**Review Article**

Carsten Gut*, Iulia Cristea and Cornelius Neumann

# High-resolution headlamp

DOI 10.1515/aot-2015-0063
Received December 23, 2015; accepted February 29, 2016; previously published online March 25, 2016

**Abstract:** The following article shall describe how human vision by night can be influenced. At first, front lighting systems that are already available on the market will be described, followed by their analysis with respect to the positive effects on traffic safety. Furthermore, how traffic safety by night can be increased since the introduction of high resolution headlamps shall be discussed.

**Keywords:** headlight; high-resolution light functions; traffic safety.

## 1 Overview

After a short introduction and motivation, the paper describes front lighting systems that are already available on the market, followed by their analysis with respect to the positive effects on traffic safety. This is followed by a discussion on how traffic safety by night can be increased by introducing high-resolution headlamps. Finally, the new light functions as well as the necessary design for the perfect headlamp will be described.

## 2 Introduction and motivation

Newly conducted surveys concerning traffic safety have shown that adverse weather conditions cause drivers the most difficulties, followed by driving during nighttime and driving through construction sites [1]. Most of the information intake about the surroundings is visual. In low light levels, visual acuity is impaired, leading to difficulties for many drivers in the night.

Leibowitz [2] divides the visual process into two subsystems, each being responsible for different driving tasks. Focal vision is devoted to identification (shape recognition), while the peripheral or ambient vision (also known as guidance visual function) provides information on spatial orientation. Reduced luminance does not affect all visual functions in the same way. While ambient vision is independent of luminance changes, maintaining its performance level, focal vision deteriorates under low illumination. As the peripheral visual functions remain unaffected, drivers should not lose their steering ability, and lane keeping should not be affected. In contrast, due to degradation of focal vision, resolution acuity, contrast sensitivity, and stereoscopic vision are also highly affected, leading to difficulties in detecting objects, pedestrians, or cyclists.

Depth perception is responsible for distance estimation [3]. As stereoscopic vision is impaired at night, drivers experience difficulties when it comes to estimating distances, particularly stopping distances [4], which finally leads to the inability to maintain an adequate distance ahead [5].

Cohen [6] and Hristov [7] conclude that peripheral vision is insufficient when it comes to lane keeping in curves. This would also explain, why driving in curves is more stressful for drivers. Gut [8, 9] finds, that with a smaller curve radii, the focal fixation points shift from the curve apex toward the vanishing point. They further conclude that fixating the vanishing point is a possible reason for vehicles leaving the lane. As this happens in curves with small radii, it can be the cause of higher risk of accident in small curves. Then again, Schweigert [10] suggests to fixate the apex, as it predicts the curvature.

According to Hoffmann [11], there is a higher probability of accidents occurring at nighttime in curves compared to straight street courses. Furthermore, the risk of accident also increases with decreasing curve radius.

Considering the previously depicted findings, the authors conclude that maneuvering their way through small curve radii due to traffic re-routing in construction sites at night can also represent a burden for drivers.

***Corresponding author: Carsten Gut,** Karlsruhe Institute of Technology, Light Technology Institute, Engesserstraße 13, Karlsruhe 76131, Germany, e-mail: carsten.gut@audi.de
**Iulia Cristea and Cornelius Neumann:** Karlsruhe Institute of Technology, Light Technology Institute, Engesserstraße 13, Karlsruhe 76131, Germany

**www.degruyter.com/aot**

## 3 State of the art

For the illumination of the road at nighttime, mainly two different light distributions are necessary: the high beam and the low beam. If we have a closer look at the low beam, it is important to mention that this light function is a compromise between a sufficient illumination of the road ahead and the avoidance of glaring other traffic participants [12]. In order to compensate the visual restrictions, mentioned in the previous chapter, engineers supplemented the two main light functions with several other functions.

The light distribution of the low beam functions is adapted to different traffic situations and environmental conditions by changing the light intensity, the light direction, and the opening angle. The adaptation of the light distribution can be seen in Figure 1. One of the first low-beam functions is the curve light [14]. The light direction is being shifted by a Bowden cable. Nowadays, the focus of light is shifted using a step motor or by intelligently dimming LEDs. This option is called synthetic curve light.

The static curve light, which is also called cornering light, increases the driver's sight of the roadside by switching on additional light sources. This function is especially useful in built-up areas, as pedestrians and cyclists can be recognized better and earlier by the driver at intersections and on narrow roads.

Aside from the curve light, many other light functions can be integrated in a vehicle. The low beam, for example, can be adapted trough specific controlling of the headlamp leveling and the flux of the light source. These functions are also called 'adaptive front lighting systems,' in short, AFS. These functions optimize the light distribution on highways, on country roads, and in city traffic. The adaptation of the light distribution is performed by using vehicle sensor data like steering angle and velocity. State-of-the-art systems even make it possible to adapt the light distribution before the event point is reached. This is working on the basis of predictive road data [15].

The visibility range of the low beam could be increased by an additional high beam. As the high beam [16] illuminates the road in a vertical angle of over -0.57°, oncoming traffic could be glared. Therefore, numerous high beam functions have been developed in the past years, which do not glare other traffic participants and simultaneously keep the visibility range of the high beam. The glare-free high beam systems are based on a camera system located behind the rear-view mirror. Oncoming traffic can be detected and deglared by the headlamp. The deglared areas are shown in Figure 2. In the first approach, the whole high beam is controlled automatically. This function is called high-beam assistant. In order to increase the performance ratio, systems like the 'vertical cut-off line systems' (vCOL) [17] and the 'Matrix LED headlamps' have been introduced [18]. The vCOL works subtractively and creates a deglare area using a cover. The Matrix LED headlamp, however, is a mechanics-free solution. A segmented light distribution is created additively. This means that several LEDs can be controlled independently. In this way, it is possible to switch off certain areas, which would otherwise glare other traffic participants. Furthermore, a Matrix LED system has a much higher transmission rate than a glare-free high beam with mechanical shutter, and therefore, it has the possibility to 'track and deglare a high number of targets with maximum speed' [19].

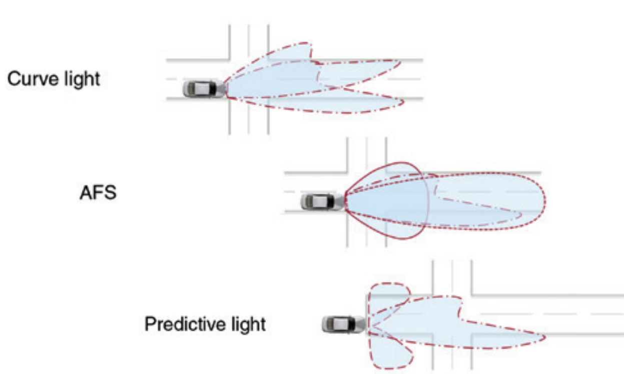


**Figure 1:** Low-beam functions [13].

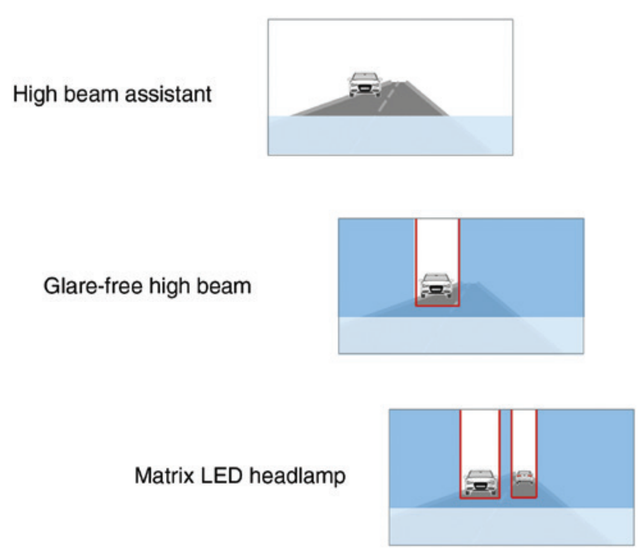


**Figure 2:** High-beam functions [13].

# 4 Effects of state-of-the-art headlamps on traffic safety

This section discusses the positive effects that already-launched light functions have had on nighttime traffic safety.

Schwab [20] finds that, since the launch of the dynamic bending light, a safety increase is to be expected. Threats located at the edge of the road can be detected earlier, thanks to the dynamic bending light. Hoffmann [11] also found positive effects regarding the cornering light.

Hamm [21] investigates the impact of adaptive headlamp systems on traffic safety compared to conventional halogen and HID headlamps. The use of motorway lighting, static, and dynamic bending lighting results in a much higher detection distance compared to the use of a dipped beam.

A static experiment conducted by Böhm et al. [22] shows improved detection distances of 30 m by use of an adaptive cutoff line (aCOL) compared to the low beam. In a further investigation, an increase in detection distance by 46 m was established [23].

Customizing the high-beam light distribution can also improve detection distances. Sprute [24] compares adaptive and vertical cutoff line systems (vCOL) with a Matrix Beam. The use of a single-line Matrix Beam system lead to recognition distances being increased by 14–18 m.

Matrix Beam systems can have several segments. Austerschulte et al. [25] investigates four systems differing in the number of segments. His results indicate that, by using a segmented high beam, the safety level for nighttime driving is raised as the light flux in the area above the cutoff line is increased by 33% compared to a regular high beam.

The influence of different vertical resolutions of a Matrix Beam system was analyzed by Michel [26] in a field study. A single-line system and a system with four lines were compared. After evaluating the subjects' statements, she concluded, 'The system with several lines proved to be advantageous during the objective and the subjective inspection.'

Summing up, the use of already-launched lighting systems leads to an early detection of obstacles, dangerous objects, and situations. As a result, accidents can be fully avoided, or the impact speed can be reduced in the event of an unavoidable collision. According to Stämpfle and Branz [27], a half-second earlier reaction of the driver can prevent 60% of rear-impact crashes and one third of frontal collisions. Driving at a speed of 100 km/h, this would mean an extra distance of 14 m.

# 5 High-resolution light functions

In the previous chapter, the effects of state-of-the-art headlamps on traffic safety can be seen. The potential of new functions of high-resolution headlamps lies in the innovative low-beam functions and increase of the performance ratio of the glare-free high beam. The low beam functions are supposed to compensate the deficits in perception, as described in Chapter 1. Gut and Berlitz [28] has already explained that one of the main goals of the new low beam functions are to support the driver in his vision and perception tasks at night in an optimal way, without distracting them or other road participants.

Basically, the high-resolution light functions can be grouped into three main categories:

- Safety functions
- Comfort functions
- Interactive functions

In the following, some examples of the three groups will be described in detail.

- Construction zone light: Out of these three, the safety function is the most important category. The 'construction zone light' is one example of this group. Funk et al. [29] describes two stripes of light being projected onto the road, which display the width of the vehicle. This is helpful for lane keeping. Thanks to this, the driver could be assisted in construction zones by this light function.
- Advanced glare-free high beam: The 'advanced glare-free high beam' is also a safety function. It is possible to increase the performance ratio by closing the gap between the shielded car and the light (shown in Figure 3).
- Advanced curve light: A light function, which shows the trajectory of the ego-vehicle, is one possible new safety light function to compensate the

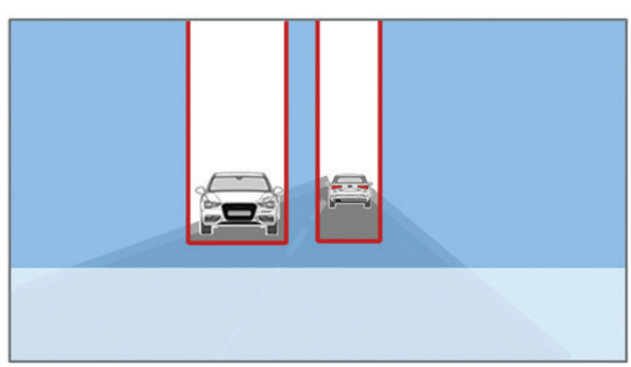

**Figure 3:** Optimized glare-free high beam.

underestimation of curve radii during nighttime. Two stripes, like in the 'construction zone light,' which adapt to the vehicle trajectory can be used.

- Light-based navigation: The 'light-based navigation' is part of the comfort functions category. In this approach, the driver is subconsciously supported by a precise and dynamic shift of the light focus, which highlights road exits and signs. The limited orientation at night can be compensated by that.
- Programmable light: The 'programmable light' is also part of the comfort functions. Here, the driver is able to configure a part of the low beam box (shown in Figure 4) by means of an input device. Additionally, the low beam can adapt to the intensity and the opening angle to the driver's needs, depending on the driving style and driving duration. It is also possible for the driver to customize the headlamp by projecting personalized logos or special light signals on the street or against a wall.
- Piloted driving light: Functions for piloted driving vehicles are part of the interactive functions category. The vision is to replace the eye contact between the driver and the pedestrian in autonomous driving vehicles. Therefore, a projection on the street signals to the pedestrian that he has been recognized by the vehicle and that it is safe to cross the street. In order to increase acceptance, the light function must be easy to interpret. The vehicle can communicate via the headlamp and tell pedestrians that it is safe to cross the road by projecting footsteps or a crosswalk on the road. Furthermore, it has to be visible for the pedestrian which car is projecting and to whom the projection is addressed. This means that the light distribution starts close to the vehicle in the direction of the pedestrian. The projection must end as close as possible to the pedestrian. Only this way it is possible to make a precise addressing.

All of the light functions, except for the 'piloted driving light' can be projected on different areas in front of the vehicle. Each position has advantages and disadvantages, which will be evaluated in Table 1. Therefore, the low beam has been divided into a near and far field according to Manz et al. [30]. He located the near field within 40 m. The far field is between 40 m and 150 m.

The advantage of the projection in the near field is that the light function is visible for the driver. That is possible because the illumination increases with the distance. If the projection distance to the next vehicle is short, the function can be allocated to the ego-vehicle. Furthermore, the impact of vehicle rolling does not significantly affect the light distribution.

If the projection is into the far field, the driver is able to react early on. If many vehicles use a function in the far field simultaneously, this can generate a confusing situation. Another disadvantage is that the activation time in the far field is restricted, as the light function of the ego-vehicle has to be deactivated if the driver drives too close to the vehicle in front. Thanks to this, the authors recommend to position the light functions into the near field within a distance of 25 m.

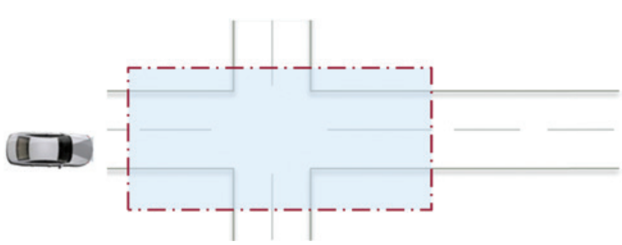

Figure 4: Programmable low beam.

# 6 High-resolution headlamp design

## 6.1 Resolution

In the first approach, the low-beam light distribution (shown in Figure 4) can be adapted almost arbitrarily by software. Therefore, it is possible to develop novel low-beam functions. In order to create a homogenous light distribution without visible pixels, the resolution of the high beam must correlate with the human eye resolution, which is 1/60° [31]. It also has to be considered that the light distribution quality of the low beam depends on different factors. 'Because of potholes in the road, wet streets, street topography as well as vehicle rolling, the

Table 1: Position of light functions.

| Near field | Far field |
|---|---|
| Advantage | |
| – High perception | – Closure of vertical gap |
| – Function allocation available | – Long response time |
| – Impact of vehicle rolling | |
| Disadvantage | |
| – Fast response time | – Low perception |
| – Distortion | – Function allocation not available |
| | – Low interaction resolution |
| | – Short activation time |

light distribution has to be regularly adjusted. Otherwise, the form of light distribution is constantly changing' [32].

As described above, another safety function is the projection of information for pedestrians. Regarding the vertical resolution, it is important to know that a headlamp mounting height of 0.65 m and a pixel size of 0.5 m in a distance of 25 m result in a resolution of 0.03°. The horizontal resolution is independent of the projection distance. Therefore, the horizontal angle can be smaller than the vertical resolution.

In the second approach (shown in Figure 3) the glare-free high beam is optimized. It becomes clear that the visibility range increases with a higher vertical and horizontal resolution, thanks to the high performance ratio of the glare-free high beam. Therefore, it is possible to decrease the gap between the shielding of the preceding car and the rest of the light. Austerschulte showed in his research [25] that the performance ratio of a glare-free high beam can be increased by a resolution increase of 0.5°. However, he also stated, that the 'activation does not increase significantly if the resolution of the segments is even higher.' Hummel [33] has shown that a resolution of 0.1° results in an overall performance ratio of over 98%. Therefore, it can be concluded that a resolution of a glare-free high beam of 0.1° is effective enough, as also proven by Moisel [34].

## 6.2 Opening angle

First of all, the vertical opening angle $\beta$ for the new light functions must be calculated. The distance between the starting point of the light distribution and the vehicle $P_{PAb}$ must be 10 m. This way, the light distribution is always in the field of view of the driver, independent of the driver's head position. The end of the light distribution results out of the projection distance $P_{PAb}$ and the projection length $P_{Pro}$. For $P_{Pro}$, a length of 15 m is assumed. If the mounting height of the headlamp $h_{Sch}$ is 0.65 m, a vertical opening angle $\beta$ of 2.23° can be calculated using equation (1).

$$\beta=\left|-\arctan\left(\frac{h_{Sch}}{l_{PAb}}\right)\right|-\left|-\arctan\left(\frac{h_{Sch}}{l_{PAb}+l_{Pro}}\right)\right| \tag{1}$$

As already discussed, light function for piloted driving must start as close as possible to front of the vehicle. One possible value is $P_{PAb}$=5 m. If the light distribution had to end after 25 m, the vertical opening angle $\beta$ would be 5.92°.

The calculated values above refer to a mounting height of 0.65 m. The values of mounting height and projection distance can vary from vehicle to vehicle. In the following chart (shown in Figure 5), the necessary opening angle can be determined.

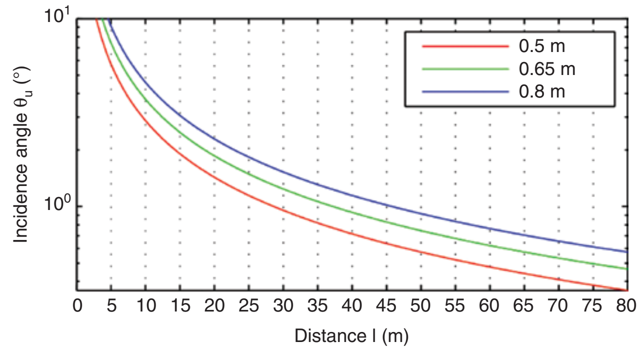


**Figure 5:** Vertical angle depending on mounting height.

In the following section, the horizontal opening angle is calculated. The worst-case scenario is a curve to the left in which the vehicle has not driven in yet (shown in Figure 6). It is assumed that the opening angle of the left headlamp must be the same as the opening angle of the right headlamp $\alpha_{LS}=\alpha_{RS}=\alpha_d$. Furthermore, the light distribution of the light function is restricted to the traffic lane of the ego-vehicle. The projection distance $l_{PAb}$ is 10 m, and the projection length $l_{Pro}$ is 15 m. The overlap distance $l_{LSRS}$ must be the same as the projection distance $l_{PAb}$ in order to avoid gaps in the light distribution. This

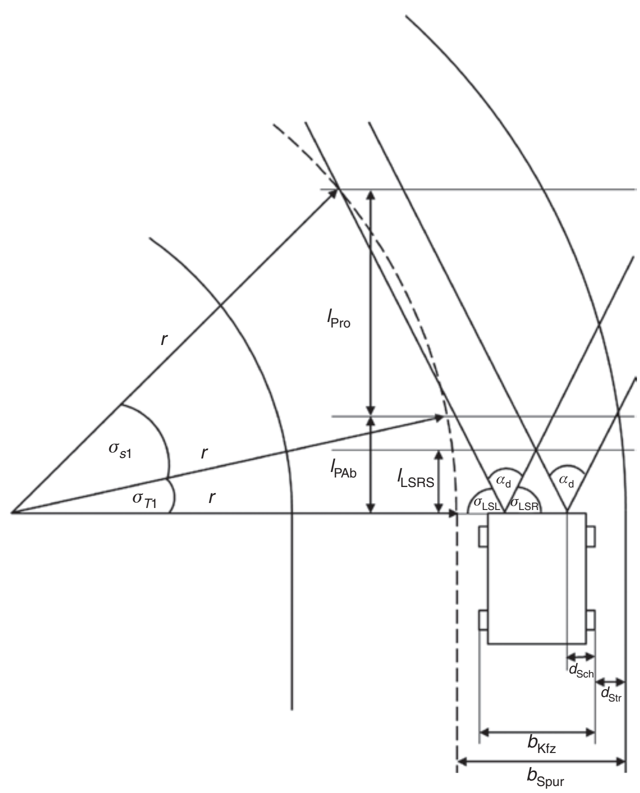


**Figure 6:** Setup for the calculation of the horizontal opening angle $\alpha_d$.

results into a first condition for the opening angle $\alpha_d$, described in equation (2).

$$\alpha_d = 2\cdot\arctan\left(\frac{\frac{b_{Kfz}}{2} - d_{Sch}}{l_{LSRS}}\right) \geq 2\cdot\arctan\left(\frac{\frac{2\text{ m}}{2} - 0.4\text{ m}}{10\text{ m}}\right) \geq 6.8^\circ \quad (2)$$

The width of the vehicle $b_{Kfz}$ is 2 m, and the distance between the headlamp and the outer edge of the vehicle $d_{Sch}$ is 0.4 m. The values apply to standard vehicles and can be taken from Manz's review [30].

The second condition is that the intersection point $S_1$ is cut by the light distribution of the left headlamp. This results into equations (3, 4).

$$r\cdot\cos(\sigma_{s1} + \sigma_{T1}) + \frac{(l_{Pro} + l_{PAb})}{\tan\left(90 - \frac{\alpha_d}{2}\right)} - d_{Str} - d_{Sch} = r \quad (3)$$

$$\sigma_{s1} + \sigma_{T1} = \sin^{-1}\left(\frac{l_{Pro} + l_{PAb}}{r}\right) \quad (4)$$

The opening angle $\alpha_d$ as a function of the curve radius $r$ is shown in Figure 7. Controlled by activation conditions and the road type, the possible curve radius can be determined.

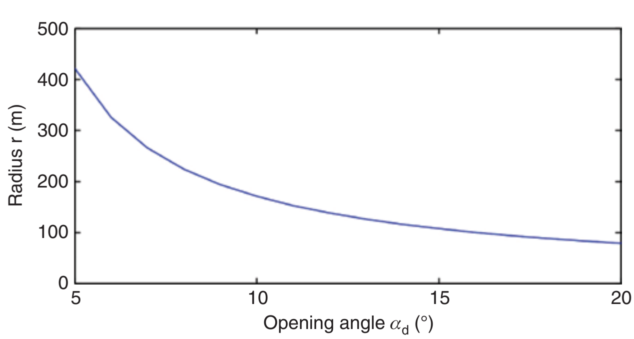


**Figure 7:** Opening angle $\alpha_d$ as a function of the curve radius $r$.

## 7 Conclusion and outlook

This paper shows how new light functions can be implemented with the help of high-resolution systems. The low-beam functions described in this paper can partially support the visual perception at night. This paper shows that it is reasonable to locate the low-beam functions in the near field. Based on that, the opening angle and the resolution were determined. A resolution of 0.1° appeared to be sufficient for a glare-free high beam. For a homogenous low-beam light distribution, a resolution of 0.016° is needed. The vertical opening angle for the light-based driver assistant functions has to be 2.23°. The horizontal opening angle as a function of the curve radius is also being determined.

Now, it is time to bring the new technologies into serial production. Currently, car manufacturers and suppliers are doing research on LCD [35], DMD [36], and laser-based scanning technology [37]. Furthermore, the sensor data and vehicle architecture must be adapted to the new requirements. If the first prototypes are available, the developed light functions can be tested in a field study with regard to perception and distraction.

## References

[1] T. Jaeckel, A. Kroll and K. Markus, AXA Verkehrssicherheitsreport. Edited by AXA Konzern AG (2015).
[2] H. W. Leibowitz and D. A. Owens, Science 197, 422–423 (1977).
[3] R. Schulz, Blickverhalten und Orientierung von Kraftfahrern auf Landstraßen (Dissertation, Technische Universität Dresden, Dresden, 2012).
[4] M. Böhm, Adaptive Frontbeleuchtungssysteme im Kraftfahrzeug: Ein Beitrag zur nächtlichen Verkehrssicherheit? (Dissertation, Technische Universität Chemnitz, Chemnitz, 2012).
[5] H. W. Leibowitz, D. A. Owens and R. A. Tyrell, Accident Anal. Prev. 30, 93–99 (1998).
[6] A. S. Cohen, Blickverhalten und Informationsaufnahme von Kraftfahrern (Bericht zum Forschungsprojekt FE 8306/3 im Auftrag der BASt, 1987).
[7] B. Hristov, Untersuchung des Blickverhaltens von Kraftfahrern auf Autobahnen (Dissertation, Technische Universität Dresden, Dresden, 2009).
[8] A. S. Cohen, in 'Handbuch Verkehrsunfallrekonstruktion. Unfallaufnahme, Fahrdynamik, Simulation', Eds. By H. Burg, A. Moser (Wiesbaden: Vieweg+Teubner, 2009) pp. 217–234.
[9] C. Gut, Untersuchung des Blickverhaltens von Kraftfahrzeugführern in Kurven bei Nacht. Studienarbeit (Karlsruher Institut für Technologie (KIT), Karlsruhe. Lichttechnisches Institut, 2011).
[10] M. Schweigert, Fahrerblickverhalten und Nebenaufgaben (Dissertation. Technische Universität München, München, 2003).
[11] A. V. Hoffmann, Lichttechnische Anforderungen an adaptive Kraftfahrzeugscheinwerfer für trockene und nasse Fahrbahnoberflächen (Dissertation. Technische Universität Ilmenau, Ilmenau, 2003).
[12] M. Böhm, C. Neumann and J. Locher, Zeitschrift für Verkehrssicherheit 55, 64–69 (2009).
[13] C. Gut, A. Petersen, P. Jahn, M. Seitz, C. Neumann, et al., in 'ELIV-Kongress zur Fahrzeugelektronik', Ed. By VDI Wissensforum GmbH (ELIV-Kongress zur Fahrzeugelektronik, Baden-Baden, 2015).
[14] Lichtquellen & Lichtsysteme. Available online at http://www.hella.com/hella-com/Scheinwerfer-620.html?rdeLocale=de.
[15] C. Funk, Heterogene Sensordatenfusion für eine prädiktive Lichtsteuerung. Dissertation (Gottfried Wilhelm Leibniz Universität Hannover, Hannover, 2013).

[16] U. Carraro, U. (Ed.), Teil 1: Sichtbarkeit aus lichttechnischer Sicht, der Dunkelheitsunfall, Rekonstruktion durch Berechnung (2009).

[17] HELLA KGaA Hueck & Co., L-LAB: Hella Meilensteine. HELLA KGaA Hueck & Co., L-LAB. Lippstadt. Available online at http://www.hella.com/hella-com/de/Scheinwerfer-620.html.

[18] M. Richter, Debüt der Matrix-LED-Technologie. HELLA und AUDI haben weltweit ersten Matrix-LED-Scheinwerfer mit Blendfreiem Fernlicht im Audi A8 präsentiert. Lippstadt (2014).

[19] W. Huhn, C. Gut, S. Omerbegovic, T. Haug and C. Funk, The advanced ADB system of the new Audi Q7. In Fudan University, China Illuminating Engineering Society (CIES), Engineering Research Center of Advanced Lighting Technology, Ministry of Education (Eds.): The 3rd International Forum on Automotive Lighting. (2015, China). The 3rd International Forum on Automotive Lighting (IFAL). Kunshan (2015).

[20] G. Schwab, Untersuchung zur Ansteuerung adaptiver Kraftfahrzeugscheinwerfer (Dissertation, TU Ilmenau, Ilmenau, 2003).

[21] M. Hamm, in 'Progress in Automobile Lighting 2001. Proceedings of the Symposium, vol. 8. With assistance of Technische Universität Darmstadt. Darmstadt, 25–26. September 2001', Ed. By H.-J. Schmidt-Clausen. (Herbert Utz Verlag Wissenschaft, München, 2001) pp. 369–380.

[22] M. Böhm, F. Kley and S. Kalthloff, in 'ISAL 2007. 7th International Symposium on Automotive Lighting, vol. 12. Technische Universität Darmstadt', Ed. By T. Q. Khanh (München: Herbert Utz Verlag Wissenschaft, 2007) pp. 451–457.

[23] M. Böhm, A. Luschinski and J. Locher, Licht ins Dunkel-Empirische Belege für einen Sicherheitsgewinn durch Lichtbasierte Assistenzsysteme. in VDI Wissensforum GmbH. Optische Technologien in der Fahrzeugtechnik, vol. 2038. VDI Wissensforum. Leonberg, 03-04.06.2008. (VDI Verlag, Düsseldorf, 2008) pp. 119–126.

[24] J. H. Sprute, Entwicklung lichttechnischer Kriterien zur Blendungsminimierung von adaptiven Fernlichtsystemen (Dissertation, Technische Universität Darmstadt, Darmstadt, 2012).

[25] A. Austerschulte, B. Dreier and E.-O. Rosenhahn, in 'ISAL 2013. 10th International Symposium on Automotive Lighting, vol. 15. Technische Universität Darmstadt', Ed. By T. Q. Khanh (München: Herbert Utz Verlag Wissenschaft, 2013) pp. 321–330.

[26] K. Michel, Segmenteinteilung eines mehrzeiligen blendfreien Fernlichts. Diplomarbeit (Westsächsische Hochschule Zwickau, Zwickau, 2014).

[27] M. Stämpfle and W. Branz, Kollisionsvermeidung im Längsverkehr – die Vision vom unfallfreien Fahren rückt näher (Active Safety through Driver Assistance. Technische Universität München, München, 2008).

[28] C. Gut and S. Berlitz, in Ed. By Société des Ingénieurs de l'Automobile, Proceedings Vision 2014. Vision 2014. Versailles, 14.10.2014 (2014).

[29] C. Funk, J. Reim and S. Omerbegovic, in 'ISAL 2015. 11th International Symposium on Automotive Lighting', Ed. By T. Q. Khanh (Technische Universität Darmstadt, 2015) pp. 131–136.

[30] K. Manz, D. Kooß, K. Klinger and S. Schellinger, Entwicklung von Kriterien zur Bewerung der Fahrzeugbeleuchtung im Hinblick auf ein NCAP für aktive Fahrzeugsicherheit. Ed. By Bundesanstalt für Straßenwesen. Bergisch Gladbach (Berichte der Bundesanstalt für Straßenwesen, 2007).

[31] B. Wördenweber, J. Wallaschek, P. Boyce and D. Hoffman, Automotive Lighting and Human Vision (Springer Verlag Berlin Heidelberg, 2007).

[32] C. Gut, I. Rotscholl and C. Neumann, in 'Optische Technologien in der Fahrzeugtechnik', Ed. By VDI Wissensforum GmbH (VDI Wissensforum, 2014).

[33] B. Hummel, Blendfreies LED-Fernlicht. 1st ed. Göttingen: Cuvillier (Audi-Dissertationsreihe 30, 2010).

[34] J. Moisel, in 'ISAL 2015. 11th International Symposium on Automotive Lighting, vol. 16', Ed. By T. Q. Khanh (Technische Universität Darmstadt, 2015) pp. 161–169.

[35] H. Hesse, Bundesministerium für Bildung und Forschung (4/1/2014): Volladaptive Lichtverteilung für eine intelligene, effiziente und sichere Fahrzeugbeleuchtung (2014).

[36] V. Bhakta and B. Ballard, in 'ISAL 2015. 11th International Symposium on Automotive Lighting', Ed. By T. Q. Khanh (Technische Universität Darmstadt, 2015) pp. 483–494.

[37] Bundesministerium für Bildung und Forschung (8/1/2014): Intelligentes Laserlicht für kompakte und hochauflösende adaptive Scheinwerfer. Berlitz, S. Available online at http://www.photonikforschung.de/fileadmin/Verbundsteckbriefe/4._LED/Beleuchtung%20LED%20barrierefrei/iLaS-Projektsteckbrief-bf.pdf.



**Carsten Gut**
Karlsruhe Institute of Technology, Light Technology Institute, Engesserstraße 13
Karlsruhe 76131, Germany
**carsten.gut@audi.de**


Carsten Gut, born in Überlingen, Germany, studied Electrical Engineering at the Karlsruhe Institute of Technology (KIT) until 2012. He started his PhD Thesis in 2012 at the Light Technology Institute at KIT. His focus is on laser based high resolution headlamps technologies and high resolution light functions. In 2012 he joined the Audi AG as a development engineer in the light and sight department.


**Cornelius Neumann**
Karlsruhe Institute of Technology, Light Technology Institute, Engesserstraße 13
Karlsruhe 76131, Germany


Cornelius Neumann studied Physics and Philosophy at the University of Bielefeld, Germany. After his PhD, he worked for the automotive supplier Hella in the advanced development for Automotive Lighting. During his time at Hella he was responsible for signal lighting, LED application and acted as a director of the L-LAB, a laboratory for lighting and mechatronics in public private partnership with the University of Paderborn, Germany. In 2009, he became Professor for Optical Technologies in Automotive and General Lighting and one of the two directors of the Light Technology Institute at the Karlsruhe Institute of Technology, Germany.

**Iulia Cristea**
Karlsruhe Institute of Technology, Light Technology Institute, Engesserstraße 13 Karlsruhe 76131, Germany

Iulia Cristea, born in Bucharest, Romania, is studying Electrical Engineering at the Karlsruhe Institute of Technology since 2010. Her major field of study is automotive lighting. In her bachelor's thesis she analyzed the discomfort glare caused by LED light sources. In her master thesis she will perform physiological studies evaluating lighting systems.