The challenges and the first practical experiences of Roadway Lighting Design in Virtual Reality

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Abstract

In roadway lighting applications where motorized traffic is involved, the installed luminaires must maintain sufficient and uniform luminance of the roadway surface perceived by the drivers of vehicles while also controlling glare in order to ensure clear visibility and detectability of obstacles on the tarmac outside the safe stopping distance. While the most recent revisions of the governing 'lighting design standard' usually applied by European roadway lighting installations is issued as EN 13201-, published in 2016 – are prepared for the technological advancements of highly directional LED based luminaires, the technical background of the recommended calculations are based on methods developed for a past era of computational calculations.

The purpose of this paper is to give a summary of the challenges faced by developing a full-scale virtual reality environment for a visual design verification of roadway lighting installations. Such systems are to be prepared for an extensive real time modeling of human vision during nighttime adaptation besides applying advanced 'shader' algorithms for a photorealistic and perception realistic rendering of tarmac reflections, environmental conditions and volume scattering effects. The rendered image presented to the user is calibrated to high-resolution luminance measurements including colorimetry.

During the development of the introduced software and hardware environment, an intensive implementation of features based on feedback provided by industry experts and a civil control group was taken care of. The findings of the surveys are leading to the proposal of an alternative lighting design calculation method implementing the contrast perception capability of an arbitrary observer for defined trial obstructions with given extents, positioning and reflection characteristics – mimicking common root causes of accidents.

1. Introduction

The total sales of outdoor LED lighting in EU17 increased a vast 4.8% in 2015 estimated outreaching EUR 2.8 Billion [1]. Almost 30% of the outdoor lighting fixture demand of the market today is roadway specific where Year over Year fixtures sales is in an expanding state, while unit costs are dropping rapidly. Energy savings by the adaptation of solid-state lighting technology can realize values of 40% - sometimes even above 60%, especially favouring legacy HPS installations and leading to serious challenges by suburban regions where fluorescent light sources are operating at thrifty power consumption settings [1].

The achievable Return on Investment is luring for authorities and operational vindication for lowering upkeep costs. While addressing a renovation project of upgrading public lighting is generally beneficial to the economy; without a proper lighting design these investments often lead to civil repining, ad hoc increased traffic accident rates.

In the EMEA region, authorities usually require the governing local standards for roadway lighting installations to be met – that is based usually on EN 13201 standard series, although there is no general enforcement to align and deviation from the necessary performance indicators is legally complicated to be justified. A main challenge of the lighting design is the characterisation of the tarmac reflectance. The surface optical properties are changing during the lifecycle due to pollution, aging, damages and weather conditions, whereas two given states can change significantly.

2. Practical issues with modern lighting designs

The road lighting recommendations widely adopted in the EMEA region consist three major distinct lighting situations. Traffic routes where motorized vehicular participation is the vast majority, Conflict areas, where steams of vehicles intersect with each other or with pedestrian traffic and residential roads. The latest revision of the standard refractors the boundaries of these instances but the calculation methods did not change [2].

As a rule of the thumb, for pedestrian and cyclist participants of traffic, illuminance properties are evaluated and for observers in driving roles, the luminance of the roadway surface at a safe stopping distance is the key parameter to be optimized.

As already stated, luminance is derived of the (commonly used) R-table established for the tarmac that is not being constant in time and may take values on a wide range. Figure 1 and 2 are showing a sample lighting scenario where EN 13201 based criteria were broadly met and still, a reference trial surface with a 48% Lambertian reflectivity is practically invisible to the observer, the reason being no contrast between the object and the surroundings.

Figure 1: Sample Lighting Scene

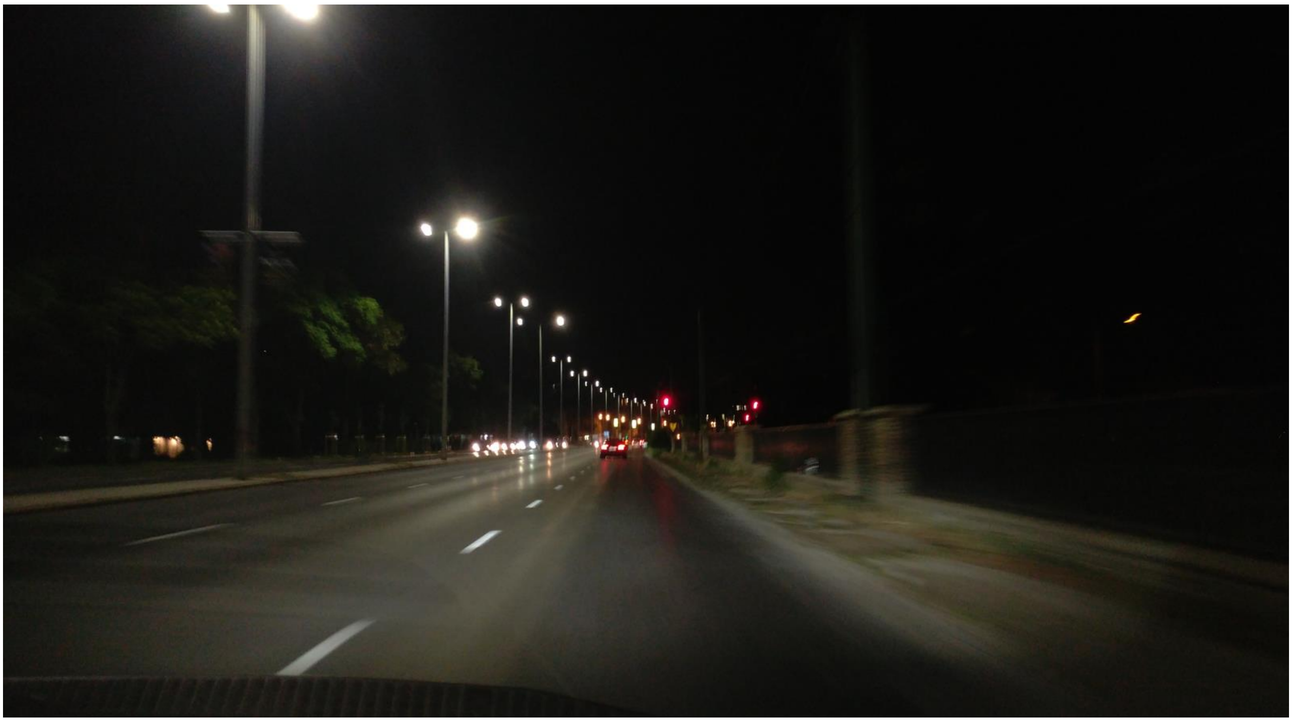

Figure 2: Sample Lighting Scene

Figure 3 on the other hand introduces a specific lighting scenario, where the same trial obstacle is not apparent to the observer – not even from close range – due to insufficient luminance on the field of view in the region of interest, only in wet surface conditions. This effect is partially caused by the immerse luminance of the direct reflection of the LED lighting fixture.

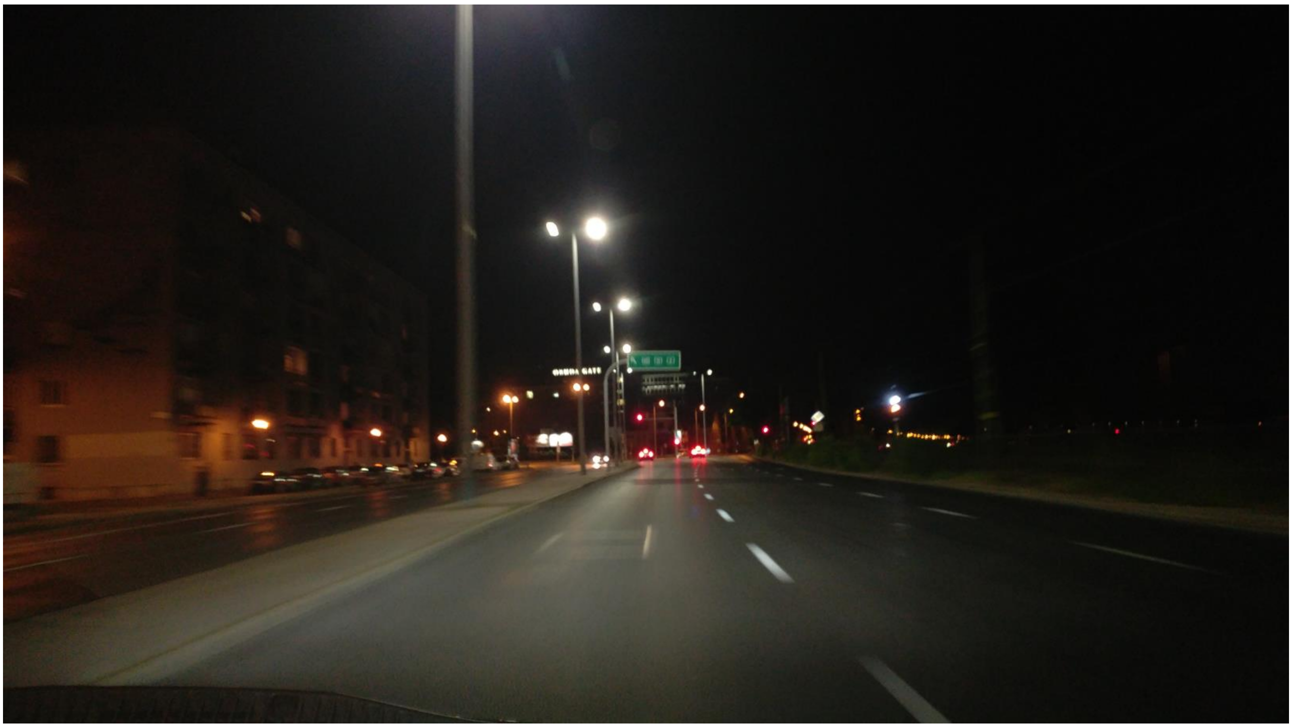

Figure 3: Sample Lighting Scene with trial obstacle close ahead

For a more brightening example, Figure 4 introduces a recent LED installation on a bridge, where this reference obstacle was found to be always clearly visible, Veiling Luminance ratio is below 0.1 without the shielding of the cockpit and task efficiency is outstanding. This clearly demonstrates the strong capabilities of highly directional, cut-off controlled solid-state optics.

Figure 4: Sample Lighting Scene of High Quality Lighting

In contrast, for road lighting standards in the North American region, in general practice there are three options to calculate optical performance and these can be used (and are often used) all at the same time. Namely, sometimes illuminance is being calculated only on a task plane and requirements are set based on the tarmac reflectivity. There is an option to design for luminance perceived by the defined driver and at last, there is an option to calculate the contrast revealing capability of the installation alongside with the luminance of the roadway. This latter method is called Small Target Visibility (STV) and is recommended for vehicular-pedestrian conflict areas. Disability glare is taken into account in all three calculation methods as Veiling Luminance ratio or being implicitly embedded in the visibility level metrics [3].

3. Elements of the Virtual Reality System

The main goal of a lighting design in a Virtual Reality is the rapid assessment of contrast perceiving capability for common root causes of accidents. There is no metric defined for the assessment of the direct experience with a given lighting design for the user, as this is a subjective performance indication. One method directly derived from the properties of this kind of simulation would be a statistical approach, where a large number of participants reaction to certain trials was evaluated.

3.1. General trial obstacles used

In the experiments conducted, there have been two kind of trial obstacles used. One represents an erosion of the tarmac and the other one simulates the detectability of a pedestrian. The latter has had five different kind of realization in order to embed possible outfits capable of creating challenging visibility tasks for drivers [4].

The three obvious trials are wearing uniform coloured cloths having a Lambertian reflectivity of 10%, 33% and 60% respectively. In the other two setup, a bi-coloured outfit was used, top segment being either 10% or 60% reflective and vice versa. The reason for these is to observe contrast loss for both negative and positive contrast scenarios at about the stopping distance. Figure 5. [6] illustrates different contrasts of pedestrians on roadways. While with negative contrast, a person wearing bright trousers and dark coat is harder to spot, the opposite is true in case of positive contrast. In the driving literature, negative contrast is often called “silhouette” and positive contrast is termed “reverse silhouette.” [5]

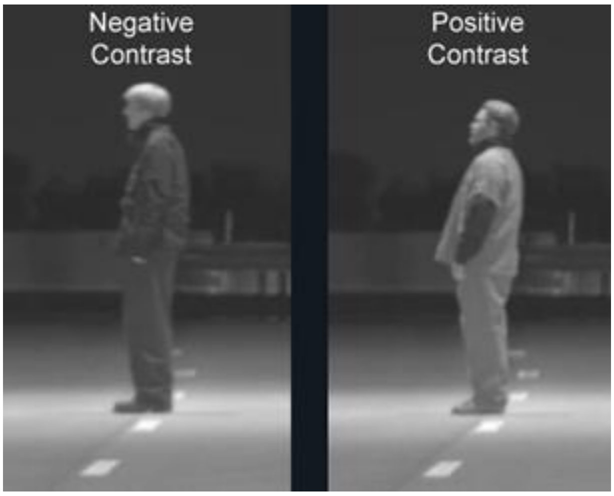

Figure 5: Negative and positive contrast [6]

The general obstacle for tarmac damage (being extremely common in Eastern Europe) has an extent of 150 [mm] in width and 50 [mm] in height and is always perpendicular to the traffic flow. For contrast calculation, a single point in the centre of the sprite was used. All the human trials are 1600 [mm] in height and 400 [mm] in width, also facing the traffic, separation of the outfit is at 600 [mm] form the bottom and calculation grid is of an evenly distributed 2 x 4 matrix, always the worst result taken into account.

3.2. Calculation of the tarmac luminance

Primarily in every rendering task, the brightness of every pixel drawn is to be calculated. In a conventional modern 3D graphics drawing engine, the part that handles lighting is usually separated of the module performing the calculations for transforming the three dimensional spatial extents to a two dimensional screen.

There are three light rendering methods concurrently being applied in practice. Using 'Forward Rendering' takes every light source in the scene and calculates its effect per pixel in a 'Fragment shader' pipeline. This approach limits the number of light sources in the scene and by increasing the number of sources, the application performance decreases radically.

'Deferred Rendering' is a term used for an approach when the imaging of the scene happens in multiple passes. The first pass draws the geometry in a buffer without any light applied. In all the following subsequent passes, the lights are rendered to these surfaces one at a time. Lighting is applied per pixel instead of per Fragment that results in a faster rendering time and improved performance. In this case, the light sources applied to any given geometry can also be limited by selective filtering.

As for the primary objective of lighting design in Virtual Realities, the lighting scenario is simplified by the preliminary condition of the known position of the observer – relative to the tarmac. In this case, a general directional light will be applied for ambient lighting – as optionally the Moonlight will be modelled - and a complex spatial calculation is used for modelling the luminous intensity distribution of the Luminaires. There is also a third type of light source in the scene perceived by the driver, the dashboard (and optionally the HUD). As this will be introduced later on, it is recommended to be a simple emissive surface with high dynamic rendering for the sake of simplicity.

Figure 6. shows a screenshot of the application without the barrel correction for VR headset of an observer pointing 1° below the horizontal with a 3° Field of View to the stopping distance and 120 [m] ahead, calculating only the luminance per pixel, surroundings excluded and having 1 [lx] ambient illumination from above the scene at an infinite distance.

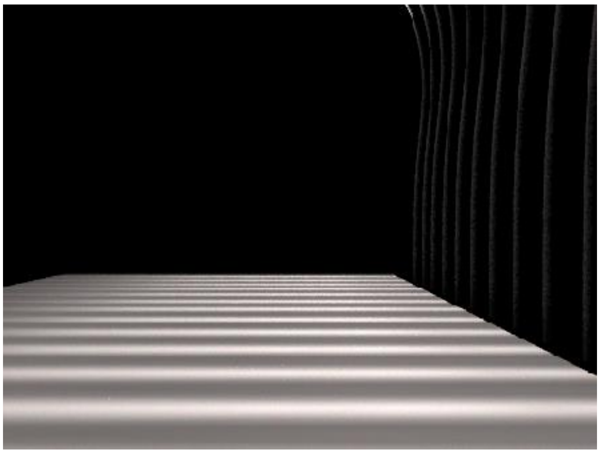

Figure 6: Simulated luminance of the roadway surface

Figure 7. shows a rendered image of a scene with 60° Field of View, color accurate lighting (left) and false color luminance representation (right).

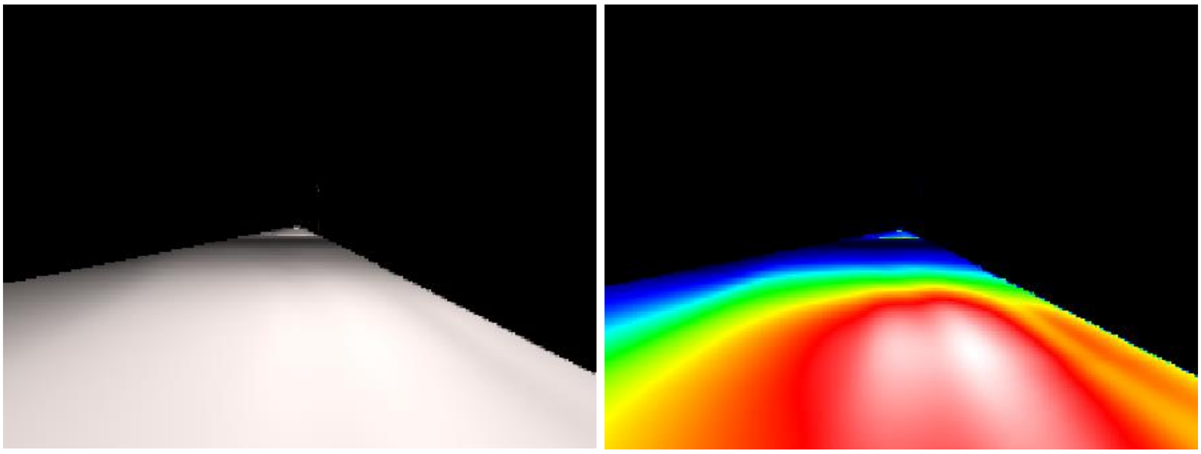

Figure 7: Simulated luminance of the roadway surface

3.3. Simulation of Veiling Luminance

Disability glare refers to a symptom caused by light scattering within the human eye causing a reduction in contrast perceiving capability. The haze projected to the retinal image lowering the detectability of edges and thus the understanding of visual information is commonly referred as veiling luminance. By IES RP-8-14 and IES RP-8-2000 based roadway lighting designs the calculation of this parameter is the direct measure of glare, while in CIE 140 and EN 13201 based calculations further utilize this parameter in the calculation of Threshold Increment (TI).

Veiling Luminance in roadway lighting design is the luminance superimposed over the eye's retinal image produced by stray light within the eye for the defined standard observer. In the EN method, L_v is computed along a single row of calculation points directly in front of the observer position. By default, the distance of the observer to the first lateral row of computation points in the grid is:

$$d_0 = 2.75 * (MH - 1.5)$$

Where MH is the mounting height. The horizontal alignment is justified to 1/4 of road width from the curb line. View orientation is 1° below horizontal. The maximum value of L_v is used to compute the relative Threshold Increment (TI).

The aim of simulating veiling luminance in a Virtual Reality environment is to model the contrast decrease for the observer by elevating ambient light level and this way decreasing edge contrast ratio to overall brightness.

The reduction of visibility is in line with the disability glare, whereas the most commonly used formula originates to [Fry] back to 1954 [7].

$$L_V = 9.2 \sum_{i=1}^{n} \frac{E_i}{\theta_i(\theta_i + 1.5)}$$

Where Ei is the illuminance from the ith glare source and θ is the angle between the viewing direction and the glare source. Other models were also evaluated, including Stiles-Holladay, Adrian and Vos [5].
This effect is exhibited in Luminance Contrast:

$$C = \frac{L_t - L_b}{L_b} = \left(\frac{(L_t - L_V) - (L_b + L_V)}{L_b + L_V}\right) = \frac{L_t - L_b}{L_b + L_V}$$

Where L_t is the Target luminance in [cd/m2] and L_b is the corresponding background luminance in [cd/m2]. Figure 8 explains the effect of contrast loss due to veiling luminance [8]. The localized scattering around the luminance hot spots is well represented in these edited images but still, it is to mention that the actual perceived effect varies from observer to observer – age being a primary variable in the visual perception.

Figure 8: Visualization of Veiling Luminance

Relative Threshold Increment (TI) is intended to cover this term in a generally applicable system by providing a measure for disability glare produced by a lighting installation that is always derived from the lighting system and is not a parameter of a luminaire. The unit of measure for TI is the percentage increase in the luminance of the road surface required in order to render an object just visible – that being the threshold of visibility – under the lighting system with glare present as compared to the luminance required to render the object just visible by the absence of glare. It is to be noted that the calculation in EN slightly differs from the CIE 150 method. Neither the less, none of these approaches consider the area of effect and extent of glare, reducing visibility on the retinal image.

3.4. Design of Experiment for Disability Glare

While there are existing models for representing disability glare in rendered images, using these in the specific Virtual Reality device caused questionable results. The goal defined is the project scope was to converge the detection time of obstacles in the virtual world to the results of a test group while the model is to be open for parametric modifications with more test subjects result available.
It was found that the luminance of the screen of the Virtual Reality headset was not sufficient to achieve glare in any sort for the user, the application of a simulated veiling luminance was necessary. There have been three factors in the design of experiment (DoE) for aligning the virtual world obstacle detection times to the results summarized in [9].

The veiling luminance of a glare source was modelled as a Weibullian probability density function of brightness super-positioned to the rendered image. It was used for high calculation speed on GPU and easy characterization. Factors were:

- Peak Intensity
- Width
- Shape factor

The general equation was formed as:

$$L_{vl} = \sum_{i=0}^{glare\ sources} \frac{k}{\gamma}\left(\frac{d}{\gamma}\right)^{k-1} e^{-(d-\gamma)^k}$$

$$k \in [0,1]$$

Where d is the distance from the glare source expressed in density independent pixels, k and gamma are the shape parameters.

Figure 9. shows a sample scene rendered for three different light sources as indicated on the polar intensity diagrams below, with two different shape parameter set (top row, middle row). The DoE gave the best aligning results (top row images) with:

$$k = 0.7813$$

$$\gamma = 0.9111$$

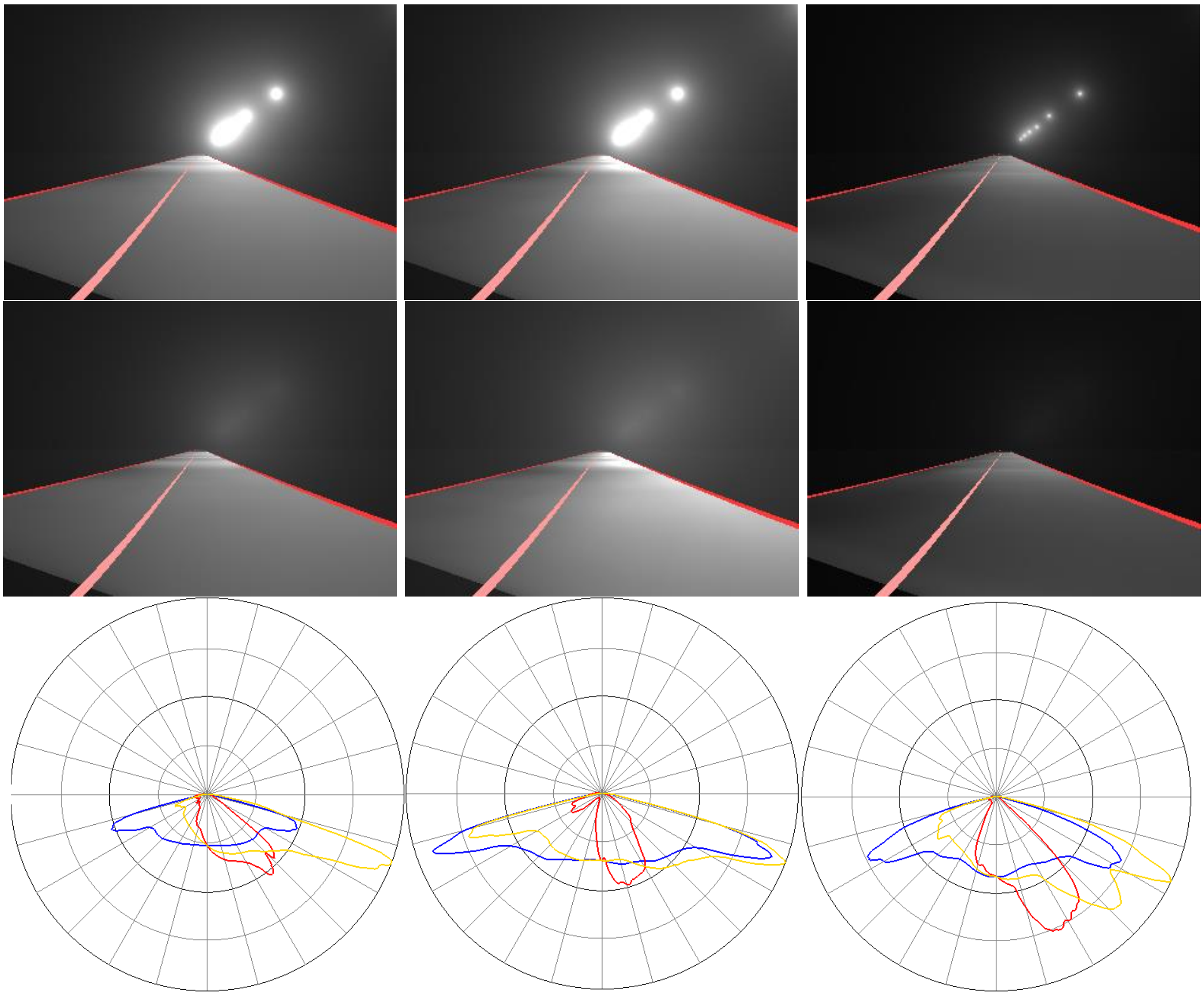

Figure 9: Comparison of different glare models with three luminous intensity distributions

3.5. Scattering Effect and Reflection over the windshield

Until this point in this paper, all the simulations of luminance were calibrated to reproduce actual luminance measurements in a Virtual world while glare was aligned to driver experience. This approach does not implement neither the scattering effect on the windshield nor the reflection of the dashboard over the windshield to the observer. This first effect is similar to Veiling Luminance from a far field object while the latter is very in par with the contrast decreasing effect of disability glare, often called Veiling Glare.
It was found that moisture on the windshield increases the reaction time to certain obstacles on the roadway. The investigation of this effect is underway and is not in the scope of this paper. As for the current state of the developed application, there is a texture map on the windshield with a slight degree of pollution that is bright where glare sources are present in the field of view and dark farther away. The exact function of brightness to distance is empirical at this point.
Figure 10. shows an example for the visible particles on the windshield and for the reflected dashboard and its effect on perceived contrast. While the dirtiness is more undesired with higher luminous intensity from the glare source towards the vehicle and becomes obvious with high average luminance of the roadway, the reflection of the interior is more of a problem with installations having good luminous intensity class (EN 13201 G Rating). This is due to the higher luminous intensity in the nadir region of the luminaire being reflected while – as it was shown – average luminance is lower.

Figure 10: Scattering and reflection on the windscreen

3.6. Simulation of Dashboard Luminance

As some key perception parameters of a lighting installation is to be evaluated in terms of the actual scene, an important element to be included is the actual view from behind the wheels. Obviously this varies case to case by varying vehicle manufactures and is thus not standardisable in this form. In the introduced software, the interior of the author's daily use automobile was used and measured with luminance meter among with known lighting scenarios.

3.7. Further TODOs

As per current state, this introduced system is semi-capable of representing real world lighting conditions and was used as a zero impact design support tool for a recent LED lighting installation. In order to improve the weight of impression in decision making, the representation of a scene needs to be more accurate. Subcomponents to be included are:

- Head motion tracking, as so far only rotation is implemented
- Optimization of glare and veiling luminance
- Inclusion of some sort of environment will be essential and re-running experiments will be necessary for a better understanding of glare in Virtual Reality.
- Higher resolution is found to be always beneficial. Antialiasing might improve visual clarity
- Proper optical simulation of the cockpit would be necessary for appropriate design evaluation

- Extension of the lighting design analysing counter beam headlight glare effect would be possible. This would strongly bias the impression of a lighting installation by favouring higher average luminance in the field of view over glare restrictions.
- Advanced texturing of the tarmac and bump mapping / normal mapping on the surface will be essential based on feedbacks provided

4. Lighting design in VR

While optimizing a lighting design in Virtual Reality, there are a number of parameters that are first observed as an impression. Most of these can be parametrized with mathematical formulae and ray-tracing. Figure 11. shows a scenario where the negative contrast of a tarmac damage is hardly visible even for a young observer (left, false colour luminance mapping) and a situation where the negative contrast of a human sized dark obstacle generates optical stress for the rapid contrast density (right, true colour rendering).

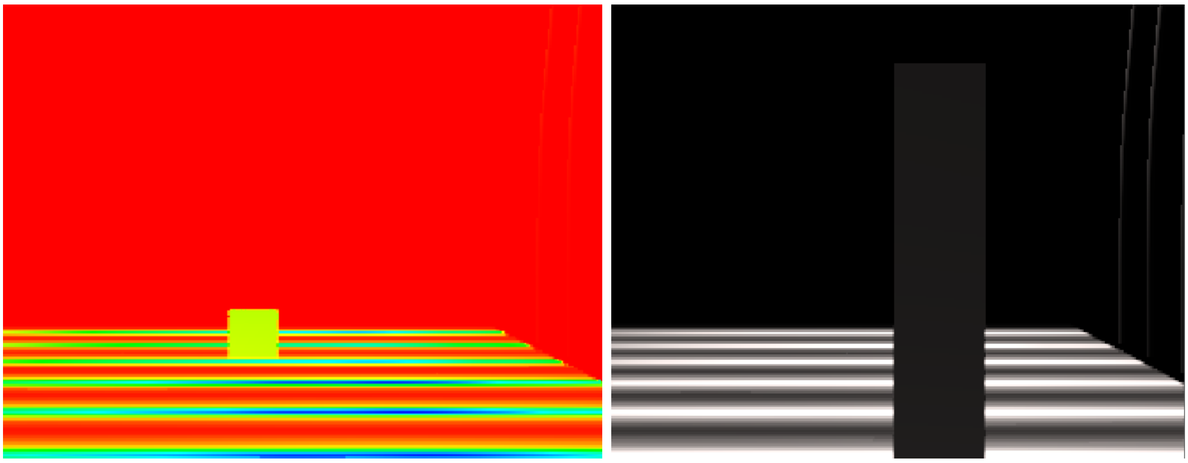

Figure 21: Luminance perception model

This latter example is demonstrated with a 60° Field of View on Figure 12. Only the bottom part of the obstacle generates contrast and thus it is challenging to estimate spatial extent, speed and distance for the driver.

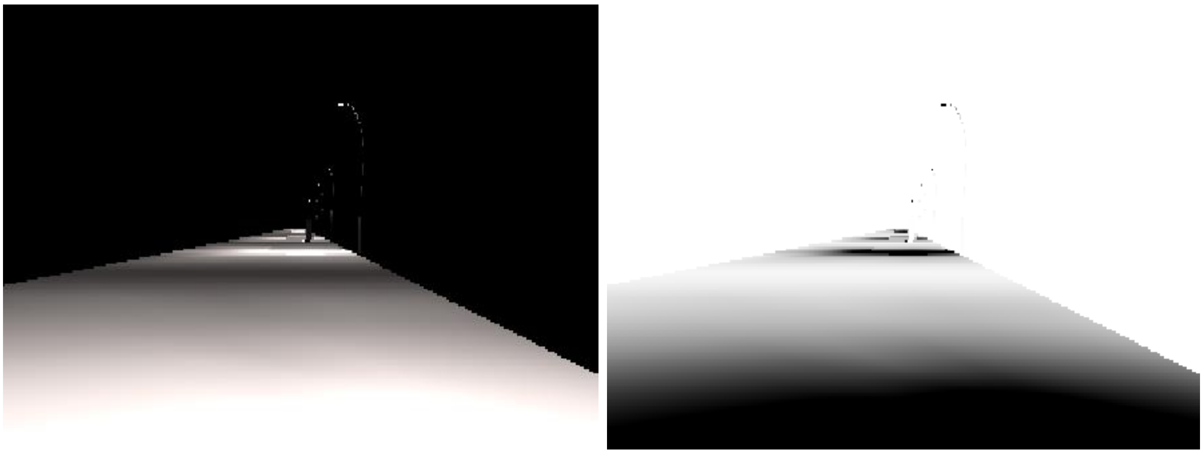

Figure 32: VR impression and its false colour luminance representation

5. Conclusions

Roadway lighting design in Virtual Realities proposes some very interesting applications with the widespread use of LED technology. Practice shows that the existing methods for designing an installation are outdated for the highly directional luminous intensity forming capabilities of modern

luminaires. Manufacturers are able to optimize custom optics for lighting scenarios that abuse EN 13201 metrics for inadequate energy savings while meeting requirements.
On the other hand, the main goal of an outdoor lighting design is to prove the validity of certain products in an installation using commonly agreed calculation methods – as of meeting the basic requirements of safety and the impression of safety for individuals involved in traffic. While the metrics introduced and the general feeling obtained using the developed Virtual Reality technology is not agreed by any authorities to override standard calculation methods; it serves the very same purpose as a genuine lighting design and may serve important information for decision-making, especially for LED roadway lighting projects.

6. References

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