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Paper

Effects of Vehicle Headlights on Target Contrast in Road Lighting Environments

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ABSTRACT

In this study road lighting measurements were made to investigate the impacts of vehicle headlights on luminance contrasts of various targets located on the road. Altogether seven different studies were made to investigate the contribution of halogen and high-intensity discharge headlights to road lighting. The measurement results indicate that in general, the use of dipped vehicle headlights, in the presence of road lighting, does not improve the visibility of various targets located on the road. In fact, in most occasions when the targets were seen darker than the background, dipped headlights reduced target contrasts and in some cases they even made the target merge into the background. The impacts of vehicle headlights are highly dependent on the vehicle, headlights type, target reflection factor, position of the target, position of the vehicle and road lighting conditions. As assumed, the effects of HID headlights on targets luminance contrasts were more significant compared to the ones of halogen headlights.

KEYWORDS: road lighting, vehicle headlights, luminance measurement, luminance contrast, target visibility, luminance photometer

1. Introduction

Road lighting is a practical tool in providing efficient and safe traffic movement and making driving conditions more comfortable. It is estimated that the implementation of road lighting reduces night-time accidents by 20…40%[1]. The impact of road lighting on reducing night-time fatal accidents is even higher[2]. In Finland, according to the road traffic legislation, motorized vehicles have to use full headlights or dipped headlights at night-time in traffic. The use of full headlights is forbidden when the road is lit with road lighting. Thus the drivers must use dipped vehicle headlights while driving on illuminated roads. The use of full headlights is also forbidden when oncoming traffic is present and full headlights can cause glare or when the vehicle is located behind others in traffic flow. The main reason for using vehicle headlights is to improve the driving safety and visibility conditions of the driver, other traffic users and pedestrians[3]. Lately, several research papers and studies related to vehicle headlights and visibility conditions of the driver have been published[4)-7)].

In night-time driving conditions the purpose of road lighting is mainly to illuminate the road surface, while the headlights provide illumination to vertical surfaces, i.e. targets on the road. Several studies on visibility measures of realistic roadway tasks indicate that in road lighting conditions targets located on the road have usually lower luminances than the background[8)-10)]. In case the target is darker than the road surface, the vehicle headlights may result in decreasing the visibility of the target and thus may have a negative effect on driving safety.

Development of vehicle headlights has led to the increase of luminous fluxes of the headlights. High-intensity discharge (HID) headlamps with much greater intensity than halogen headlamps are becoming more and more common. Despite the regulatory constraints concerning beam patterns, there is a potential conflict between the need to increase the intensity of vehicle headlights in order to improve driver's visibility and the use of headlights in road lighting conditions.

This study set out to investigate the use of road lighting and dipped headlights at the same time and whether this may have a conflicting effect on luminance contrasts of various targets located on the road or at the side of the road.

2. Measurement set-up and equipment

Luminance contrast measurements were made on Ring Road III which is an important highway in the southern Finland. It is the outermost of the three beltways in the Helsinki region. On Ring Road III the measurements were made on a recently built extension section. The section consists of two carriageways separated by central reservation. Each carriageway has two traffic lanes. In this section the road lighting installation is new and consists of Idman Manta 611HGV luminaires with HPS lamps (250 W). Pole spacing is 55 m and mounting height is 12 m. Figure 1 shows the light intensity distribution of the luminaire. The road lighting installation is dimmable. In this section of Ring Road III the measured average road luminance is 1.85 cd/m^2, overall luminance uniformity 0.58 and longitudinal luminance uniformity 0.49[11]. The relatively low luminance uniformities offer the opportunity to study the variation of luminance contrasts in different target locations. The road pavement type was asphalt concrete AB 22/150.

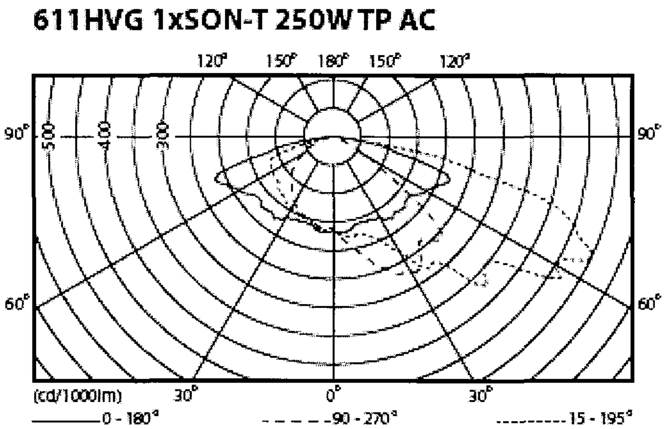
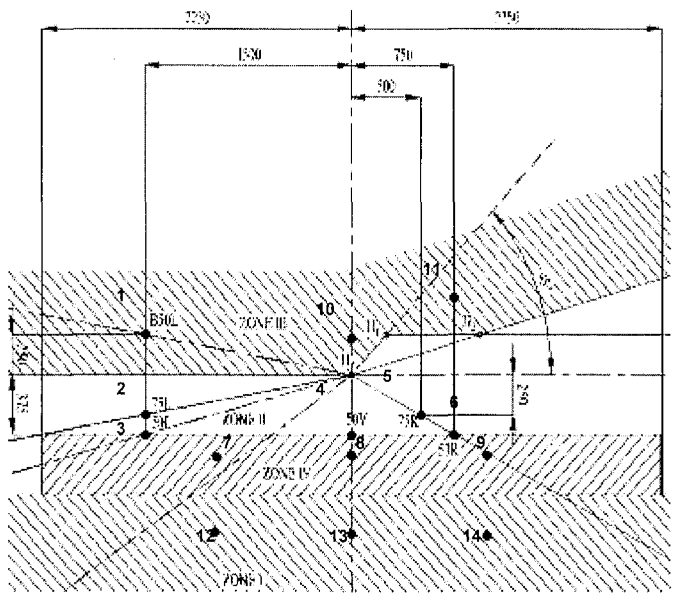


Figure 1 Photometric distribution of road lighting luminaire Idman Manta 611HGV

The lamp type is Philips high pressure sodium SON-T 250 W.

The vehicles used were a Renault Laguna 2003 and Audi A6 Avant 2006 whose headlights had been verified according to the UNECE (United Nations Economic Commission for Europe) regulations 112 and 98[12][13]. The headlights of the Renault Laguna are halogen H1/H7 (55 W) and the headlights of Audi are high-intensity discharge Xenon Plus D2S (35 W). Figure 2 shows illuminances of the dipped halogen headlights and the dipped HID headlights measured according to the UNECE regulations.

Three different target types were used in the luminance contrast measurements. The targets were 20 cm × 20 cm flat square surfaces positioned perpendicular to the road surface. The size of the targets corresponds roughly to the least clearance between the road surface and the body structure of normal cars. This so called small target represents a critical object which is the most difficult to perceive but still dangerous for a normal-sized vehicle[8][14]. The targets had reflection factors 0.09, 0.20 and 0.50 and could be considered as being Lambertian. The other targets were a wooden pedes-



Measuring point	Halogen, left headlamp	Halogen, right headlamp	HID, left headlamp	HID, right headlamp
1	0.3	0.3	0.4	0.4
2	3.8	4.3	11.7	11.5
3	7.2	7.6	17.5	16.7
4	13.7	13.8	60.3	59.4
5	16.6	15.5	62.8	60.8
6	21.5	19.9	64.4	61.6
7	13.5	15.2	37.6	37
8	20.9	21.3	54.7	52.9
9	23.8	22.1	48.2	46.7
10	0.5	0.4	0.4	0.5
11	0.3	0.4	0.3	0.4
12	17.1	17.5	25.9	26.8
13	17.7	18.1	31.6	32.8
14	20.2	19.1	31.3	32.0

Figure 2 Dipped halogen headlights and dipped HID headlights measured according to the UNECE regulations 112 and 98

Headlamp screen for right-hand traffic, measuring points and measured illuminance values

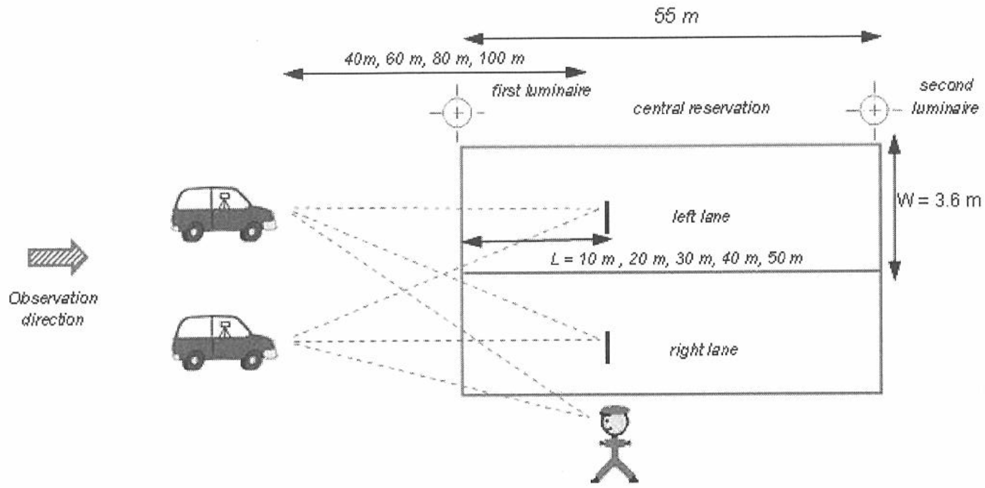


Figure 3 Measurement set-up
Measuring distance varied from 40 m to 100 m and the targets were located between the two luminaires at intervals of 10 m. Measuring height was 1.2 m. Luminaire spacing was 55 m.

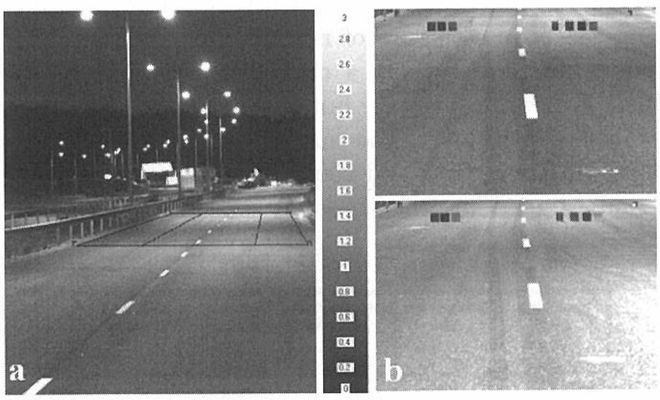


Figure 4 (a) The pilot location on Ring Road III and luminance distributions of the measuring area
Luminances are shown in gray scale presentation and different gray scale levels represent different luminance values. The unit of the palette values is cd/m^2.
(b) An example of the effects of vehicle headlights on targets contrasts in the presence of road lighting
Exceptionally all three small targets and the cylinder target were placed on the road and illuminated with dipped halogen headlights. Luminances are shown in gray scale presentation. The vehicle Renault Laguna 2003 was positioned on the right lane 40 m from the targets.

trian dressed in a grey shirt and gray pants with reflection factor of 0.16 and a cylinder target (reflection factor 0.20) with height of 20 cm and diameter of 20 cm.

Figure 3 shows the measurement area and the positioning of the vehicle and the various targets on the carriageway and at the roadside. The vehicle was always placed on the central axis of the right or the left lane. The targets were placed on the central axis of the right and left lanes, but the pedestrian target was also positioned on the side of the road. Measuring distances varied from 40 m to 100 m and the targets were located between the two luminaires at intervals of 10 m. The luminance photometer was placed 1.2 m above the road surface corresponding to the average height of the eyes of the driver.

Figure 4(a) shows the pilot location and luminance distributions of the measuring area. Luminances are shown in gray scale presentation. Figure 4(b) shows an example of the effects of vehicle headlights on targets contrasts. In this example all three small targets (ρ=0.20, 0.09, 0.50) were placed on both lanes and the cylinder target was placed on the right lane. Targets were illuminated with dipped halogen headlights from a distance of 40 m. The vehicle was positioned on the right lane.

The measurements and analysis were made using imaging luminance photometer LMK Mobile Advanced and computer programs LMK 2000 and Road LumiMeter v2.0. The LMK Mobile Advanced is based on the digital camera Canon EOS 350D and a CMOS Canon ASP-C is used as a sensor. The size of the luminance image is 1728(H) × 1152(V). Softwares LMK 2000 and Road Lumimeter v2.0 were used to analyze the measured data.

3. Measurements

In this work road surface luminance and luminance contrast measurements were carried out to investigate the contribution of headlights to target visibility in road lighting conditions. Luminances contrasts of the targets were measured in different locations, at different measurement distances and under different lighting and weather conditions. The contrasts of the targets were calculated using the measured target luminance (L_t) and background luminance (L_b)[15]:

$$C = \frac{L_b - L_t}{L_b} \quad \cdots\cdots (1)$$

when $L_b > L_t$ and

$$C = \frac{L_t - L_b}{L_t} \quad \cdots\cdots (2)$$

when $L_b < L_t$.

By using this definition of the luminance contrast, the calculation of contrast for $L_b > L_t$ (negative contrast) is similar to the commonly used contrast equation ($C = (L_t - L_b) / L_b$), except for the "sign" which changes to positive. The range is from 0 to +1. In the case of $L_b < L_t$ (positive contrast), the original denominator L_b is replaced by L_t, and the range also becomes from 0 to +1. Thus the negative and positive contrast test conditions can be combined to derive one luminance contrast scale for the analysis of vehicle headlights effects. Following the above definitions for luminance contrast the same absolute contrast values are taken to lead to equal visual performance for targets both darker and lighter than the background[15]. A contrast of zero corresponds with a situation in which $L_t = L_b$; the target without colour contrast being invisible.

In this work the background luminances of the targets were calculated separately for every target using the average luminance of the areas around the target close to the target boundaries. This definition of the background luminance value is similar to the one used in Small Target Visibility calculations, but includes more measuring points for contrast calculation[16].

The luminance contrast measurements were divided into seven different studies, which are shown in Table 1.

Study I focused on the influence of halogen headlights on contrasts of small targets (20 cm × 20 cm) having varying reflection factors. Luminances of the targets and target backgrounds were measured with and without the effect of dipped headlights (Renault Laguna 2003). The targets were located on the central axis of the lane in front of the vehicle and the measuring distances were 40 m, 60 m, 80 m and 100 m. The targets were positioned between the luminaire spacing at intervals of 10 m. In Study I the vehicle and the luminance meter always moved parallel to the central axis of the left lane.

Study II focused on investigating the effects of dipped halogen headlights on the contrasts of small targets (20 cm × 20 cm) located off-axis. The targets with different reflection factors were placed on the left lane and on the right lane as shown in Figure 3. The vehicle (Renault Laguna 2003) was placed on both lanes in turn and the target contrasts were measured with and without the effects of dipped headlights. The positions of the vehicle and the targets were consistent to Study I.

Table 1 Seven different studies, which were made to investigate the contribution of halogen and high-intensity discharge headlights to road lighting
Short description and main parameters of each study.

	Study description	Investigated parameters
Study I	Effects of vehicle headlights (halogen) on contrast of small targets located on-axis	Road lighting installation, halogen headlights, vehicle distance, target position (long.), target reflectance
Study II	Effects of vehicle headlights (halogen) on contrast of small targets located off-axis	Vehicle position (trans), target position (trans.)
Study III	Effects of vehicle headlights (halogen) on contrast in different road lighting levels and weather conditions	Road lighting level, pavement type, weather conditions
Study IV	Effects of high-intensity discharge headlights on target contrast	High-intensity discharge headlights, vehicle distance, target position
Study V	Comparison between contrasts under high-intensity discharge headlights and halogen headlights	Headlights type, vehicle type
Study VI	Contrast measurements using different visual targets	Various targets, target shape and size, target reflectance
Study VII	Effects of oncoming traffic on road surface luminances and target contrasts	Oncomming traffic, vehicle position, target position

Table 2 Study III: Average road surface luminances (L_{av}), overall luminance uniformities (U_o) and longitudinal luminance uniformities (U_l) of different lighting conditions used in the luminance contrast measurements

Lighting conditions	L_{av}	U_o	U_l
Summer, dry surface, 100%, worn pavement (AB 22/150)	1.85	0.58	0.49
Winter, wet surface, dimming 50 %, worn pavement (AB 22/150)	1.63	0.26	0.27
Summer, dry surface, dimming 50 %, new pavement (SMA 16/100)	0.89	0.4	0.25
Summer, dry surface, 100 %, new pavement (SMA 16/100)	1.99	0.4	0.24

In Study III the effects of dipped halogen headlights were studied under four different lighting conditions. The conditions with measured road lighting quality parameters are shown in Table 2. First the effects of dipped headlights were studied at different lighting levels by using dimming control of the road lighting. Secondly, the effects of dipped headlights on small target contrasts were measured in different weather and season conditions. The measurements were made at winter when road surface was wet and road surroundings were covered with snow, and at summer when road surface was dry. Finally, the measurements were made with a new road surface pavement (SMA 16/100, stone mastic asphalt) to study how the wearing of the road surface affects the luminance contrasts of the targets. The positions of the vehicle and the targets were consistent to Study I.

Study IV focused on investigating the effects of dipped high-intensity discharge headlights on luminance contrasts of small targets (20 cm × 20 cm) located on the road with installed road lighting. In Study IV the measurement geometry was exactly the same as in Study Ⅰ and Study Ⅱ.

Study Ⅴ compared the effects of dipped halogen headlights and dipped high-intensity discharge headlights on target contrasts.

In Study Ⅵ, in addition to 20 cm × 20 cm flat surface targets, a wooden pedestrian (reflectance 0.16) and a cylinder target (reflectance 0.20) were used. The main objective of Study Ⅵ was to analyze if target size and shape have an effect on luminance contrasts. In study Ⅵ the pedestrian was also placed on the side of the road (Figure 3) to create a realistic and common night-time driving scene with the pedestrian walking on the roadside or aiming to cross the road.

Study Ⅶ focused on road surface luminance changes caused by the headlights of oncoming traffic. The objective was to analyze how luminance contrasts of the targets change when the oncoming vehicle headlights illuminate the road surface close to the target. The oncoming vehicle (Renault Laguna 2003) was placed at different distances from the targets in the longitudinal and in the transverse directions.

4. Results

4.1 Vertical illuminances on the surface of the target

Vertical illuminances on the surface of small target were measured to study how the illuminances varied according to the measuring distance and the target position on the road in relation to the luminaires. Figure 5(a) shows the illuminances caused by the road lighting installation (100% power) on the surface of the target at each measuring point of both lanes. The variations are due to the light distribution of the luminaires and the geometry of the road lighting installation.

Figure 5(b) shows vertical illuminance values on the surface of the target caused by the dipped headlights of both vehicles and full halogen headlights. The measuring distances were 40 m, 60 m, 80 m and 100 m. The road pavement type was asphalt concrete AB 22/150. The dipped HID headlights resulted in significantly higher illuminance values compared to the dipped halogen headlights. Due to the vehicle structure, HID headlights were situated approximately 10 cm higher from the road surface than in the case of halogen headlights. This was found to have a major role on the vertical illuminance levels of small targets.

The purpose of road lighting is mainly to illuminate the road surface, while the headlights provide illumination to vertical surfaces, i.e. targets on the road. In road lighting conditions targets located on the road have usually lower luminances than the background and targets contrasts are highly dependent on targets positions in relation to the luminaires (Figure 5(a)). When, the impact of dipped headlights is added to the effect of road lighting, the vertical illuminance on the target surface increases while the road surface luminances close to the target do not change significantly. For example, if the target is located on the left lane 30 m from the first luminaire, the vertical illuminance on the surface of the target is 11.5 lux (Figure 5(a)). When the vehicle, with dipped halogen headlights on, is positioned 40 m from the target, the vertical illuminance increases to 21.3 lux (Figures 5(a) and 5(b)) while the illuminance levels on the road surface, close to the target increase approximately 1 lux. As the result the target luminance increases much more compared to the road surface luminances, which leads to decreased luminance contrast and worse target visibility. However, if the target, located on the road, is very light and has high reflectance it may result having higher luminance than the background (positive contrast) when illuminated with road lighting. In this case, the vehicle headlights actually increase target luminance contrast and improve target visibility by illuminating the target more.

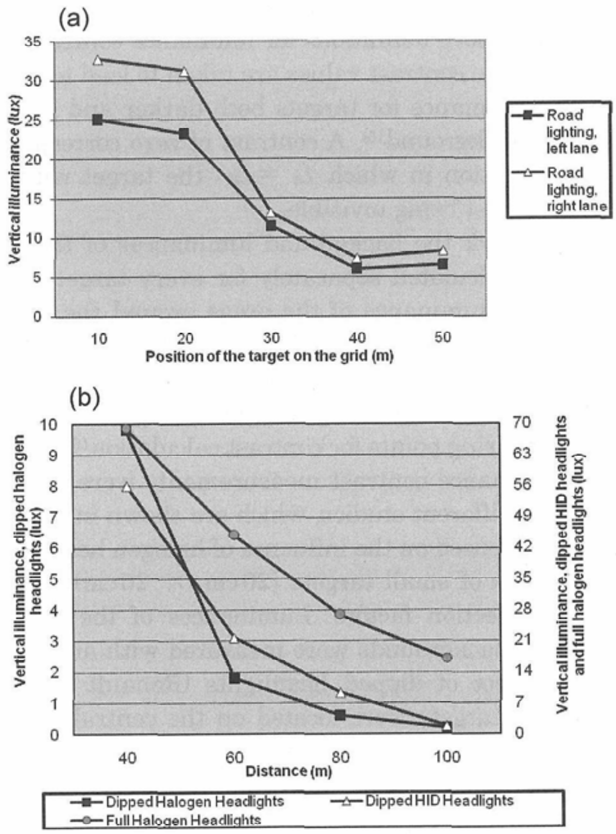
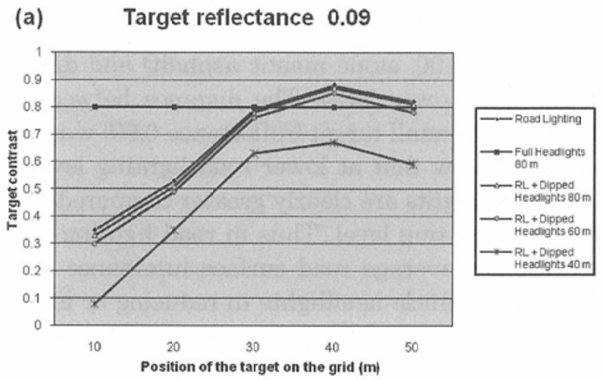


Figure 5 (a) Vertical illuminance caused by the road lighting installation on the surface of small target along the central axis of both lanes
(b) Vertical illuminance caused by dipped halogen headlights, dipped HID headlights and full halogen headlights on the surface of small target along the central axis

4.2 Study I

A first series of luminance contrast measurements was carried out for different target locations (10 m, 20 m, 30 m, 40 m and 50 m from the first luminaire; Figure 3), first without road lighting and with full halogen headlights on, and then with the road lighting on and with or without dipped halogen headlights. Figure 6 shows luminance contrasts of small targets with reflectance of 0.09 and 0.50 located in front of the vehicle on the central axis of the left lane. Figure 6 indicates the variation of contrasts of dark (reflectance 0.09) and light (reflectance 0.50) targets according to the position of the target between the luminaire spacing. Luminance contrasts of the small target with reflection factor 0.09 are between 0.35...0.88 when road lighting is on and vehicle headlights off. The target is seen darker than the background in every target location. Contrasts of the light target are between 0.38...0.68 and in first two locations (10 m, 20 m) the target is seen lighter than the background (has higher luminance than the road surface, positive contrast).

For distances greater than 80 m, the dipped halogen headlights had little effect on target contrasts. For example at a distance of 100 m, the effect of dipped halogen headlights was below plus - minus few per cents. At a distance of 60 m the effects of headlights became more significant, especially with the light target. At a distance of 40 m the effects of headlights became dominant. For example the dark target located at 10 m from the first luminaire merged almost completely into the background (Figure 6(a)).



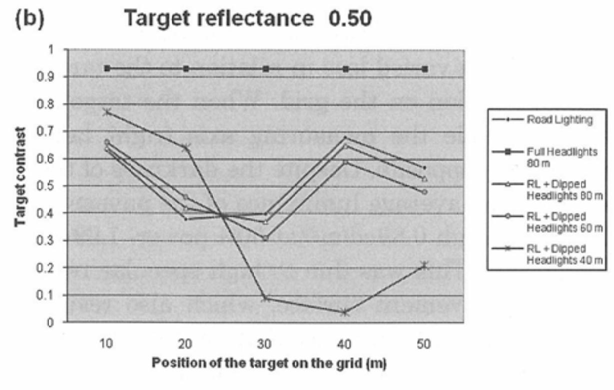


Figure 6 Study I: Luminance contrasts of small targets (20 cm × 20 cm) located in front of the vehicle
Targets illuminated with road lighting (measured from 80 m), full headlights or road lighting and dipped headlights (measuring distances 80 m, 60 m, 40 m)

When the small target (ρ=0.50) was placed on the road in first two positions (10 m and 20 m), the vehicle headlights had a positive effect on target visibility improving the target contrasts. In other three cases dipped headlights reduced the contrasts of the targets. Critical occasions were observed when the vehicle was located at a distance of 40 m from the target and the target was positioned 30 m and 40 m from the first luminaire. The luminance contrast of the target located 30 m from the first luminaire changed from negative to positive due to the effect of vehicle headlights. In series of measurements with the light target (ρ=0.50), having only full headlights on resulted in highest luminance contrasts (Figure 6(b)).

The effect of halogen headlights on target contrasts was highly dependent on the distance between the vehicle and the target. The effects of dipped headlights became more significant when the distance between the target and the vehicle reduced and also when the target had higher reflectance. The contrasts of the targets and the degree of the headlights effects depended highly on the target position on the road in the longitudinal direction.

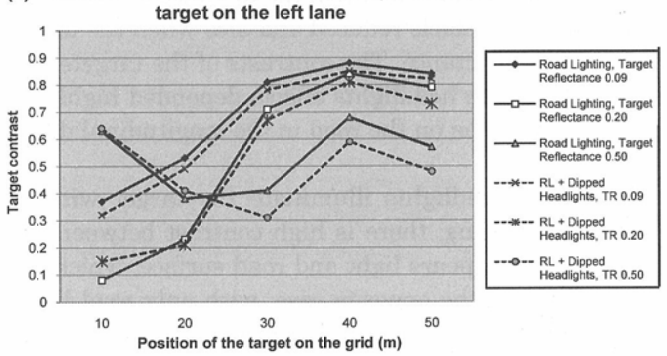
When full headlights illuminate the target without fixed road lighting, there is high contrast between the target, which appears light and road surface, which appears black. In the opposite case, with only road lighting on, the target is apparently darker than the illuminated road surface. When the impact of dipped headlights is added to the effects of road lighting, both the road surface and the target are illuminated. This usually results in lower contrasts compared to the situation when only road lighting is on.

In reality, very few targets in traffic have higher reflection factor than 0.50. Previous studies indicate that targets with reflectance of 0.20 and lower are prevailing in night time driving conditions[17)18)]. Such targets are usually seen darker than the background, and when headlights illuminate the target the luminance contrast is reduced. Hence the measurement results of this paper indicate that, in general, dipped headlights have an undesirable and ambiguous effect on target contrasts in road lighting conditions.

4.3 Study II

In Study II off-axis targets were used to investigate the effects of dipped halogen headlights, in contribution to road lighting, on target luminance contrasts. Small targets were placed on the right lane and on the left lane (Figure 3). The car (Renault Laguna 2003) was placed on both lanes in turn. Figure 7 shows the measured contrasts with vehicle distance of 60 m. In measurements shown in Figure 7 the vehicle was placed on the left lane 60 m away from the targets and the effects of headlights were studied using the targets located on the central axis of both lanes. Figure 7(a) represents contrasts of the targets located in front of the vehicle and Figure 7(b) contrasts of the targets located on the right lane (eccentricity 3.4°). The effects of vehicle headlights are shown by dashed curves. The results indicate that the target contrasts are not only dependent on their longitudinal position between the luminaires, but also on their position in the transverse direction. The effects of dipped headlights on the off-axis target contrasts are greater, which can be explained by the geometry of headlamp beam patterns. The contrasts of the targets located on the right lane decreased more than those located in front of the vehicle. Targets located on the right lane also resulted more often in significantly lower contrasts, merging into the background because of the illumination from dipped headlights.

(a) Measurements at a distance of 60 m, vehicle and target on the left lane



(b) Vehicle on the left lane, target on the right lane

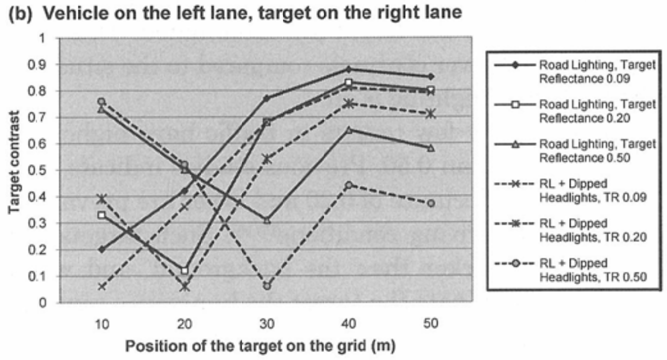


Figure 7 On-axis (6a) and off-axis (6b) luminance contrast measurements at a distance of 60 m

The car is located on the left lane and the targets on the central axis of both lanes. Road lighting (RL) was on.

When the vehicle was placed on the right lane, the effects of dipped headlights on the targets placed on the left lane were not as strong as on targets located in front of the vehicle. Reducing the distance between the vehicle and the targets increased the influence of the headlights on target contrasts.

The measurements showed that the effects of dipped halogen headlights vary in relation to the position of the target in the transverse direction because of the geometry of headlight beam patterns and light distribution of the road lighting luminaires. Contrasts of the targets located on the right lane (vehicle on the left lane) changed the most, and contrasts of the targets located on the left (vehicle on the right lane) the least, which was an expected result. In general, dipped headlights had a negative effect on off-axis target contrasts.

4.4 Study III

Study III focused on the effects of dipped halogen headlights on target contrasts in different lighting conditions (Table 2). Figure 8(a) shows one set of the measurement results from two different road lighting scenes: one with worn pavement (AB 22/150, asphalt concrete) and full road lighting and another one with new pavement (SMA 16/100, stone mastic asphalt) and dimmed road lighting (power 50%). The distance between the vehicle and the small target (reflectance 0.09) was 60 m. The results show that at lower road lighting level the effects of headlights are clearly greater compared to the higher road lighting level. Thus in road lighting conditions with low average road surface luminance levels, the impact of vehicle headlights in reducing or increasing target visibility is higher. This is a conflicting interaction of vehicle headlights and road lighting.

In the case of new stone mastic asphalt pavement (dark), luminance contrasts of the targets located on the measuring axis varied less in relation to the target longitudinal position on the grid. When the targets were positioned aside the measuring axis (right lane) the situation was opposite. Despite the darkness of the new pavement, the average luminance of the pavement was surprisingly high 0.89 cd/m^2 (at 50% power; 1.99 cd/m^2 at 100% power). This was due to high specular reflection of the new pavement surface, which also resulted in lower road surface luminance uniformities.

The luminance contrast measurements were also made at winter and compared to those made at summer. The vehicle was placed at a distance of 60 m from the small targets and both the vehicle and the targets were positioned on the left lane. In winter the road surface was wet and road surroundings were covered with snow. In summer the road surface was dry. Figure 8(b) shows

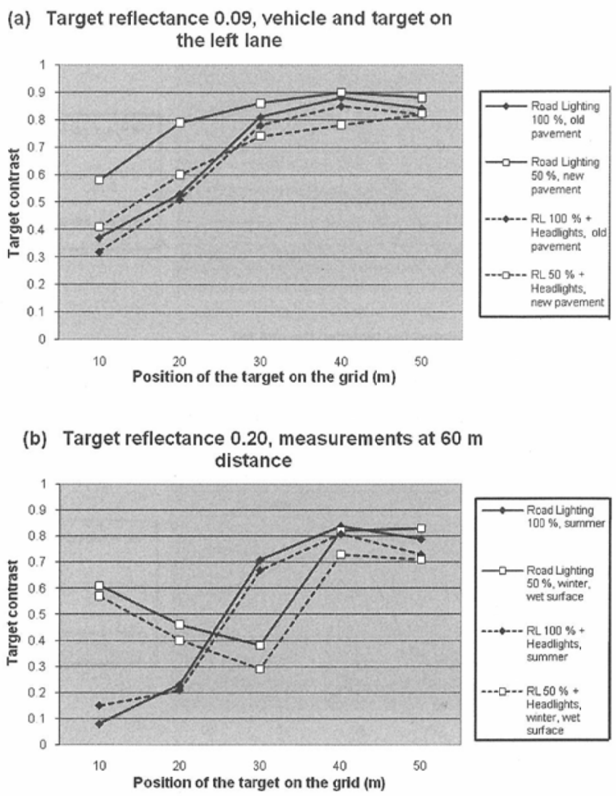


Figure 8 (a) Contrast measurements at a distance of 60 m for two road lighting levels and different road surface pavements
A car (Renault Laguna 2003) and a target with reflectance of 0.09 were placed on the left lane.
(b) Contrast measurements at a distance of 60 m in winter with wet road surface and in summer with dry road surface
Targets were placed on the left lane in front of the vehicle.

the measured contrasts of a small target with reflection factor of 0.20. Figure 8(b) shows the contrasts measured with full road lighting in summer compared to those in winter with 50% power dimming. Again, the lower road surface luminance level increased the effects of vehicle headlights on target contrasts. Due to the higher reflection factor of the target (0.20) the vehicle headlights decreased target visibility more compared to the target with 0.09 reflection factor. The variation of luminance contrast in relation to the target longitudinal position was different in winter conditions compared to the summer conditions. This can be mainly explained by higher specular reflection of the wet road surface and the different road surface luminance distribution.

4.5 Study IV

In Study IV the same measurements as in Studies I and II were made with dipped high-intensity discharge headlights (Audi A6 Avant 2006). The effects of HID headlights on small target contrasts were very significant and even at a distance of 80 m the contrasts of the targets were substantially reduced due to headlights. However, in some occasions when the target was light (reflectance 0.50), HID headlights improved target contrasts significantly.

Figure 9 presents the effects of HID headlights on the contrasts of light (reflectance 0.50) and dark (reflectance 0.09) small targets. The contrasts of the dark target (reflectance 0.09) decreased substantially when the vehicle with dipped HID headlights was placed at a distance of 80 m (Figure 9(a)). For example, a target located at 10 m from the first luminaire became barely visible (C =0.14, negative contrast). When the vehicle was placed at a distance of 40 m, the HID headlights had a negative effect on target contrasts located at 30 m, 40 m and 50 m from the first luminaire but, positive effect on target located at 10 m from the first luminaire (Figure 9(a)). It is worth noticing that in case with only road lighting on, the target was seen darker than the background in all positions (negative contrast), but in case with road lighting and HID headlights on (40 m), the target was always seen brighter than the background (positive contrast).

Unlike the dark targets, the light targets are not always seen as dark against the background due to their higher reflectance. For example in Figure 9(b), in case with only road lighting on, the target with reflectance of 0.50 is seen brighter than the background in first two positions (10 m, 20 m). Adding the effect of vehicle headlights, the target luminance is increased resulting in higher luminance contrasts.

Luminance contrasts of the target with reflection factor 0.50 decreased exceedingly at the measuring distance of 80 m, when the target was placed 30 m, 40 m and 50 m from the first luminaire, and increased when the target was positioned 10 m and 20 m from the first luminaire. The luminance contrast of the light target at a vehicle distance of 40 m increased in all occasions and the target had higher luminance than the background (positive contrast).

The luminance contrasts of small targets varied highly depending on the target longitudinal position and the distance between the target and the vehicle. Target position on different lanes resulted either in higher or lower luminance contrasts depending on its position in the longitudinal direction and on the vehicle distance.

The results of Study IV indicate that when the distance between the target and the vehicle is longer than 60 m, the HID headlights have mostly a negative effect on target contrasts. When the vehicle is located close to the target, the effect of HID headlights on contrast is

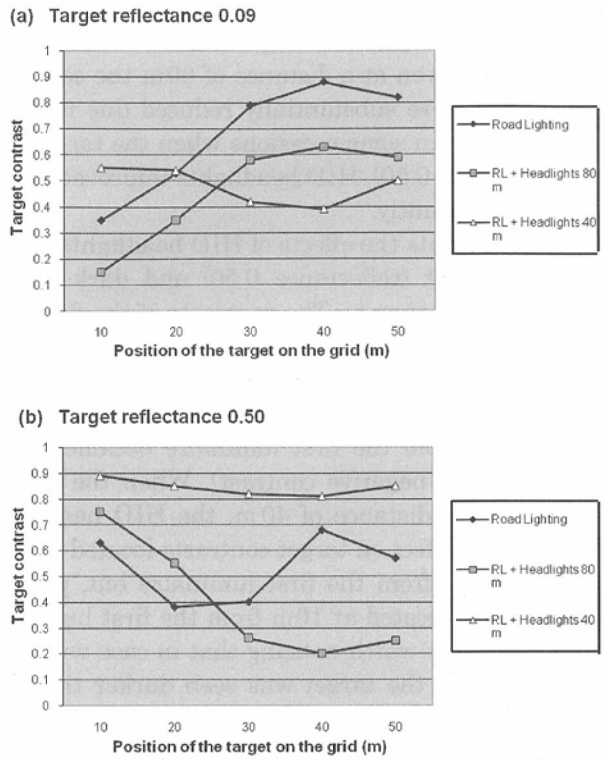


Figure 9 The effects of HID headlights on luminance contrasts of the small targets
Measurement results from vehicle distances of 80 m and 40 m
(a) Target reflectance 0.09
(b) Target reflectance 0.50

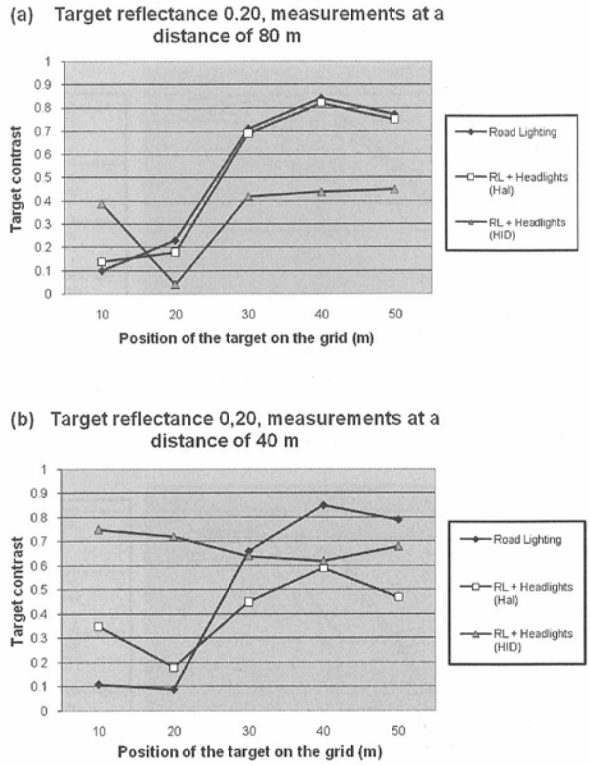


Figure 10 Luminance contrast measurements with dipped HID headlights and dipped halogen headlights
(a) Measuring distance 80 m and small target reflectance 0.20
(b) Measuring distance 40 m and small target reflectance 0.20

partly positive and the lighter the target the higher the effect. However, at longer distances the impact of dipped HID headlights is undesirable. For example on major roads and highways with high driving speeds, the stopping distances are long and it is very important for the driver to detect the target located on the road from the safe distance. However, according to the measurements especially at longer distances, the effect of HID headlights in contribution to road lighting resulted in decreased luminance contrasts. This is because in road lighting conditions targets located on the road have usually lower luminances than the background[8)-10)].

4.6 Study V

Study V combined the Studies I, II and IV together comparing the effects of HID headlights to the effects of halogen headlights. Figure 10 presents measured contrasts of a small target with 0.20 reflection factor at different distances with dipped HID and halogen headlights. As shown in Figure 10(a), the HID headlights have much higher effect on target contrasts compared to the halogen headlights. This is due to the higher luminous intensity of the HID headlights and the vehicle structure. At longer distances this results in better target contrasts only with bright targets and only in few target positions. This is contradictory to the introduction of HID headlamps in their characteristics of providing better visibility conditions by producing more light. Also vehicle structure and especially the location of headlights in relation to the road surface were found to have a major effect on contrasts of small targets.

As the distance between the vehicle and the target decreases, the illuminating effect of headlights becomes higher. At a distance of 40 m the effect of HID headlights is so significant that targets are seen brighter than the background regardless of the target position. As can be seen from Figure 10(b), despite the great variation in luminance contrasts in the case when only road lighting is on, the contrasts are quite constant in the case when both road lighting and dipped HID headlights are on. The luminance contrasts are also rather high and target visibility is better than in the case when the halogen headlights are on in addition to road lighting.

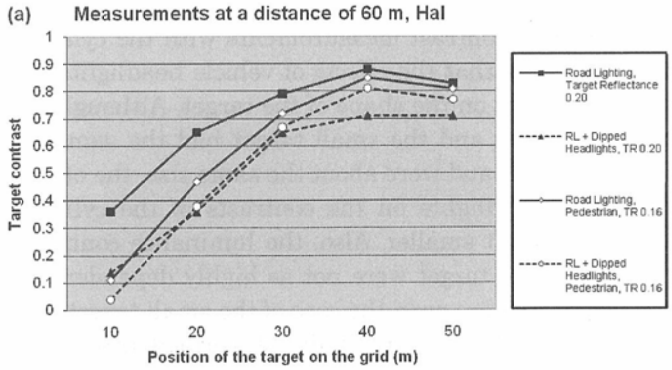
At first two positions (10 m and 20 m from the first luminaire) the HID headlights increased the target contrast exceedingly when compared to road lighting, but at further positions (40 m and 50 m from the first luminaire) the contrast value decreased (Figure 10(b)). In the case with only road lighting on, the target was seen darker than the background in all except the first position, but in the case with road lighting and HID headlights on, the target was seen brighter that the background in all positions.

4.7 Study VI

Targets with size of 20 cm × 20 cm were used in the development of the current road lighting practice[19]. Also in the American National Standard Practice for Roadway Lighting 18 cm × 18 cm square targets are used for Small Target Visibility calculations[16]. However, in reality it is very hard to predict which targets are likely to be on a given section of the road, and how critical they are to the safety of the driver. Thus the research approach in Study VI was to measure luminance contrasts of different targets in exactly the same set-up conditions. In Study VI, in addition to the small targets, the wooden pedestrian target (reflectance 0.16) and the cylinder target (reflectance 0.20) were used.

Figure 11 shows contrasts of the small target (reflectance 0.20) and the pedestrian at distances of 60 m and 80 m. Figure 11(a) presents contrasts measured with halogen dipped headlights. The targets were placed at a distance of 60 m in front of the vehicle and the measurements were made on a new road pavement (SMA 16/100, stone mastic asphalt). The results indicate that halogen headlights have stronger effect on a contrast of the small target than on a contrast of the pedestrian target. This can be partly explained by the lower reflection factor of the pedestrian target, but mainly this occurs because of the different sizes of the targets and the geometry of the headlights beam patterns. When the pedestrian target is illuminated with headlights, the luminances of the lower part of the target change more compared to the upper parts of the target. This is because the headlight beam patterns have strict regulations concerning the light output above the horizontal plane. Large targets like pedestrians also have different luminance contrasts in different parts of their bodies due to the non-uniform background luminance distributions.

Figure 11(b) shows contrasts of the small target and the pedestrian target measured with HID dipped headlights at a distance of 80 m. The vehicle was placed on the left lane, the small target on the right lane and the pedestrian on the roadside. The road surface pavement was worn (AB 22/150, asphalt concrete). The HID headlights increased the target contrasts at the first grid position (10 m) and reduced targets contrasts at all



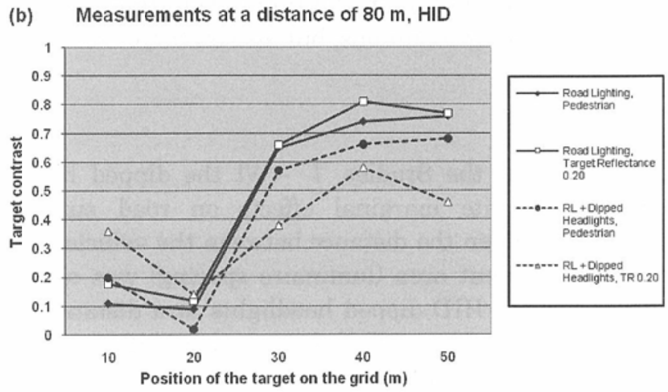


Figure 11 Luminance contrast measurements for different visual targets
(a) Measurements with dipped halogen headlights
The pedestrian target (reflectance 0.16) and the small target (reflectance 0.20) are placed in front of the vehicle.
(b) Measurements with dipped high-intensity discharge headlights
The pedestrian is placed on the roadside and the small target on the right lane.

other positions. The effect of HID headlights was quite obvious even at a distance of 80 m and despite the fact that the vehicle was placed on the left lane. The headlights effects on the contrasts of pedestrian target were not as strong as on the small target.

The main difference between the pedestrian target and the small target was that the small target creates basically one luminance contrast with the background, while the pedestrian target has many different luminance contrasts in different points. The pedestrian is substantially larger in size and thus different parts of the target may be seen more and less dark compared to the background because of the background non-uniformity. The pedestrian may also be seen partly against the road surface and partly against the roadside. Thus, despite the decreasing of contrast due to vehicle headlights, the pedestrian target may still remain visible because of the certain parts of the pedestrian which may have a luminance contrast adequate enough.

Luminance contrast measurements with the cylinder target showed that the effects of vehicle headlights are also dependent on the shape of the target. Although the cylinder target and the small target had the same reflection factors and were about the same size, the effects of vehicle headlights on the contrasts of the cylinder were somewhat smaller. Also, the luminance contrasts of the cylinder target were not as highly dependent on the target position as in the case of the small target.

The measurements in Study VI verified that luminance contrasts of targets are not only dependent on the position of the target, the target reflectance factor, and road lighting conditions, but also on target size and shape.

4.8 Study VII

According to the Studies I – VI the dipped headlights had quite marginal effects on road surface luminances when the distance between the vehicle and the measurement area (luminaire spacing) was above 60 m. Only the HID dipped headlights at a distance of 40 m had a significant effect on road surface luminances.

In actual traffic conditions also oncoming traffic is usually present. Oncoming vehicles headlights illuminate the road surface and the target from behind, and thus also have an effect on target luminance contrasts. Study VII focused on investigating how road surface luminances and luminance contrasts of the small targets change when the oncoming vehicle headlights illuminate the road surface and the target. The oncoming vehicle (Renault Laguna 2003) was placed at different distances from the targets in the longitudinal and in the transverse directions. The measurement results showed that when the headlights illuminate the road surface, the contrasts of the targets which are seen darker than the background increase to some extend. If the targets are seen light against the background the effects are reversed.

The effects of the oncoming vehicle headlights were highly dependent on the position of the targets and the vehicle. For example in occasion when the oncoming vehicle was located at a distance of 20 m from a target in the longitudinal direction and at distance of 1 m in the transverse direction, the luminance contrast of the target with 0.20 reflection factor increased from 0.19 to 0.63. The change is quite significant and due to the oncoming vehicle headlights the target on the road actually became clearly visible. Increasing the dimensions to 50 m and to 3 m resulted in contrast changes of only 4% compared to the luminance contrast without the oncoming vehicle headlights.

According to the measurements of Study VII the oncoming vehicle headlights have in general a positive effect on target luminance contrast. This follows the assumption that usually in road lighting conditions targets located on the road are seen darker than the background[8)-10)]. However, despite the increased luminance contrast, the oncoming vehicle headlights may result in substantially decreased driver's visibility conditions due to glare.

5. Discussion

The contrast measurements indicate that in road lighting environments, in general, dipped headlights reduce contrasts of various targets located on the road or on the roadside. It is, however, very difficult to determine how these effects relate to the safety of the driver in different traffic conditions. A major problem of these kinds of measurements is that it is not known what targets are likely to appear on the road and which targets are critical for the safety of the driver. In driving, luminances of the target and the target background are changing constantly and the target cannot be expected to be stationary.

In road lighting conditions visual targets may also have non-uniform luminance and colour contrasts. It is also quite obvious that the targets will not be completely diffuse and usually can not be considered as being Lambertian. Visual targets like pedestrians may also have different clothes with different colouring and different reflection characteristics. These are all problems that different road lighting measurement and calculation methods are facing in one way or another. A number of field measurements and traffic accident statistics are needed to determine the overall effects of vehicle headlights on target visibility in road lighting environments.

One potential extension scenario for these luminance contrasts measurements would be to study the impact of multiple vehicle headlights on road luminances and target luminance contrasts. It would also be useful to conduct similar luminance contrast measurements with different vehicle and headlight types. For example trucks and pick-up cars could be included in the measurements. Also, if oncoming traffic is considered in the measurements, the negative effects of glare on driver's visibility conditions should be investigated.

In this paper luminance contrast calculations were made by using somewhat distinct contrast formulas compared to the conventional definition of the contrast. This was made to simplify the comparison and the diagrammatic representation of the results. It can be argued that positive and negative contrast targets are quite different visual tasks for the driver and thus can not be directly compared with each other. However, according to Janoff positive and negative contrast tasks are highly related and have correlation coefficient close to one[15].

Small Target Visibility design described in the American National Standard for Roadway Lighting is based on visibility and luminance contrasts of 18 cm × 18 cm small targets with reflectance of 0.50[16]. Thus the measurements of this work correlate with STV design method. It is obvious that small targets with high reflection factor are susceptible to the impact of vehicle headlights and thus the effects of vehicle headlights should be included in STV calculation. Of course, this means that calculations have to be settled on some design values of certain typical vehicle headlight types.

Major sources of error in the measurements are estimated to be the possible differences in vehicle and target positioning when measuring different variations of the same type of measurement. Because the measurements were done at different times and at different seasons, background noises (external factors such as skyglow, moonlight and so on) were measured but found to be negligible. The system measurement error for luminance measurement repeatability of the LMK Mobile Advanced, according to the manufacturer's certificate, is ±1.9%.

6. Conclusions

The contrast measurements indicated that in general, the use of dipped vehicle headlights, in the presence of road lighting, does not improve the visibility of various targets located on the road. In fact, in most cases when the targets were seen darker than the background dipped headlights reduced target contrasts and in some cases they made the target merge into the background. It can be argued that there is a strong conflicting effect in the use of vehicle headlights in road lighting environments. One solution may perhaps be the use of parking lights instead of dipped headlights in the presence of road lighting. This may, however, result in other unwanted effects concerning traffic safety. The use of parking lights may reduce the visibility of other vehicles in traffic and also the illumination of road surroundings will become completely dependent on the installed road lighting.

The effects of dipped headlights were highly dependent on the position of the vehicle, location of the target in relation to luminaires, target reflectance, target shape and size, vehicle type and headlight type, road lighting installation, road characteristics and weather conditions.

Dipped halogen headlights had little effect on target contrasts when the distance between the target and the vehicle was more than 80 m. However, with decreasing distance, the effect of dipped headlights became higher. Road lighting usually resulted in lower target luminance contrasts compared to the situation when only full headlights were on. When the road lighting and dipped headlights were both on, luminance contrasts were usually lower compared to the situation with only road lighting on.

The dipped high-intensity discharge headlights had more significant effects on target contrasts than the dipped halogen headlights. At longer distances the negative impact of dipped HID headlights on target visibility were emphasized. On major roads with high driving speeds and long stopping distances this may cause problems. This should be considered in further vehicle headlights development. At shorter distances the effects of HID headlights were so strong that even very dark targets were usually seen as light against the background and in most cases the HID headlights increased the luminance contrasts of the targets.

It is difficult to determine the relationship between the use of dipped headlights in addition to road lighting and the safety of the driver. It is also to be resolved how the negative effects of dipped headlights relate to the safety critical tasks that drivers have to see to avoid collisions. Further research is needed to determine these issues.

The luminance contrast measurements presented in this work do not represent any specified standard conditions in studying the contribution of vehicle headlights on road lighting. They do, however, indicate the remarkable changes that vehicle headlights can have on the luminance contrasts of various targets located on the road or the roadside in different road lighting scenes.

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