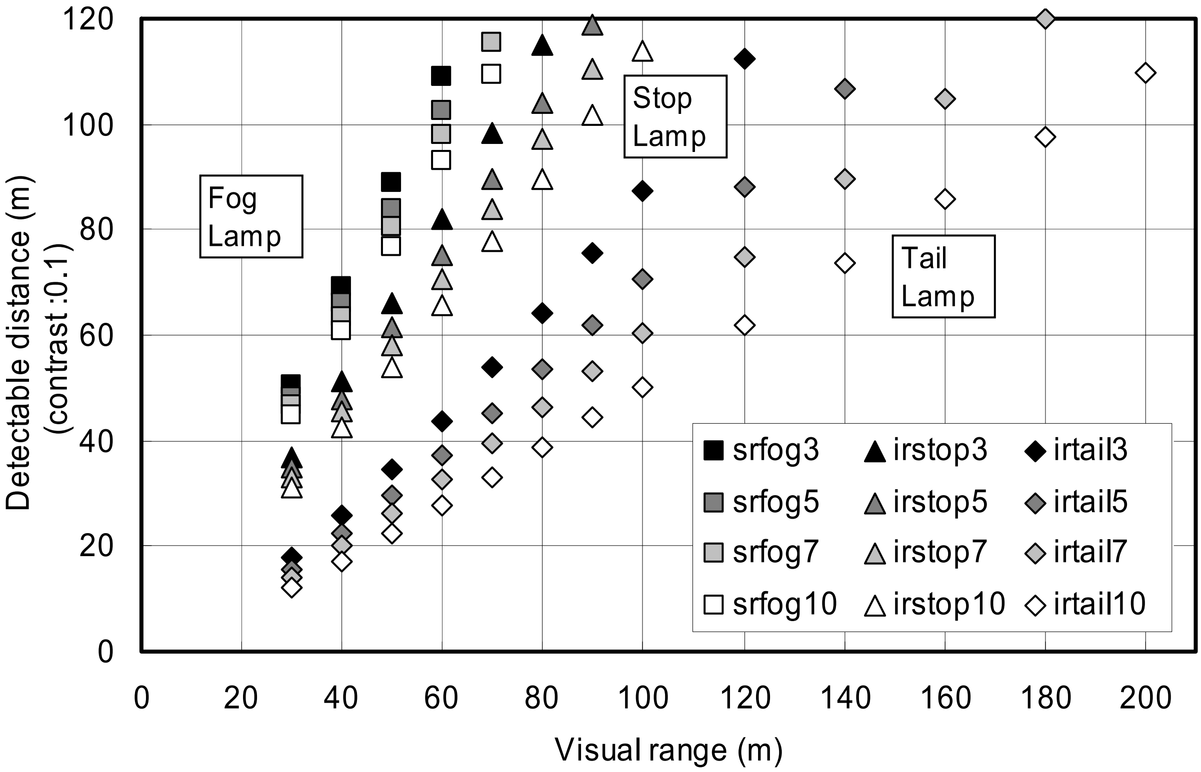

Figure 9 Effect of illuminance conditions on detectable distance as a function of visual range.

4. CONCLUSIONS

In this study, the field experiment was conducted to assess the visibility of the three types of rear lamps: tail lamps (three), stop lamps (three) and rear fog lamps (two). The four subjects assessed the visibility of these lamps in daytime fog under static conditions. The rear fog lamps indicated sufficient visibility performance in the daytime fog. However, the tail lamps were almost invisible under low visibility conditions of daytime fog. To assess the effectiveness of luminous intensity on visibility performance, a model for estimating the background luminance in daytime fog was developed based on measurements of the background luminance under various environmental conditions of transmissivity and illuminance. This result was the same as Hagiwara, et. al., 2001 indicated.

Contrasts of eight types of rear lamp were calculated using this model. When subjective visibility assessment reached invisible, estimated contrast coincided with the threshold contrast of Blackwell. Detectable distances of the rear lamps were estimated using calculated contrast. In this study, detectable contrast was 0.1 according to measured results. It was quite difficult for the tail lamp to achieve sufficient visibility during dense fog in daytime. However, the rear fog lamps could provide sufficient visibility under severe conditions. Moreover, the contrasts of rear fog lamp were 10 times greater than those of the brake lamps.

Also, to increase visibility performance of the rear lamps, the illuminance condition should be considered for low visual ranges. From this study, it might be concluded that all vehicles should be equipped with rear fog lamps.

However, this study did not consider buses and trucks. Drivers following buses or trucks could be exposed to lower visibility conditions. There are many aspects to consider, such as type and position of lamp, shape of vehicle body, and type of the pavement. Furthermore, this study did not mention the effect of visibility performance on driving behavior like distance between two cars, speed, and lateral movement fluctuation. We need to clarify these problems in the near future to improve highway safety.

ACKNOWLEDGEMENTS

This research was supported by the Sagawa Transportation Social Foundation. The experiment was conducted in collaboration with the Japan Auto Parts Industries Association. The authors gratefully acknowledge the technical support of Koito Manufacturing Co., LTD., Stanley Electric Co., LTD. and Ichiko Industries, LTD.

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