THE INFLUENCE OF TRUCK DRIVER EYE POSITION ON THE EFFECTIVENESS OF RETROREFLECTIVE TRAFFIC SIGNS

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16. Abstract

The amount of light reflected from a retroreflective traffic sign decreases with an increase in the observation angle--the angle between the headlamp, the sign, and the eyes of the driver. Mainly because of the increased seated eye height of truck drivers, the actual observation angles are greater for them than they are for car drivers. Consequently, there is concern about the impaired detection and legibility of retroreflective signs for truck drivers.

The present study evaluated the relative amount of light reaching drivers of different types of vehicles by using survey data collected in 1989 by the Transport and Road Research Laboratory (TRRL) in England. The TRRL data included driver eye heights and headlamp mounting heights for 445 vehicles. The present analysis considered three sign locations on a straight roadway: left shoulder, center, and right shoulder. Two viewing distances were included: 152 m (500 feet) (typical of a sign-legibility distance), and 305 m (1000 feet) (typical of a sign-detection distance). The analysis considered both the differential amount of illumination impinging on the signs from headlamps of trucks and cars, as well as the differential amount of the light reflected from the signs in the direction of truck drivers and car drivers.

The main results are that for the viewing distance of 152 m, the amount of light reaching a truck driver can be as low as 25% of the light reaching a car driver; the corresponding percentages for the viewing distance of 305 m are as low as 68%. These reductions were then related to the expected effects on sign legibility and detection. The results imply that the increased eye height of truck drivers could have a major effect on the legibility of retroreflective traffic signs, but only a modest effect on their detection.

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INTRODUCTION

At the increased seated height of truck drivers, the nighttime brightness of retroreflective traffic signs is adversely affected, and consequently their detection and legibility are diminished. This problem arises because retroreflective materials reflect light back towards the source of illumination in a narrow cone, with the highest intensity near the center of the cone along the axis of illumination. In the traffic situation, this means that retroreflective signs are most efficient at reflecting light directly back to the headlamps. For car drivers this is close to optimal, since the observation angles formed by the locations of the drivers' eyes, traffic signs, and headlamps are relatively small. Because of increased seated eye height, these angles are somewhat larger for truck drivers. Consequently, the amount of light reflected back to the eyes of a truck driver is substantially less than to the eyes of a car driver. While the preceding is not a new argument (e.g., Sivak and Ensing, 1989), we are not aware of any quantitative evaluation of the magnitude of the problem. The present study was designed to provide such an evaluation.

An additional relevant factor is the mounting height of headlamps. In general, the headlamps of trucks are mounted higher than those of cars. This leads to a difference between the two types of vehicles in the amount of light incident on the sign, although not enough to negate the effect of increased eye height on observation angle. Nevertheless, the present analysis took this difference into account.

The primary data for the present analysis were individual driver eye heights and headlamp mounting heights obtained by Cobb (1990) for a sample of 452 vehicles in England that included cars and trucks. The analysis involved the following steps, each performed for each vehicle type, two selected viewing distances, left and right headlamp, three mounting positions of traffic signs, and a typical retroreflective sign material: (1) calculate the angular location of the sign with respect to the headlamp, (2) using this angular information, estimate the relative amount of headlamp illumination *incident* on the sign, (3) calculate the observation angle, (4) using this observation angle and the retroreflective capability of a typical sign material, estimate the relative amount of light *reflected* towards the eyes of the driver for each headlamp, and (5) using the relative amounts of incident and reflected light, obtain the total light reaching the eyes of the driver.

APPLICABILITY OF COBB'S DATA TO THE U.S. SITUATION

The data from Cobb (1990) are appropriate for the present purpose, since they contain joint measurements of two variables of interest--driver eye height and headlamp mounting height--for each observed vehicle. Other potentially relevant studies (e.g., Cunagin and Abrahamson, 1979; Farber, 1982; Olson, Cleveland, Fancher, Kostyniuk, and Schneider, 1984) measured only driver eye height. To address the potential concern that the English vehicle population studied by Cobb might be substantially different from the U.S. vehicle population, the following two analyses were performed. The first analysis compared selected percentile values for car driver eye heights in Cobb (1990) with the corresponding estimates for the 1981 U.S. car population reported by Olson et al. (1984). This comparison shows a reasonable similarity between the two sets of data. For example, Olson et al. estimated that the eye height of 106.7 cm (42 inches) corresponds to the 25th percentile, while Cobb's 25th percentile is 110.0 cm (43.3 inches). Similarly, Olson et al. estimated that the eye height of 114.3 cm (45 inches) corresponds to the 79th percentile, while Cobb's 75th percentile is 115.5 cm (45.5 inches). The second analysis compared the ranges of headlamp mounting heights reported by Cobb for *all vehicles* with the current FMVSS mounting-height requirements (Office of the Federal Register, 1990). Again, there is reasonable correspondence between these two sets of data. Cobb's headlamp mounting heights range from 55 cm (21.7 inches) to 120 cm (47.2 inches), compared to the FMVSS limits of 55.9 cm (22 inches) and 137.2 cm (54 inches).

RELEVANT ASPECTS OF RETROREFLECTION

The amount of light reaching an observer from a retroreflective sign at a given distance depends on the amount of light incident on the sign, and the efficiency of the sign material to reflect light in the direction of the observer. The present analysis took into account both of these factors.

Incident light

Because of differences in mounting height of headlamps, a different part of the same headlamp beam, when mounted on a truck as opposed to a car, is directed towards a given point in space. To the extent that truck lamps are mounted higher, the amount of light reaching the sign might be greater for trucks. We evaluated this effect by (1) calculating, for each vehicle, the angular location of selected sign positions relative to the headlamp, and (2) using this angular information, estimating the amount of headlamp illumination incident on the sign from U.S.-type low beams. This analysis was performed for the left and right headlamp, and for each sign position.

Retroreflective efficiency

The retroreflectance of a given material towards a given point in space depends on its inherent efficiency and the geometry between the headlamp, the sign, and the observer. This geometry is characterized by a set of angles, including observation, entrance, rotation, presentation, and viewing angles (Johnson, 1979). However, for the traffic situations of interest in the present study (involving straight roadway and small entrance angles), observation angle is of dominant importance. The observation angle, in our situation, is the angle formed by the headlamp, the sign, and the eyes of the driver (i.e., the angle between the illumination axis and the observation axis). The observation angle must be quite small (2° or less; preferably 0.5° or less) for presently available retroreflective materials to function effectively. We calculated the observation angle for each vehicle, headlamp, viewing distance, and sign position, and used this information to estimate the relative amount of light reflected towards the eyes of the driver.

METHOD

Primary data

The primary data for this study, driver eye heights and headlamp mounting heights, came from a vehicle lighting survey performed in 1989 by TRRL (Transport and Road Research Laboratory) in England and reported by Cobb (1990). Cobb's report contains percentile information; raw data for the individual vehicles were provided to us by TRRL.

The survey involved measuring light output from all signaling lamps, aim of low-beam headlights, their output in two directions, as well as driver eye height and headlamp mounting height. The sample of 452 vehicles consisted of "178 cars (including 11 car-derived vans), 86 light goods vehicles (including 2 mini buses and 1 ambulance), 94 rigid heavy goods vehicles (including 2 coaches) and 94 articulated vehicles" (p. 5). The survey was conducted at several sites in southern England. The vehicles at these sites were selected at random, but participation was voluntary.

We relabeled the light goods vehicles to *light trucks*, and we combined heavy goods vehicles with articulated vehicles to form a group labeled *heavy trucks*. Of the 452 vehicles in Cobb's study, 445 were measured for both headlamp mounting height and driver eye height. Consequently, these 445 vehicles (165 cars, 94 light trucks, and 188 heavy trucks) constituted the sample in the present study.

Additional vehicular data

The observation angle depends not only on the headlamp mounting height, driver eye height, and sign position, but also on the lateral and longitudinal separations of driver eye position and headlamps. These dimensions were not included in the survey by Cobb (1990). Consequently, in our calculations we used these dimensions as parameters that depended on the type of the vehicle. These parameters (see Table 1) were selected to be reasonable values for current U.S. fleets.

Table 1. Parameter values in present calculations.

Vehicle Group	Lateral Separation Between		Longitudinal Separation Between Lamps and Driver Eyes
	Left Lamp and Driver Eyes	Right Lamp and Driver Eyes	
Cars	15 cm (6")	99 cm (39")	206 cm (81")
Light Trucks	18 cm (7")	112 cm (44")	206 cm (81")
Heavy Trucks	30 cm (12")	168 cm (66")	152 cm (60")

Effect of observation angle on retroreflectivity

Table 2 lists typical data relating observation angle to the amount of retroreflected light. The information in Table 2 is for encapsulated-lens material. [Another commonly used material--enclosed lens--is an inherently less efficient retroreflector, with a typical efficiency ratio of 3:1. However, both materials are highly sensitive to the observation angle (Johnson, 1979).] The information on the effect of the observation angle was provided to us by 3M for each of the seven standard traffic-sign colors. The data for each color were then normalized by setting the amount of reflected light for an observation angle of 0.1° to 1. Since all colors showed similar normalized angular effects, the normalized data for the seven colors were then averaged to produce the information in Table 2. This information indicates, for example, that if the coefficient of retroreflection at observation angle 0.2° is 300 cd/lux/m^2 (a typical value for a white encapsulated lens), then the corresponding coefficient of retroreflection at observation angle of 0.9° is only 26.4 cd/lux/m^2 (300 x 0.077/0.875).

Table 2. Relative reflectance as a function of observation angle for encapsulated-lens material. (Typical values obtained by averaging normalized data for the seven standard colors.)

Observation angle (°)	Relative reflectance
0.10	1.000
0.15	0.946
0.20	0.875
0.25	0.792
0.30	0.699
0.35	0.604
0.40	0.509
0.45	0.420
0.50	0.340
0.55	0.269
0.60	0.211
0.65	0.165
0.70	0.131
0.75	0.107
0.80	0.091
0.85	0.082
0.90	0.077

Sign positions

Three standard sign positions (right shoulder, center, and left shoulder) were used in the present calculations (see Figure 1). They all involved a straight, flat, two-lane roadway. These three sign positions were used as typical in recent studies by Woltman and Szczech (1989) and Sivak, Gellatly, and Flannagan (1991).

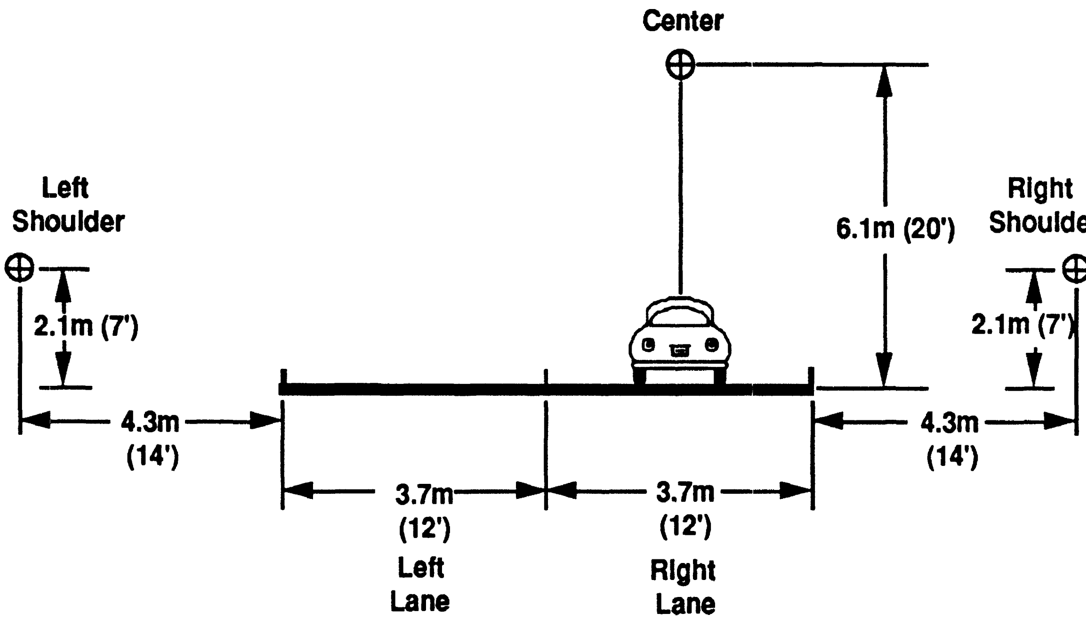

Figure 1. Sign positions (after Woltman and Szczech, 1989).

Viewing distances

We considered two viewing distances: 305 and 152 m (1,000 and 500 feet). The longer distance was selected as a reasonable *detection* distance for traffic signs, while the shorter distance as a reasonable *legibility* distance.

Headlamp illumination

The present calculations used a luminous intensity matrix of a U.S. low-beam headlamp (Westinghouse 6014) that was used in previous studies on legibility of traffic signs (Woltman and Szczech, 1990; Sivak, Gellatly, and Flannagan, 1991). The luminous intensity values were available in one-half degree steps. Interpolation was used to derive the intensity of the actual angles of interest. The same low-beam matrix was used for all types of vehicles.

RESULTS

This section summarizes the relevant data from Cobb (1990) and presents a step-by-step analysis of the amount of light reaching a driver who is either 152 m (500 feet) or 305 m (1000 feet) from the sign.

Headlamp mounting height and driver eye height

The data from Cobb (1990) on headlamp mounting height and driver eye height are summarized in Tables 3 and 4. The subsequent calculations are based on the mean data.

Table 3. Headlamp mounting height to the center of the lens (in meters) from Cobb (1990).

Vehicle Group	Headlamp Mounting Height			
	Mean	Minimum	Maximum	Standard Deviation
Cars	0.62	0.55	0.83	0.04
Light Trucks	0.76	0.56	0.95	0.09
Heavy Trucks	0.85	0.57	1.20	0.11

Table 4. Driver eye height (in meters) from Cobb (1990).

Vehicle Group	Driver Eye Height			
	Mean	Minimum	Maximum	Standard Deviation
Cars	1.14	1.00	1.58	0.08
Light Trucks	1.63	1.07	2.23	0.23
Heavy Trucks	2.33	1.89	2.70	0.17

Consequences for a viewing distance of 152 m (500 feet)

Incident light on signs. The mean angular location of each sign (with respect to the headlamp) is described in Table 5 for each vehicle group. This information, along with an intensity matrix for a standard U.S. low beam, was used to derive Table 6, which lists the luminous intensity directed towards the signs for each vehicle type. These calculations assume that both the headlamp beam pattern and the on-the-road headlamp aim is the same for all types of vehicles. [Cobb's data (1990) indicate that the headlamps of heavy trucks were generally aimed lower than those of cars. If that were the case for the U.S. situation, then the amount of light reaching the signs from heavy trucks would be lower than the amount calculated here.]

Table 5. Mean horizontal (x) and vertical (y) coordinates (in degrees) of angular locations of signs in relation to the headlamp at a viewing distance of 152 m (500 feet).

Vehicle Group	Lamp	Sign Position					
		Left		Center		Right	
		x	y	x	y	x	y
Cars	Left	-3.45	0.57	0.22	2.06	2.50	0.57
	Right	-3.88	0.57	-0.22	2.06	2.08	0.57
Light Trucks	Left	-3.42	0.52	0.24	2.00	2.53	0.52
	Right	-3.90	0.52	-0.24	2.00	2.05	0.52
Heavy Trucks	Left	-3.29	0.48	0.37	1.97	2.66	0.48
	Right	-4.03	0.48	-0.37	1.97	1.92	0.48

Table 6. Luminous intensity (in cd) directed towards signs from a U.S. low beam at a viewing distance of 152 m (500 feet).

Vehicle Group	Lamp	Sign Position		
		Left	Center	Right
Cars	Left	522	358	2085
	Right	510	353	2101
Light Trucks	Left	543	366	2271
	Right	529	357	2297
Heavy Trucks	Left	565	371	2395
	Right	541	354	2462

Relative amount of reflected light towards the driver. Table 7 lists the observation angles for each sign and each vehicle group. Table 8 presents the interpolated relative retroreflectances for encapsulated-lens material, given the observation angles in Table 7 and retroreflectance values in Table 2.

Table 7. Mean observation angles (in degrees) by vehicle group at a viewing distance of 152 m (500 feet).

Vehicle Group	Lamp	Sign Position		
		Left	Center	Right
Cars	Left	0.199	0.226	0.217
	Right	0.463	0.430	0.396
Light Trucks	Left	0.329	0.355	0.343
	Right	0.572	0.546	0.513
Heavy Trucks	Left	0.554	0.580	0.571
	Right	0.863	0.848	0.821

Table 8. Relative retroreflectances for encapsulated-lens material by vehicle group at a viewing distance of 152 m (500 feet). (Retroreflectance at 0.1° is equal to 1.)

Vehicle Group	Lamp	Sign Position		
		Left	Center	Right
Cars	Left	0.876	0.832	0.847
	Right	0.399	0.456	0.517
Light Trucks	Left	0.644	0.594	0.617
	Right	0.243	0.275	0.322
Heavy Trucks	Left	0.264	0.234	0.245
	Right	0.081	0.077	0.087

Total light reaching the eyes of the driver. Table 9 takes into account both the differential amount of light impinging on the sign (Table 6) and the differential amount reflected in the particular direction (Table 8). The entries in Table 9 were obtained by (1) cross-multiplying the information in Table 6 and Table 8 for each lamp, (2) obtaining the sum of this product for left and right lamps, and (3) normalizing this sum by setting the corresponding sum for cars to be 1.0.

Table 9. Relative amount of light reaching the eyes of drivers for encapsulated-lens material by vehicle group at a viewing distance of 152 m (500 feet).

Vehicle Group	Sign Position		
	Left	Center	Right
Cars	1.00	1.00	1.00
Light Trucks	0.72	0.69	0.75
Heavy Trucks	0.29	0.25	0.28

Consequences for a viewing distance of 305 m (1000 feet)

The calculations for the viewing distance of 305 m (1000 feet) are presented in Tables 10 through 14. These tables are analogous to Tables 5 through 9 for the viewing distance of 152 m (500 feet).

Table 10. Mean horizontal (x) and vertical (y) coordinates (in degrees) of angular locations of signs in relation to the headlamp at a viewing distance of 305 m (1000 feet).

Vehicle Group	Lamp	Sign Position					
		Left		Center		Right	
		x	y	x	y	x	y
Cars	Left	-1.73	0.28	0.11	1.03	1.25	0.28
	Right	-1.94	0.28	-0.11	1.03	1.04	0.28
Light Trucks	Left	-1.71	0.26	0.12	1.00	1.27	0.26
	Right	-1.95	0.26	-0.12	1.00	1.02	0.26
Heavy Trucks	Left	-1.65	0.24	0.19	0.98	1.33	0.24
	Right	-2.02	0.24	-0.19	0.98	0.96	0.24

Table 11. Luminous intensity (in cd) directed towards signs from a U.S. low beam at a viewing distance of 305 m (1000 feet).

Vehicle Group	Lamp	Sign Position		
		Left	Center	Right
Cars	Left	794	847	3461
	Right	763	792	3341
Light Trucks	Left	816	875	3653
	Right	778	810	3503
Heavy Trucks	Left	841	906	3811
	Right	780	806	3568

Table 12. Mean observation angles (in degrees) by vehicle group at a viewing distance of 305 m (1000 feet).

Vehicle Group	Lamp	Sign Position		
		Left	Center	Right
Cars	Left	0.100	0.107	0.104
	Right	0.221	0.213	0.205
Light Trucks	Left	0.165	0.172	0.169
	Right	0.277	0.270	0.263
Heavy Trucks	Left	0.281	0.287	0.284
	Right	0.426	0.422	0.416

Table 13. Relative retroreflectances for encapsulated-lens material by vehicle group at a viewing distance of 305 m (1000 feet). (Retroreflectance at 0.1° is equal to 1.)

Vehicle Group	Lamp	Sign Position		
		Left	Center	Right
Cars	Left	1.000	0.992	0.996
	Right	0.840	0.853	0.867
Light Trucks	Left	0.925	0.915	0.919
	Right	0/742	0.755	0.768
Heavy Trucks	Left	0.734	0.723	0.729
	Right	0.463	0.470	0.481

Table 14. Relative amount of light reaching the eyes of drivers for encapsulated-lens material by vehicle group at a viewing distance of 305 m (1000 feet).

Vehicle Group	Sign Position		
	Left	Center	Right
Cars	1.00	1.00	1.00
Light Trucks	0.93	0.93	0.95
Heavy Trucks	0.68	0.68	0.71

DISCUSSION

Main findings

The main findings can be summarized as follows:

(1) At any given distance, the amount of light reflected to the eyes of truck drivers from retroreflective traffic signs is less than the light reflected to the eyes of car drivers.

(2) This effect is greater for drivers of heavy trucks than light trucks.

(3) This effect is more pronounced at the viewing distance of 152 m (500 feet) than at 305 m (1000 feet).

(4) This effect is similar for the three sign locations tested (left shoulder, center, and right shoulder).

Implications

The two viewing distances were selected to represent a reasonable value for sign detection (305 m) and for sign legibility (152 m). What are the practical implications of the present findings for detection and legibility of signs? For the viewing distance of 305 m (1000 feet), in the worst cases (center and left signs), the amount of light reaching a driver of a heavy truck is about 68% of the light reaching a driver of a car (see Table 14). This represents a drop of about 0.17 log units. We used the data of Olson, Battle, and Aoki (1989) to interpret the effect of such a drop in light on detection distance. The data of Olson et al. show a generally linear relation between log luminance and detection distance. These data suggest that a 0.17 log unit drop in light results in a reduction in detection distance of about 30 m (100 feet), or about 10% from the assumed detection distance of 305 m (1000 feet).

For the viewing distance of 152 m (500 feet), in the worst case (center sign), the amount of light reaching a driver of a heavy truck is only about 25% of the light reaching a driver of a car (see Table 9). This represents a drop of about 0.6 log units. Legibility of signs is affected by both the contrast between the legend and background, as well as the luminances of these two components (Olson, Sivak, and Egan, 1983). The effect under consideration--a reduction of light reaching the observer--will have no effect on contrast. Consequently, any effects on legibility would be because of changes in the absolute levels of the legend and background luminances. However, the effect of luminance depends on the initial level of luminance, surround luminance, letter size, colors involved, age of the observer (with older observers being more affected), direction of the contrast, and contrast level (Olson et al., 1983; Allen, Dyer, Smith, and Janson, 1967). For example, the data of Allen et al. (1967) indicate that for positive contrast (light legend on dark background), a reduction in the legend luminance from 6.8 cd/m^2 (2 ft-L) to 1.7 cd/m^2 (0.5 ft-L) (a drop of about 0.6 log units) would reduce correct identification (of three-letter words) from about 55% to about 35% (a drop of about 36% from the baseline performance) for legend-to-background contrast of near 100%, and from about 45% to 35% (a drop of about 22% from the baseline performance) for contrast of 75%. However, at high initial luminances, a drop of 0.6 log units would produce smaller or no reductions in legibility.

In conclusion, this analysis suggests that the effect of the increased eye height of truck drivers could have a major effect on the legibility of retroreflective traffic signs, but only a modest effect on their detection. Reduced observation angles for truck drivers or inherently more efficient retroreflective sign materials would alleviate the potential problems.

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