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Summary 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 night-time detection and legibility of retroreflective signs for truck drivers. The present study evaluated the relative amount of light reaching drivers of different types of vehicle 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, centre, 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.

Influence of truck driver eye position on effectiveness of retroreflective traffic signs

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1 Introduction

At the increased seated height of truck (lorry) drivers, the night-time 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 centre 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[1], we are not aware of any quantiative 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 usually leads to more light incident on the sign from trucks than from cars, 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[2] 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:

(*a*) Calculate the angular location of the sign with respect to the headlamp.

(*b*) Using this angular information, estimate the relative amount of headlamp illumination *incident* on the sign.

(*c*) Calculate the observation angle.

(*d*) 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.

(*e*) Using the relative amounts of incident and reflected light, obtain the *total* light reaching the eyes of the driver.

2 Applicability of Cobb's data to the US situation

The data from Cobb[2] 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[3–5] measured only driver eye height. Since of primary interest in this study were the implications for the situation in the US, we performed two analyses to address the potential concern that the English vehicle population studied by Cobb[2] might be substantially different from the US vehicle population. The first analysis compared selected percentile values for car driver eye heights in Cobb[2] with the corresponding estimates for the 1981 US car population reported by Olson *et al.*[5]. 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 corresponds

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to the 25th percentile, while Cobb's 25th percentile is 110.0 cm. Similarly, Olson *et al.* estimated that the eye height of 114.3 cm corresponds to the 79th percentile, while Cobb's 75th percentile is 115.5 cm. The second analysis compared the ranges of headlamp mounting heights reported by Cobb for *all vehicles* with the current US mounting height requirements[6]. Again, there is reasonable correspondence between these two sets of data. Cobb's headlamp mounting heights range from 55 cm to 120 cm, compared to the US limits of 55.9 cm and 137.2 cm.

3 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.

3.1 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:

(*a*) calculating, for each vehicle, the angular location of selected sign positions relative to the headlamp, and

(*b*) using this angular information, estimating the amount of headlamp illumination incident on the sign from US-type low beams.

This analysis was performed for each headlamp, and for each sign position.

3.2 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 characterised by a set of angles, including observation, entrance, rotation, presentation, and viewing angles[7]. 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 (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.

4 Method

4.1 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[2]. 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 minibuses 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 as *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.

4.2 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. 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 US fleets.

4.3 Effect of observation angle on retroreflectivity

Table 2 lists typical data relating observation angle to the amount of retroreflected light for the entrance angle of −4°. The information in Table 2 is encapsulated lens material. (Another commonly used material—enclosed lens— is an inherently less efficient retroreflector, typically about one third as efficient as encapsulated lens material. However, both materials are highly sensitive to observation angle, but relatively insensitive to entrance angle[7].) The information on the effect of observation angle was provided to us by a sign manufacturer (see

Table 1 Parameter values in present calculations

Vehicle group	Lateral separation between left lamp and driver eyes (cm)	Lateral separation between right lamp and driver eyes (cm)	Longitudinal separation between lamps and driver eyes (cm)
Cars	15	99	206
Light trucks	18	112	206
Heavy trucks	30	168	152

Table 2 Relative reflectance as a function of observation angle for encapsulated lens material at an entrance angle of −4° (typical values obtained by averaging normalised data for the seven standard colours)

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

Acknowledgements) for each of the seven standard traffic-sign colours. The data for each colour were then normalised by setting the amount of reflected light for an observation angle of 0.1° to 1. Since all colours showed similar normalised angular effects, the normalised data for the seven colours 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^{-1} m^{-2} (a typical value for a Class II[8] white encapsulated lens), then the corresponding coefficient of retroreflection at observation angle of 0.9° is only 26.4 cd lux m^{-2} (300 × 0.077/0.875).

4.4 Sign positions

Three standard sign positions (right shoulder, centre, 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[9, 10].

4.5 Viewing distances

We considered two viewing distances: 152 m and 305 m (500 and 1000 feet). The shorter distance was selected as a reasonable *legibility* distance for traffic signs, while the longer distance as a reasonable *detection* distance.

4.6 Headlamp illumination

The present calculations used a luminous-intensity matrix of a US low-beam headlamp (Westinghouse No. 6014) that was used in previous studies on legibility of traffic signs[9, 10]. The luminous intensities were based on a new and clean headlamp. (Dirt can reduce the light output by up to 50%[2].) The isocandela diagram of this headlamp is shown in Figure 2. The luminous intensity values were available in 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.

5 Results

This section summarises the relevant data from Cobb[2] and presents a step-by-step analysis of the amount of light reaching a driver who is either 152 m or 305 m from the sign.

The data from Cobb[2] on headlamp mounting height and driver eye height are summarised in Tables 3 and 4. The subsequent calculations are based on the mean data.

Table 3 Headlamp mounting height to the centre of the lens (m) from Cobb[2]

Vehicle group	Headlamp mounting height (m)			
	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 (m) from Cobb[2]

Vehicle group	Driver eye height (m)			
	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

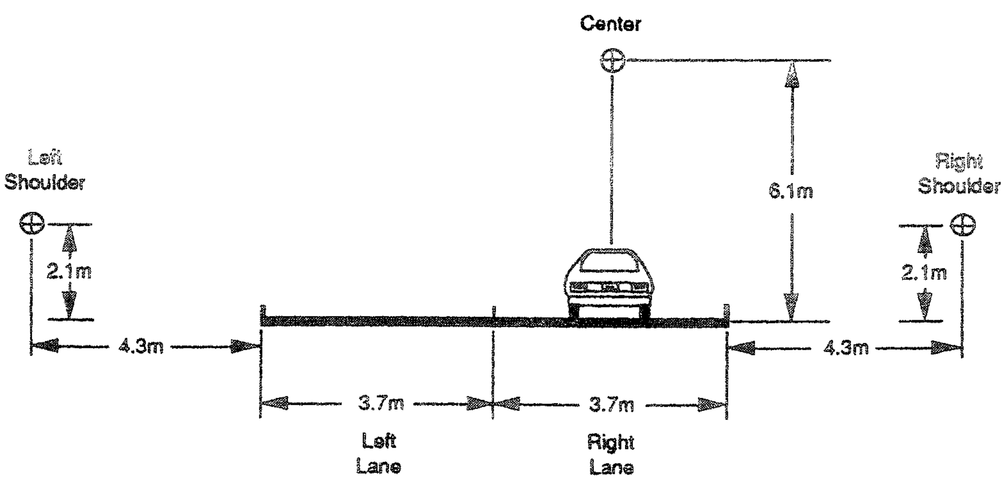

Figure 1 Schematic representation (not to scale) of the sign positions (after Woltman and Szczech[9])

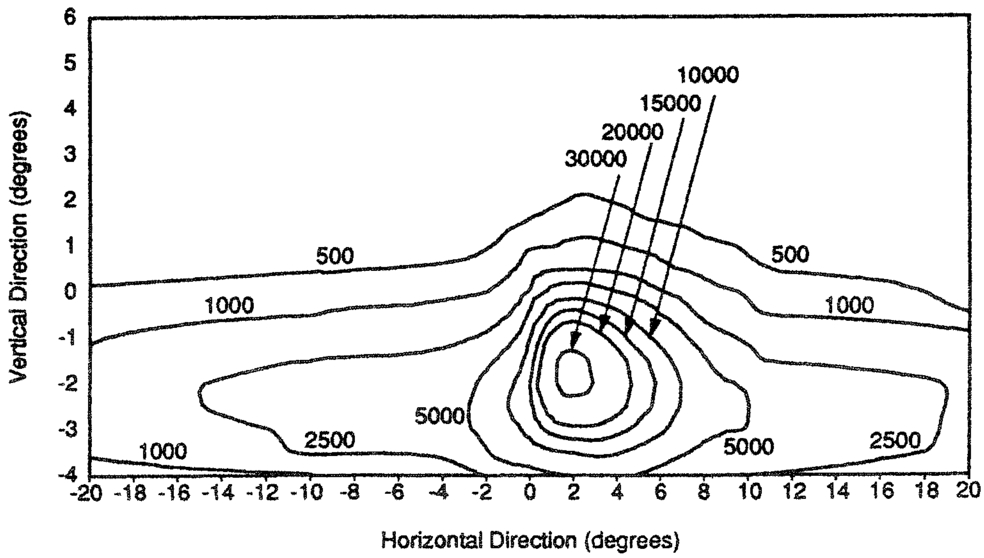

Figure 2 Isocandela diagram of the headlamp used in the calculations

5.1 Consequences for a viewing distance of 152 m

(*a*) *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 US 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 and correct for all types of vehicles. (Cobb's[2] data indicate that the headlamps of heavy trucks were generally aimed lower than those of cars. If that were the case for the US situation, then the amount of light reaching the signs from heavy trucks would be lower than the amount calculated here.)

(*b*) *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.

(*c*) *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:

(i) cross-multiplying the information in Table 6 and Table 8 for each lamp

(ii) obtaining the sum of this product for left and right lamps

Table 5 Mean horizontal (*x*) and (*y*) coordinates (°) of angular locations of signs in relation to the headlamp at a viewing distance of 152 m

Vehicle group	Lamp	Sign position					
		Left		Centre		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 (cd) directed towards signs from a US low beam at a viewing distance of 152 m

Vehicle group	Lamp	Sign position		
		Left	Centre	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

Table 7 Mean observation angles (°) by vehicle group at a viewing distance of 152 m

Vehicle group	Lamp	Sign position		
		Left	Centre	Right
Cars	Left	0.199	0.266	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 (retroreflectance at 0.1° is equal to 1)

Vehicle group	Lamp	Sign position		
		Left	Centre	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

(iii) normalising this sum by setting the corresponding sum for cars to be 1.0.

5.2 Consequences for a viewing distance of 305 m

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

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

Vehicle group	Sign position		
	Left	Centre	Right
Cars	1.00	1.00	1.00
Light trucks	0.72	0.69	0.75
Heavy trucks	0.29	0.25	0.28

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

Vehicle group	Lamp	Sign position					
		Left		Centre		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 (cd) directed towards signs from a US low beam at a viewing distance of 305 m

Vehicle group	Lamp	Sign position		
		Left	Centre	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 (°) by vehicle group at a viewing distance of 305 m

Vehicle group	Lamp	Sign position		
		Left	Centre	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 (retroreflectance at 0.1° is equal to 1)

Vehicle group	Lamp	Sign position		
		Left	Centre	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

Vehicle group	Sign position		
	Left	Centre	Right
Cars	1.00	1.00	1.00
Light trucks	0.93	0.93	0.95
Heavy trucks	0.68	0.68	0.71

6 Discussion

6.1 Main findings

The main findings can be summarised as follows:

(*a*) At both distances tested, 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.

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

(*c*) This effect is more pronounced at the viewing distance of 152 m than at 305 m.

(*d*) This effect is similar for the three sign locations tested (left shoulder, centre, and right shoulder).

6.2 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, in the worst cases (centre 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[11] to interpret the effect of such a drop in light on detection distance. The data of Olson *et al.*[11] 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, or about 10% from the assumed detection distance of 305 m.

For the viewing distance of 152 m, in the worst case (centre 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[12]. 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 a variety of factors, including the initial level of luminance, surround luminance, letter size, colours involved, age of the observer (with older observers being more affected), direction of the contrast, and contrast level[12, 13]. For example, the data of Allen *et al.*[13] indicate that for positive contrast (light legend on dark background), a reduction in the legend luminance from $6.8\,\mathrm{cd\,m^{-2}}$ to $1.7\,\mathrm{cd\,m^{-2}}$ (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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