The dynamic range of driving simulation

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Keywords : Driving simulation; Visual Perception; Visual Performance; HDR display; Tone Mapping; Computer Graphics.

1 Introduction

Driving simulation has become a quite common virtual reality tool, addressing various fields such as video games, vehicle design, driving lessons, and behavioral studies (Fisher et al., 2011). As in other fields of virtual reality, driving simulator providers have developed a number of visual effects, in order to render a variety of environmental situations. For instance, night driving, rain, fog and glare can be simulated taking state-of-the art techniques from Computer Graphics (CG) literature in order to mimic either a physical phenomenon (e.g. photometry in automotive lighting) or its effect on the driver perception (e.g. fog), and in order to minimize the perceptual gap between the displayed image and the computed image, with Tone Mapping Operators (Reinhard et al., 2005). According to Andersen (2011), some visual factors are critical for the external validity of driving simulations (i.e. validity with respect to actual driving). He emphasizes luminance and contrast as the most important visual factors for the main critical driving situations: night driving, rain, fog, and complex urban environments.

In this context, High Dynamic Range (HDR) rendering and display may improve the realism of a number of visual cues relevant for driving. However, the implementation of CG algorithms is not straightforward, and a tradeoff is needed between cost (financial and computational), performance, and market (or user) demand. Moreover, in many driving situations, the driver's visibility is good, and looking at the relevant visual cues is easy, both in real and virtual environments. In these situations, the benefit of HDR images is often seen as too low, considering the associated costs and constraints.

In this chapter, we discuss to what extend HDR rendering and display has improved, or can improve driving simulators, and why HDR has not invaded the field yet. We will focus on driving simulation as a tool for

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behavioral studies; automotive design is considered in another chapter of this book.

Section 2 give some evidence that HDR issues are not considered in most current driving simulator studies, even in vision-demanding situations. Then, we argue (section 3)that some low-level visual factors, relevant for driving, are photometry-dependent, and thus should benefit from a real-time HDR imaging and display system. After a short discussion in section 4 about HDR rendering and display issues in computer graphics, Section 5 reviews the few existing driving simulation studies where photometry and HDR components have been considered, and discusses what kind of realism is now available, or will be in the near future, in terms of realism, either physical, perceptual or functional (Ferwerda and Pattanaik, 1997), and what for. This includes a small number of simulations using a true HDR display device. We conclude (section 6 by discussing the reasons why HDR has not invaded the field of driving simulation yet: it is interesting, to our sense, to better understand the obstacles in order to push the development of HDR rendering and display with a better efficiency. We also propose some technical and experimental perspectives, towards a more intensive development of HDR video for driving simulations and vision science issues relevant in driving situations.

2 No need for HDR video in driving simulations?

It is not to say that driving simulator developers don't care about rendering issues. For instance, some level of realism may be important in videogames (you ought to be state-of-the art, with respect to the videogame market), and improves the driver's sense of immersion. But perceptive realism is only needed when visual performance or visual appearance issues arise, such as at night, in low visibility situations, or in complex situations where the visual saliency of objects in the scene may attract the driver's visual attention (Hughes and Cole, 1986), and needs to be carefully simulated if one wants the driver's visual behavior in the simulator to be similar to a real driver's behavior.

This is the main point: perceptual realism is not a key issue in mainstream applications. For instance, in a recent review about the driver's visual control of the vehicle's lateral position (Lappi, 2014), low visibility conditions are not even mentioned. Only a few people around the world are concerned with visual performance or visual appearance in a car: first because it helps for the vehicle design (see chap. 19 of this book), second because it is needed for behavioral realism in driving situations where visual perception is a complex task (Brémond et al., 2014).

Night driving is a good example of a driving situation where both high and low luminance levels are expected to appear, leading to a high luminance range. Automotive and road lighting sources may appear in the field of view (with luminance values up to 25 10^9 cd.m^{-2} with Xenon automotive lighting), while dark areas at night are in the mesopic range (below 3 cd/m^2), and may be in the scotopic range in some areas (below 0.005 cd/m^2), where the Human Visual System behavior and performance are different from what happens in the daylight photopic range (CIE, 2010, 1951).

Evidence show that visual performance lowers when driving at night (Owens and Sivak, 1996; Wood et al., 2005), and some among those performances (labeled as *focal vision*) are more impaired than other (*ambient vision*) (Owens and Tyrrell, 1999). Moreover, usual Low Dynamic Range (LDR) display devices cannot display scotopic and low mesopic luminance values, nor glaring lights. Thus, one would expect night-time driving simulation to carefully consider illumination issues, glare, and take advantage of HDR rendering and display. But this is not what happens. For instance, it is striking that in their review of perceptual issues in driving simulations, Kemeny and Panerai (2003) did not even mention driving at night as an issue.

Considering the number of driving simulation studies in the last 15 years, the number of published studies which include a night driving condition is unexpectedly small, and to the best of our knowledge, around 30 (see also Wood and Chaparro (2011)). Moreover, available night-time simulations almost never provide any detail about the technical settings or performance of the night-time condition. For instance, the *Material and method* section of the papers will not even mention night driving (Panerai et al., 2001) or will offhandedly state that “The main part of the evaluation consisted of eight spells of driving, featuring different combinations of lighting condition (day/night)” (Alexander et al., 2002). Interestingly, most of these studies have been published in medical and biological journals (Gillberg et al., 1996; Banks et al., 2004; Campagne et al., 2004; Contardi et al., 2004; Pizza et al., 2004; Åkerstedt et al., 2005; Silber et al., 2005; Schallhorn et al., 2009), and address hypo-vigilance and drug use issues. In a few papers, the lack of information about night driving settings is mitigated by a Figure showing the visual appearance of the night driving simulation (Konstantopoulos et al., 2010; Schallhorn et al., 2009); this somehow enforce the feeling that experimenters have a low level of control over illumination issues. This also appears in a series of driving simulation experiments at night, where the ambient luminance is controlled using neutral density filters (Alferdink, 2006; Bullough and Rea, 2000) or goggles (Brooks et al., 2005) in daylight simulated scenes (the “day for night” cinematographic technique), at the cost of unrealistic visual environments.

This lack of reported technical or photometric details also occurs with fog. For instance, in an important driving simulation study published in *Nature* (Snowden, 1998), showing that speed perception is altered in fog, little information was available about the simulated fog. Indeed, in most papers reporting driving simulator studies in fog (Saffarian et al., 2012), no information is given about the fog density; no technical information is provided either, and one is left to guess that the simulator use openGL fog, that is, a contrast attenuation associated with the object's distance. This means that a minimal model of fog is deemed acceptable, as we have seen for night simulation; it is possible, indeed, with OpenGL, to fit the physical law of contrast attenuation in fog (Koschmieder's law, see Middleton (1952)), however no information is given in this respect in the above papers. For instance, Broughton et al. (2007) compared the driver's behavior in three visibility conditions: two fog densities are compared with a no-fog condition. The fog conditions are described in terms of "visibility limit", which probably means that the authors used a non-physical tuning of the OpenGL fog. Moreover, simulating artificial lighting (automotive lighting, road lighting, etc.) with OpenGL is rather complex (Lecocq et al., 2001).

3 Visual factors which impact the driving behavior

Meanwhile, it is a common knowledge that vision is the main sensory channel to collect information while driving (Allen et al., 1971; Sivak, 1996), and in a driving simulator, CG images are supposed to provide the driver's visual information.

The link between the displayed images and driving behavior is not direct, it is mediated by notions from vision science, such as luminance and contrast (Andersen, 2011), the visibility level (Adrian, 1989; Brémond et al., 2010b), the adaptation luminance (Adrian, 1987a; Ferwerda et al., 1996), motion, distance and speed perception (Snowden, 1998; Cavallo et al., 2002; Caro et al., 2009), scotopic and mesopic vision (Gegenfurtner et al., 1999), glare (Spencer et al., 1995), or the visual saliency of the relevant/irrelevant objects in a scene (Brémond et al., 2010a), such as road markings (Horberry et al., 2006) and advertising. These visual factors first impact the visual performance, and then the driving behavior. These are photometry-based concepts, and were not controlled in the above-cited driving simulator studies.

For all these issues, a photometric control of the images is mandatory. In some cases, a High Dynamic Range display may be needed, or alternatively, tone mapping operators may help minimizing the gap between ideal and displayed visual information. For instance, road lighting design needs some criterion, and the Visibility Level (VL) has been proposed as the visibility for the driver of a reference target, on the road (Adrian, 1987b). The American standard includes this concept in the Small Target Visibility assessment of road lighting (IESNA, 2000), and the French standard also includes this VL index (AFE, 2002).

In order to assess an operator's quality, one needs some quality criterium. It is not so easy, and for instance, the correlation is weak between visual appearance, visual performance and visual saliency in an image (Brémond et al., 2010b), so that some choice is needed. In previous evaluations, visual appearance was considered first in most benchmarks (Eilertsen et al., 2013).

While visibility is considered by practitioners as a key perceptual issue in night driving, is it possible to preserve the visibility level of objects with a TMO? Some authors have proposed operators in order to control some kind of visual performance (Ward, 1994; Pattanaik et al., 1998), and Grave and Brémond (2008) proposed an operator focusing on preserving the VL. For dynamic situations, Petit and Brémond (2010) proposed a TMO preserving visibility, based on Irawan et al. (2005) and Pattanaik et al. (2000). So some effort have been done in order to design Tone Mapping Operators shaped by visual performance constraints. On the other hand, the main effort in TMO design has been devoted so far to appearance criteria, such as color appearance and lightness perception, rather than visual performance criteria.

4 HDR rendering

High Dynamic Range issues have a specific flavor in Computer Graphics. The split between image computation and image display is also relevant, but the problems are not the same. First, using HDR virtual sensors for HDR image computation is now possible, since GPUs can manage `float` values. The main constraint is to run in real-time, rather than sensor design or noise issues. Indeed, it is possible with pixel shaders to allocate some sensitivity to the virtual sensors (that is, computing the CG images in `float` units), even if the image computation does not simulate light propagation in the virtual scene in physical units.

The figure is quite different for HDR image display. HDR display device are now available, since Seetzen et al. (2004) demonstrated a prototype of a High Dynamic Range display device at SIGGRAPH in 2004 (see part IV of this book for an update on HDR display). Commercial HDR display devices are now available based on Seetzen's ideas (first from Brightside, now from Dolby). But this technology is still very expensive, compared to conventional displays, and as a results, HDR display devices are very rare in Human Factors laboratories.

An important issue for driving simulators is that a large Field of View (FoV) is often needed, which is almost impossible to address with existing HDR display devices. For instance, most low-cost driving simulators use 3 displays, and in many driving situations, a field of view of 150° is needed (for instance if you have to cross an intersection). Virtual Reality helmets can be viewed as an alternative, as far as the field of view is concerned, but

HDR displays are not available for these devices at the moment.

So the 8-bit frontier is still hard to cross for driving simulator's display, and the Computer Graphics pipeline, which is expected to link the rendering part to the display part of the loop, tends to use Tone Mapping Operators in order to overcome the lack of HDR displays. As we have mentioned above in the case of visual performance preservation, this led to a number of TMO (see Reinhard et al. (2005)), followed by some concerns about the evaluation of these operators.

What would be a good design criterion for a TMO dedicated to driving simulation? Real time is mandatory. Second, temporal fluidity is needed, in order to avoid rapid change and oscillations in the visual adaptation level, which may be due to a light source appearing in (or leaving) the field of view (Petit et al., 2013). This can be done by simulating the time course of visual adaptation (Pattanaik et al., 2000). Third, as we have emphasized above, fidelity in terms of visual performance (rather than visual appearance) is relevant in most driving simulation applications, because the main goal of driving simulation experiments is the study of the driver behavior, which in turn depends on the visual cues he finds in his environment.

5 Photometric control of CG images in driving simulations

Maybe the reader found this chapter, up to now, a bit pessimistic about the success of an HDR approach in driving simulation. The picture should be mitigated however, and it is worth mentioning some papers where the photometric tuning of night driving simulations is taken seriously. The first one, to our knowledge, is from Mortimer (1963), with a very special driving simulator however: at that time, in 1963, there was no Personal Computer available, and the simulator was purely electro-mechanical. In the Computer era, Featherstone et al. (1999) conducted a field study, collecting reference data about car's headlights at night, and tuned the rendering of the simulator in terms of contrast, color and luminance[1]. Kemeny and his team, at the Renault Virtual Reality center, conducted several studies focusing on the simulation of automotive lighting (Dubrovin et al., 2000; Panerai et al., 2006), based on a simulation of light propagation, projecting lightmaps from the headlamps to the road surface (see also Weber and Plattfaut (2001)). Horberry et al. (2006) and Brémond et al. (2013) put some effort in controlling the photometry of the rendered images of night driving, which makes sense because these papers address road marking and road hazard visibility, respectively.

[1]Considering the available display devices at that time, it is unlikely that they could tune the luminance range to glaring situations, as they suggest in their paper.

At night, glare is a key issue, as usual displays cannot produce a glare sensation. To overcome this problem, Spencer et al. (1995) have proposed a biologically inspired algorithm which simulates the effects of glare on vision (bloom, flare lines, lenticular halo) in CG images. Some technical solutions have also been proposed to simulate fog with controlled photometry, with a display calibration and a physical OpenGL tuning (Cavallo et al., 2002; Espié et al., 2002), and the simulation of halos around light sources (Lecocq et al., 2002; Dumont et al., 2004). The main issue with fog is contrast attenuation, rather than luminance values.

In addition, many driving simulator developments have not been published, because they are conducted by industrial firms which do not want to make their internal development public. They communicate however about HDR issues, and HDR rendering is mentioned in technical documents of some driving simulation software. For example, SCANeR HEADLIGHT Interactive Simulation (Oktal, 2015) supports HDR rendering for realistic night drive experiments. Note that the OKtal software is widely used by automobile companies in France (e.g. Renault, Valeo, PSA). In Germany, VIRES also supports HDR rendering (VIRES Virtual Test Drive software) (Vires, 2015). HDR rendering is also mentioned among OpenDS features (Math et al., 2013; OpenDS, 2015), a recently developed open-source driving simulator, which is originated from of the FP7 EU-project GetHomeSafe (GetHomeSafe, 2015). Some details of these technical developments are sometimes published, as in the case of Pro-SiVICTM , a software developped by CIVITEC, where HDR textures are used in the sensor simulation for Advanced Driver Assistance Systems prototyping (Gruyer et al., 2012). Optis is also active on HDR issues, with the SPEOS software and the Virtual Reality Lab (Optis, 2015).

The direct use of HDR display device in driving simulations is still in its infancy. Recently, Shahar and Brémond (2014) were the first to use a true HDR display device (47' Dolby/Sim2 Solar), under photometric control, in order to conduct a driving simulation where night driving behaviors with and without LED road studs were compared. The automotive lighting, road lighting and LED road stud photometry were tuned to realistic values, using direct photometric measurements of the road surface, the road markings and the LED themselves on the screen.

The main issues was to run in real time, with three screens (1920×1080 pixels). The geometric configuration of the simulator was chosen in such a way that when the road studs were switched ON, they were very likely to appear in the central screen, so that it was decided to run the simulation with one HDR display device in front of the driver, and two LDR display devices, on each side of the driver. The main purpose of these lateral screens was to give the driver some sense of his own speed.

Several technical challenges needed to be addressed, among them the number of light sources and the lighting simulation itself (Dang et al., 2014).

The IFSTTAR visual loop, developed under Open Scene Graph, supports two HDR renderings: one originated from TMO proposed by Petit and Brémond (2010), the other adapted from a TMO proposed by Reinhard et al. (2002). Since a thousand of road studs were required in this study, a particular way of controlling the light sources was adopted to guarantee a high level of frame rate, a key issue in real-time simulations. Each light source was simulated based on the photometric characteristics of real LED road studs, as measured in the Ifsttar photometry Lab; their intensity was made dynamically controllable during the simulation. The LED road studs were divided in groups, each of them being controlled by a virtual group manager. This organization was particularly useful in this study, since the road studs were turned on/off automatically by these group managers depending on the vehicle's position. Another challenge was the simulation of a realistic night driving conditions with high luminance range, with bright areas due to the studs, the road lighting and to the headlamps of incoming vehicles, while very dark areas were also needed in the nighttime countryside landscape.

This experiment used a HDR display device, however with 8-bit (LDR) input images from the driving simulation visual loop. Thus, the benefit of the HDR display was the luminance dynamic, not the luminance sensitivity. The next challenge will be to develop a full HDR driving simulator visual loop, and feed a HDR display device with HDR videos.

6 Conclusion

This rapid overview of the potential benefits of HDR rendering and display for driving simulations leads to a balanced conclusion. On the one hand, dynamic range is marginally addressed in current driving simulation studies. The main reason is that the expected benefits of HDR are associated to low-level vision issues. Although they are known to have an impact on the driver's behavior, this impact is limited to some specific situations, such as night and fog driving, or drivers with low vision.

Whereas a smart tuning allows some qualitative control of the visual appearance in virtual environments, in quantitative behavioral studies there is a need for some photometric control of the displayed images. This includes physical, optical and photometric data about light sources, participating medias and surfaces.

Of course, another reason for the limited interest for HDR in the driving simulation community depends on the cost, in a cost-benefit approach. A photometric description is important for HDR imaging, at some cost: photometric description of the virtual environments, need for photometric data for surfaces and light sources, real-time issues, etc. Not to mention HDR display, which is still very expensive, uneasy to use with current video output formats, and seldom required, even in night-time driving simulations published in peer-review journals. Also, most of the tone mapping literature (both TMO and on TMO evaluation) focuses on appearance criteria (subjective fidelity, etc.), not on performance criteria (visibility, Reaction Time, etc.) which would be needed for driving simulations in low visibility conditions.

But there is another side of this story, and we have tried to show that in some important cases, the control of image photometry allows to expect a much better fidelity between Virtual Reality and actual driving, in terms of "Where do we look?" and "What do we see?". This, in turn, is known to impact the driving behavior. Thus, HDR imaging, rendering and display open the way to new driving simulation applications, to situations where the external validity was poor in previous studies: photometric parameters were known to impact the behavior, but they were not controlled.

This is why we plan, in the near future, to conduct experiments to assess the influence of an HDR display device on psychovisual and driving tasks. To that purpose, the impact on specific perceptive mechanisms underlying the driving behavior on a driving simulator will be compared, first on a LDR display (that is, HDR imaging followed by a TMO), then on a HDR display.

For instance, the contribution of an HDR display device on speed perception will be assessed in a driving context. This can be done by estimating the "time-to-collision", using moving stimuli on both kind of display devices. As the perceived speed is expected to depend on the luminance contrast Stone and Thompson (1992); more specifically, at low contrast or at night, the perceived speed of an object is underestimated (Blakemore and Snowden, 1999; Gegenfurtner et al., 1999). Thus, it can be assumed that this bias is closer to the real one with a HDR display device compared to a LDR. Therefore, using HDR display device may allow investigating reduced visibility situations such as nighttime driving or glare. More broadly, a benefit is expected when conducting driving simulation studies on an HDR display device when speed perception is a key figure (either the driver's own speed or the speed of other vehicles), especially in reduced visibility situations.

New lighting systems (signaling, lighting, headlamps beams, stop lights) may also benefit of HDR driving simulations. This was done, for instance, to study the impact of a motorcycle's lighting design on its perceived speed (Cavallo et al., 2013), as well as for the driver's behavior facing a new concept of dynamic signaling with LED road studs (Shahar and Brémond, 2014).

7 Acknowledgment

Special thanks to David Callu, Fabrice Vienne & Eric Dumont, for their helpful advices on this manuscript.

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