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Regulatory-compliant energy-saving potential for the passing beam of matrix LED headlamps

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1. Abstract

The carbon footprint of modern vehicles and their mechatronic systems is more important than ever. Research by the publicly funded Nalyses project and the HELLA company shows that the headlamps use phase makes a significant contribution to the life cycle footprint taking into account the current electricity mix [1]. Today, functionalities such as adaptive curve light or glare-free high beam ensure comfort and safety by assessing the state of the vehicle and evaluating the driving scenario ahead. In future, this evaluation will be expanded and used to adapt the headlamp to the driving scenario in such a way that as little light as possible is emitted, but as much light as necessary. In order to achieve this goal, an overall evaluation of the regulatory compliant energy saving potential is crucial in a first step and leads to constraints for a dynamic adaption while driving. In this paper, the potential is illustrated by evaluating UNECE Regulation No. 149 and optimizing luminous intensity distributions. Depending on the different resolutions of matrix LED headlamps, this approach can result in a significantly lower luminous flux. On the other hand, the results are point-like distributions that raise the question of whether the regulation still provides for sensible minimum requirements for modern matrix LED headlamps. The results are further presented in a simulated virtual environment with regard to the resulting luminance in different driving scenarios. We then present an approach to integrate regulatory requirements into a control algorithm by setting optimization constraints and saturating the control. Finally, we classify the found luminous intensity distributions qualitatively according to common lighting criteria. In summary, although the investigated minimum distributions are by no means desirable for drivers themselves, they form the basis on which energy-saving distributions for illuminated areas and twilight scenarios could be adaptively controlled in the future.

Keywords: matrix LED headlamps, regulatory compliance, sustainability, lighting function development, simulation

2. Introduction

Sustainability is omnipresent today, influencing also the field of lighting function development. HELLA carried out research into energy-efficient driving more than 10 years ago [2]. This paved the way for specifically evaluating the possibilities for reducing the energy consumption of certain lighting functions such as the passing beam. With the aim of reduction, the idea of dimming the passing beam in illuminated areas is a logical step, leading to reduction potentials of 20 % without the driver noticing [3]. Recent studies have also shown that using adaptive lighting functions tailored to different road lighting scenarios can meaningfully reduce the energy consumption of headlamps [4]. This work aims to take this process to the very top by simulatively evaluating the maximum possible energy-saving potential of different matrix LED headlamps with regard to today's regulation requirements.

The basis of today’s regulations for headlamp development is given by the UNECE Regulation No. 149 [5]. The idea of evaluating the optimization potential of adaptive front lighting systems with regard to ECE regulations is far from new. In the past, these considerations have already led to recommendations such as the use of adaptive prefield intensities in adverse weather conditions, the use of adaptive side lighting and the use of an adaptive motorway beam [6].

With this work, we aim to explore the potential for energy savings by presenting adapted luminous intensity distributions that minimally comply with the requirements of UNECE Regulation No. 149. In this paper, we have focused on the AFS standard passing beam, namely the Class C passing beam. The requirements for this type of beam can be subdivided into lower bounds and upper bounds (see Figure 1). In general, the requirements consist of multiple measurement points and areas, where each element specifies a certain threshold for the luminous intensity distribution. In addition, “BLL” and “BRR” define upper limits for a line-shaped element. All limits are included as constraints into an optimization that is introduced in chapter 3.

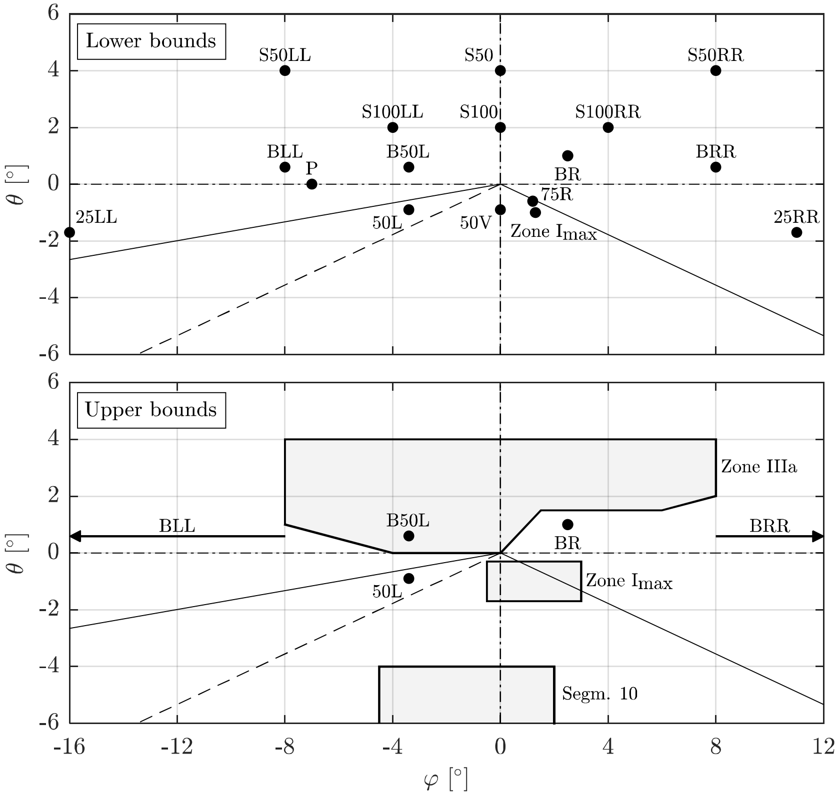

Figure 1: Positions of the luminous intensity limit values for right-hand traffic headlamps that are providing a AFS passing beam Class C according to [5]

For the evaluation of the minimum compliant passing beams, we use a model-based approach utilizing MATLAB and Unity. We further introduce four different headlamp compositions. Each headlamp consists of the prefield light module (see Figure 2) and either one of the matrix light modules A-D (see Figure 3). The models of the light modules are measured or simulated luminous intensity distributions given in the IESNA standard file format [7]. Each light source of the modules is measured individually and can therefore be controlled separately in simulation.

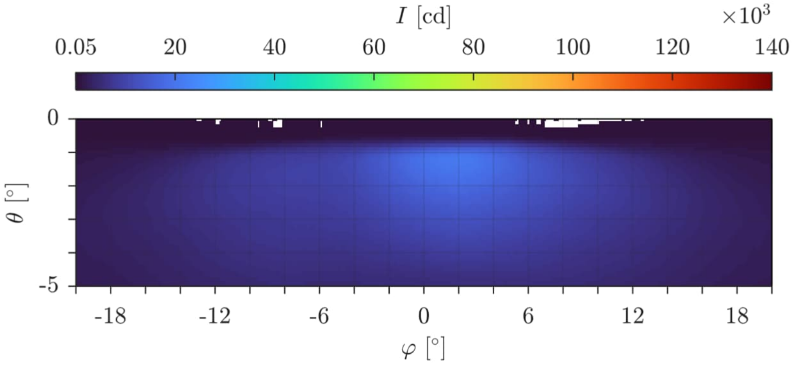

Figure 2: Luminous intensity distribution of the prefield light module with one controllable light source ($K_{Pre} = 1$)

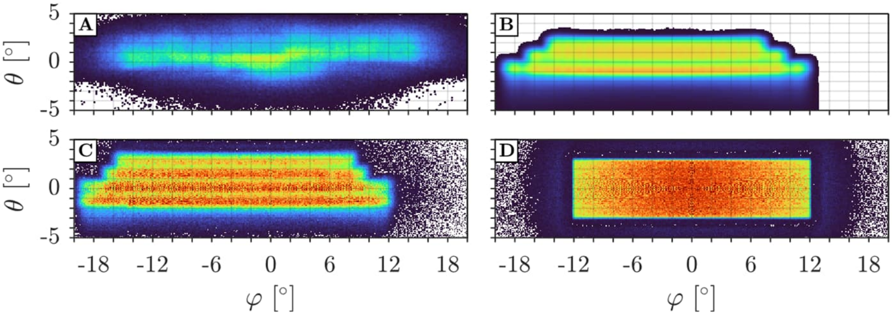

Figure 3: Luminous intensity distributions of the matrix light modules with increasing number of individually controllabe light sources K, whereas $K_A = 21$, $K_B = 48$, $K_C = 102$ and $K_D = 16384$. Colorbar of Figure 2 applies.

3. Constrained luminous intensity Optimization

In order to realize a passing beam that meets the minimum regulatory requirements, the provided luminous intensity distributions are optimized through constrained optimization that is adapted from [8].

For notation, let H denote a headlamp consisting of two light modules M (the prefield Pre and either A, B, C or D, see also Figure 2 and Figure 3). We assume that the measured luminous intensity distribution matrix for each light source $k = 1 \dots K$ of light module M is given by $\boldsymbol{I}_{M,k} \in \mathbb{R}_{\geq 0}^{m \times n}$. The distributions are represented as matrices of dimension $m \times n$, where the dimensions correspond to measurement angles – specifically to the horizontal angle φ_n and vertical angle θ_m.

For the purpose of optimization, each matrix $\boldsymbol{I}_{M,k}$ is converted into a column vector by vertical concatenation. With $P = m \cdot n$, the overall matrix containing the luminous intensity data of one light module is given by, for example $\boldsymbol{I}_M^A \in \mathbb{R}_{\geq 0}^{P \times K_A}$. This results in the luminous intensity matrix for a complete headlamp, for example $\boldsymbol{I}_H^{A,Pre} = [\boldsymbol{I}_M^{Pre}, \boldsymbol{I}_M^A] \in \mathbb{R}_{\geq 0}^{P \times (K_{Pre} + K_A)}$. Every LED k of headlamp H with luminous intensity distribution $\boldsymbol{I}_H$ can be controlled by the dimvalue $d_k \in [0,1] \subset \mathbb{R}$, leading to a vector $\boldsymbol{d}_H \in [0,1]^{K \times 1}$ for every headlamp.

For the desired luminous intensity distribution of the optimization a zero vector $\boldsymbol{I}_{\min}^* = \boldsymbol{0}^{P \times 1}$ is chosen to find the minimized distribution. Then, a vector $\boldsymbol{I}_{\max}^* \in \mathbb{R}_{\geq 0}^{P \times 1}$ with large but finite positive values is selected to find the maximized distribution.

Next, we introduce constraints to take the regulatory requirements into account. First, we denote $\boldsymbol{I}_{\mathrm{c,min}} \in \mathbb{R}_{\geq 0}^{P \times 1}$ and $\boldsymbol{I}_{\mathrm{c,max}} \in \mathbb{R}_{\geq 0}^{P \times 1}$ as constraint vectors representing the lower and upper bounds with respect to Figure 1. If no constraint applies, $\boldsymbol{I}_{\mathrm{c,min}}$ is 0 and $\boldsymbol{I}_{\mathrm{c,max}}$ is large but positive finite. Furthermore, $I_{\mathrm{c},50} \in \mathbb{R}_{\geq 0}$ and $I_{\mathrm{c},100} \in \mathbb{R}_{\geq 0}$ denote the limit values for the sum of the points S50LL, S50, S50R and S100LL, S100, S100RR respectively. This is because the regulation specifies a maximum allowed sum for the two sets of points. To incorporate these sum constraints into the optimization, the headlamp-specific matrices $\boldsymbol{I}_{H,c,50} \in \mathbb{R}_{\geq 0}^{P \times K}$ and $\boldsymbol{I}_{H,c,100} \in \mathbb{R}_{\geq 0}^{P \times K}$ are introduced. All elements in these matrices are zero except for the constrained points, where they are set to the corresponding luminous intensity values of the headlamp.

Finally, the optimization problem is defined as

$$\min_{\boldsymbol{d}_H} \sum_{p=1}^{P} (\boldsymbol{I}^* - \boldsymbol{I}_H \cdot \boldsymbol{d}_H)^2$$

$$c.t.: 0 \leq \boldsymbol{d}_H \leq 1,$$

$$\boldsymbol{I}_H \cdot \boldsymbol{d}_H \geq \boldsymbol{I}_{c,min},$$

$$\boldsymbol{I}_H \cdot \boldsymbol{d}_H \leq \boldsymbol{I}_{c,max},$$

$$\textstyle\sum_{p=1}^{P} \boldsymbol{I}_{H,c,50} \cdot \boldsymbol{d}_H \geq I_{\mathrm{c},50},$$

$$\textstyle\sum_{p=1}^{P} \boldsymbol{I}_{H,c,100} \cdot \boldsymbol{d}_H \geq I_{\mathrm{c},100}.$$

The optimization problem is solved in MATLAB using the *lsqlin* solver (linear least squares with constraints), employing the interior-point algorithm as the optimization method.

4. Results

The following chapter presents the results of the optimization problem defined in Chapter 3, executed using the headlamp configurations and regulatory requirements introduced in Chapter 2. Figure 4 illustrates both the minimized and maximized outcomes.

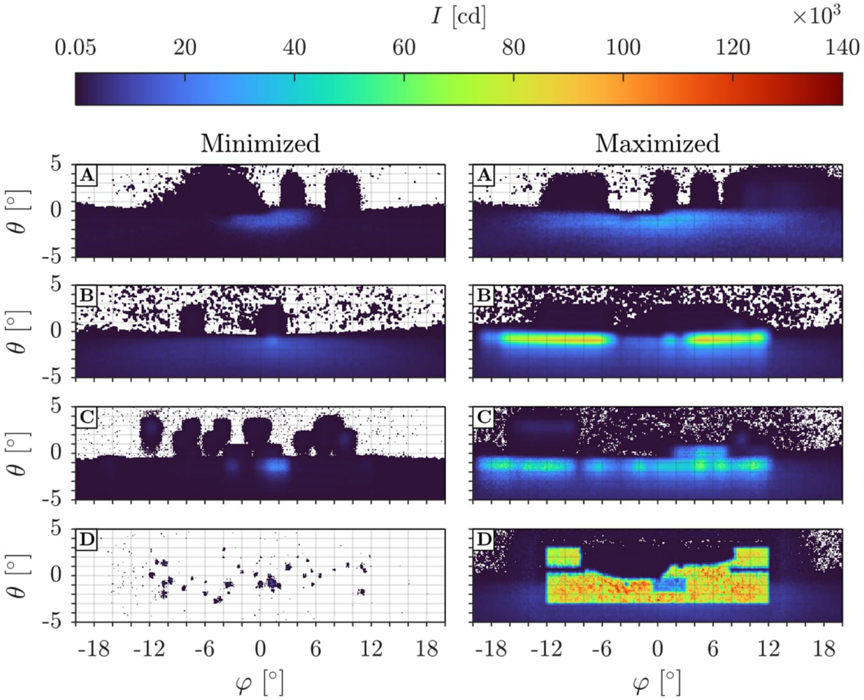

Figure 4: Optimized luminous intensity distributions of the four considered headlamps according to the optimization of Chapter 3. Generally, the number of controllable LEDs rises from top to bottom.

First of all, the figure clearly demonstrates the strong correlation between the number of controllable LEDs and the ability to shape the luminous intensity distribution, with configuration *D* exhibiting the most distinctive distribution pattern. The minimized distribution of *D* is point-shaped. The prefield is turned off and the LEDs of the matrix module are mostly off, except for a few LEDs that precisely illuminate only those points required by regulation. On the other hand, the maximized distribution of *D* visibly shows a precise “cut” around the maximum regulation requirements so that for example Zone IIIa and Zone I_{max} are clearly identifiable. As the results show either greatly reduced or increased distributions, the luminous flux, and thus the energy consumption, is expected to be greatly reduced or increased. The results also raise the question whether the regulation can still be used sensibly to rate high definition matrix LED headlamps.

This question is emphasized by the resulting luminance distributions in the "Hyperion" night driving simulation shown in Figure 5 [9]. The minimized distribution at night only consists of spots but is as regulatory compliant as the default distribution at night.

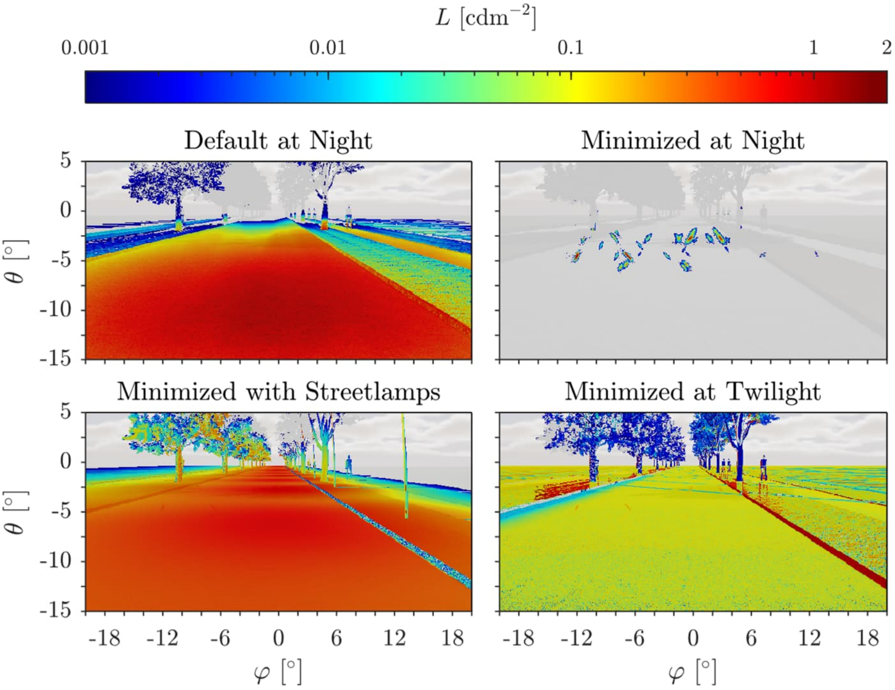

Figure 5: Luminance distributions in Hyperion for driving scenarios modelled after the street in front of the Heinz Nixdorf Institute, using the headlamp with light module *D*. The well-lit scene without shadows is displayed with high transparency in the background.

The plots at the bottom show two possible driving scenarios (with streetlamps and during twilight) where a minimized passing beam or at least a reduced beam could be used – possibly without affecting the driver.

Lastly, the resulting luminous flux thus the resulting energy consumption is evaluated in Figure 6. If the headlamps were dimmed to the regulatory minimum, the energy consumption would be reduced to 20,99 % for A, 55,41 % for B, 11,42 % for C and even 0,27 % for D in comparison to the default beam. The goal for the future should be to lower the energy consumption of the default passing beams from the maximums in the direction of the regulatory minimums.

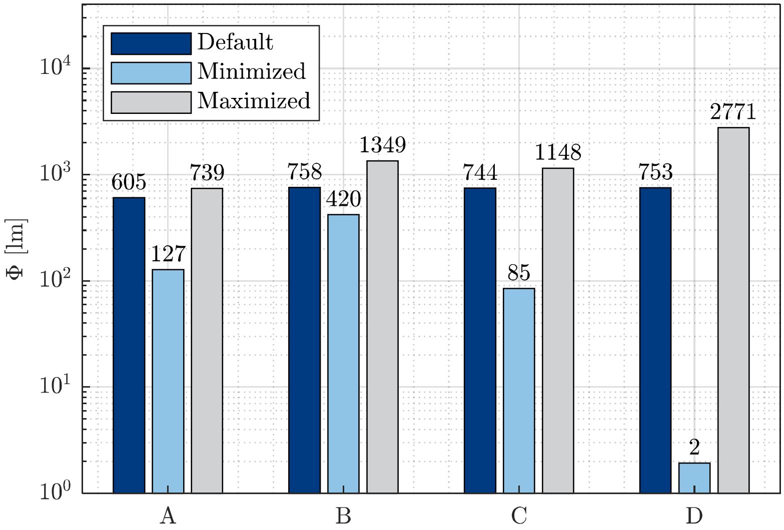

Figure 6: Luminous flux comparison for every headlamp composition.

5. Conclusion and Outlook

In Summary, it can be said that we have taken energy saving to the very top in this work and demonstrated the great potentials for energy saving from a regulatory perspective. Even though the distributions probably cannot be used in practice without adjustments, they represent the highest possible regulatory energy savings. Furthermore, since some distributions are point-shaped and target the small areas and points defined our work raises the question of whether the regulation is capable of evaluating high-resolution matrix LED headlamps.

Looking ahead, the next two figures illustrate the next steps. First, the considered luminous intensity distributions are qualitatively classified with common lighting criteria in Figure 7. The figure shows that the default distribution is the most balanced. Future work will focus on the minimized distribution in comparison to the default distribution. On the one hand, we strive towards energy efficiency and second, as a side-effect, glare prevention and visibility could be improved by a dimmed distribution in illuminated areas as stated in the introduction.

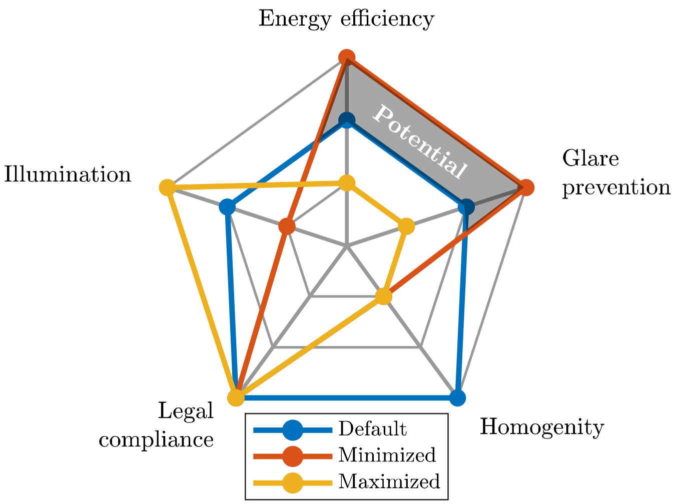

Figure 7: Qualitative classification of the three types of luminous intensity distributions considered in this work.

Lastly, a luminance-based control framework is proposed in Figure 8 which can be used to dim the passing beam in illuminated driving scenarios. The optimization and the controller require a model of the luminance L (including $\boldsymbol{I}_H$) and provide dimvalues d. The desired Luminance $L^* \in \mathbb{R}_{\geq 0}$ can possibly include the Luminance of the environment. ΔL is the difference between the desired Luminance L^* and the resulting luminance of the feedforward control in the environment. The present work is implemented by constraining the optimization and introducing a saturation based on the dimvalues $\underline{d}_c$ and $\overline{d}_c$ corresponding to the distributions found. In future work, the whole luminance-based control will be presented and assessed in the night drive simulation Hyperion to strive to the goal of energy saving.

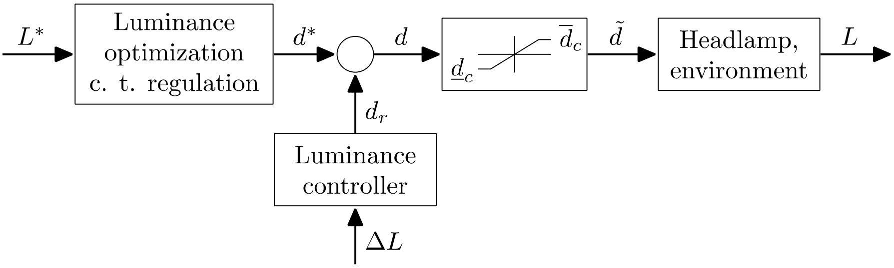

Figure 8: Luminance-based control that inherits the regulatory constraints in the optimization and in a saturation to saturate the controller.

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